Material System Analysis of Nine Raw Materials: Barytes, Bismuth, Hafnium, Helium, Natural Rubber, Phosphorus, Scandium, Tantalum and Vanadium

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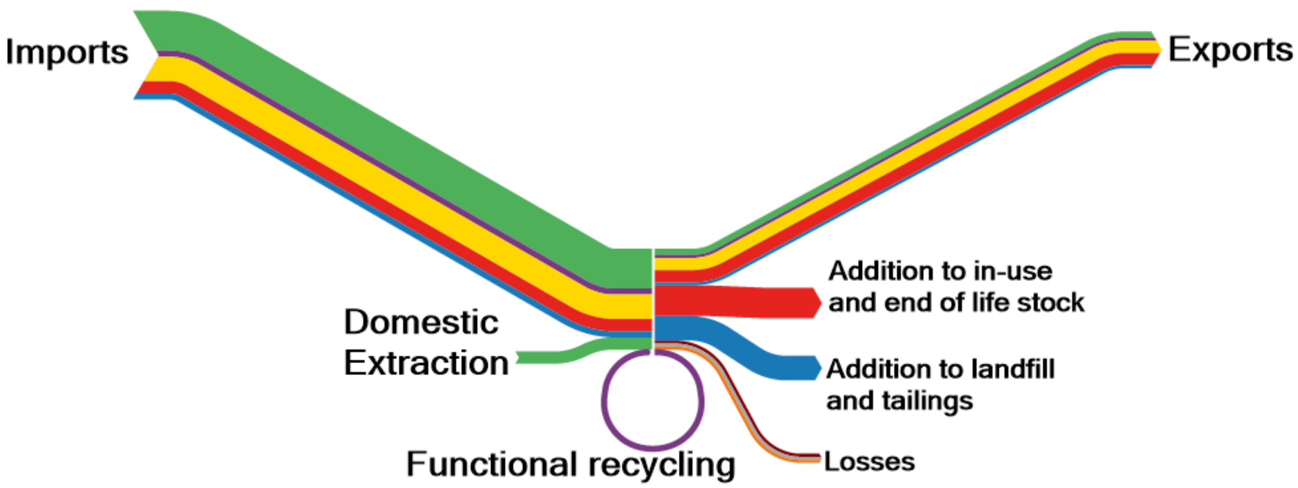

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Contributions of the authors:

- Cristina Torres de Matos coordinated the work, led the MSA for natural rubber and elemental phosphorus, reviewed all the MSA studies and compiled the report;

- Chloé Devauze and Mariane Planchon led the MSA for barytes, bismuth, vanadium and tantalum;

- Dominic Wittmer led the MSA for scandium and reviewed the MSA of hafnium and vanadium;

- Birte Ewers, Andreas Auberger and Monika Dittrich led the MSA for hafnium and helium;

- Cynthia Latunussa helped in the development of natural rubber and elemental phosphorus MSA and reviewed the MSA of barytes, helium and tantalum;

- Umberto Eynard reviewed the MSA of bismuth and the report;

- Fabrice Mathieux supervised the work and reviewed the report.

Abstract

Consistent information on raw material value chains is key for sustainable resources management, to guarantee supply of raw materials and strengthen the EU industry competitiveness. The European Commission launched the development of Material System Analysis (MSA) studies in 2015, to assess the flows of materials through the EU economy, including extraction, stock accumulation and end-of-life management e.g., through disposal or recovery in the EU. The MSA studies consider the entire life cycle of a selected material. This highlights hotspots and bottlenecks in a material value chain. Awareness of weak points in the value chain can guide actions designed to increase the resilience of the supply chain, also in the face of disrupting events. MSA, by virtue of accounting for materials in stock, can also help identifying opportunities to source materials from urban mine or waste streams, allowing to improve the overall circularity of the EU. The systemic view of the MSA also lends itself to develop and support scenarios and outlooks.

The current report includes the MSA for the raw materials: barytes, bismuth, hafnium, helium, natural rubber, elemental phosphorus, scandium, tantalum and vanadium. These materials have been or are considered critical raw materials in the EU.

The materials cycles analysed show a very strong dependence on imports along the value chain. The EU is highly dependent on imports of primary materials and intermediate products and has a consolidated manufacturing stage for all the materials analysed (except for helium).

The EU is efficient in collecting end-of-life products, however most of the targeted materials are lost due to in-use dissipation, non-functional recycling, or disposal in other waste streams. This indicates that the EU is not yet able to decrease its dependency of primary material using secondary materials domestically recycled. However, for some materials (e.g. elemental phosphorus) significant efforts are undertaken to change this situation in the future to improve the EU circularity.

The developed MSA are comprehensive datasets that may provide crucial knowledge to help the development and monitoring of EU polices including: the EU list of Critical Raw Materials, the new EU Industrial Strategy, the Green Deal transition plan, the EU Raw Materials Initiative and the EU Circular Economy Action Plan.

1 Introduction

Critical raw materials are raw materials that have both a high economic importance and a high supply risk. In 2011, the European Commission published its first list of critical raw materials, which is updated every three years. (European Commission, 2011, 2014, 2017a, 2020). The Commission put an action plan in place to increase the resilience of their supply chains, by 1) stimulating their domestic production; 2) enhancing their efficient use and recycling; 3) diversifying sourcing from 3rd countries. Additionally, the EU Green Deal (European Commission, 2019) and the EU industrial strategy clearly highlight the need for unhindered access to raw materials, in particular of critical raw materials that are necessary to key priorities of the EU policies such as low carbon technologies, digital, space and defence applications.

In order to ensure sustainable resources management of these raw materials, consistent information on their value chains is key. In the context of the EU Raw Materials Initiative (European Commission, 2008) the European Commission launched the development of Material System Analysis (MSA) studies in 2015 (BIO by Deloitte, 2015). An MSA is an assessment of the flows of materials through the EU economy, including extraction, stock accumulation and end-of-life management e.g., through disposal or recovery in the EU. The MSA studies consider the entire life cycle of a selected material which is crucial for developing sound sustainable resource management strategies.

A MSA highlights hotspots and bottlenecks in a material value chain. Awareness of weak points in the value chain can guide actions designed to increase the resilience of the supply chain, also in the face of disrupting events. MSA, by virtue of accounting for materials in stock, can also help identifying opportunities to source materials from urban mine or waste streams, allowing to improve the overall circularity of the EU (European Commission, 2020c). The systemic view of the MSA also lends itself to develop and support scenarios and outlooks.

The first series of 28 MSA was published in 2015 (BIO by Deloitte, 2015), a second series covering three materials in 2018 (Passarini et al., 2018) and in 2020 five MSA were developed for battery related raw materials (Matos et al., 2020).

The focus of this report is on nine raw materials that entered the list of critical raw materials in 2017. The current report includes the MSA for the raw materials: barytes, bismuth, hafnium, helium, natural rubber, elemental phosphorus, scandium, tantalum and vanadium.

The report describes the main findings of the MSA studies, using a consistent structure. Chapters 2 to 10 are summaries of the MSAs studies for the nine raw materials, while chapter 11 draws conclusions on these nine MSAs. Each MSA summary is composed of: 1) a description of the material supply chain highlighting the stages where the EU has productive capacity and those where the EU is dependent from external sources; 2) a summary of the main MSA results in terms of stocks and flows, which includes a distribution of the end uses in the manufacturing stage and use stage, and a visualisation by a simplified Sankey diagram; 3) a set of indicators that translate the material situation for the EU, in terms of recycling, collection rates and self-sufficiency of the EU; 4) a section describing the main sources of information and assumptions.

1.1 MSA methodology

The MSA methodology was developed and published for the European Commission with an EU scope in 2015 (BIO by Deloitte, 2015) and has been revised in 2020 (Torres de Matos et al, 2020). The MSA applies the basic principles of Material Flow Analysis (MFA) on the EU economy, namely the systems approach and the mass balance (on system and process level).

MSA maps and quantifies raw or advanced materials along their overall life cycle in the European Union, including: extraction, processing, manufacturing, use, collection, recycling, reuse and disposal. Additionally, it includes relevant material stocks in: tailings; landfills; products in the use phase, domestic reserves, and foreign reserves (see blue boxes in Figure 1)

Figure 1 shows the MSA system, which visualises the flows and stocks considered in an MSA. They are listed in Annex 1.

In comparison with the MSAs performed in 2015 the updated MSA methodology increases the resolution of the MSA system as described in (Torres de Matos et al, 2020) and presented in Figure 1

The indicators used to characterise the situation of each material in the EU are the following:

Table 13. Different indicators that describe the material situation in the EU.

Indicator	Formula
End-of-life recycling input rate (EOL-RIR)	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)
End-of-life recycling rate (EOL-RR)	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)
Collection Rate	F1.4/(M4.1)
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)
Self-sufficiency Processing	C1.1/M2.1
Self-sufficiency Manufacturing	D1.1/M3.1

1.2 Approach followed by the project team

The MSA of each individual material were performed according with the following distribution between experts and the JRC (see Table 14). The JRC coordinated the work done, reviewed each MSA and assembled the current report.

Table 14. Distribution of the MSA studies between the experts involved in the work

Raw Material	Author
Barytes	Chloé Devauze, Mariane Planchon from In Extenso Innovation Croissance
Bismuth	Chloé Devauze, Mariane Planchon from In Extenso Innovation Croissance
Hafnium	Birte Ewers, Andreas Auberger, Monika Dittrich from Ifeu Heidelberg
Helium	Birte Ewers, Andreas Auberger, Monika Dittrich from ifeu Heidelberg
Natural Rubber	Cristina Torres de Matos from JRC
Elemental Phosphorus	Cristina Torres de Matos from JRC
Scandium	Dominic Wittmer from JRC
Tantalum	Mariane Planchon and Chloé Devauze from In Extenso Innovation Croissance
Vanadium	Chloé Devauze, Mariane Planchon from In Extenso Innovation Croissance

The MSA studies draw on five consecutive reference years, from 2012 to 2016. For natural rubber and elemental phosphorus, the dataset includes also the years 2017 and 2018. The geographic coverage of the studies was the EU (without the UK). Priority has been given to official and publicly available data sources. However, for some materials information was collected from stakeholders in the validation workshops. This report summarises for each material the flows and stocks of the year 2016, except for natural rubber and elemental phosphorus that reports the 2017 dataset and vanadium that reports 2015 dataset. For Vanadium, the year 2016 was considered atypical due to the collapse of the main primary vanadium-slag supplier.

The detailed calculations and the results for the full period covered (2012-2018) are stored in MSA excel files retained by the European Commission.

These MSA studies were presented and discussed with raw material experts, as described in section 1.2.1.

1.2.1 Validation workshops

The MSA studies here summarised were presented to raw material experts on two occasions during their development: 1) criticality validation workshop; 2) webinars prepared for each of the targeted materials.

In the **criticality validation workshop**, the first draft results of the MSA studies were presented to raw material experts during workshop organised by the SCRREEN project together with DG GROW and the JRC to support the 2020 EU criticality assessment and the material system analysis. This workshop took place from 10 to 12 of September 2019 and had the following objectives: 1) validate the data and data sources used in both studies (the criticality assessment and the material system analysis); 2) exchange data, information and knowledge (including sources for missing data) on the target raw materials. A dedicated section was organised for each raw material. The draft MSA excel files with the result achieved for the flows of extraction and processing stages were distributed to the participants before the workshop and the related/draft results were presented in the workshop, followed by discussions. The comments received during and after the workshop were addressed, and the data collected were incorporated in the development of the complete MSA datasets.

After the preparation of complete draft MSA datasets **a validation workshop** was organised as webinar by the JRC for each raw material to discuss the results of the studies. Table 15 describes the dates of each of the webinars organised by the JRC. Important stakeholders from the value chain of each raw material were invited and attended the webinars. The webinar for elemental phosphorus was organised together with the European Sustainable Phosphorus Platform (ESPP) which made a wider discussion on topics related to the current situation of P_4 recycling and alternatives to the PCl_3 vector possible. The lists of organisations who participated to the workshops are provided in the Annexes. Before the webinar the complete excel dataset, summary reports and a list of questions had been distributed among the webinar participants. Like in the first workshop the inputs and comments received were addressed and used to prepared the final MSA dataset here summarised for each of the 9 materials.

Table 15. Dates of validation workshop webinars for each raw material

Raw Material	**Webinar date**
Barytes	26th of May 2020 at 14:00
Bismuth	26th of May 2020 at 16:00
Hafnium	25th of May 2020 at 14:00
Helium	25th of May 2020 at 16:00
Natura Rubber	25th of June 2020 at 14:00
Elemental Phosphorus	9th of July 2020 at 9:00
Scandium	9th of October 2020 10:00
Tantalum	28th of May 2020 14:00
Vanadium	28th of May 2020 16:00

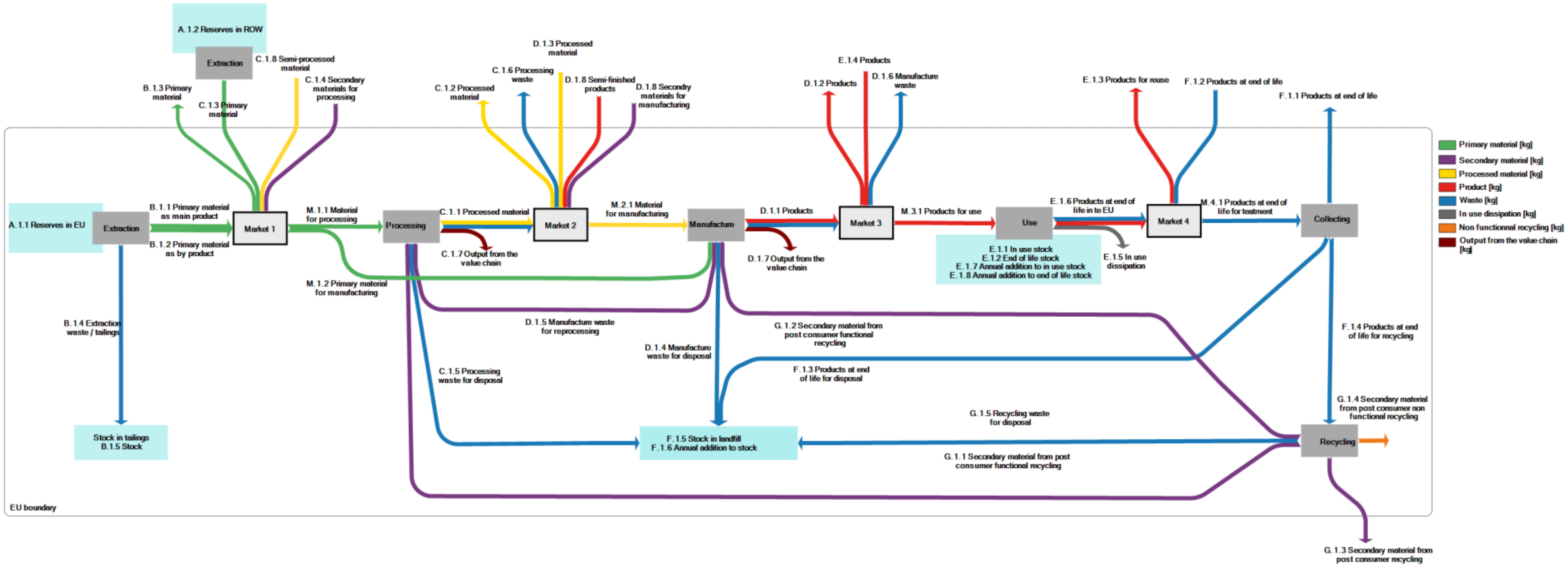

Figure 1. MSA system with all the processes (material life cycle stages), flows and stocks considered in a MSA. The system border is the geographical border of the EU (Matos et al, 2020).

2 Material system analysis of Barytes

2.1 Value chain

Baryte is a naturally occurring mineral ($BaSO_4$), mainly present in stratiform deposits, as well as vein and residual deposits. Extraction of natural baryte occurs by surface and underground mining. After natural baryte is extracted, it is usually sorted (physical separation from other compounds e.g. gravity separation, flotation methods) and crushed on or near the mining site, to get ground baryte, micronized baryte, baryte aggregate, etc.

In the majority of cases, baryte produced on the mining site is sold as ground material, i.e. directly in the manufacturing of final products (Barytes Association, 2019), (WMD, 2019a). Additional processes may be conducted in some exceptional cases, to obtain the quality and colour required for several given applications. For these applications, high purity and brightness of barytes are key for the industry. However, the associated volumes remain low compared to the overall baryte market. Therefore, no processing stage is considered in the value chain of baryte: instead, only one stage is used to reflect on production and trade figures of baryte before manufacturing. This approach is consistent with data availability.

There is no identified secondary source of baryte: the main applications using baryte are dissipative (baryte cannot be recovered from use in the oil and gas industry, and from applications such as paints) and baryte is not recovered from end of life products (e.g. from fillers) (Barytes Association, 2019), (Ladenberger et al., 2018).

Baryte is the main industrial source of barium. It is mainly used as an industrial mineral, with the use of barium metal remaining minor. Various compounds are used in the manufacturing of end-products. Barium sulfate ($BaSO_4$) is used as weighting agent in the oil and gas industry, as well as heavy filler in car brake pads, rubber and plastics, and some medical applications. Barium carbonate ($BaCO_3$) is mostly used in glass, e.g. for electronic applications (LED glass for television and computer screens, etc.) as well as heavy filler in paint and coatings. Other compounds include barium titanate (in electronic applications) and barium oxide (in glass).

The main end-use of baryte is in the oil and gas industry (as weighting agent in drilling fluid). Baryte is used, to a lesser extent, in the rubber, plastic and paint industries (as heavy filler) and in chemical applications (including paints, for its brightness and colour).

The Figure 2 below presents the value chain of baryte and its main intermediates and end-uses. The analysis conducted focuses on natural baryte only: intermediate compounds such as blanc fixe, obtained from synthetic baryte, are therefore not included in the value chain (Barytes Association, 2019). A consolidated baryte industry is established in the EU, with all value chain steps taking place in the region.

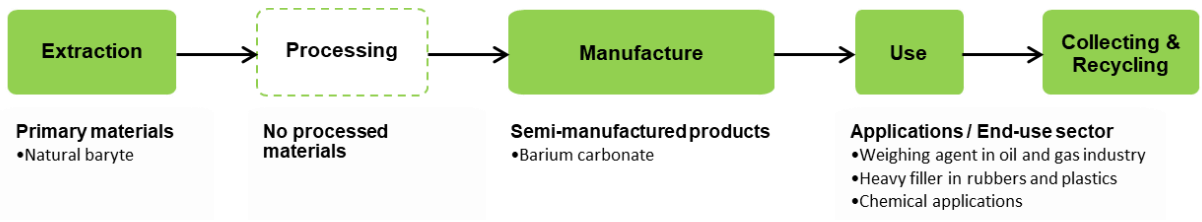

Figure 2. Value chain of baryte.

2.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of barium (kt Ba) rather than in mass of baryte ($BaSO_4$), and are representative of the year 2016. The values presented here are not raw data but aggregated results.

Identified global resources of baryte are estimated to be around 740 million tonnes, and USGS estimated total resources of baryte (identified or not) around 2 billion tonnes. There is no data on the distribution of the global resources by country. Global baryte reserves amount to 171 million tonnes of Ba content in 2016 (290 million tonnes of $BaSO_4$ content), mainly located in Kazakhstan (29%), China (13%), Turkey (12%) and India (11%), accounting in total for more than 65% of global reserves (USGS, 2018).

In 2016, the world baryte production was 5,372,398 tonnes Ba content according to World Mining Data (WMD, 2019b). The top producer country was China (38%), followed to a lesser extent by India (12%), Morocco (10%) and Iran (8%), accounting in total for 69% of the global primary supply. The global production data is slightly higher than USGS and BGS data, but is consistent for the top producer country production; several figures are estimates in USGS and BGS datasets, including for the main producer countries (BGS, 2018), (USGS, 2016).

In the EU (without UK), baryte resources are located in various countries. The Minerals4Eu project provides quantified data at country level, but does not provide a complete figure at EU level. The database includes estimates based on various reporting codes, and non-comparable datasets (e.g. historic estimated, inferred reserves, etc.) (Lauri, 2018), (European Commission, 2017b). Baryte reserves in the EU are estimated at 13.8 million tonnes, with Bulgaria accounting for up to 5% of global reserves worldwide. Other countries with baryte reserves are France, Germany, as well as Slovakia and Croatia (Minerals4EU, 2015), (BGS, 2005).

In the EU, the production of primary baryte was located in Bulgaria, Germany and Slovakia (respectively 41%, 40% and 19% of the European production in 2016). Italy was also a producer of primary baryte until 2011 (unknown production since). Natural baryte domestic production amounted to 73 kt Ba in 2016, mainly of high purity baryte intended to applications other than oil drilling. Among the total EU production, 56 kt Ba was exported, see

Figure 3 (Export Primary material).

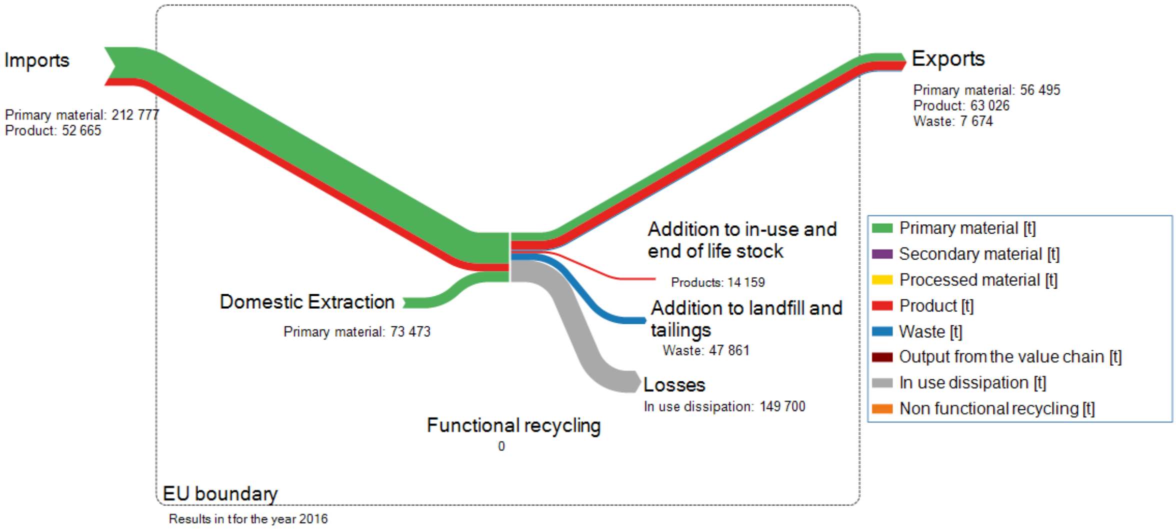

Figure 3. Simplified Sankey diagram for baryte for the year 2016 in the EU (without the UK). Imports of products include also imports of intermediate products 32 kt Ba.

Input to EU baryte manufacturing mostly came from imports of natural baryte from outside the EU (estimated at about 213 kt of Ba content in 2016, see

Figure 3 – Imports Primary material). It is considered that there was no use of secondary baryte in EU, whether from domestic supply or imports of scrap. Imports of barium carbonate (about 32 kt of Ba content in 2016, included in imports of products in Figure 3), a semi-manufactured material used for instance in chemical applications, supplemented the input for the manufacturing stage.

The EU manufacturing industry uses barium sulphate and barium carbonate (247 kt of Ba) in the production of different end-products, a result consistent with the literature (Baryte Association, 2019)[1]. The main end-use segments of baryte include the oil and gas well drilling industry (as weighting agent in drilling fluids), the rubber and plastics industry (as filler application, e.g. for use in vehicles, in soundproofing material, in moulded components, floor mats, or in paints for its filler properties) and in the chemical industry (in paints for its brightness and colour, and in glass applications e.g. for electronic devices such as LED glass for TV screens). Figure 4 shows the distribution by end-use sector of Ba-containing finished products manufactured (pie-chart on left-hand side) and used (pie chart on right-hand side) in the EU.

[1] The Barytes Association indicates that the European consumption is about 600 kt of baryte, i.e. about 353 kt of Ba content, including the UK, Norway and Turkey.

Figure 4. Shares of finished-products containing baryte manufactured in the EU and shares of finished-products containing baryte used in the EU (taking into account exports and imports of products).

On the basis of the total finished baryte products used in the EU (224 kt Ba) and lifespan distributions assumed for the main end-use segments of baryte, the European in-use stock and end-of-life stock increased by about 14 kt Ba in 2016 (see Figure 3). The total stock of products in-use was quantified at about 903 kt Ba. The in-use dissipation amounted to 150 kt Ba in 2016.

From the total amount leaving the use phase (60 kt Ba): 0% effectively resulted in functional recycling in the EU, about 33 kt Ba were disposed from end-of life products 19 kt Ba were exported for reuse (included in the exports of products, in Figure 3) and 8 kt Ba were exported for waste treatment (included in the exports of waste, in Figure 3).

2.3 Indicators

Table 16 summarises recycling and EU self-sufficiency indicators.

There are 58% of Ba in end-of-life products that are collected. However, baryte is not effectively recovered at the recycling stage, and all collected volumes are therefore sent for disposal (Barytes Association, 2019), (Ladenberger et al., 2018), (Baryte Association, 2019). (see Table 16) The majority of the uses of Ba are dissipative and no functional recycling was observed in the EU, leading to an EOL-RIR and EOL-RR of 0%.

Regarding self-sufficiency for Ba the EU demand for primary baryte cannot be met by domestic supply (limited mine production in the EU) and strongly relies on imports of primary material (natural barium sulphate) and semi-manufactured material (barium carbonate) from outside the EU. For the extraction stage 58% of the primary material consumed in the EU comes from domestic extraction. On the other end the EU has an established manufacturing of Ba products and it is sufficient for filler applications and chemical applications. For these applications the amount of barytes consumed in the use phase (M3.1) is lower than what is manufactured in the EU (D1.1), resulting in a self-sufficiency higher than 100%. The EU imports Ba products but the trade balance is positive.

Table 16. Different indicators that describe the barytes situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	0%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	0%
Collection Rate	F1.4/(M4.1+F1.2)	58%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	32%
Self-sufficiency Processing	C1.1/M2.1	-
Self-sufficiency Manufacturing	D1.1/M3.1	111%

2.4 Data sources, assumptions and reliability of results

The main sources of production and trade data are the World Mining Data (WMD, 2019b), the British Geological Survey (BGS, 2018), (BGS, 2005), the US Geological Survey (USGS, 2018), (USGS, 2016) and Eurostat. Additional information was gathered from expert network reports in literature such as SCRREEN (Lauri, 2018), (Ladenberger et al., 2018) and expert communications (Barytes Association, 2019), (WMD, 2019a), (Huxtable Associates, 2019). Overall, basic extrapolation was applied to primary data to compute reliable estimates of baryte flows and stock in the EU.

Due to lack of information, some assumptions based on average estimates were made for evaluating the characteristics of baryte-containing products (lifetime, market share, end-of-life, trade, etc.). For this reason, higher uncertainty likely affects the estimate of barytes flows at use and end of life. During the workshops several of the estimates were confirmed or improved, which adds more robustness to the results.

3 Material system analysis of Bismuth

3.1 Value chain

The main primary source of bismuth is recovery as a by- or co-product of lead and tungsten extraction and processing, and also – more rarely – from tin and copper ores processing (USGS, 2019). It occurs naturally in the minerals bismuthinite (sulfide), bismutite (carbonate) and bismite (oxide), but is very rarely extracted as main metal (European Commission, 2020d).

The main production routes of bismuth extraction from lead ores are the electrolytic route or the thermal route, depending on bismuth content in ores. Bismuth is also extracted from tungsten ores by flotation, although little information is available on the processes used to recover bismuth after tungsten artisanal or industrial mining (European Commission, 2020d).

The processing of bismuth into refined metal of a purity at least 99.8% is mainly operated through the thermal route, while the electrolytic refining is preferred to obtain higher purity, up to 99.999% (pharmaceutical grade) (European Commission, 2020d). Bismuth is further processed into semi-manufactured products, mainly as ingots, powders, alloys (such as lead alloys and copper alloys) or chemicals.

The main end-uses of bismuth are in chemical applications: for the pharmaceutical industry and cosmetics, as well as in pigments, paints or catalysts. Bismuth is also used to a lesser extent in metallurgy: in low melting alloys, to be used as solder alloys in various sectors (e.g. electric and electronic equipment); and to be incorporated as additive into steel, aluminium and cast-iron.

The Figure 5 below presents the value chain of bismuth and its main intermediates and end-uses. A consolidated bismuth industry is established in the EU, with all value chain steps taking place in the region.

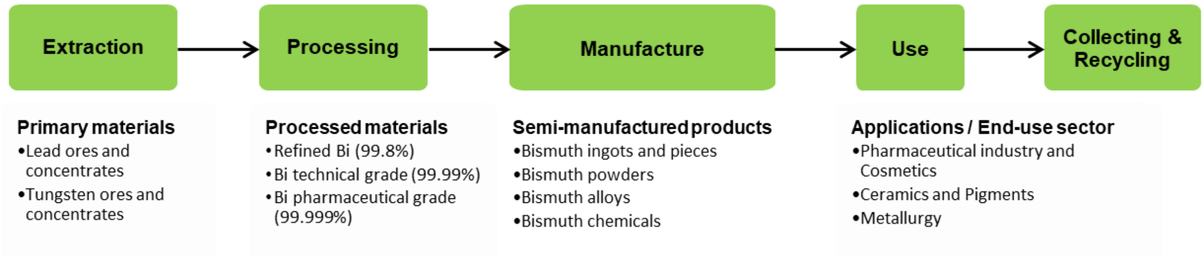

Figure 5. Value chain of bismuth.

3.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of bismuth (t Bi) and are representative of the year 2016. The values presented here are not raw data but aggregated results.

There is no quantitative estimate of global resources of bismuth, which constitutes less than 0.001% of the Earth's continental crust. Global bismuth reserves amount to 370 thousand tonnes of Bi content in 2016, mainly located in China (65%) and Vietnam (14%), accounting together for up to 80% of identified global reserves (USGS, 2019).

In 2016, the world bismuth production was 10 kt Bi content according to World Mining Data (WMD, 2019b). The main producer country was China (70%), followed by Vietnam (14%) and Mexico (7%). The data is consistent with USGS figures, but more than twice higher than BGS figures, due to a gap of the latter for Chinese production (USGS, 2019), (BGS, 2018).

In the EU (without UK), there is no aggregated estimate of bismuth resources. Bismuth is however considered to be present in a number of ore deposits in various countries. There are no known reserves of bismuth in other EU countries than Bulgaria and France, and no quantified data is available for the two countries on current reserves (Brown et al., 2018).

In the EU, bismuth is extracted as a by-product of lead and tungsten ores, there is very limited information of actual volumes of primary bismuth extracted and refined bismuth. Primary bismuth production is estimated at 484 t Bi content (see Figure 6), with most of it not being reported before the processing stage.[2]

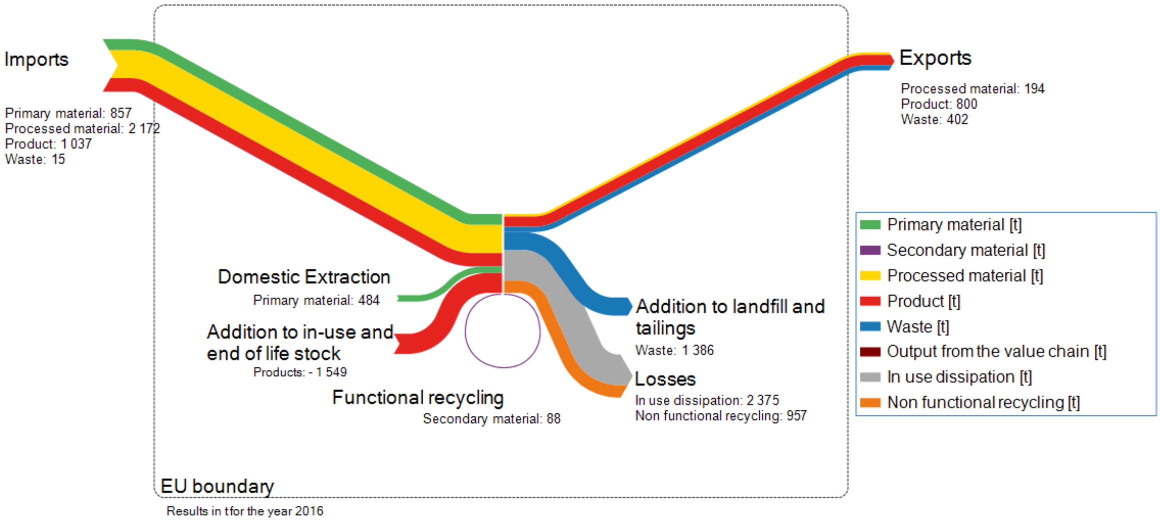

Figure 6. Simplified Sankey diagram for bismuth for the year 2016 in the EU (without the UK).

Input to the EU bismuth processing is considered to be mostly from imported supply, with 857 t Bi content in 2016, i.e. about 60%, imported as primary material (one of the main suppliers being Vietnam) (BGR / DERA, 2019). It is considered that there was no use of secondary bismuth in EU, whether from post-consumer recycling or imports of scrap.

Production of refined bismuth metal in the EU was estimated to amount to 1,000 t of Bi content[3] in 2016 (DERA / BGR, 2015) in Belgium, of which only 194 t Bi was exported outside of the EU. Bismuth processing generated about 429 t Bi in waste, disposed in the EU. Imports of refined bismuth (about 2 172 t of Bi content in 2016) supplemented the input for the manufacturing stage (see Figure 6). In addition to production of bismuth metal, there are several smelters of bismuth in the EU processing bismuth lead alloys (with about 7% Bi contained), for instance in Bulgaria, Germany and Sweden. The production of such alloys varies from year to year, depending on the market. Although there is no quantified data available on production of refined bismuth in alloys in these member states, it can be considered that the associated volumes are limited when compared to the reported 1,000 tonnes of Bi metal produced in Belgium.

The EU demand of bismuth (in the form of ingots, pellets, alloys or chemicals) for the manufacturing of end-products was estimated at about 2 875 t of Bi content for 2016, a result consistent with literature sources (DERA / BGR, 2015)[4]. The main end-use segments of bismuth include chemical applications (for instance in the cosmetic or the pharmaceutical industry, or as pigment in ceramic glaze), low melting alloys applications (e.g. as solders in electric and electronic equipment) and as metallurgical additives (in aluminium or steel alloys, and malleable iron).

Figure 7 shows the distribution by end-use sector of Bi-containing finished products manufactured (pie-chart on left-hand side) and used (pie chart on right-hand side) in the EU.

[2] BGS data reports a mine production of bismuth in Bulgaria about 3 t Bi content for the 2012-2014 period (estimated data). This is consistent with the fact that most of bismuth may not be reported as such during the extraction stage.

[3] Data reported for the 2012-2014 period by DERA / BGR, considered consistent for the 2015-2016 period as well.

[4] DERA / BGR reports consumption data for 2012 for several countries: 1,000t for Germany, 3,500t for China, 650t for USA, and 630t for Japan.

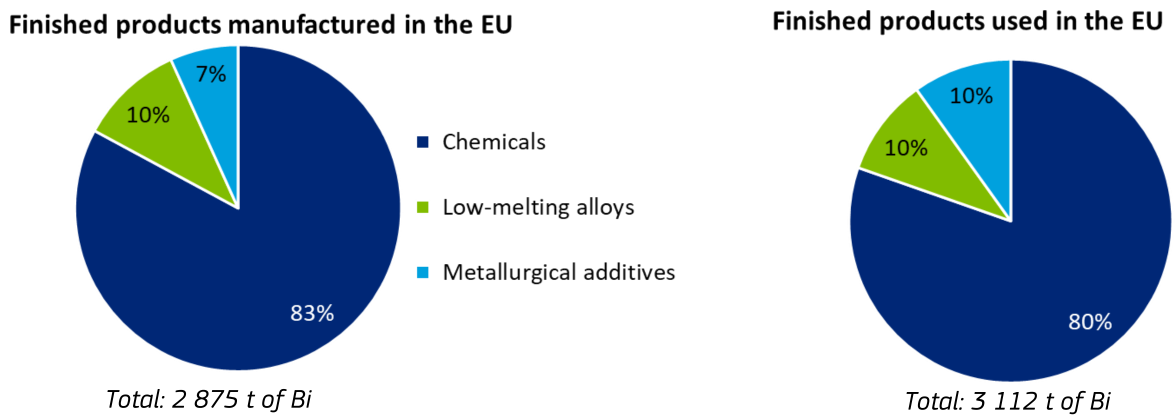

Figure 7. Shares of finished-products containing bismuth manufactured in the EU and shares of finished-products containing bismuth used in the EU (taking into account exports and imports of products).

On the basis of the total bismuth inflow (3 112 t Bi) to use and lifespan distributions assumed for the main end-use segments of bismuth, and due to decreasing use of bismuth applications, the European in-use stock reduced by about 1 525 t Bi in 2016 (see Figure 6). The total stock of products in use is quantified at about 26 429 t Bi.

The total output from use amounted to 2 286 t Bi, of which 0% effectively resulted in functional recycling in the EU. Overall, about 957 t Bi was disposed of from end-of-life products. About 387 t Bi contained in products at end-of-life were exported from the EU (included in the exports of products, in Figure 3).

3.3 Indicators

There is 43% of bismuth in end-of-life products that are collected, see Table 17. However, bismuth is not effectively recovered at the recycling stage as it is a minor metal (e.g. in alloys and related products), and all collected volumes are therefore sent for disposal (Ladenberger et al., 2018), (Sundqvist et al., 2018). Input to bismuth processing and manufacturing entirely relies on primary supply, as there is no identified source of secondary bismuth (from old scrap) and because most of the applications are dissipative (e.g. for the pharmaceutical or the cosmetic industries). Therefore, both EOL-RIR and EOL-RR are considered to be null.

EU self-sufficiency for extraction, processing and manufacturing are also reported in Table 17. For bismuth the EU relies on imports for all life-cycle stages. In 2016 only 36% of bismuth consumed in the EU were extracted internally, the rest was imported. About 34% of processed material consumed in the EU was sourced internally. 92% of the finished products consumed in the use stage were produced in the EU.

Table 17. Different indicators that describe the bismuth situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	0%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	0%
Collection Rate	F1.4/(M4.1+F1.2)	43%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	36%
Self-sufficiency Processing	C1.1/M2.1	34%
Self-sufficiency Manufacturing	D1.1/M3.1	92%

3.4 Data sources, assumptions and reliability of results

The main sources of production and trade data are the World Mining Data (WMD, 2019b), DERA / BGR (DERA / BGR, 2015), the British Geological Survey (BGS, 2018), the US Geological Survey (USGS, 2019) and Eurostat. Additional information was gathered from expert network reports in literature such as SCRREEN (Brown et al., 2018), (Ladenberger et al., 2018), (Sundqvist et al., 2018) and expert communications (BGR / DERA, 2019). Overall, basic extrapolation was applied to primary data to compute reliable estimates of bismuth flows and stock in the EU.

Due to lack of information, some assumptions based on average estimates were made for evaluating the characteristics of bismuth-containing products (lifetime, market share, end-of-life, trade, etc.). For this reason, higher uncertainty likely affects the estimate of bismuth flows at use and end of life. The feedback from validation workshop helped in confirming and improving the estimates made, which adds more robustness to the results.

4 Material system analysis of Hafnium

4.1 Value chain

Hafnium is contained in zirconium ores at a zirconium to hafnium ratio of approximately 50:1. The main ore mineral is zircon sand ($ZrSiO_4$). Baddeleyite (ZrO_2) plays only a minor role. EU reserves are minor when compared to global reserves, and there is currently no production of Zirconium ores in the EU. The main producers of zirconium ores are Australia, South Africa, China, Mozambique and the US.

Hafnium is produced industrially as a by-product of nuclear-grade zirconium metal. Hafnium-free zirconium has a very low neutron-absorption cross section, a characteristic which is desirable for metallic cladding of nuclear fuel rods. Hafnium, in contrast, absorbs neutrons avidly and can be used for reactor control rods. In other physical and chemical characteristics, hafnium and zirconium are almost identical making the separation of hafnium from zirconium very challenging. Therefore, the separation is only carried out if hafnium-free zirconium is needed for nuclear applications. Hence, only a very small fraction of the hafnium contained in zirconium ores is extracted. From the 3% of zirconium, which are actually consumed in the form of zirconium metal, just two thirds are used by the nuclear industry. This means that only 2% of the hafnium in zirconium ores is actually won.

There are only a handful of hafnium producing countries globally with France and the US being the largest. France is the only producer in the EU. In France, Hafnium is produced from Zirconium dioxide, a semi-processed material produced from Zircon sand. A mixture of zirconium dioxide and carbon black is made to react with chlorine at high temperature, producing hafnium-containing zirconium tetrachloride. After purification, hafnium tetrachloride is separated from zirconium tetrachloride using distillation. Hafnium tetrachloride is then reduced to the pure metal by the Kroll process which is refined to hafnium oxide and hafnium ingots by calcination and electro refining.

Hafnium is used for products in different end-use sectors. The biggest end-use sectors are aviation and electricity generation where hafnium is used as additive in superalloys in aircrafts engines and gas turbines. Further applications are nuclear control rods, plasma cutting tips, semiconductors, sputtering targets for optical coatings and catalyst precursors.

The figure below presents the value chain of hafnium and its main intermediates and end-uses.

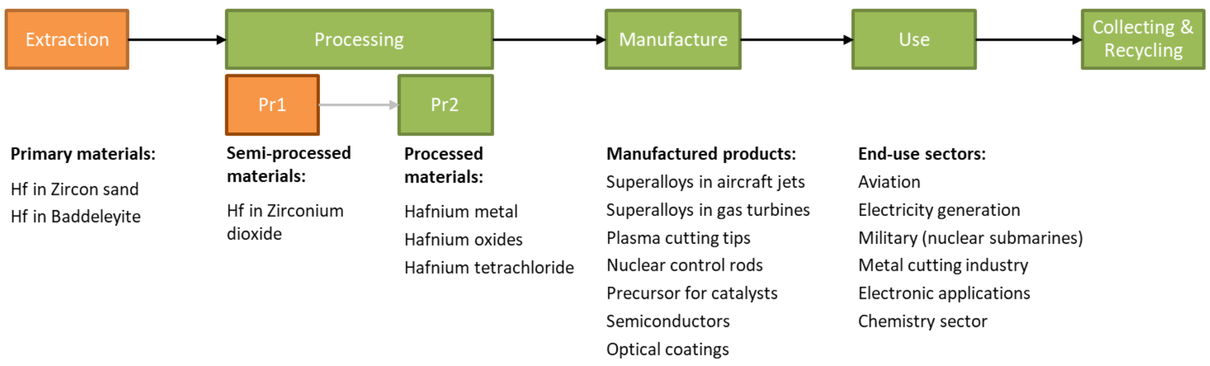

Figure 8. Value chain of hafnium, steps in green occur in the EU, steps in orange occur only outside of the EU.

4.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of hafnium (t Hf) and are representative of the year 2016. The values presented here are not raw data but aggregated results. All numbers are rounded to 1 tonne.

Hafnium reserves in the EU are estimated at 6 800 t Hf content. Global resources are estimated at 1 million t Hf content.

Hafnium is exclusively produced as a by-product of zirconium metal. In 2016, around 28 kt of hafnium contained in zirconium ores were extracted. It is important to note that only a minor fraction (< 1%) of the hafnium contained in zirconium ores extracted is recovered and enters the value chain for hafnium. The main fraction is considered as lost (as impurities in zircon and zirconium products). There is currently no production of zirconium ores in the EU.

The EU imported 3 kt of hafnium contained in zirconium ores and concentrates in 2016, while exports of zirconium ores and concentrates amounted to 112 t of hafnium. However, these flows did not enter the value chain for hafnium.

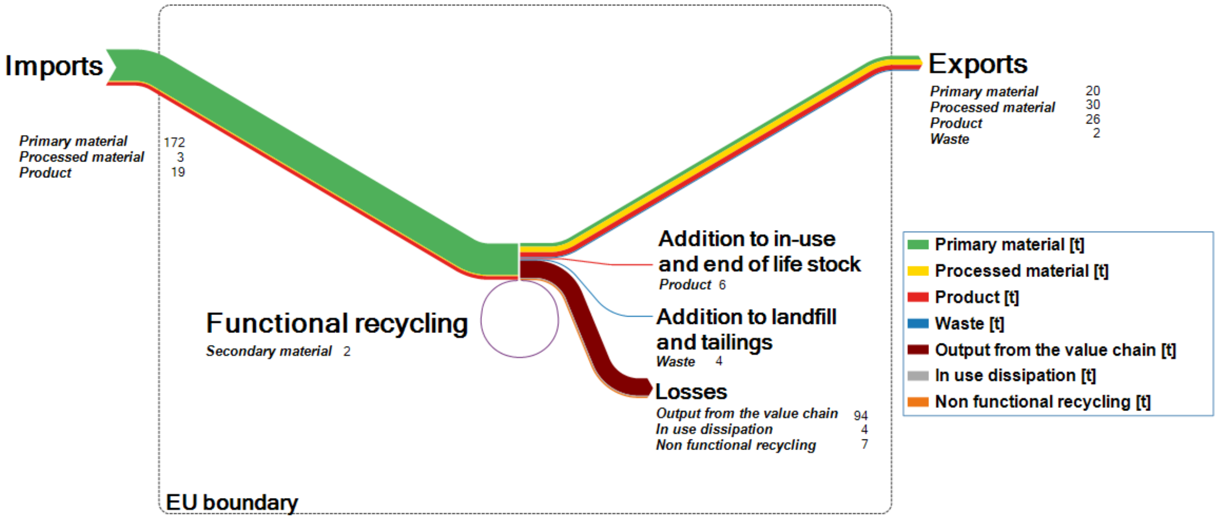

Figure 9. Simplified Sankey diagram for hafnium for the year 2016 in the EU (without the UK).

In the EU hafnium was exclusively produced from the semi-processed material zirconium dioxide of which 172 t of Hf content were imported and 20 t of Hf content were exported as shown in Figure 9. From this input 94 t of Hf contained in zirconium dioxide were used for the production of zirconium products only, hence in Figure 9 they are considered to have left the hafnium value chain.

Global production of hafnium in the form of hafnium metal, hafnium oxides and hafnium tetrachloride is estimated at 75 t in 2016. As the value for 2016 is atypical (probably due to an incident at the producing plant in France (AREVA 2017)), the average value for 2012-2015 of 90 t at global level is also mentioned at this point. At the processing step, production in France amounted to 39 t Hf in 2016 (Alkane, 2016) and 58 t Hf based on the average value for 2012-2015, the latter was the one used for further calculations.

Figure 9 also shows that 30 t of processed hafnium were exported, while 3 t of processed hafnium were imported. 31 t of processed hafnium were sent to manufacturing in the EU. About half was used for the manufacture of superalloys for aircraft jets and gas turbines. Other products include electrodes for plasma cutting, nuclear control rods, catalyst precursors (hafnium tetrachloride), semiconductors and sputtering targets for optical coatings (hafnium oxides), see Figure 10.

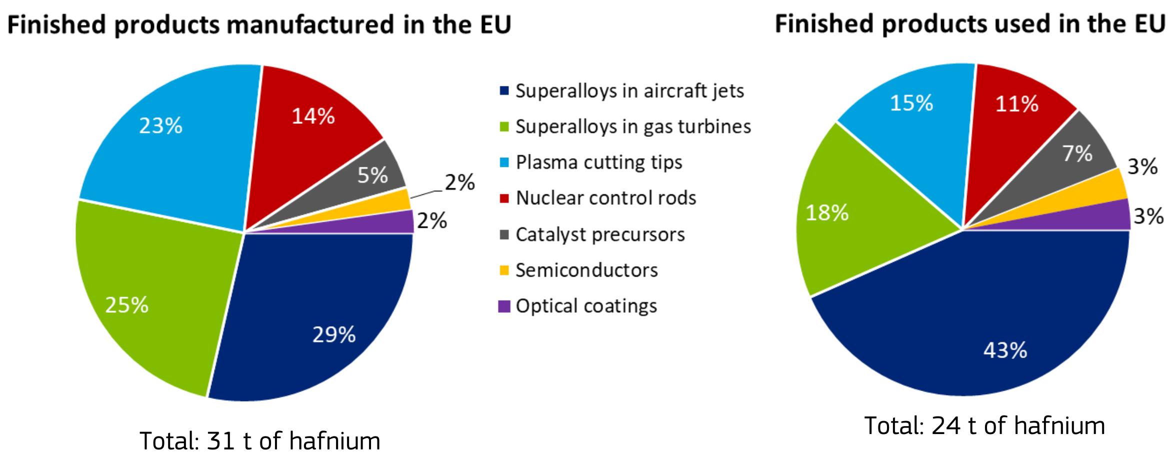

Figure 10. Shares of finished-products containing hafnium manufactured in the EU and shares of finished-products containing hafnium used in the EU (taking into account exports and imports of products).

At the manufacturing stage, products containing 26 t of hafnium were exported, while products containing 19 t of hafnium were imported in 2016 (see Figure 9). Manufacturing waste from the production of superalloys was estimated at 1.7 t Hf.

As presented in Figure 10 24 t of hafnium in products were used in the EU. Based on the lifespan of the finished products, the stock of hafnium in manufactured products in use and at end of life is estimated to be 295 t Hf and 34 t Hf, respectively. It mainly consists of hafnium contained in superalloys in aircraft and gas turbines. Additions to in-use stock amount to 6 t Hf (see Figure 9). In-use dissipation (of sputtering targets and plasma cutting tips) is estimated at 4 t Hf (see Figure 9).

13.2 t of hafnium contained in products at end-of-life are collected for treatment in the EU. From those 4.4 t Hf are sent for disposal (nuclear fuel rods and as losses in recycling), 7.1 t Hf for non-functional recycling and 1.7 t Hf to functional recycling in the EU (superalloys).

4.3 Indicators

Based on the scarce data that is available we assume that the EOL-RIR is in the range of 0-1%. UNEP and USGS assume a recycling rate of <1%. The recycling indicators are summarised in Table 18.

Table 18. Different indicators that describe the hafnium situation in the EU.

Indicator	Formula	2012
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	<1%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	13%
Collection Rate	F1.4/(M4.1+F1.2)	83%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	0%
Self-sufficiency Processing	C1.1/M2.1	188%
Self-sufficiency Manufacturing	D1.1/M3.1	130%

EU self-sufficiency for extraction, processing and manufacturing are also reported in Table 18. For hafnium the EU relies on imports for extraction and is self-sufficient for processing and manufacturing, exporting more than the amount imported. These results demonstrate that the EU processing and manufacturing capabilities are sufficient to cover the demand for processing material and for superalloys in gas turbines, for plasma cutting tips and for nuclear control rods: for these applications the amount of hafnium consumed in the use phase (M3.1) is lower than what is manufactured in the EU (D1.1), resulting in a self-sufficiency higher than 100%.

The EU imports Hf products but the trade balance is positive. For superalloys in aircraft jets and other applications (e.g. catalysts, semiconductors and optical coatings) the EU self-sufficiency is 85% and 95%, respectively.

4.4 Data sources, assumptions and reliability of results

The main sources of data for the development of this MSA were the World Mining Data (WMD, 2019b), the US Geological Survey Mineral Yearbooks and commodity summaries (USGS, 2017), (USGS, 2019), publicly available reports of Hafnium producing companies (Framatome and its predecessor AREVA/CEZUS) (Framatome, 2019), (AREVA, 2017), and presentation from the mining company ALKANE (ALKANE, 2017), and industry associations and consultancies (MMTA, 2019), (Lipmann, 2015), official trade and industrial production data from Eurostat (Prodcom, Comext). Further sources include journal articles (Xiao et al, 2015) and expert interviews with manufacturers (Siemens AG).

Due to lack of information, many assumptions, e.g. on hafnium content in zirconium ores, lifespan of products containing hafnium, dissipation rates, shares of products manufactured in EU and products at end-of-life kept by users had to be taken by the project team, and then validated during validation workshop. In general, upstream data are more robust than downstream data.

Compared to other materials, data gaps are large and reliability of results is limited by data availability especially for the downstream flows. So far, no data are available on trade flows at the collection and recycling stages nor on manufacturing waste generated during production nor on secondary production. We assumed that the global shares are representative for the use of manufactured products in the EU, and that the product groups do well represent the products containing hafnium. Based on the expert opinion that superalloys are recycled to produce new superalloys, we assumed that roughly 20 % of Hf in EOL-superalloys are sent to recycling.

5 Material system analysis of Helium

5.1 Value chain

Most of the industrial gas and therefore helium markets of the United States, Europe, South America and Asia are dominated by five large international gas companies that control the worldwide market for helium (Air Products, Linde, Praxair, Air Liquide, Taiyo Nippon Sanso). Because independent distribution and service in these important regions are limited, the barrier to entry in the distribution to and service of even the smallest of helium customers is very high (National Research Council of the National Academics, 2010).

Helium is produced almost exclusively as a by-product during the liquefaction of natural gas (LNG) and the denitrification of natural gas. Purification of carbon dioxide-rich natural gas and extraction in air separation plants (LTA) is a second method, but only occupies a subordinate role (Elsner, 2018).

The only primary extraction facility of helium from natural gas in Europe is located in Odolanów, Poland. It is operated by the state-owned Polish Mining and Gas Extraction Company (PGNiG). Cryogenic distillation is used to separate crude helium which is purified and liquefied for transport on site. Helium is then sold directly as a finished product, no additional processing or manufacturing is undertaken. (PGNiG, 2020)

Helium (4He) is used in large quantities in health technology (MRIs), for controlled atmospheres, as a lifting gas/balloon gas, in the aerospace industry, for metal hardening, in the semiconductor industry, in analytics, in gas-shielded welding, in metal coating, for leak detection, in laser technology, in research facilities, but also in numerous other applications, such as the filling of gas storage tanks for airbags (Elsner, 2018).

A special case is Helium-3 (3He). It is created as a result of the decay of tritium, a by-product of nuclear fission in nuclear reactors (Elsner, 2018). Helium-3 is used in cryogenic research, neutron detectors and as contrasting agent for MRIs, in all of which it is indispensable. According to Elsner (2018), global demand is estimated by the US Department of Energy to be around 70 m^3.

The figure below presents the value chain of helium and its main end-uses. The EU has an established helium industry covering the entire material value chain.

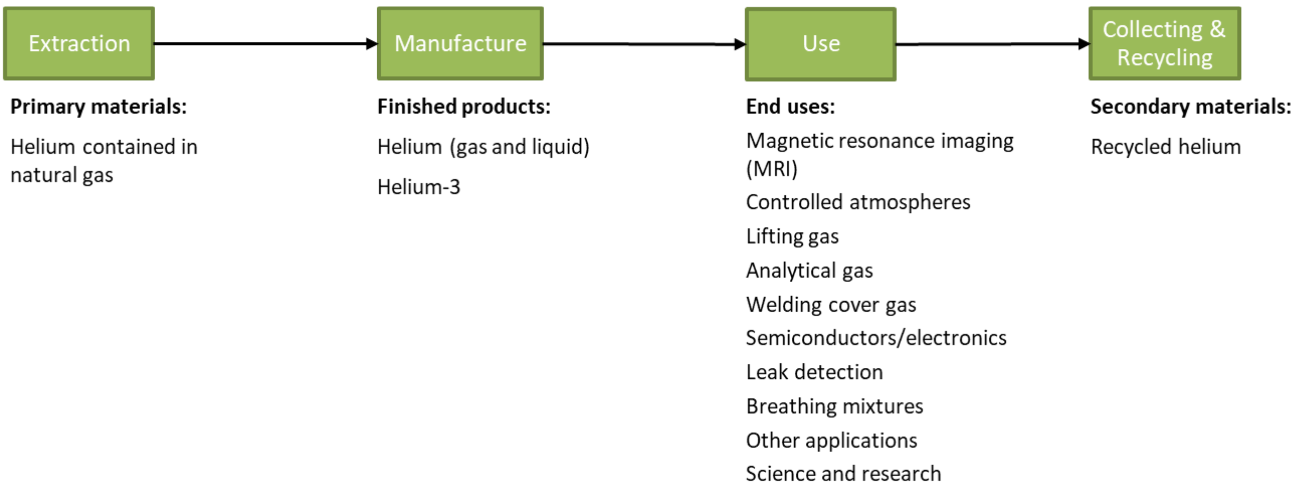

Figure 11. Value chain of helium.

5.2 Description of the main flows and stocks

Flows and stocks are accounted in volume of helium (m^3 He) and are representative of the year 2016.

Global reserves (without EU) are estimated to be 7 425 million m^3 of helium (USGS, 2019b). In the EU only Poland has helium reserves which are estimated to be 25 million m^3. Poland produced 2.8 million m^3 Helium in 2016 from the extraction and separation from natural gas. In the EU helium is also obtained from air in three air separation plants with helium production capacities (Elsner, 2018). Production volumes from these plants are only known for Leuna (Germany) with 12 121 m³ helium in 2016. The two other facilities are Le Blanc-Mesnil (France) and Ijmuiden (Netherlands). The total annual production of helium as by-product in the rest of the world is 166.7 million m³ He.

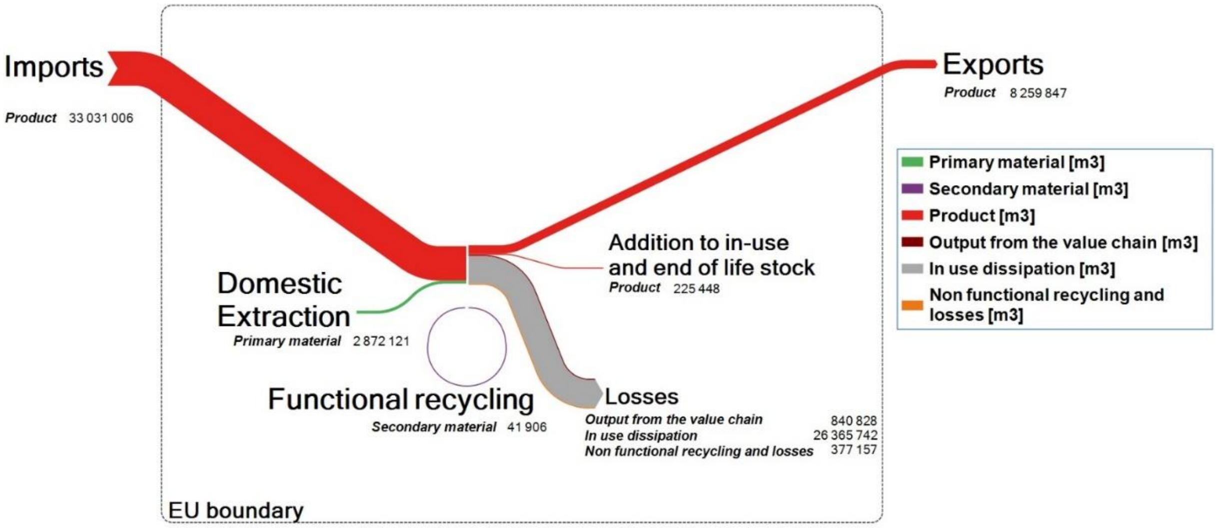

Figure 12. Simplified Sankey Diagram for helium for the year 2016 in the EU (without the UK).

Figure 12 shows that the EU exported 8.2 million m³ of Helium were and 33 million m³ He were imported in 2016. It is estimated that 0.8 million m³ were lost during storage and transport, leaving the EU He value chain.

In total 27.2 million m³ of Helium were used in the EU, see Figure 13.

Helium is a just-in-time product as storage of Helium is expensive. A small stock estimated at 7.2 million m³ He, however, is found in MRIs. It is assumed that MRIs contain 900 m³ helium on average per MRI machine (Elsner, 2018). Annual addition to in-use stock was estimated at 0.22 million m³ He based on the change in the number of MRI units (see Figure 12). The dissipative losses during usage were calculated per application and amount to 26.5 million m³ helium. The production of secondary material from post-consumer functional recycling in EU was estimated at 0.38 million m³ He, while losses during recycling were 43 thousand m³ He (see Figure 12).

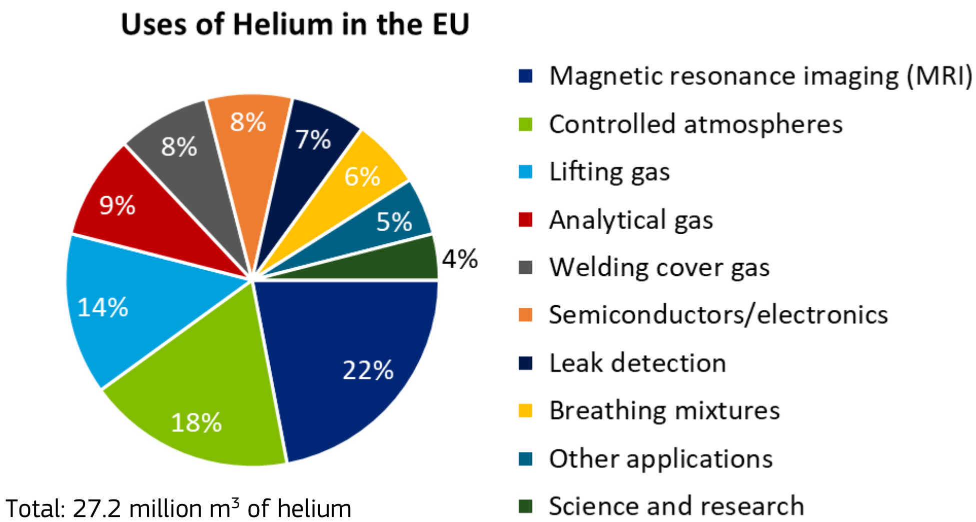

Figure 13. Uses of helium in the EU (by share of helium used in the application)

There are procedures for helium recycling in the EU. However, in most cases helium is reused internally if captured and thus not counted as EOL recycling. According to Elsner (2018), the only case of actual EOL-recycling is during refilling of MRIs where the captured helium is sold as balloon gas, which was considered to be non-functional recycling and only able to capture 10% of the He present in MRI. However, according to MRI producers, many companies have abandoned the idea for safety and economic reasons. Most applications, however (e.g. the use as lifting gas), are not suitable for collecting gas as helium is consumed during the application. If it is recovered, it is usually reused internally. The project team therefore assumed an in-use dissipation rate of 95 to 100 % for all other applications.

5.3 Indicators

The majority of the uses of helium are dissipative except for a small percentage of helium that is captured during the refilling of MRI and used in balloons (non-functional recycling) or that is recovered from other applications and sold back to the distribution companies, which leads to a low EOL-RIR of 1%. The collection rate is high and as much as 100% since all the helium collected for treatment at end-of-life was considered to be directed to recycling, however only 10% is functionally recycled (EOL-RR). The recycling indicators are summarised in Table 7.

EU self-sufficiency for extraction, processing and manufacturing are also reported in Table 7. For helium the EU relies on imports for its manufacturing stage and only 12% of the total helium consumed in EU is domestically produced.

Table 19. Different indicators that describe the helium situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	1%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	10%
Collection Rate	F1.4/(M4.1)	100%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	100%
Self-sufficiency Processing	C1.1/M2.1	-
Self-sufficiency Manufacturing	D1.1/M3.1	12%

5.4 Data sources, assumptions and reliability of results

The main sources for production data are the US Geological Survey (USGS, 2019), the German Mineral Resources Agency (Elsner, 2018) and the Polish Mining and Gas Extraction Company (PGNiG, 2020). Trade data are taken from Eurostat's trade database for helium (HS Code 28042910).

In general, upstream data are more robust than downstream data. Data on extraction and manufacture are based on direct sources and can therefore be considered as reliable. Knowledge gaps exist with respect to losses of helium during production and at the use stage, as well as on the amount of helium recycled. Assumptions on in-use-dissipation rates and on in the amount of helium per MRI were taken. The feedback from the validation workshop helped in confirming and improving the estimates made, which adds more robustness to the results.

6 Material system analysis of Natural Rubber

6.1 Value chain

Natural rubber is a biotic material which is harvested from rubber trees (*Hevea brasiliensis*), mainly growing in tropical forests close to the equator. *Hevea brasiliensis* is a native species of the Amazon region, but has been introduced in several other regions for rubber production. South-east Asian countries, mainly Indonesia and Thailand, are the biggest global producers and biggest suppliers of natural rubber to the EU.

Natural rubber is mainly harvested from the rubber tree in the form of latex, which is a white emulsion. While latex can also be sourced from other tree species, its applicability is not as straightforward as that extracted from *Hevea brasiliensis*.

The rubber tree is a perennial crop that is harvested throughout the year. Natural rubber is extracted by making a cut in the bark of the rubber tree, commonly designated as tapping. The rubber can start to be harvested when the tree reaches at least 45 cm in circumference, which corresponds to a tree age of about six years. The maximum yield is reached around the fifth to the tenth year of tapping. A rubber tree is productive for 20 to 40 years, where the length of the productive period is largely determined by the tapping intensity. Afterwards replanting is required and the old tree can be harvested to provide wood for furniture.

After tapping, the latex can be processed into different rubber products and grades. Traditionally, it is coagulated using formic or acetic acid, and then pressed between pairs of rollers to form sheets or crepes. In the final process, the natural rubber is washed and dried. Dried natural rubber is usually vulcanised, a chemical process that involves heating and the addition of sulphur or other cross-linking additives. This process improves the elasticity and durability of the untreated natural rubber. Vulcanised rubber is then further processed into different rubber products.

Recycling biotics is different from the majority of the abiotic materials. For the majority of the cases, the recovered biotic - the equivalent to "old scrap" - simply can't be re-used in the same application or with the same properties as the original raw material due to contamination issues. Natural rubber is mostly used in a mix with synthetic rubber to obtain the desired hard rubber product performances. With the available technology it is not possible to recycle rubber products and extract natural rubber from these mixtures, therefore recycling is always a mix of natural and synthetic rubbers.

Natural rubber is used in the production of tyres and General Rubber Goods (GRGs). The latter can be used in transport, industrial and household equipment and in final consumer goods such as sportswear, footwear, food contacting materials and condoms.

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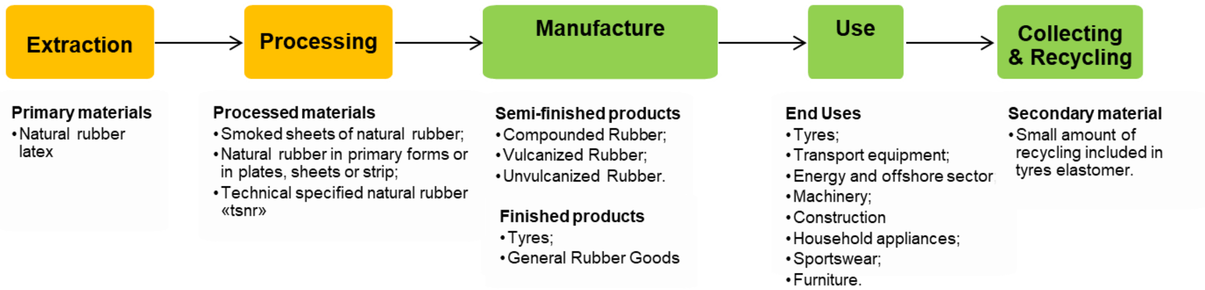

Figure 14 below presents the value chain of natural rubber and its main intermediates and end-uses. Figure 15 represents a detail of the manufacturing stage to explain how the different intermediates (semi-finished products) are transformed in the final products and its final applications. The Figure shows that the tyres industry mainly consumes natural rubber in its primary forms (e.g. latex and smocked sheets). Compounding and vulcanisation of these primary forms of natural rubber is performed onsite by the tyre manufacturers. GRGs industry may consume directly the primary forms or the natural rubber mixtures in compounded and vulcanised rubber commodities.

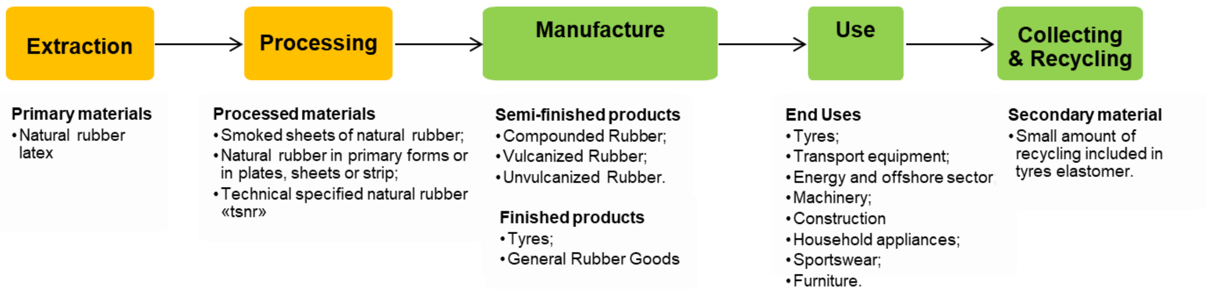

Figure 14. Value chain of natural rubber, steps in green occur in the EU, steps in orange occur only outside of the EU.

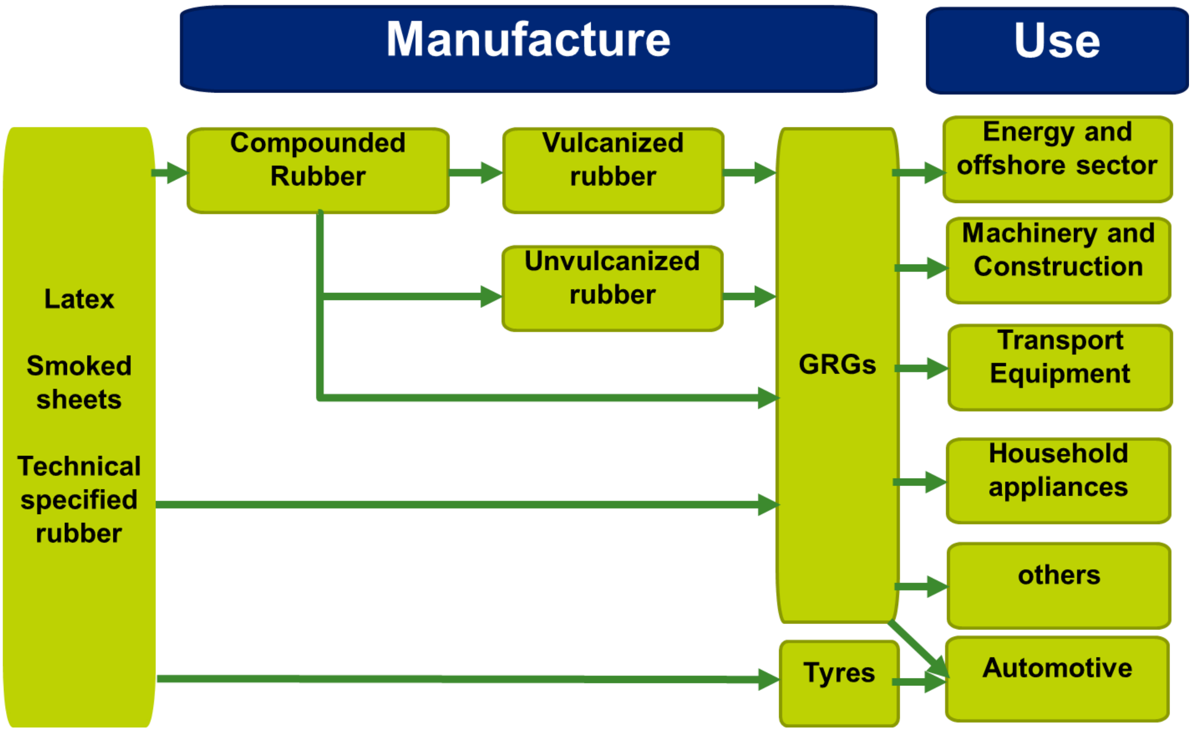

*Figure 15. Details for the manufacturing and use steps in the natural rubber value chain, in regards to the commodities entering GRGs and tyres manufacturing processes. *Tyres manufacturing companies usually perform their own formulations and vulcanisations processes.*

6.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of natural rubber (kt NR) and are representative of the year 2017. The values presented here are not raw data but aggregated results.

The overall acreage of national rubber plantations is estimated around 12 million hectares (FAO, 2019). The average yield in 2017 was 1 214 kg/ha (FAO, 2019). Rubber plantations are facing competition with other crops (palm oil, grains etc.) that together with the geographical constraints limits the flexibility to expand the total acreage of natural rubber plantations. The global production of natural rubber achieved 13 869 kt NR in 2018 (IRSG, 2019), dominated by Thailand and Indonesia, which account for more than 57% of global production.

There is no production or reserves of natural rubber latex in the EU. Today 99% of the natural rubber consumed in the world comes from areas where *Hevea brasiliensis* trees are cultivated. These trees can be cultivated mainly in tropical forests, close to the equator. There is a particular EU interest in developing additional natural rubber sources that can grow in other geographical regions and notably in Europe.

The production of processed material such as: smoked sheets of natural rubber, technical specified natural rubber «tsnr», smoked sheets or other primary forms of natural rubber with near 100% natural rubber occur near the extraction sites. Therefore, there is also no production of these commodities in the EU.

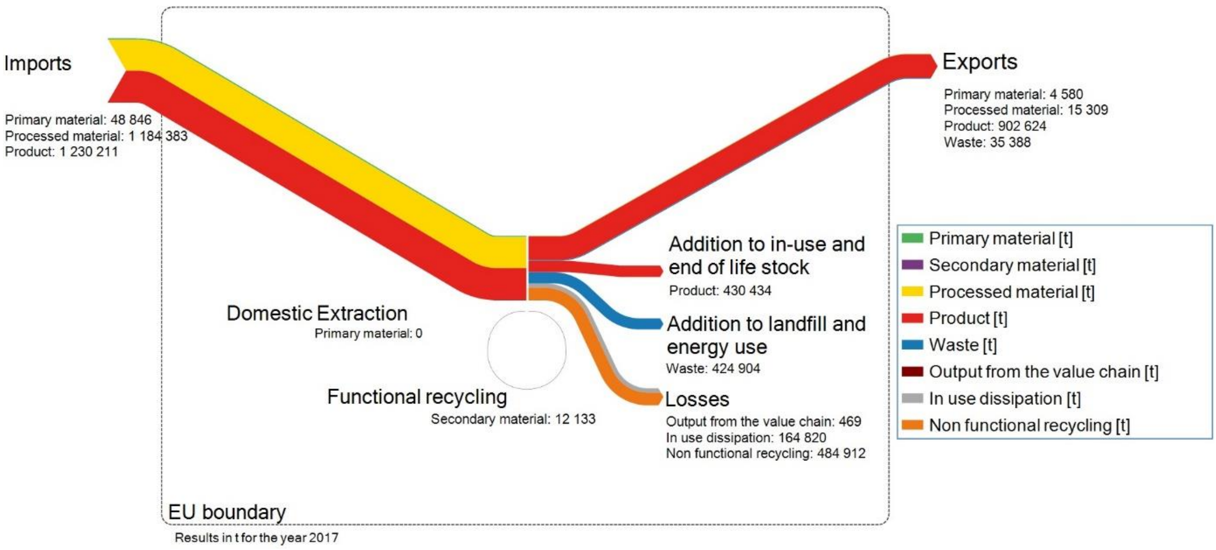

Figure 16. Simplified Sankey diagram for natural rubber for the year 2016 in the EU (without the UK). Imports of products also include imports of intermediate products 25 kt of NR in compounded rubber and vulcanised rubber.

The input to the EU manufacturing is achieved by imports and a small amount of recycled material 12 kt NR (see Figure 16 – Functional recycling). As described in Figure 16 the EU imports 49 kt NR of latex (primary material containing 60% of natural rubber), 1 184 kt NR of processed natural rubber and 25 kt NR of intermediate materials (compounded rubber and vulcanised rubber, included in imports of products in Figure 16). There are re-exports of latex and processed natural rubber of 20 kt NR (see Figure 16: Exports for Primary material + processed material).

With these inputs the EU manufactures 878 kt NR in tyres and 305 kt NR in GRGs and 44 kt NR in intermediates (which are exported). As shown in Figure 17 the GRGs are used in different applications: 63% in transport equipment, 11% in energy and offshore sectors, 9% engineering (e.g. machinery) and construction, 10% household appliances and other 7% applications such as food contacting materials and sportswear.

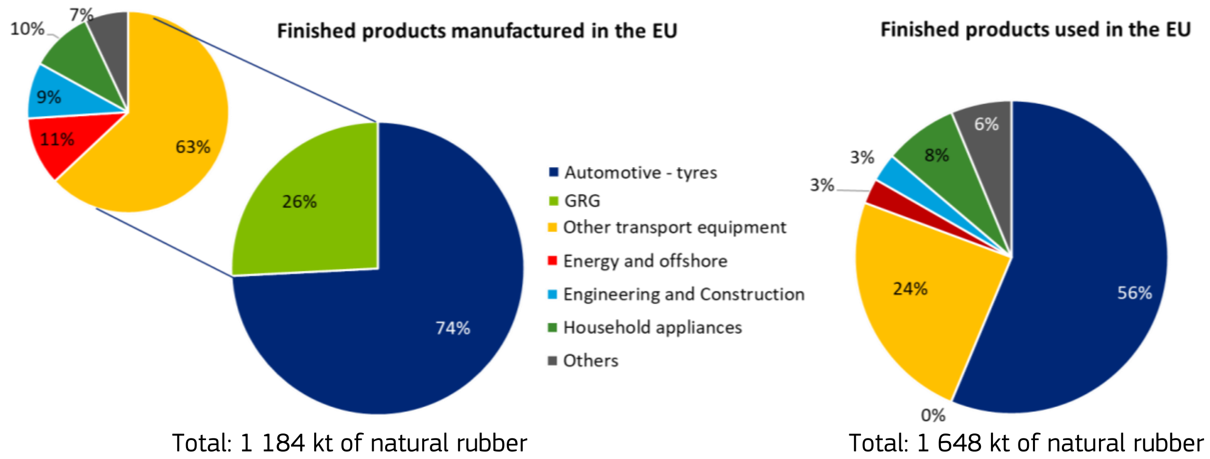

Figure 17. Shares of finished-products containing natural rubber manufactured in the EU and shares of finished-products containing natural rubber in the EU (taking into account exports and imports of products).

The EU imported 1 205 kt of natural rubber in finished products (total value of Figure 16 – Imports product accounts also with 25 kt NR in intermediates) which included GRGs, new tyres, tyres in new vehicles and tyres in vehicles for reuse. From the manufacturing stage the EU exports 903 kt of natural rubber in finished products.

On the basis of the total natural rubber inflow to use (1 648 kt NR) and lifespan distributions assumed for the main end-uses of natural rubber, the European in-use stock increased by about 430 kt of natural rubber in 2017. The total stock of products in-use was quantified at about 11 720 kt of natural rubber. The in-use dissipation amounted to 165 kt in 2017.

The total volume leaving the use phase amounted to 935 kt NR, of which a 12 kt NR resulted in functional recycling in the EU. The recycling of rubber products does not permit a recycling or reuse of natural rubber per se, but of a mix of natural and synthetic rubbers. The majority of the natural rubber collected is however recycled in a multitude of applications - such as synthetic turf, children playgrounds, sport surfaces, moulded objects, asphalt rubber, acoustic & insulation applications - substituting other raw materials than natural rubber (for example, virgin EPDM in synthetic turf, polyurethane in moulded objects). End-of-life recycling of GRG products is limited either due to contamination issues (e.g. dismantling of End-of-life vehicle seals, tubes etc.) or due to the mere impossibility to recycle/collect the application (condoms, clinical gloves, etc.) ((ETRMA), 2019a), (European Commission, 2017c).

From the 424 kt disposed natural rubber, 76% (319 kt) is burned for energy recovery, while the rest ends up in landfill or in unknown whereabouts.

6.3 Indicators

Table 20 summarises recycling and EU self-sufficiency indicators.

There are 53% of natural rubber collected for recycling into other applications than tyres and GRGs. (see Table 20). Today, with the available technology only a small portion of the natural rubber is functionally recycled ((ETRMA), 2019a). Less than 2% of the total elastomer of some tyres is composed of recycled material, functional recycling in GRG is also very low. Therefore, the EOL-RIR and EOL-RR is lower than 1%.

Regarding self-sufficiency for natural rubber, there was no extraction or processing capacity in the EU and manufacturing relies solely on imports and on small amount of natural rubber recycled internally. On the other hand, the EU has an established manufacturing of natural rubber products, producing 79% of the natural rubber products consumed in the EU.

Table 20. Different indicators that describe the natural rubber situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	1%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	1%
Collection Rate	F1.4/(M4.1)	53%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	0%
Self-sufficiency Processing	C1.1/M2.1	0%
Self-sufficiency Manufacturing[5]	D1.1/M3.1	79%

[5] Manufacturing of natural rubber includes final products and semi-finished products. The self-sufficiency manufacturing indicator was calculated accordingly.

6.4 Data sources, assumptions and reliability of results

The main sources of production and trade data are the Food and Agriculture Organization (FAO, 2019), International Rubber Study Group (IRSG, 2019) and Eurostat Prodcom and Comext (Eurostat, 2019). Additional information was gathered from the reports and personal communications from the European tyres and rubber manufactures ((ETRMA), 2019a), ((ETRMA), 2017), ((ETRMA), 2019b), ((ETRMA), 2016, 2019c), (ETRMA, 2020). Data on end-of-life tyres was also collected from ETRMA reports. Assumptions on lifespan, collection and recycling of end products containing natural rubber were collected from scientific publications (Graedel et al., 2015) or from reports of end-of-life vehicles and second hand car market (ADEME, 2015), (COWI, 2011).

Data on tyres and GRGs goods production and trade are widely available. However, estimates on natural rubber content were created on assumptions based on the information coming from ETRMA and European patent Office.

7 Material system analysis of Elemental Phosphorus

7.1 Value chain

Elemental phosphorus (commonly known as white/yellow phosphorus or/and red phosphorus) here refers to the specific forms of the element phosphorus (P) in which it is produced as an isolated element (P_4). It is produced from Phosphate rock in dedicated electrothermal reducing furnaces and it is the starting material to many high-grade phosphorus products. Elemental phosphorus represents only a small part of the total use of "Phosphate rock" (c. 2-3% worldwide, ESPP 2020), most of which is processed for the production of phosphoric acid for fertilisers or other inorganic phosphate chemicals (commonly referred to as the wet acid route). Several forms of elemental phosphorus P_4 exist, such as: white phosphorus, made up of four phosphorus atoms in a tetrahedral structure (P_4); red phosphorus, which is an amorphous form of P; diphosphorus (P_2), violet phosphorus (with a tubular structure) and black phosphorus with a crystalline sheet structure. However, currently only white and red phosphorus are commercially significant.

The production of P_4 is typically done through the Wöhler process, where a phosphate rock (apatite) is heated to 1500 – 1700 °C with an electric furnace in a mixture with coke and silica. Elementary phosphorus is liberated as vapor during the process and condensed to produce white phosphorus P_4. The process is purely thermal and no electrochemistry is involved (ESPP, 2020). This is a very energy intensive process consuming up to 14 MWh per tonne of P_4.

P_4 is used in the production of several derivatives such as: red phosphorus, phosphorus trichloride (PCl_3), Phosphorus pentoxide (P_2O_5), phosphorus pentasulfide (P_2S_5), sodium hypophosphite (NaH_2PO_2) and phosphine (PH_3). Globally, most of the P_4 is used to produce phosphoric acid of high purity (up to 85% of H_3PO_4), this is commonly referred to as the thermal route. However, a gradual shift to manufacturing purified phosphoric acid produced through the wet acid route has taken place, because it has lower production costs costs (energy) than "thermal" acid produced via elemental phosphorus, resulting in a global capacity decrease for P_4 production (Jasinski, 2016), (de Boer, 2019) despite stable or increasing demand for end-use products..Detergents and animal feed phosphates are more or less no longer produced from thermal acid today, and substitution of thermal phosphoric acid by purified "wet acid" is occurring for the larger current uses of purified phosphoric acid: food phosphates, metal processing.Thermal phosphoric acid, which inherently offers very high purity, remains essential to several applications such as semi-conductors etching, pharmaceuticals, catalyst production.

A large range of EU industrial sectors are dependent on P_4 and P_4 derivatives that can't be obtained from the wet acid route. These include not only the chemical industry that produces phosphorus chemicals (such as phosphonates and flame retardants) but also downstream user industries such as metal production, lubricants, pharmaceuticals, crop protection and food and beverages (ESPP, 2020). Figure 18 presents the value chain of white phosphorus P_4. Figure 19 represents a detail of P_4 main intermediates and end-uses. As it can be seen, several applications may be obtained from both the thermal route and the wet route. Detailed description of P_4 derivatives and their uses can be found in the ESPP newsletter which also summarises the main conclusions of the validation webinar co-organised with ESPP (ESPP, 2020).

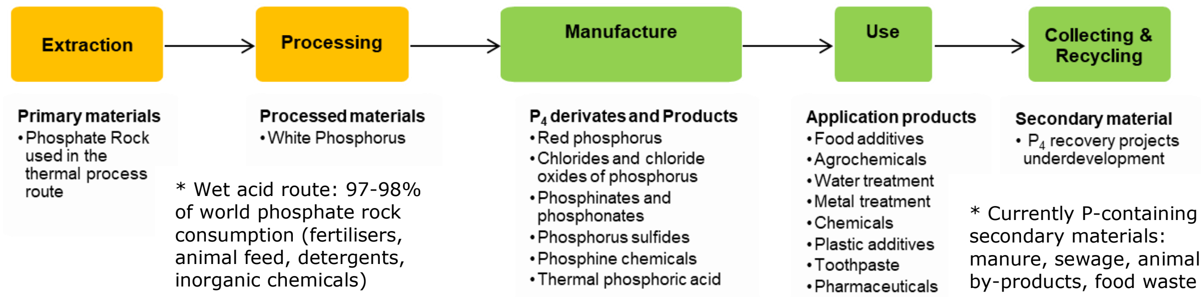

Figure 18. Value chain of elemental phosphorus P_4, steps in green occur in the EU, steps in orange occur only outside of the EU.

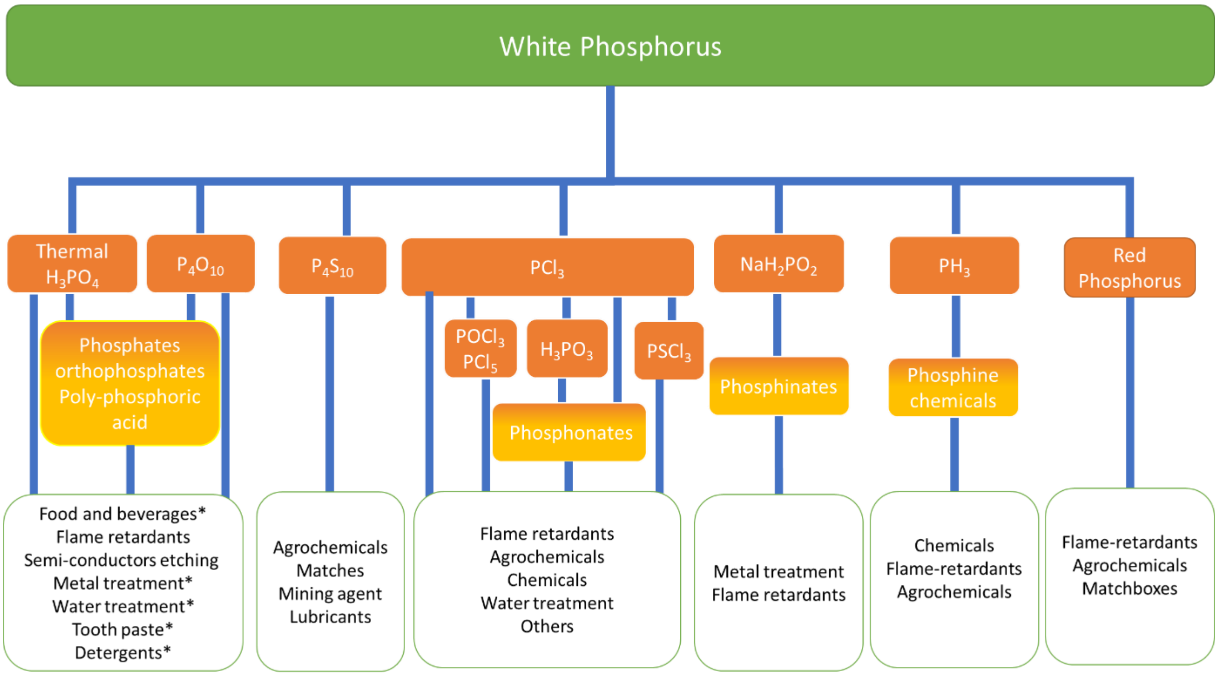

*Figure 19. Simplified chemical family of P_4, derivatives, intermediates, products and final applications * applications that can be obtained from thermal phosphoric acid or purified wet phosphoric acid.*

7.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of phosphorus (P) (kt P) and are representative of the year 2017. The values presented here are not raw data but aggregated results.

The resources of phosphate rock are relatively abundant globally. Known reserves are highly concentrated in a few countries, mainly Morocco. Worldwide reserves are estimated to be 68 705 million tonnes of phosphate rock, 1 000 million tonnes are reported for Finland and near 3 000 million reported for Estonia (USGS, 2019), (Soesoo and Kirsimäe 2020). Phosphorus is one of the most abundant elements in the planetary crust, although concerns exist regarding supply shortage. Studies predict that phosphate rock reserves will be depleted sometime in the next 100 years (Tercero et al., 2018). Even if P_4 represents a small part of the total use of "Phosphate rock" it still competes with the wet route for its availability.

The precise world production of elemental phosphorus is not known, it was estimated to be between 900 - 1 200 kt/year (European Commission, 2020d). The main producer in the world is China, which was responsible for 87% of the world production in 2016 (IHS, 2017). However, in China the majority of the production is used internally and China domestic demand is protected with an export tariff. Kazakhstan is the second biggest producer and the major world supplier, followed by Vietnam and the United States. Production in the United States is limited to one plant and also used in the internal market. In the EU there is no production of white phosphorus (P_4) since the bankruptcy of Thermphos B.V. in 2012 (de Boer, 2019).

The demand for elemental phosphorus has declined during the past 10 to 20 years, which resulted in a significant capacity decrease in both Europe and North America. The decline in demand is not because of lower demand for end-uses, but is the result of substitution of "thermal acid" by "wet acid" for the currently largest uses of P_4: food additives and metal processing. In contrast, the P_4 production capacity in China has increased rapidly. Like China, also Vietnam has increased production capacity in the last 10 years (until 2016). However, this expansion (both from China and Vietnam) has slowed down in the last years (IHS, 2017).

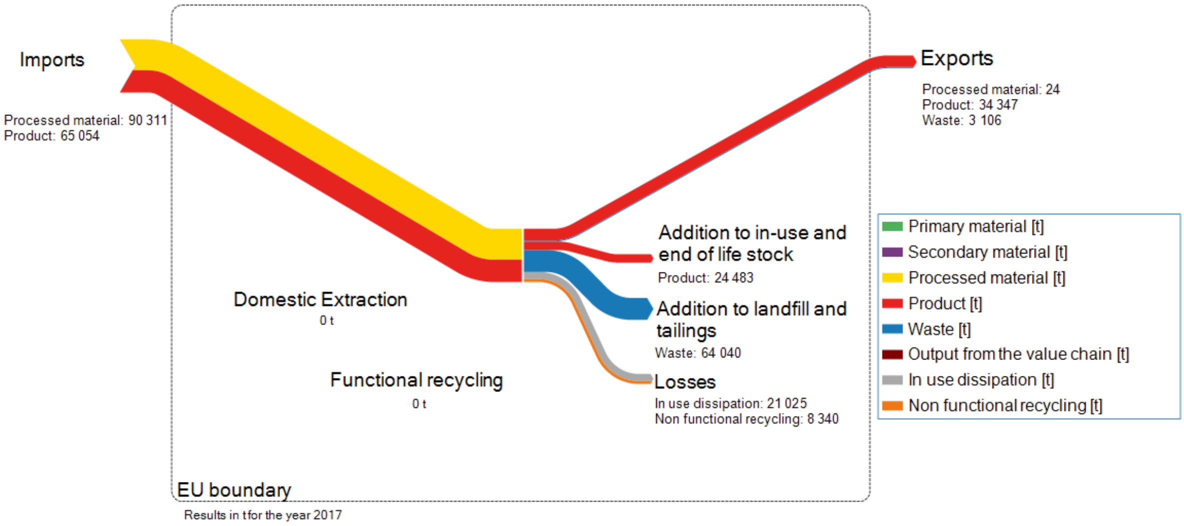

Figure 20. Simplified Sankey diagram for elemental phosphorus for the year 2016 in the EU (without the UK).

Production of P_4 ceased in the EU in 2012. Therefore, none of the phosphate rock extracted in the EU is processed to P_4. In 2017 90 kt of P_4 was imported to the EU, see Figure 20.

The main derivatives produced in the EU from P_4 are thermal phosphoric acid, PCl_3 (which is a vector for several chemicals including $POCl_3$ and PCl_5), P_2O_5 and P_2S_5. Red phosphorus, NaH_2PO_2 and PH_3 represent smaller markets in the EU. With the information collected it was possible to estimate that around 20% of the imported white phosphorus is converted to phosphoric acid. It is however difficult to estimate the volumes of thermal phosphoric acid the EU is trading, since the trade flows are dominated by the wet acid. In total the EU imports of first order P_4 derivates were 36 kt P (including thermal acid 25 kt P) and other intermediates such as $POCl_3$, H_3PO_3 and phosphonates, used in production of end-use products (see Figure 21). Phosphonates can be both intermediate products (e.g. N-(phosphonomethyl)iminodiacetic acid (PMIDA) for the production of glyphosate) or final products used as: flame retardants, industrial detergents and water treatment agents. With the available trade codes it is however difficult to separate intermediate products from finished products.

Overall, the EU manufactured end products containing 116 kt P. P_4 is used in a wide range of industries, Figure 21 shows the estimated share of P_4 used in different end products manufactured in the EU such as: food additives, plastics, agrochemicals, water and metal treatment and other uses such as paint additives and detergents. In detergents this concerns phosphonates, not “detergent phosphates” (sodium tri poly phosphate).

Figure 21. Shares of finished-products containing elemental phosphorus manufactured in the EU and shares of finished-products containing elemental phosphorus used in the EU (taking into account exports and imports of products). This are estimates based on inputs form ESP, independent industry expert Willem Schipper and trade data (see notes in section 7.4).

P_4 is also used in lithium-ion batteries, the project team estimated that about 0.4 kt of P were put on the market in $LiFePO_4$ batteries, in 2017, and probably in LiPF6 in the future. Even if currently, it represents a very small use of P_4, the demand of lithium-ion batteries is expected to increase in the near future and P_4 is a possible alternative to nickel or cobalt electrode chemistries.

The EU imported 29 kt of P in finished products (total value of import in products in Figure 20 accounts also for the intermediates), this created an inflow into use of 122 kt of P (see Figure 21). Taking into account this inflow and lifespan distributions assumed for the main end-uses of P_4, the European in-use stock increased by about 24 kt of P in 2017. The total stock of products in-use was quantified at about 476 kt of P. The in-use dissipation amounted to 21 kt P in 2017.

The total amount leaving the use phase to collection was 75 kt of P. This amount of P was mainly lost through disposal in the collection and recycling stages (64 kt), exported (3 kt) or through non-functional recycling which was estimated at about 8 kt of P, considering the use in fertilisers. Today functional recycling of P from flame retardants is not significant but it could be larger in the future with the development of the recycling technologies. Additionally, there are processes to potentially produce elemental phosphorus P_4 from phosphorus-rich waste streams, where the phosphorus will originate mainly from wet-acid route not P_4 (such as, phosphorus in fertilisers or animal feeds ending up in manure, sewage, animal by-products, food waste). However, these processes are today only at the pilot scale and no industrial installation is yet under construction, nor operational, neither in the EU nor elsewhere. A detailed description of the technologies under development is provided in the ESPP newsletter (ESPP, 2020).

7.3 Indicators

Table 21 summarises recycling and EU self-sufficiency indicators.

There are 34% of elemental phosphorus collected for recycling from waste streams (from P_4/derivatives waste streams) into other applications such as fertilisers (non-functional recycling). The phosphorus obtained with the current recycling technologies do not allow the substitution of white phosphorus in the EU manufacturing. Technological developments may change this situation in the future. Therefore, today the EOL-RIR and EOL-RR are null for P_4.

Regarding self-sufficiency for phosphorus, the EU has no extraction or processing capacity. Therefore, the EU manufacturing of P_4 end products relies solely on imports. On the other end the EU has an established manufacturing industry based on the imported P_4 and derivatives. The volumes of P_4 contained in end products consumed in the use phase (M3.1) are lower than what the EU is manufacturing, resulting in a self-sufficiency higher than 100% for these end products.

Table 21. Different indicators that describe the white phosphorus situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	0%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	0%
Collection Rate	F1.4/(M4.1)	34%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	0%
Self-sufficiency Processing	C1.1/M2.1	0%
Self-sufficiency Manufacturing[6]	D1.1/M3.1	104%

7.4 Data sources, assumptions and reliability of results

The main sources of production and trade data are the Eurostat Prodcom and Comext (Eurostat, 2019). UN Comtrade database was also used to calculate the imports of phosphorus into the EU because Eurostat Comext estimates were considered underestimated by the experts attending the validation webinar. Additional information was gathered from the reports of the European sustainable phosphorus platform (ESPP, 2020),

[6] Manufacturing of phosphorus includes final products and semi-finished products. The self-sufficiency manufacturing indicator was calculated accordingly.

independent industry expert Willem Schipper and experts attending the webinar. Assumptions on lifespan, collection and recycling of end products containing phosphorus were collected from scientific publications (Belboom et al., 2015), (Chen & Graedel, 2016), (Graedel et al., 2015), (van Dijk et al, 2016).

Data on phosphorus flows is scarce and the fact that there are two routes towards essentially some applications (such as food additives, metal treatment) makes it difficult to differentiate between the wet based and thermal based products, which are specific to the P_4 value chain. Several assumptions regarding P content in commodities and its conversion into different and end products were necessary to produce estimates for the trade flows and end uses shares. For this reason, higher uncertainty likely affects the estimate of elemental flows in particular at manufacturing and use stages. The feedback from validation workshop helped in confirming and improving the estimates made, which adds more robustness to the results.

8 Material system analysis of Scandium

8.1 Value chain

Scandium is generally obtained as by-product (BRGM 2017) due to the relative price advantage compared to winning as main product. The different types of sources can be grouped into (i) by-products from aluminium (red mud) or titanium slags, and (ii) leachants from various products from mining routes, including residues, slags, and tailings, from nickel laterites, titanium pigment waste acids, zirconium chloride production, uranium mining. Beside leaching, technologies applied for this second case involve also solvent extraction, precipitation, and calcination methods (Wang et al., 2011). For several years, by-production from rare earth elements and iron was a major source of supply (Bayan Obo mine) (Gambogi 2019, Grandfield 2019), whereas thortveitite, the most relevant scandium mineral, is not used for pyrometallurgical recovery of scandium because of the high energy intensity of the winning processes. There are no relevant secondary resources for scandium.

Most often, scandium oxide (“scandia”, 99.9%), which is used as feedstock for any following processing steps, is obtained from these sources by thermal decomposition of the precipitate at or close to the mine site. Three major routes are commonly distinguished.

Firstly, scandium oxide is used to produce scandium master alloy, a high grade aluminium scandium alloy with ca. 2 % Sc content. The master alloy (“Al-Sc hardener”) is then used as base material for aluminium scandium alloys. Major applications of Al-Sc alloys (0.2% scandium) are light weight applications like specific airplane fuselage, specific sport equipment (high-end bicycle frames, baseball bats etc.). This route is referred to as “metal route” as the scandia is directly used in combination with aluminium metal to form alloys, keeping its metallic characteristics during its lifetime (in contrast to the other routes). Secondly, scandium oxide is used as dopant of zirconia electrolytes in the production of Solid Oxide Fuel Cells (SOFCs). Thirdly, scandium oxide is fluorinated to obtain an intermediate compound scandium fluoride (ScF3), which is then transferred to scandium metal by means of calcium metal or via an aluminothermic reduction (Blazy, 2013). Scandium metal is then used for scientific or laboratory applications. Further scandium compounds are used for niche applications like in metal halide lamps.

On the global scale, the main end-uses are SOFCs, light-weight vehicles (airplanes), sporting goods like high end bicycle frames or baseball bats. Minor applications include ceramics, electronics, lasers, lighting, and radioactive isotopes (laboratory and scientific uses).

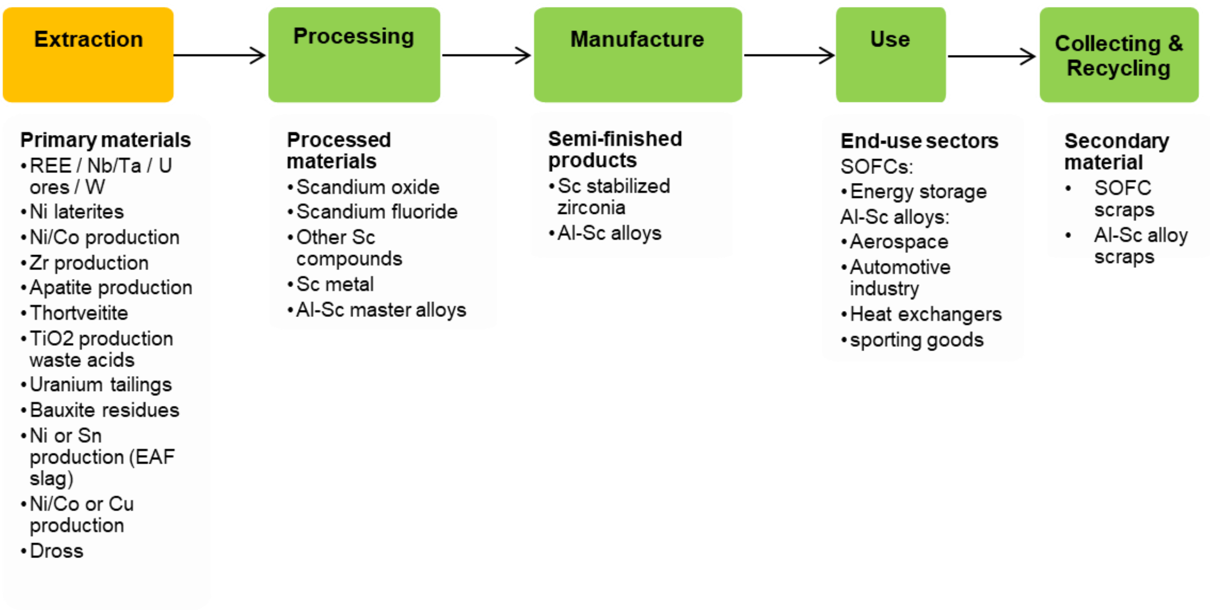

Figure 22. Value chain of scandium, steps in green occur in the EU, steps in orange occur only outside of the EU.

8.2 Description of the main flows and stocks

Flows and stocks are accounted for the EU in mass of scandium (kg Sc) and are representative of the year 2016. The values presented here are not raw data, but aggregated results.

The global resources of scandium are estimated to range between 2 and 20 million tonnes, however, there is no data on their distribution by country. There are no scandium reserves determined for possible future scandium mines, where scandium would be the main product. Instead, estimates exist for scandium volumes contained in mines, where other materials are the main products. These amount to more than 16 000 tonnes of scandium content in 2016. Countries with major reserves include China, Australia, Russia, Philippines, India, Canada, Turkey, Ukraine, Jamaica and Greece (Gambogi 2020), while significant parts of these have not been quantified yet.

In 2016, the world scandium production was estimated to 15 tonnes of scandium content, all of which won as by-product. The top producer countries were China, Russia, the Philippines, and Ukraine (Gambogi 2020). Pilot plants have been set up in Turkey and Greece, however, these have not yet been contributing to industrial production levels. The data situation appears incomplete and not updated for all countries.

In the EU (without UK), there is no aggregated estimate of scandium resources. There are no scandium reserve figures published for the EU, but it is foreseen to extend the scandium production from red mud, a residue from aluminium production, from lab scale to production scale in near future.

There is no recovery of scandium from ores in the EU. There is also no production of scandium oxides or scandium fluorides in the EU.

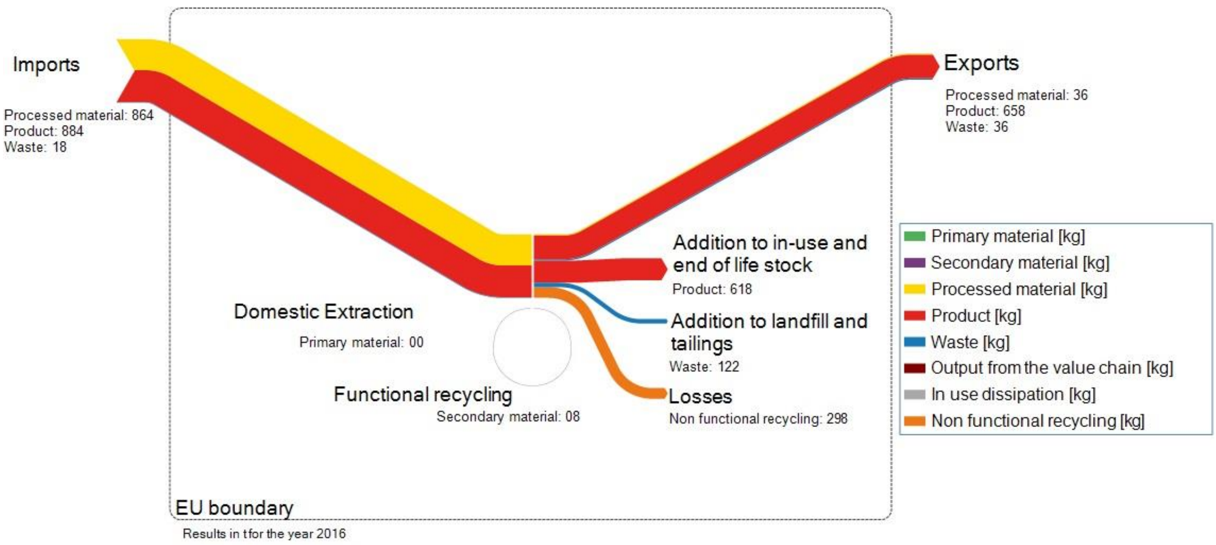

Figure 23. Simplified Sankey diagram for scandium for the year 2016 in the EU (without the UK). Imports of processed material include 792 kg Sc in scandium compounds and 72 kg Sc in Sc-Al master alloys or scandium metal, respectively. Imports of products include 255 kg Sc of Al-Sc alloys, SOFCs and airplanes containing Sc.

Due to the lack of domestic sources, the input to the EU processing stage comes from imports of Sc compounds like fluorides (792 kg Sc, within the 864 kg Sc of processed material imported, see Figure 23). The EU is focused on producing Sc-Al master alloys (ca. 800 kg Sc in 2016). From this production it exports 36 kg Sc. Imports of scandium in master alloys and Sc metal supplementing the manufacturing stage are estimated at 72 kg Sc (with high fluctuations over time, included also in the imports of processed material in Figure 23), all of which entering the metal route (see section 8.1), i.e. used for the processing of scandium alloys.

The overall EU manufacturing of Al-Sc alloys was estimated to 836 kg in 2016. This amount was supplemented with 255 kg Sc of Al-Sc alloys imported, for the production of airplanes, aerospace aircraft, sporting goods and other high-performance applications. The Sc content in exports of finished products were 569 kg Sc and also 89 kg Sc in products for re-use.

In contrast to the global average, where the main share of Sc is used for the production of Solid Oxide Fuel Cells (SOFCs), in the EU there is no SOFC manufacturing known that uses scandium. Results show that alloy uses dominate the domestic manufacturing and use in the EU (100 %, and 86 %, respectively) (Figure 25). No data is available on the production volumes of individual final product types. Figure 24 shows the estimate on the finished products used in the EU (pie chart on right-hand side).

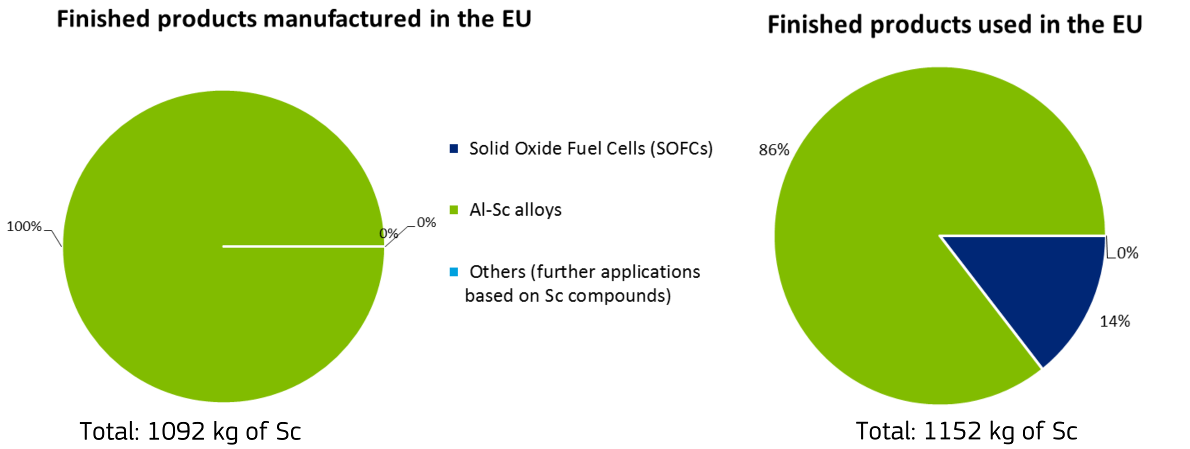

Figure 24. Estimated shares of finished-products containing scandium manufactured in the EU and shares of finished-products containing scandium used in the EU (taking into account exports and imports of products).

Based on the total scandium inflow to the use phase (1152 kg Sc), about 618 kg Sc were accumulated in the EU in-use stock in 2016. The total output from use amounted to 534 kg Sc. Functional recycling in the EU is considered minor (<10 kg) compared to post-consumer non-functional recycling, which amounts to 298 kg Sc. Losses from collecting and recycling are calculated to 122 kg Sc.

8.3 Indicators

Table 22 summarises recycling and EU self-sufficiency indicators for scandium.

The collection rate of Sc is relatively high (87%). However, there is no recycling of scandium in SOFCs reported in the EU, in contrast to the global scale. In addition, functional recycling of the scandium contained in Al-Sc alloys, like in airplane fuselage, is missing, as it is commonly used in the processing of ordinary aluminium or "low-value" aluminium alloys. As a result, the EOL-RIR of Sc is marginal and the EOL-RR is 2%.

Self-sufficiency for scandium varies along the supply chain. The self-sufficiency at extraction is zero, due to the missing extraction in the EU. For processing and manufacturing, the self-sufficiency amounts to 96% and 95%, respectively (Table 22).

Table 22. Different indicators that describe the scandium situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	< 1%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	2%
Collection Rate	F1.4/(M4.1)	87%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	0%
Self-sufficiency Processing	C1.1/M2.1	96%
Self-sufficiency Manufacturing	D1.1/M3.1	95%

8.4 Data sources, assumptions and reliability of results

The main sources of reserve and production data is the data published by US Geological Survey, which was significantly amended by scientific papers. Trade and production data relate basically to Eurostat Comext and Prodcom (Eurostat, 2019), while scandium contents of the related categories are missing. Further information, also semi-quantitative and qualitative data, was gathered from scientific papers and presentations, and from experts attending the webinar. Assumptions on lifespan, collection and recycling of end products were missing and had to be estimated based on the current level of understanding of the scandium system. Data on scandium flows is scarce, and the limited data availability implies massive uncertainties in estimated or calculated values. The situation that there is scandium used in diverse parallel routes, with different options to reach master alloys, makes it difficult to differentiate between the various scandium compounds required as feedstock. In fact, for the purpose of this analysis, the import/export categories of Eurostat were too rough to allow the elimination of the large uncertainties in the scandium analysis. Multiple assumptions regarding scandium content in these categories, and often in addition regarding the shares of the categories that are actually scandium bearing, were necessary to produce estimates for the trade flows and end uses shares. For this reason, high uncertainty affects the estimates of scandium flows at all stages.

The results and assumptions were checked for plausibility at the validation workshop. While the procedure is the same as for the other raw materials analysed, the degree of uncertainty is at a significantly higher level for this material.

9 Material system analysis of Tantalum

9.1 Value chain

The main primary source of tantalum is tantalum minerals (such as tantalite-columbite, microlite, wodginite, struverite, as well as cassiterite) hosted in igneous rocks (e.g. pegmatites, granites, carbonatites). Most tantalum is produced as a co-product as it occurs in complex mineral form, often associated in ore bodies with niobium, tin or lithium.

The main production route for tantalum concentrates from tantalum minerals includes industry-standard open pit, underground and placer mining methods, e.g. drill, blast, and muck cycles, prior to further comminution and concentration (BGS, 2011). The major part of supply in recent years comes from artisanal mining.

Tantalum can also be extracted as a by-product of tin smelter waste. Therefore, the second source of tantalum are tin slags (tin smelter waste), which are the other main feedstock to tantalum processors, converted to a 'syncon' – synthetic concentrate- of a tantalum content suitable for standard chemical processing, usually by pyrometallurgical processing. Such source can be responsible for 20% to 50% of total Ta production, depending on available supply and prices (MSP-REFRAM, 2016b).

The third source of tantalum is recovery from secondary sources, such as new scrap from manufacturing of Ta powders and ingots as well as manufacturing of Ta containing products (and, non-significantly, end-of-life scrap) (MSP-REFRAM, 2016b).

Production of tantalum metals and chemicals is a multi-stage process. The first stage is to convert tantalum concentrates to an intermediate chemical – generally potassium tantalum fluoride (K_2TaF_7) or tantalum oxide (Ta_2O_5). Those processed materials are then converted into intermediate products, such as chemicals (for example tantalum chlorides) or metal powders. Metal powder is produced by sodium reduction of the potassium tantalum fluoride in a molten-salt system at high temperature. The tantalum powder can be of two grades, metallurgical grade (met-grade) at 99.95% purity or capacitor grade (cap-grade) at 99.99% purity. The metal can also be produced by the carbon or aluminium reduction of the oxide or the hydrogen or alkaline earth reduction of tantalum chloride. The choice of process is based on the specific application and whether the resultant tantalum will be further consolidated by processing into ingot, sheet, rod, tubing, wire and other fabricated articles. Other intermediate products can be Ta ingots, carbides and mill products.

Tantalum intermediate products are then converted into semi-finished products, which are incorporated into finished products. Tantalum cap-grade powders are used to manufacture capacitors, integrated in electronic devices. Tantalum met-grade powders and Ta ingots are both used to produce superalloys (mainly for aerospace applications) and sputtering targets. Tantalum pentoxide is the starting point for other tantalum intermediate products, including tantalum chemicals (e.g. tantalum chloride $TaCl_5$, lithium tantalite $LiTaO_3$, etc.) and tantalum carbide TaC. Tantalum chemicals have a very wide range of applications and are intermediates in the manufacture of other products that are often destined for the electronics industry. Tantalum carbides are used in cutting tools. Tantalum mill products have a very wide range of uses, including chemical processing equipment, ballistics and surgical implants.

The main end-uses of tantalum include electric and electronic devices containing Ta capacitors, aerospace applications containing Ta superalloys, sputtering targets, cutting tools, mill products, metallurgical applications, optical applications, biomedical applications and other miscellaneous applications.

The Figure 25 below presents the value chain of tantalum and its main intermediates and end-uses. The Figure 26 presents the detail of the various steps of the manufacturing stage, and the links between intermediate, semi-finished and finished products.

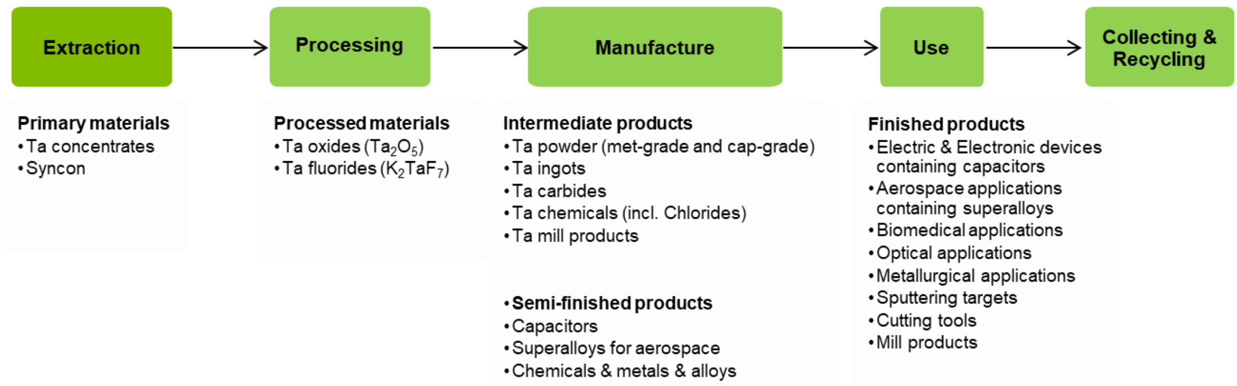

Figure 25. Value chain of tantalum.

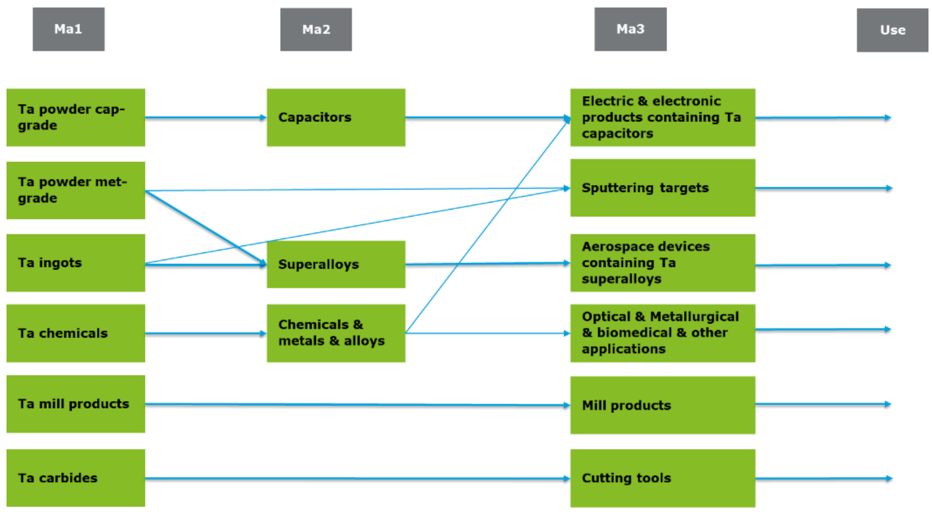

Figure 26: Details for the manufacturing step in the tantalum value chain.

A consolidated tantalum industry is established in the EU, with all value chain steps taking place in the region, except the mine production of natural tantalum concentrates.

9.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of tantalum (t Ta) and are representative of the year 2016. The values presented here are not raw data but aggregated results.

Identified global resources of tantalum, most of which are in Brazil, Australia, Africa, Asia and Middle East, are considered "adequate to meet projected needs for the foreseeable future, at least next 500 years" (BGS, 2011) (USGS, 2019) but are not quantified. An old estimate of 2011 indicates that global tantalum resources are estimated at 260 kt (Ta content), distributed in Brazil (40%), Australia (21%), Africa (16%), Asia (10%), Russia (10%) and Canada (2%) (BGS, 2011), (USGS, 2019).

Global Ta reserves amount to more than 100 thousand tons of Ta content in 2016, mainly located in Australia and Brazil, but also Africa and Asia (USGS, 2019).

In 2016, the world tantalum production from mining (Ta minerals) was 1 350 tonnes Ta content according to World Mining Data (WMD, 2019b), consistent with USGS and BGS data. The top producer countries were the Democratic Republic of Congo (51%) and Rwanda (18%), accounting for more than two third of global primary supply, followed by China (7%) and Brazil (6%) (WMD, 2019b). Nevertheless, data reported from those two top producers are always subject to uncertainties, due to the difficulties of tracing artisanal mining total output despite numerous initiatives to increase transparency (OECD, iTSCi etc.).

Despite discrepancies from source to source, about 50-80% of Ta world production is from primary resources, 10-30% from scrap recycling and 10-20% from Sn slags (MSP-REFRAM, 2016a), (Sundqvist et al., 2018). The contribution of scrap recycling and Sn slags is increasing continuously.

In the EU (without UK), Ta resources are located in Finland, Spain, France, Portugal, Sweden, and also Austria, Bulgaria, Czech Republic, Germany, Italy and Slovakia (Lauri, 2018). No recent aggregated estimate is available for the EU. Based on a 2011 data, EU28 resources of tantalum can be estimated at 1 900 t of Ta (BGS, 2011); and no Ta resources occur in the UK.

Ta reserves in the EU are located only in Spain and France. As the French reserves are confidential, EU reserves are estimated to be at least equal to Spanish reserves, i.e. approximately 8 600 t (MSP-REFRAM, 2016a).

Tantalum ores and concentrates production from tantalite is null in the EU as there are no mines in the EU (MSP-REFRAM, 2016a). A very small production of tantalum syncon, extracted as by-product of tin slag, occurs in France (at the Imerys kaolin mine in Echassières), for about 6 t Ta annually (BRGM, 2015). In Germany, historically the company HC Starck has been processing tin slags at its Laufenburg site for conversion into synthetic concentrates for its own in-house use, but the quantities are confidential. In Spain, Strategic Minerals is planning to develop industrial production of syncon from tin slag.

In 2016, the EU production of tantalum syncon was very small (6 t Ta from France), and all exported to Brazil and India (Salus Mineralis, 2019), see Figure 27.

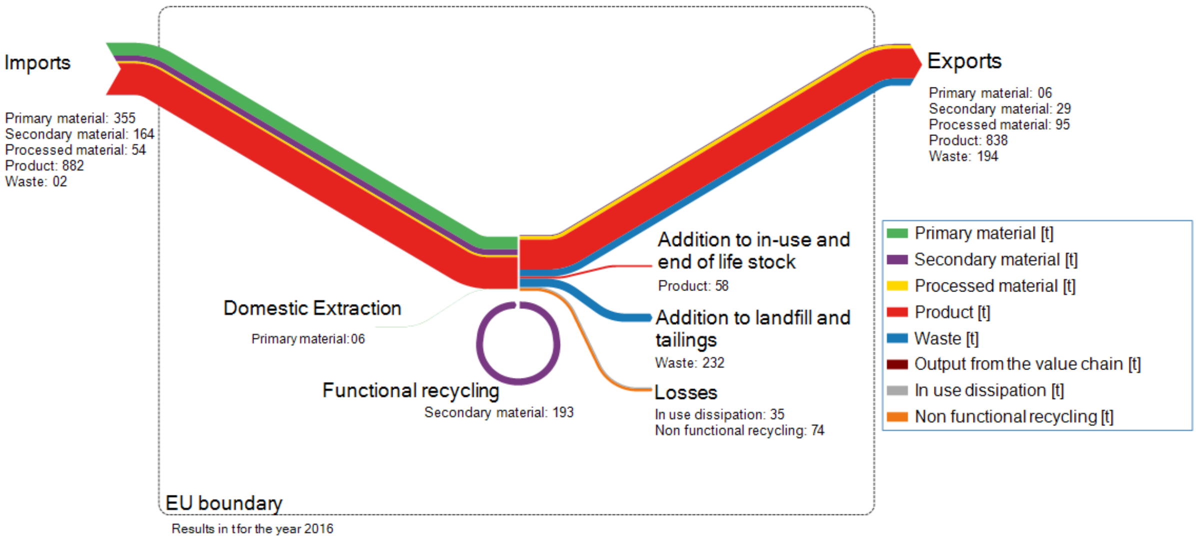

Figure 27. Simplified Sankey diagram for tantalum for the year 2016 in the EU (without the UK). Figure for functional recycling includes both new (108 t Ta) and old scrap (85 t Ta).

Input to EU tantalum refining sector (Processing stage) comes entirely from imports of tantalum primary raw materials (tantalum ores, syncon, tin slag) and secondary raw materials (scrap 2 t Ta, see Figure 26). The input is estimated at about 355 t Ta in primary material and 164 t Ta in secondary material, altogether equal to 519 t of Ta content in 2016 (see Figure 27 this includes also imports of secondary material sent to manufacturing of 44 t Ta) (Tantalum-Niobium International Study Center, 2019). Main importers are Germany, Estonia and France. Secondary tantalum from domestic scrap (old scrap, new scrap from semi-finished products fabrication as well as new scrap from finished products manufacturing, referring to "functional recycling" in Figure 26) is also an important input (193 t Ta content) for the production of tantalum processed materials.

The production of tantalum processed materials (tantalum oxides Ta_2O_5 and fluorides K_2TaF_7) in the EU amounted to 634 t of Ta, of which (data not shown) 95 t were exported ("export of processed material" in Figure 27). As Ta is extremely valuable, new scrap is entirely recycled (108 t Ta) so there is few remaining Ta in waste from EU production of refined tantalum sent to disposal (33 t Ta, within the waste in landfill in Figure 26) (Salus Mineralis, 2019).

The EU manufacturing, which is divided in several steps as described in Figure 25, was supplemented with imports of: i) tantalum processed materials (about 54 t Ta content); intermediate products such as Ta powders, ingots, mill products, carbides and chemicals (totalising 398 t Ta), semi-finished products such as capacitors, superalloys, chemicals, metals and alloys (totalising 188 t Ta) and 108 t of Ta in manufacturing scrap. While exports amounted 838 t Ta in intermediates, semi-finished products, finished products and products for re-use (137 t Ta). Overall, the amount of Ta in finished products in the EU was 555 t Ta content. The main end-use segments of Ta include electronic devices containing capacitors, aerospace applications containing superalloys, sputtering targets, mill products, cutting tools, optical, biomedical, metallurgical and other miscellaneous applications.

Figure 28 shows the distribution by end-use sector of Ta-containing finished products manufactured (pie-chart on left-hand side) and used (pie chart on right-hand side) in the EU.

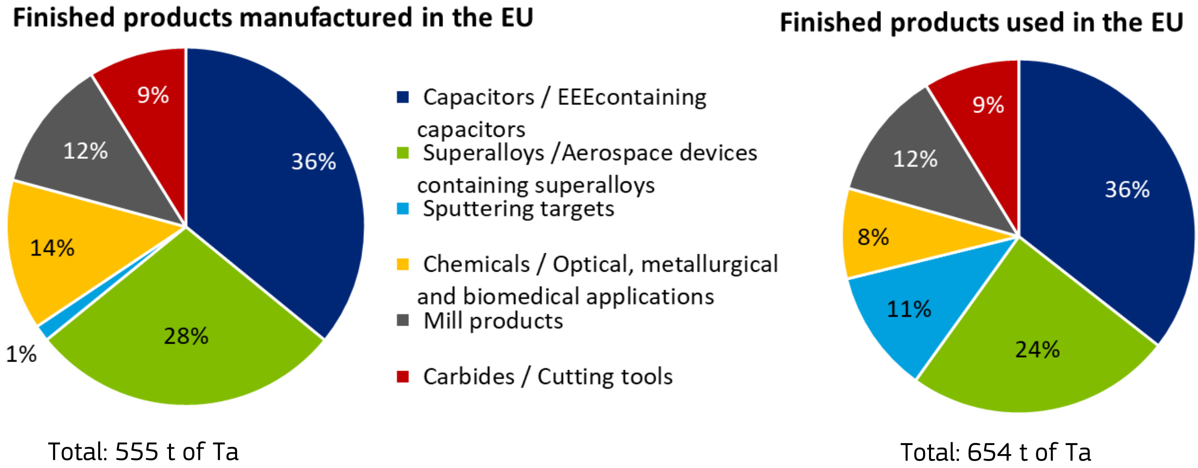

Figure 28. Shares of finished-products containing tantalum manufactured in the EU and shares of finished-products containing tantalum used in the EU (taking into account exports and imports of products).

On the basis of the total Ta inflow (654 t Ta) to use and lifespan distributions assumed for the main end-use segments of tantalum, about 58 t Ta were accumulated in the European in-use stock in 2016 (see Figure 27 – Addition to in-use and end of life stock). The total stock of products in-use is quantified at about 5 841 t Ta, in 2016.

The total output from use amounted at 559 t Ta, of which only 15% was collected and sorted for functional recycling in the EU (85 t). Overall, about 74 t Ta were lost in slags and 132 t disposed. The export of about 29 t Ta contained in old scrap and waste reduced the total amount of secondary Ta domestically processed.

9.3 Indicators

Table 11 summarises recycling and EU self-sufficiency indicators.

The collection rate is estimated to be 45% in 2016. As mentioned before the input to tantalum processing are supplemented by secondary tantalum forms including both new scrap and old scrap. In the EU in 2016 the ratio of old scrap consumed by the EU industry to the EU demand for tantalum in the manufacturing stage (end-of-life recycling input rate (EOL-RIR)) results in 13%. While the ratio of functional recycling of old scrap and tantalum collected results in 40% (end-of-life recycling rate (EOL-RR)).

Regarding self-sufficiency for tantalum the EU relies on imports for all life-cycle stages. The demand for primary tantalum cannot be met by domestic supply (no mine production and export of all syncon production) and entirely relies on imports of primary materials from outside the EU (about 355 t of Ta content, see Figure 27). The results demonstrate that the EU manufacturing capabilities are sufficient to cover the demand. The amount of tantalum consumed in the use phase (M3.1) is lower than what is manufactured in the EU (D1.1 and amount of semis and intermediates exported), resulting in a self-sufficiency higher than 100%. The EU imports Ta products but the trade balance is positive.

Table 23. Different indicators that describe the tantalum situation in the EU.

Indicator	Formula	2016
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	13%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	40%
Collection Rate	F1.4/(M4.1)	45%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	1%
Self-sufficiency Processing	C1.1/M2.1	52%
Self-sufficiency Manufacturing[7]	D1.1/M3.1	103%

9.4 Data sources, assumptions and reliability of results

The main sources of production and trade data are the World Mining Data (WMD, 2019b), the Tantalum-Niobium International Study Center (TIC, 2019), the British Geological Survey (BGS, 2011), the US Geological Survey (USGS, 2019), and the French Geological Survey (BRGM, 2015). Additional information was gathered from expert network reports in literature, such as MSP-REFRAM (MSP-REFRAM, 2016a), (MSP-REFRAM, 2016b) and SCRREEN (Lauri, 2018; Sundqvist et al., 2018) and expert communications (Salus Mineralis, 2019). Overall, basic extrapolation was applied to primary data to compute reliable estimates of tantalum flows and stock in the EU.

Due to lack of information, some assumptions based on average estimates were made for evaluating the characteristics of tantalum-containing products (lifetime, market share, end-of-life, trade, etc.). For this reason, higher uncertainty likely affects the estimate of tantalum flows at use and end-of-life. The feedback from validation workshop helped in confirming and improving the estimates made, which adds more robustness to the results.

[7] Manufacturing of Ta includes final products and semi-finished products. The self-sufficiency manufacturing indicator was calculated accordingly.

10 Material system analysis of Vanadium

10.1 Value chain

The main source of primary vanadium is from deposits of phosphate rock, titaniferous magnetite, and bauxite (as main or by-product). Titaniferous magnetite ore is identified as the most important source of vanadium, and the ore concentrate usually contains 1.0% to 1.5% V_2O_5 (Vanitec, 2019a). Vanadium may also be found in deposits of fossil fuels such as oil and coal. Most vanadium is produced as a by-product.

Vanadium is mainly produced from titaniferous magnetite (26% from titaniferous magnetite mines and 59% from vanadium slag generated during the processing of titaniferous magnetite ore in steel production), whereas the remainder (15%) is won from other resources (including catalysts and residuals of power plants fired with heavy oils) (Yang et al., 2018). Vanadium recovered from the recycling of vanadium slag and oil catalysts are primary sources of vanadium because vanadium is naturally present in titaniferous magnetite and in crude oil (enriched in dedicated processes) and extracted from these sources as by-product.

Secondary sources of vanadium include new scrap from manufacturing and old scrap from products at end of life. An example for new scrap is vanadium bearing steel scrap, in which vanadium is added during steel processing. This source is a limited contributor to vanadium supply.

Certain literature and data references consider vanadium production from vanadium slag or spent catalysts as secondary sources; however, this is considered as misleading, because these do no concern material recovered from vanadium recycling.

The main production route, vanadium from titaniferous magnetite, includes the crushing, ground screening and magnetic separation to remove the gangue material (Cardarelli, 2008). Vanadium oxide can be produced directly from titaniferous magnetite concentrate by applying the roast leach process; or indirectly, by using the reduction-smelting process.

In addition, vanadium contained in enriched steel slag is extracted through the pyrometallurgical route directly in the form of ferrovanadium (without vanadium oxide as intermediate material) (Yang et al., 2018). Finally, vanadium may be recovered from spent catalysts used for the refining of crude oil, and from fly ash got from heavy fuel combustion. Regarding the route of spent catalysts, vanadium is recovered after various roasting and precipitation steps (to remove carbon and sulphur content and then to separate various metals contained in the spent catalyst); with regard to fly ash, the extraction of vanadium occurs either by hydrometallurgical or pyrometallurgical route (Sundqvist et al., 2018).

From the vanadium oxide obtained through these various processing routes, the majority (80% worldwide) is used to produce ferrovanadium, which is incorporated in steel and alloy applications to increase the strength, hardness and fatigue resistance of steels and alloys, respectively. Vanadium oxide is also used directly in chemical applications.

The main end-uses of vanadium are in alloy steels, in particular high-strength low-alloy (HSLA) steels and special steels (for steel tools such as axles, crankshafts, etc.), as well as stainless steel. Vanadium is also used for the production of superalloys (used e.g. in jet engines) and of cast iron to gain rigid structures. Finally, vanadium oxide is used for chemical applications, as catalyst (in sulfuric acid and maleic anhydride manufacturing) or in pigments. It can also be used in energy storage as an alternative to Li-ion batteries. This application is still limited at moment.

Figure 29 presents the simplified value chain of vanadium and describes its main intermediates and end-uses.

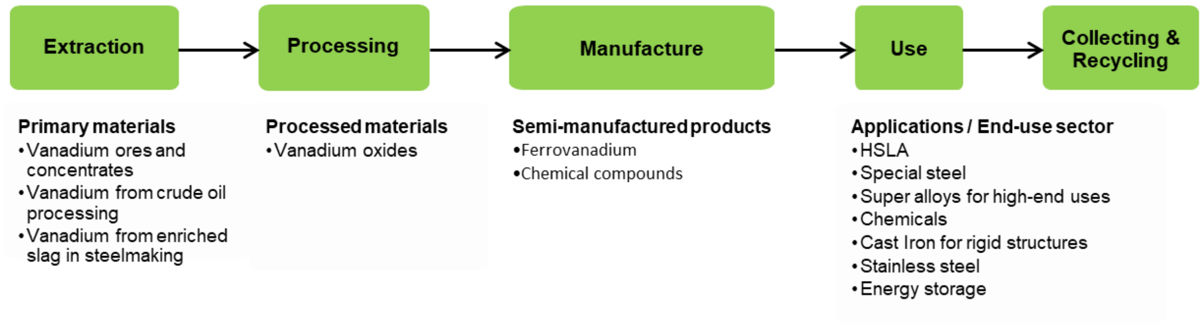

Figure 29. Value chain of vanadium.

10.2 Description of the main flows and stocks

Flows and stocks are accounted in mass of vanadium (kt V) and are representative of the year 2015. In 2016 the liquidation of a former main producer in South Africa resulted in reduced imports of vanadium contained in steel slags and ultimately led to an abrupt significant disruption in the European market supply and subsequently to a lower production of processed vanadium in European countries. 2016 can therefore not serve as reference year. It should be noted that the market changed dynamically following this disruption in 2016. The values presented here are not raw data but aggregated results.

Identified global resources of vanadium are estimated to be higher than 63 million tonnes. There is no data on the distribution of the global resources by country. Global vanadium reserves amount to 15 million tonnes of V content in 2015, mainly located in China (34%), Russia (33%), South Africa (23%) and Australia (12%) (USGS, 2019).

In 2015, the world vanadium production was 80 kt V content including at least part of vanadium recovered from by-products such as vanadium slag and refining and burning of heavy oils (WMD, 2019b). The top producer countries were China (53%), South Africa (22%), and Russia (20%), accounting for more than 95% of the global primary supply. The data of WMD is considered robust, despite being slightly higher than the related USGS and BGS data, which may aggregate values in V_2O_5 content and V content.

There is no aggregated estimate of vanadium resources in the EU (without UK). These are located in various countries (Bulgaria, Estonia, Finland, Poland and Sweden). Data is available only for Sweden, with historic resource estimates at 106 kt of V (24.6 million tonnes at 0.43% of V content) and inferred resources in the JORC reporting code estimated at 280 kt of V (140 million tonnes at 0.2% of V content) (Minerals4EU, 2015).

There are no current vanadium reserves in the EU, as for many countries these deposits are considered economically unviable (Bulgaria, Estonia and Finland) (Lauri, 2018).

There is no production of vanadium from ores and concentrates in the EU (Brown et al., 2018). A small share of vanadium extracted from by-products and used for vanadium oxide processing is considered to originate from European supply (about 1 000 t V content) (TTP Squared, 2019), see Figure 30.

Potential future sources of vanadium include vanadium contained in iron ore extracted in the EU, and land-filled without recovery of vanadium. This could represent up to 500 kt V content according to experts (Treibacher Industrie, 2019), however, such extraction is currently not economically viable.

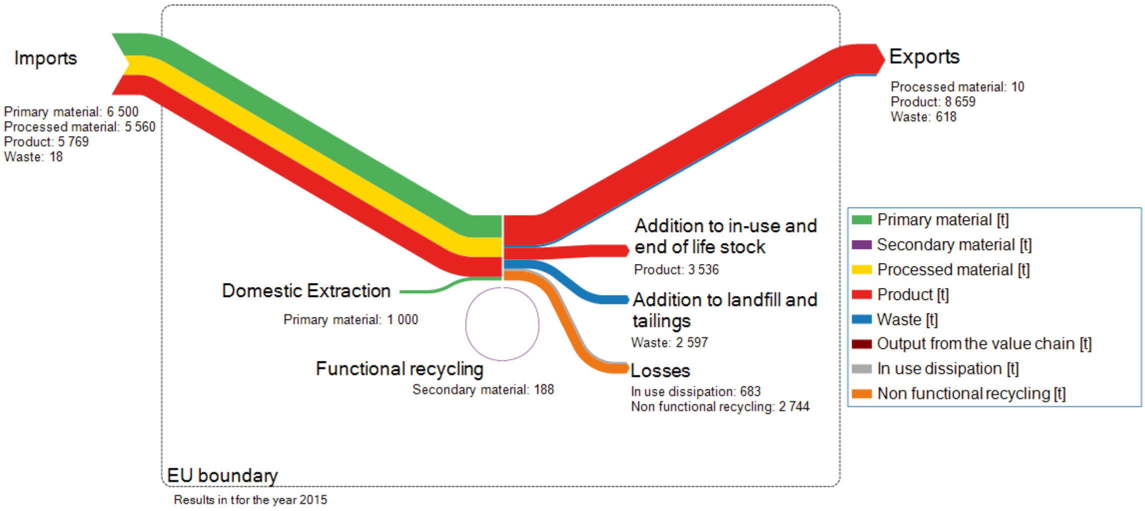

Figure 30. Simplified Sankey diagram for vanadium for the year 2015 in the EU (without the UK).

Input to EU vanadium processing comes mostly from EU imports of by-products (estimated at about 6.5 kt of V content in 2015, see Figure 30), including enriched steel slag, and from refining and burning heavy oils (TTP Squared, 2019). The importing countries are Austria and Germany, where the vanadium is processed. Secondary vanadium from domestic scrap is a small contributor (0.03 kt of V content in 2015). It is considered that there is no import of secondary vanadium in EU for the production of vanadium oxides, see Figure 30.

Production of vanadium oxides in the EU amounted to 6 kt of V content in 2015, of which only 0.01 kt of V content were exported outside of the EU, see Figure 30. Vanadium processing from steel slag and other by-products generated about 1.3 kt of V content in waste, disposed in the EU.

Imports of vanadium oxides (about 5.6 kt of V content in 2015, see Figure 30) supplemented the input for the manufacturing stage. About 96% of the vanadium oxide supplied to the EU was used for the production of ferrovanadium, an intermediate used in the manufacturing of end products. The EU was a net importer of ferrovanadium, with 1.6 kt of V content supplied in the EU in 2015. Ferrovanadium manufacturing generated about 0.5 kt of V content in waste disposed in the EU.

The overall EU vanadium content (in the form of ferrovanadium or vanadium oxide) supplied in end-products manufactured in the EU was estimated at about 13 kt of V content for 2015, a result consistent with literature sources (Vanitec, 2019b) and insight provided during the dedicated expert workshop. The main end-use segments of vanadium include HSLA steels (for instance in chassis parts of vehicles), special steels (e.g. in crankshafts), superalloys applications (e.g. for jet engines) and chemical applications (e.g. catalysts for sulphuric acid production). The other applications represent less than 5% of vanadium uses.

Figure 31 shows the distribution by end-use sectors of V-containing finished products manufactured (pie-chart on left-hand side) and used (pie chart on right-hand side) in the EU.

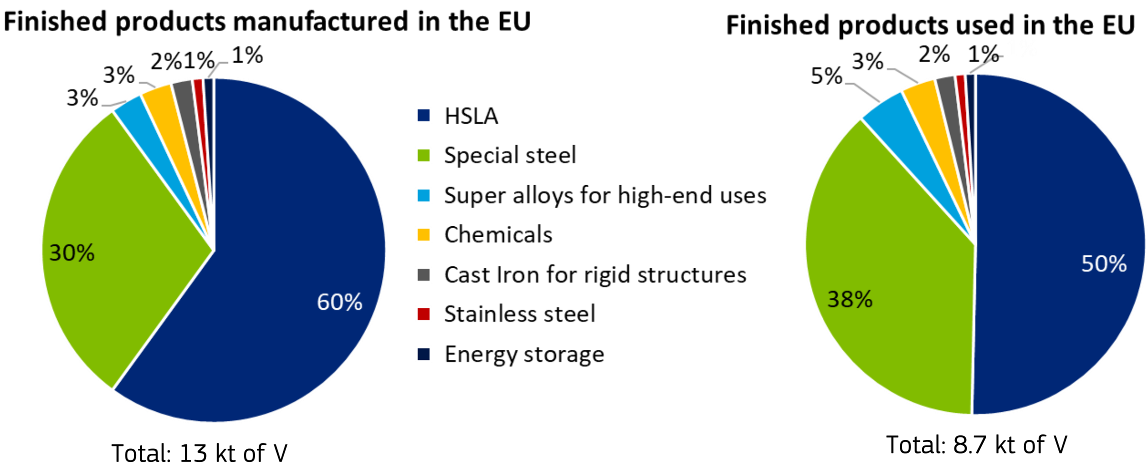

Figure 31. Shares of finished-products containing vanadium manufactured in the EU (left chart) and shares of finished-products containing vanadium in the EU (right chart) taking into account exports and imports of products.

On the basis of the total vanadium inflow (8.7 kt V) to use and lifespan distributions assumed for the products of the main end-use segments of vanadium, about 3.5 kt V were additionally accumulated in the EU in-use stock in 2015. The total stock of products in-use is estimated at about 147 kt V.

The total output from use amounted 4.4 kt V, of which only 4% effectively resulted in functional recycling in the EU (0.2 kt). Overall, about 2.7 kt V were practically lost in slags and 0.9 kt V disposed (due to inefficient collection and recycling waste), while in use dissipation amounted 0.7 kt V in 2015. The export of about 0.7 kt V contained in products at end-of-life (for reuse or waste treatment) reduced the total amount of vanadium available for domestic secondary processing.

10.3 Indicators

Table 12 summarises recycling and EU self-sufficiency indicators derived for vanadium.

Even with a collection rate of 74% of end-of-life products containing vanadium the majority of the vanadium recycled is lost during recycling. Secondary sources of vanadium from old scrap from products at end of life (e.g. vanadium bearing steel scrap, in which vanadium is added during steel processing) are limited contributors to vanadium supply in the EU. The EOL-RIR was calculated at 1% in 2015 and the ratio of functional recycling of old scrap and vanadium collected results in 27% (end-of-life recycling rate (EOL-RR)).

Table 24. Different indicators that describe the vanadium situation in the EU.

Indicator	Formula	2015
EOL-RIR	(G.1.1+G.1.2)/(B.1.1+B.1.2-B1.3+C.1.3+C.1.4+C1.8+D.1.3+D1.9+G.1.1+G.1.2)	1%
EOL-RR	(G1.1+G1.2+G1.3)/(E1.6+F1.2-F1.1)	27%
Collection Rate	F1.4/M4.1	74%
Self-sufficiency Extraction	(B1.1+B1.2)/(M1.1+M1.2)	13%
Self-sufficiency Processing	C1.1/M2.1	38%
Self-sufficiency Manufacturing[8]	D1.1/M3.1	188%

Regarding self-sufficiency the EU relies on imports of primary and processed materials. Only 13% of the demand for primary vanadium can be met by domestic supply and 38% of processed material consumed is produced in the EU. The EU manufacturing capabilities are sufficient to cover the demand of vanadium products

[8] Due to material specific application, manufacturing of V includes both final products and semi-finished products. The self-sufficiency manufacturing indicator was calculated accordingly.

in the use phase. The amount of vanadium consumed in the use phase (M3.1) is lower than what is manufactured in the EU (D1.1 and amount of semi-finished products exported), resulting in a self-sufficiency higher than 100%. The EU imports V products but the trade balance is positive.

10.4 Data sources, assumptions and reliability of results

The main sources of production and trade data are the World Mining Data (WMD, 2019b), the British Geological Survey (BGS, 2018), the US Geological Survey (USGS, 2019) and Eurostat, as well as TTP Squared (TTP Squared, 2019), Treibacher Industrie (Treibacher Industrie, 2019) and Vanitec (Vanitec, 2019a, 2019b). Additional information was gathered from expert network reports in literature such as SCRREEN (Lauri, 2018; Sundqvist et al., 2018; Yang et al., 2018), (Brown et al., 2018) and expert communications. Overall, basic extrapolation was applied to primary data to compute reliable estimates of vanadium flows and stock in the EU.

Due to lack of information, some assumptions based on average knowledge were made for evaluating the characteristics of vanadium-containing products (lifetime, market share, end-of-life, trade, etc.). For this reason, higher uncertainty likely affects the estimate of vanadium flows at use and end-of-life. The feedback from validation workshop helped in confirming and improving the estimates made, which adds more robustness to the results.

11 Conclusions

This section presents the conclusions for each MSA study and discusses also the main results achieved across several selected key applications.

The MSA of **baryte** revealed that the EU is dependent on imports of baryte, in particular on primary and intermediate forms (e.g. natural barium sulphate and barium carbonate). The EU is an established manufacturer of Ba products and demand for filler applications and chemical applications is satisfied by domestic production (imports are lower than exports). For weighting agent products, 5% of the consumption in the use phase is fulfilled with imported Ba products. Today there is no functional recycling able to decrease the dependence of barytes from outside sources.

The MSA of **bismuth** showed that the EU is dependent on imports of bismuth in all life cycle stages and in particularly of processed materials (unwrought bismuth, bismuth powders, bismuth waste and scrap). Both EOL-RIR and EOL-RR are considered to be null due to the fact that there is no identified source of secondary bismuth (from old scrap) and most of the applications are dissipative (e.g. for the pharmaceutical or the cosmetic industries).

Data on **hafnium** is scarce due to small number of stakeholders operating in the global market. However, the results demonstrate that the EU relies on imports for extraction and is self-sufficient for processing and manufacturing stages. The demand for processing material, superalloys in gas turbines, for plasma cutting tips and for nuclear control rods is lower than the EU processing/manufacturing capacities (imports are smaller than exports). This is mainly due to the existence of hafnium refinery capabilities in France (Framatome). For superalloys in aircraft jets and other applications (e.g catalysts, semiconductors and optical coatings) the 20% of the EU demand is achieved thought imports. The EOL-RIR of hafnium in the EU is in the range of 0-1%.

For **helium** only 12% of the demand is domestically produced in the EU. The majority of the uses of helium are dissipative, which leads to a low EOL-RIR of 1% (comparing this refilling amount with the total helium input to the EU).

Regarding **natural rubber** there is no EU production of both primary and processed forms, therefore the import reliance of this stages is 100%. The main applications of natural rubber are tyres (74%) and general rubber goods (26%). The EU has an established manufacturing of natural rubber products, producing 79% of the products consumed. The EOL-RIR and EOL-RR is lower than 1% because only a small portion of the natural rubber input is used in some tyres and functional recycling in GRG is also very low.

The EU has also no processing capacity to produce **elemental phosphorus P_4** and is fully dependent on imports of P_4 and its derivatives. These imports supply the EU manufacturing industry that is able to produce more than what it requires in terms of finished phosphorus products. There are several technological developments that may allow to recycle P_4 from waste streams in the future. However, currently there is no industrial scale recycling of phosphorus with the characteristics that allow for the substitution of P_4 in the EU manufacturing.

For **scandium** the EU is dependent on imports along the life cycle, in particular at the extraction phase because of missing Sc extraction in the EU. The collection rate of Sc is high (87%) due to high collection efficiencies for Al-Sc alloys but, as the recovery of Sc from these products is very limited, its functional recycling is almost null (EOL-RIR <1% and EOL-RR 2%).

The MSA of **tantalum** depicts a high EU dependency on imports because there is no mine exploration in the EU and all the syncon production in France is exported. The processing stage also relies on imports to fulfil the EU demand: half of the demand of the processing products was produced internally. EU manufacturing is able to cover the EU necessities. From all the materials analysed, tantalum is the only material where the recycling of new scrap and old scrap are important supplements to the manufacturing input. These contributions resulted in an EOL-RIR of 13% and an EOL-RR of 40%.

The MSA of **vanadium** revealed a high EU dependency on imports of primary material at both extractive and processing stage. The domestic extraction represented 13% of the total input of vanadium to the EU processing. The demand for vanadium in EU consumption of finished products was mainly satisfied by domestic manufacturing, which is well established in the EU. The contribution of recycling from old scrap to the EU vanadium supply is minor, representing only 1% of the total input (EOL-RIR).

The materials analysed show a very strong dependence on imports along the value chain: They are all highly dependent on imports of primary materials and intermediate products. The EU has a consolidated manufacturing stage for all the materials analysed (self-sufficiencies higher than 72%) except for helium (12%). For barytes, hafnium and vanadium the EU manufacturing capacity surpasses the EU demand.

The EU is efficient in collecting end-of-life products for all the materials analysed (collection rate higher than 34%), however the targeted materials are lost due to in-use dissipation, non-functional recycling or in recycling waste streams. This indicates that the EU is not yet able to decrease its dependency of primary material using secondary materials domestically recycled. However, for some materials (e.g. elemental phosphorus) significant efforts are undertaken to change this situation in the future and improve the EU circularity (ESPP, 2020). Additionally, the stocks in use may become another potential source of raw material in the future with the development of recycling technologies.

There is still room for improving the MSA methodology. During the development of the current MSA studies the project team encountered the necessity to increase the detail in the processing and manufacturing stages, as several materials require more than one step in those stages. Therefore, it is recommended to add substages to manufacturing and processing including also the necessary trade flows of intermediate materials and products in the Sankey diagram.

The developed MSAs here summarised are comprehensive datasets that may provide crucial knowledge to help the development and monitoring of EU polices. In fact, data gathering and results of this MSA study contributed to the creation of the 2020 list of critical raw materials for the EU (European Commission, 2020e). The new EU Industrial Strategy (European Commission, 2020b), the Green Deal transition plan (European Commission, 2019), and the EU Circular Economy Action Plan (European Commission, 2020c) all benefit from the analyses on materials undertaken since the EU Raw Materials Initiative (European Commission, 2008).

Although the main conclusions of the present report clearly concern the nine individual materials, it makes sense to enlarge the discussion and discuss implication and learnings of these MSAs for various sectors, as was for example done for the five MSA studies of battery raw materials (Matos et al, 2020). Figure 32 shows the distribution of the nine targeted materials in a selection of four key applications (as the more relevant in relation to the current policy actions) it highlights that: chemicals market dominates the applications of bismuth; rubbers and plastics dominate the applications of barytes and natural rubber; half of the hafnium processed in the EU is used in superalloys, as well as the majority of Scandium, while tantalum applications are divided between superalloys and electrical equipment. The technological developments expected for the future may change these scenarios: one good example is the projected increase in the demand of batteries which can increase the uses of white phosphorus in $LiFePO_4$ electrodes and increase the demand of vanadium in energy storage, as an alternative to lithium. It also shows the potential for inter-sectoral competition for certain raw materials, especially in the event of supply disruptions.

This Figure 32 also shows the relevance of the MSA studies not only for raw materials policies but also for several sectorial initiatives in the EU. For example: 1) knowledge regarding the flows of chemical products in the EU could be important for the future Chemicals Strategy for Sustainability (European Commission, 2020a); 2) information of the whereabouts of rubber and plastic could be important to the EU strategy for plastics in a circular economy (European Commission, 2018a); 3) superalloys are important to aerospace and decarbonisation technologies that are important both for the EU Space Programme (European Commission, 2020b) and the Green Deal (European Commission, 2019); and 4) information on the flows of materials used in electrical equipment is important for the digitalisation of the EU industry and services (European Commission, 2020b) and for the strategic action plan for batteries (European Commission, 2018b). The present MSA results could potentially be used to support future policy initiatives in these areas.

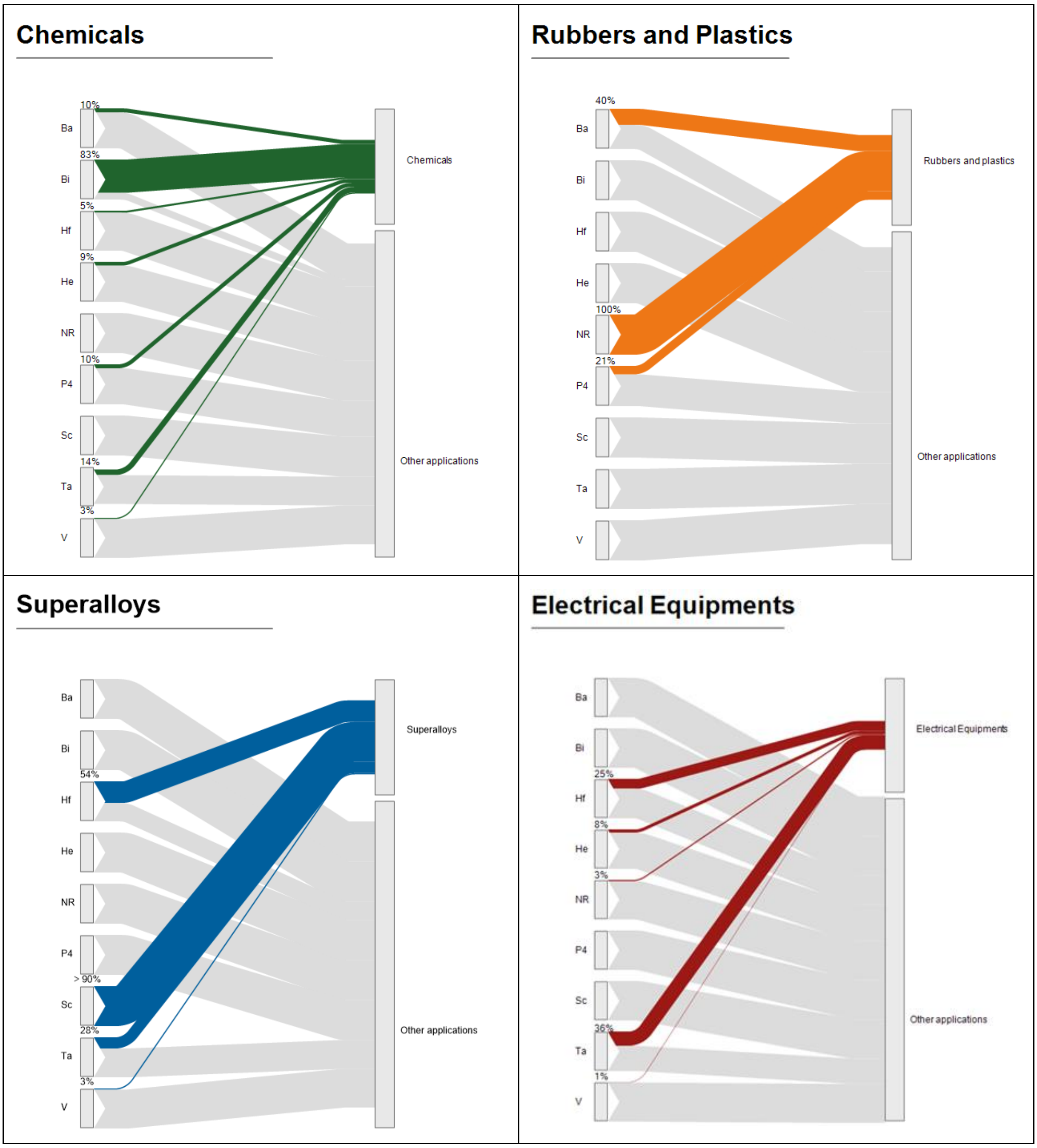

Figure 32. Distribution of the uses of the targeted materials in four applications: chemicals, rubber and plastics, superalloys and electrical equipment.

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List of abbreviations

Ba	Baryte
BGS	British Geological Survey
BRGM	French Geological Survey
Bi	Bismuth
EOL	End-of-life
EOL-RR	End-of-life recycling rate
EOL-RIR	End-of-life recycling input rate
ESPP	European Sustainable Phosphorus Platform
ETRMA	European Tyre & Rubber Manufacturers Association
GRG	General Rubber Good
Hf	Hafnium
He	Helium
HSLA	High-strength low-alloy
MRI	Magnetic Resonance Imaging
MSA	Material System Analysis
NR	Natural rubber
P	Elemental phosphorus
Sc	Scandium
SOFC	Solid Oxide Fuel Cell
Ta	Tantalum
TIC	Tantalum-Niobium International Study Center
USGS	United States Geological Survey
V	Vanadium
WMD	World Mining Data

Annexes

Annex 1. Material Flow/Stock Parameters

Table A1. List of material flows and stocks parameters.

Material Flow/Stock Parameter
A.1.1 Reserves in EU A.1.2 Reserves in ROW
B.1.1 Production of primary material as main product in EU B.1.2 Production of primary material as by product in EU B.1.3 Exports from EU of primary material B.1.4 Extraction waste disposed in situ/tailings in EU B.1.5 Stock in tailings in EU M.1.1 Material send to processing in the EU M.1.2 Primary material send to manufacturing
C.1.1 Production of processed material in EU C.1.2 Exports from EU of processed material C.1.3 Imports to EU of primary material C.1.4 Imports to EU of secondary material C.1.5 Processing waste in EU sent for disposal in EU C.1.6 Exports from EU of processing waste C.1.7 Output from the value chain C.1.8 Imports of semi-processed material send to processing in the EU M.2.1 Processed material send to manufacturing
D.1.1 Production of manufactured products in EU D.1.2 Exports from EU of manufactured products D.1.3 Imports to EU of processed material send to manufacturing
D.1.4 Manufacture waste in EU sent for disposal in EU D.1.5 Manufacture waste in EU sent for reprocessing in EU D.1.6 Exports from EU of manufacture waste D.1.7 Output from the value chain D.1.8 Imports to EU of products requiring further manufacturing steps in the EU D.1.9 Imports of secondary material send to manufacturing in the EU M.3.1 Manufactured products send to use in the EU
E.1.1 Stock of manufactured products in use in EU E.1.2 Stock of manufactured products at end-of-life that are kept by users in EU E.1.3 Exports from EU of manufactured products for reuse E.1.4 Imports to EU of manufactured products E.1.5 In use dissipation in EU E.1.6 Products at end-of-life collected for treatment in EU E.1.7 Annual addition to in-use stock of manufactured products in EU E.1.8 Annual addition to end-of-life stock of manufactured products at end-of-life that are kept by users in EU M.4.1 Products at end-of-life in EU collected for treatment
F.1.1 Exports from EU of manufactured products at end of life F.1.2 Imports to EU of manufactured products at end of life F.1.3 Manufactured products at end-of-life in EU sent for disposal in EU F.1.4 Manufactured products at end-of-life in EU sent for recycling in EU F.1.5 Stock in landfill in EU F.1.6 Annual addition to stock in landfill in EU
G.1.1 Production of secondary material from post-consumer functional recycling in EU sent to processing in EU G.1.2 Production of secondary material from post-consumer functional recycling in EU sent to manufacture in EU G.1.3 Exports from EU of secondary material from post-consumer recycling G.1.4 Production of secondary material from post-consumer non-functional recycling G.1.5 Recycling waste in EU sent for disposal in EU

Annex 2. Workshop attendance list

Table A2. List of organisations participating in the barytes workshop.

Organisation	Country
University of Geneva	Switzerland
Universidad de Salamanca	Spain
Euromines	Belgium
Independent consultant	United States

Table A3. List of organisations participating in the bismuth workshop.

Organisation	Country
University of Geneva	Switzerland
Stena Recycling International	Sweden
Universidad de Salamanca	Spain
Euromines	Belgium

Table A4. List of organisations participating in the hafnium workshop.

Organisation	Country
VTT Technical research Centre of Finland Ltd	Finland
Euromines	Belgium
Alkane	Australia

Table A5. List of organisations participating in the helium workshop.

Organisation	Country
Air Liquide	France
Irish Centre for Research in Applied Geosciences (iCRAG)	Irland
Euromines	Belgium

Table A6. List of organisations participating in the natural rubber workshop.

Organisation	Country
International Rubber Study Group	Singapore
Continental AG	Germany
ETRMA	Belgium

Table A7. List of organisations participating in the elemental phosphorus workshop.

Organisation	Country
Clariant	Germany
Cefic	Belgium
MIT Metallurgy & Inorganic Technology	Austria
Italmatch	Italy
Italmatch	Germany
Prayon	Belgium
Fosfa	Czech Republic
Proman	Germany
Lanxess	Germany
PCC Group	Poland
Zschimmer & Schwarz	Germany
European Commission	Belgium
Perimeter solutions	Germany
European Crop Protection Association	Belgium
Bozzetto Group	Italy
BASF	Germany
University of Leoben	Austria
ICL group	Germany
WS consulting	Netherlands
Clariant	Germany
University of Amsterdam	Netherlands
European Sustainable Phosphorus Platform	Belgium
Febex	Switzerland

Table A8. List of organisations participating in the scandium workshop.

Organisation	Country
Bundesanstalt für Materialforschung und -prüfung (BAM)	Germany
Mytilineos S.A., Metallurgy Business Unit	Greece
Brunel University, London	United Kingdom
University Swinburne	Australia
Platina Resources Ltd.	Australia
Fachhochschule Nordwestschweiz (FHNW)	Switzerland
Rusal	Russia
II-VI Performance Metals Division	United States
KBM Affilips B.V., Master alloys R&D	Netherlands
TANIOBIS	Germany
Scandium International Mining Corp.	Belgium

Table A9. List of organisations participating in the tantalum workshop.

Organisation	Country
Tantalum-Niobium International Study Centre (T.I.C.)	Belgium
Eurometaux	Belgium
European Copper institute	Belgium
ORANO TN	France
BRGM	France
Sinergeo.pt	Portugal
Euromines	Belgium

Table A10. List of organisations participating in the tantalum workshop.

Organisation	Country
Tantalum-Niobium International Study Centre (T.I.C.)	Belgium
World Mining Data	Austria
BRGM	France
JULIENNE RESOURCES	France
TREIBACHER INDUSTRIE AG	Netherlands
Euromines	Belgium

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