SCRREEN
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Solutions for CRitical Raw materials - a European Expert Network

REPORT ON THE FUTURE USE OF CRITICAL RAW MATERIALS

AUTHOR(S):
LUIS TERCERO ESPINOZA, ANTONIA LOIBL, SABINE LANGKAU (FRAUNHOFER ISI)
ARJAN DE KONING, ESTER VAN DER VOET (LEIDEN UNIVERSITY)
SIMON MICHAUX (GTK)

CONTRIBUTIONS

Fraunhofer ISI: Framework of the deliverable, introduction, context of the work, link to WP 2.1 and 2.2, profiles for cobalt, neodymium, dysprosium, platinum, palladium & rhodium, integration.

Leiden University: Profiles for gallium, indium, niobium, tantalum & tungsten.

GTK: Profiles for barytes, magnesium and phosphate rock.

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INTRODUCTION

Ensuring a sufficient raw material supply to meet demand is an economic necessity. In the context of the Raw Materials Initiative (RMI), the term "critical" is introduced for raw materials that: (1) have a significant economic importance for key sectors while (2) suffering from high supply risks and (3), for which there is a current lack of substitutes (Commission of the European Communities 2008). Through a series of exercises (European Commission 2011, 2014c, 2017a), lists of critical raw materials (CRM) have been prepared for the EU using two basic methodologies in an effort to provide up-to-date focus points for policy and industry action to secure the supply of raw materials necessary for the European economy.

Useful for highlighting risks as the CRM lists are, it remains necessary to dive into the individual details of each raw material market in order to understand the issues and develop adequate risk mitigation strategies at the appropriate levels (from R&D funding by national governments to product design or short-to-medium term stockpiling by individual companies). Furthermore, CRM lists are generally data-driven/backward-looking in their methodology. Therefore, it becomes necessary to supplement lists of CRM with additional, especially forward-looking information (European Commission 2017b; cf. European Commission 2010, 2014a). The Minerals4EU project prepared a simplified overview of the factors to consider for an understanding/modelling of raw materials markets and for sketching *future* raw materials supply and demand (Wittmer und Sievers 2015), as shown in Figure 1.

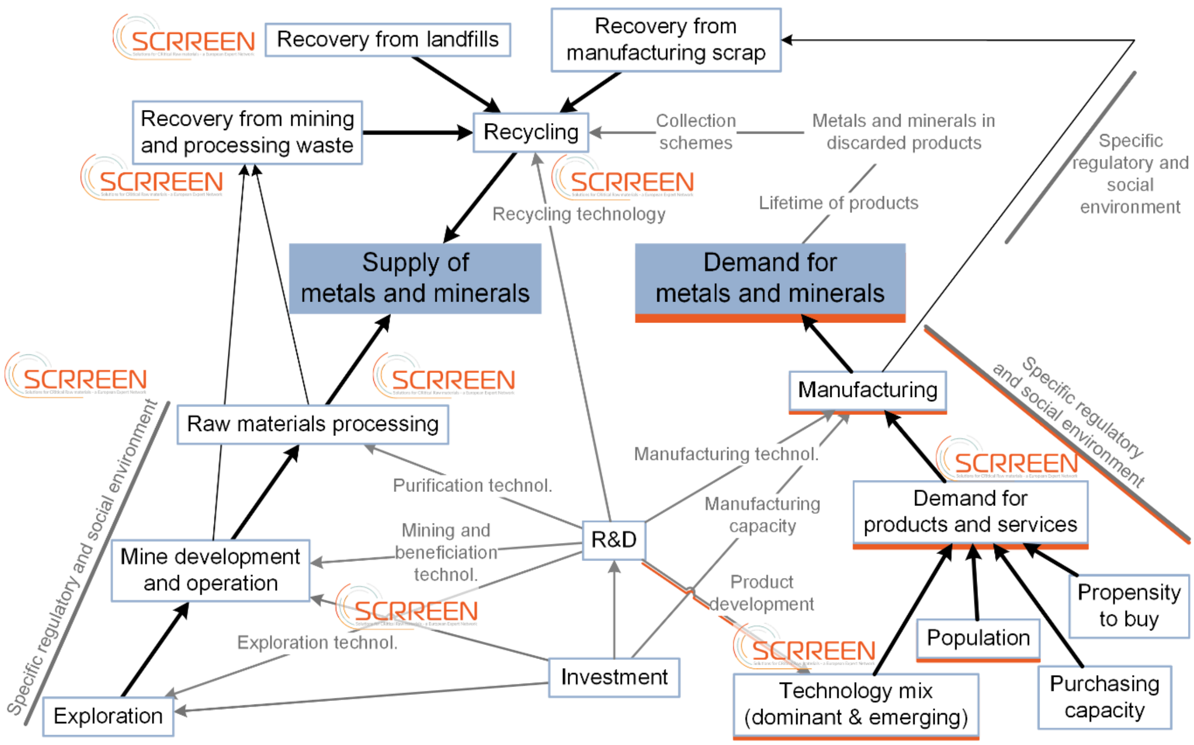

Figure 1: Simplified sketch of the dynamic relationships between different aspects of raw materials supply and demand. The Work Packages of the SCRREEN project are roughly located in the picture. The focus of this report is on the demand of raw materials (underlined in orange). Figure modified from Tercero Espinoza und Wittmer (2015).

This report is the third and last Deliverable in Work Package 2 and follows both on the work done in Minerals4EU and that described in D2.1 "Report on the current use of critical raw materials" and D2.2 "Report

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on major trends affecting future demand for critical raw materials" of the SCRREEN project. The objective is to provide a framework for estimating critical raw material needs for the EU for a time horizon of 10-20 years and to apply this framework to selected critical raw materials.

PROVIDING CONTEXT TO THE WORK

A variety of factors is known to influence demand for raw materials such that it is not possible to precisely determine what demand will be in the future. Nevertheless, it is necessary to estimate what developments in demand or different raw materials are possible and to decide which of these developments need exceptional action in order to focus political and industrial measures. Delivering on the first point, the generation of quantitative scenarios for raw material demand (and supply) has become an established tool (Hoenderdaal et al. 2013; Sverdrup et al. 2015; Marscheider-Weidemann et al. 2016). The second point, i.e. deciding whether a development is "normal" or "extraordinary", is still an open issue in the literature and work was undertaken within SCRREEN to close this gap and to better elucidate the different influences that lead to changing demand for raw materials over time. This work, focusing on metals and published by Langkau und Tercero Espinoza (2018), is briefly presented below. The limitation to metals follows from practical considerations of data availability. The relevance of metals as critical raw materials is undisputed; however, the criticality of other types of raw materials (industrial minerals, biotic materials) is by no means questions by this limitation of scope.

SUMMARY EXAMINATION OF DEMAND CHANGE IN THE PAST

As sketched in Figure 1, factors such as world population, disposable income, regulations, incentives, policy, trade regimes, prevalent-technology mix, etc. affect the demand for raw materials in general and for metals in particular. Many researchers have made the observation ("intensity of use" hypothesis) that the expansion of manufacturing and construction by industrialization causes the intensity of metal use to rise with GDP in low-income countries while shifting consumer preferences in higher-income countries cause per-capita demand to stagnate (Roberts 1990; Stürmer 2013; Pei und Tilton 1999). However, as Crowson (2017) points out, the intensity of use hypothesis alone is not sufficient to explain development in material demand as it neglects the influence of technological change. Especially in the case of metals, the influence of technological change in end-use applications may also be significant and has gained particular attention. In particular, an exceptional increment in demand due to emerging technologies is considered likely for the so-called "technology metals" (Hoenderdaal et al. 2013; Marscheider-Weidemann et al. 2016; Moss et al. 2011; Moss et al. 2013; e.g. indium, germanium, gallium, rhenium, selenium or rare earths; Blagoeva et al. 2016).

In addition to the emergence of new technologies (including their invention, innovation and diffusion), continual improvement of technologies is a constitutive part of technological change (Pei und Tilton 1999). Continual improvement of production technologies is generally connected with a decrease in costs (e.g. for labour, energy, material), which tends to make products less expensive and more accessible to consumers, possibly leading to higher overall demand. In the case of improved material efficiency, a decrease in metal demand could be expected but this may be counteracted or even overcompensated by increased demand for the (now cheaper) products—the so-called "rebound effect" (Pfaff und Sartorius 2015). Furthermore, technological change (in the shape of emerging technologies as well as continually improved technologies) also includes enhancements of recycling and other aspects of a circular economy, which lead to a reduced primary demand for materials. Finally, new technological developments do not necessarily mean their raw material

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requirements are additive to that of established applications. Instead, the introduction of new technologies can also result in the substitution of an established technology, possibly shifting raw material requirements to a different set of raw materials.

Consequently, technological change can have increasing effects on demand for some materials and, at the same time, decreasing effects for others. Therefore, a better understanding of the development of metal demand over time requires a combination of aspects of GDP growth, changes in consumer preferences and gradual as well as radical technological change. As a first approach to examine all factors at once, the relative change in global primary production for 30 metals over 21 years (1993–2013) is shown in Figure 2 as a proxy for demand development within this period.

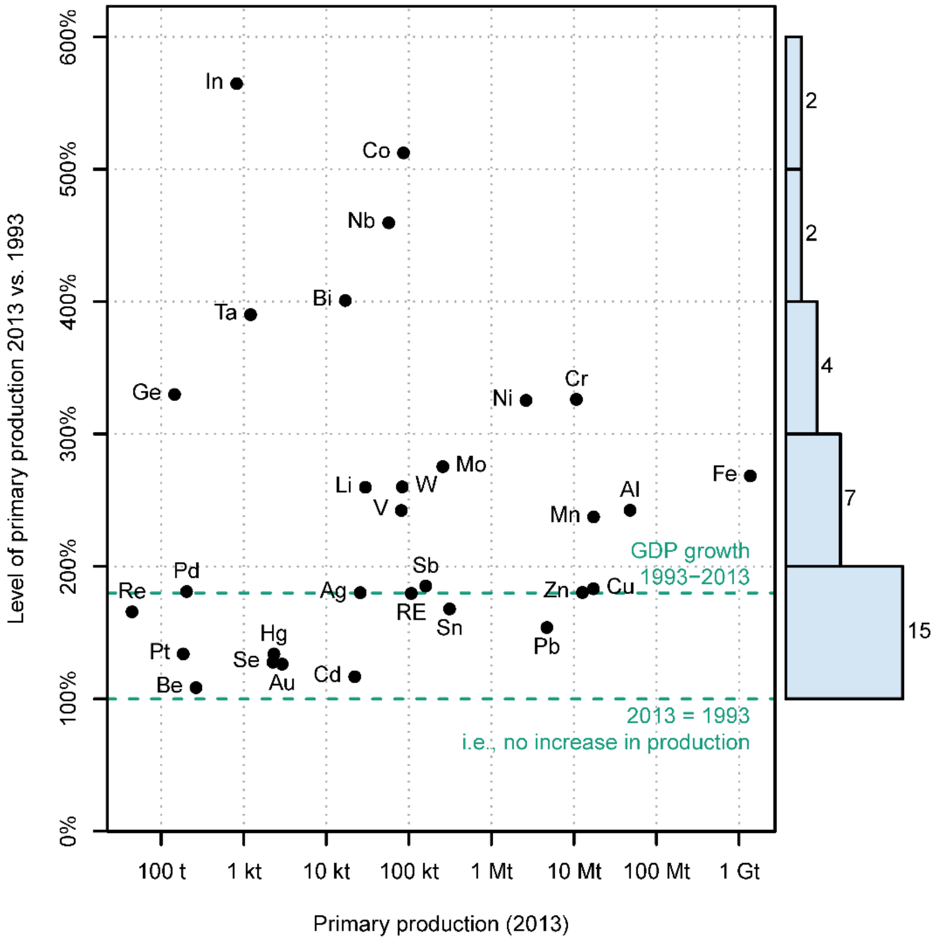

Figure 2: Relative increase in primary production of 30 metals. Units: t = metric tons, kt = thousand metric tons, Mt = million metric tons, Gt = billion metric tons; GDP growth in constant 2010 US$. Figure taken from Langkau und Tercero Espinoza (2018).

Examination of Figure 2 reveals that, while primary production for none of the metals has decreased, the degree of increase is largely variable: from essentially zero (Be) to more than 500 % of the original level (In and Co) while the world economy grew to approximately 180 % of its level in the time period considered. The histogram on the right of Figure 2 shows the count of raw materials falling in each interval.

Half of the metals (15 of the 30 metals considered) increased to less than 200 % of their total production in 1993 by 2013. Therefore, they increased in a similar manner to GDP or less than GDP. Note that this group

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comprises metals with a total primary production ranging from small (< 10 kt) over medium (< 1 Mt) to large (> 1 Mt) total size. The same is to be noticed for the 15 metals that experienced significantly stronger growth than GDP (intensity of use above 1). However, for all five metals having a ratio of $demand_{2013}/demand_{1993}$ of about or more than 400 % (tantalum, bismuth, niobium, cobalt and indium), the total primary production is <100 kt. Therefore, this level of increase in primary production (as a proxy for demand) appears exceptional (five out of 30, < 20 %). Furthermore, combined with the information on market size, this result appears to substantiate the intuition that small or medium size makes a metal market more prone to exhibit exceptional growth due to emerging technologies, while larger metal markets (more than 1 Mt) can buffer demand peaks due to emerging technologies more easily. However, nine metals (Pd, Ag, Re, Hg, Pt, Se, Au, Cd and Be) with market sizes<100 kt grew to less than 200 % of their 1993 levels by 2013. Therefore, a small to medium size and association with nascent and emerging technologies (e.g. Pt and Pd with autocatalysts and fuel cells) are not sufficient to trigger outstanding demand growth.

INFLUENCE OF TECHNOLOGICAL CHANGE ON CHANGING DEMAND

Nine metals—covering a broad range of values in relative change in demand between 1993 and 2013 and having reasonably complete data series obtainable from published sources—were selected for more in depth examination in order to better explore the connection between technological change and demand growth. The selected metals were In, Co, Li, Al, Co, Sn, Ag, Pt, and Pd and their demand time series are shown in Figure 3. The data series encompass the period 1993–2013, as was the case for the primary production data shown in Figure 2. Note, however, that Figure 2 and Figure 3 are not directly comparable because, for some metals, recycling is also considered in Figure 3 (see caption for more details). The conclusions drawn on the trends for each metal remain nevertheless valid.

While it is clear that past developments cannot simply be transferred or extrapolated to future estimations, learning as much as possible from the available knowledge of historic developments is an established approach in scenario-based science on future developments (Gerhold et al. 2015). In this regard, the work described here aims to contribute to the development and interpretation of future scenarios of metal demand by improving our basic understanding of historic developments.

CLOSE TO STAGNATION: SILVER, PLATINUM AND PALLADIUM

The demand for Ag for industrial applications increased only by about 45 % from 1993 to 2013. This comparably small increase can be attributed to the decreasing use of Ag-ions in photography due to digitalization. In fact, the demand for silver in photography decreased to approximately 1/4 of its value in 1993. Hence, the development of silver demand for photography is a good example for decreasing demand due to substitution of a technology as part of technological change. A comparatively strong growth in coins and medals partly compensated for the decline of silver use in photography, but was not enough to offset it completely. All other applications grew about or less than overall economic growth.

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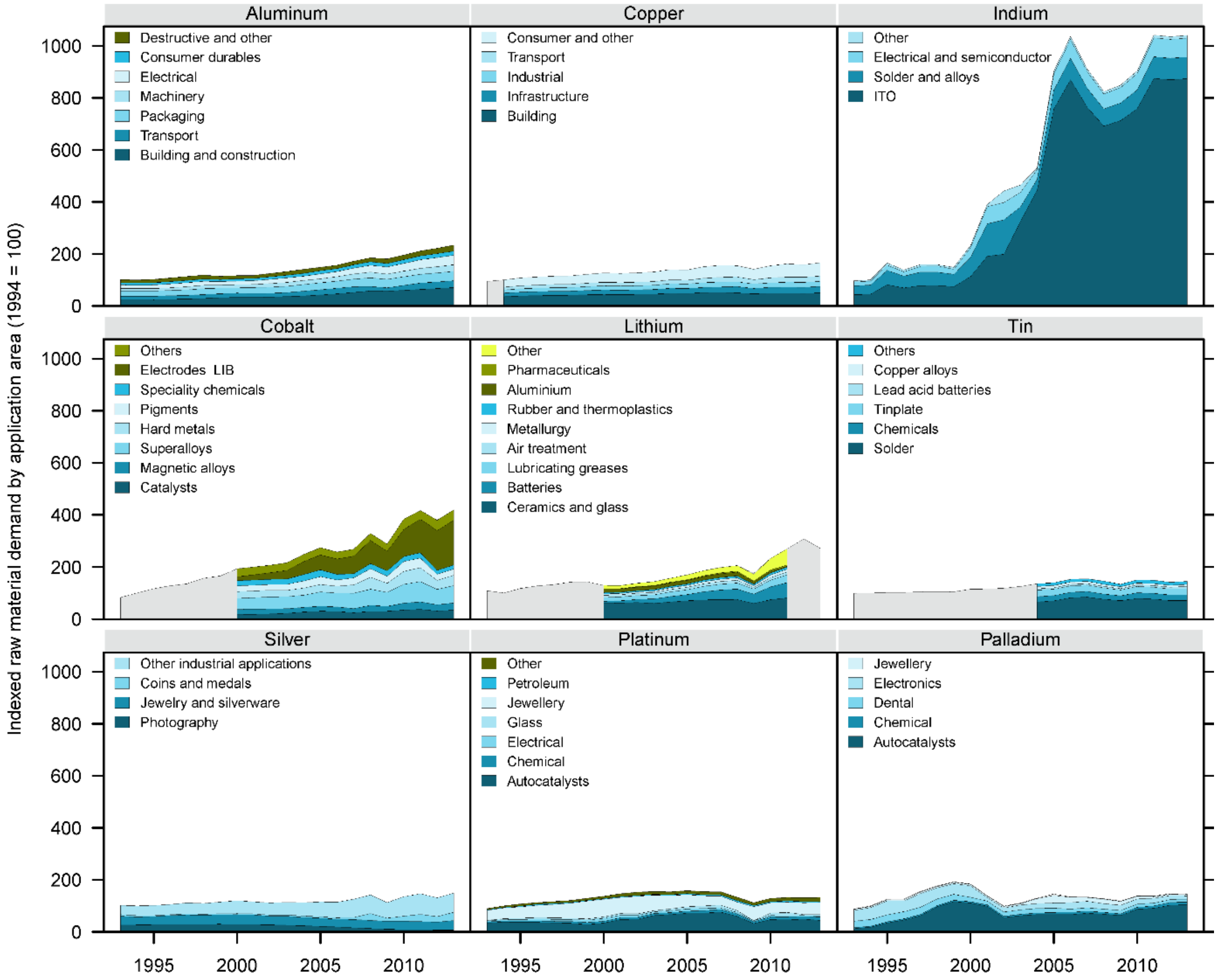

Figure 3: Demand trends for selected raw materials. The numbers for aluminum, copper, indium, tin and silver include demand for both primary and secondary material (i.e. including recycling of old and new scrap) whereas the numbers for cobalt, lithium, platinum and palladium are for primary material only. Figures for platinum and silver only cover physical demand for industrial applications. Figure taken from Langkau und Tercero Espinoza (2018).

Similarly, physical demand for industrial applications for Pt and Pd increased only by ≈ 50 and 70 %, respectively, between 1993 and 2013. There are at least two important factors to consider when putting these numbers into context. First, Pd can substitute for Pt in different applications, though generally at the expense of performance. Since Pt is more expensive, there have been extensive attempts to reduce the demand for Pt by using the less expensive Pd in various ways and with different success for decades. Second, the high price of Pt and Pd is a strong incentive for promoting efficiency (reduced material intensity per unit) and recycling. As a result, growth in most applications for both Pt and Pd ranges from contracting (e.g. dental and electronic uses) to essentially stagnating (jewellery, electrical uses). Only demand for Pt and Pd for catalysts increased more than overall economic growth. The single most significant driver of demand increase for Pt and Pd in the period under consideration was, therefore, autocatalysts.

The impact of recycling becomes clear when comparing the development of demand with and without the demand for secondary supplies (Johnson Matthey 2018a). When considering the demand for primary production only, the demand of Pt and Pd for catalysts in 2013 appears to be 340 % of the demand in 1993.

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Including demand for recycled supplies, however, leads to a ratio of $demand_{2013}/demand_{1993}$ = 420 %, i.e. recycling significantly mitigated the increase in demand for primary material.

SURPRISINGLY SLOW GROWTH: LITHIUM AND TIN

It appears initially surprising that overall Li demand “only” doubled between 1993 and 2013. This is especially surprising when considering that lithium ion batteries (LIB) became dominant for portable electronic devices within this period and that a LIB contains approx. 4 % Li by weight (TUBAF 2013), which led to an increase in demand for this application by a factor of $\gtrapprox 7$ between 2000 and 2011. However, not all end-use applications of Li grew in a similar manner in the period under consideration. Noteworthy is the almost 5-fold increase in the “other” category, which unfortunately cannot be elucidated further. The use of Li in pharmaceuticals also increased significantly ($demand_{2011}/demand_{2000} > 4.5$), but this end-use only accounts for ≈ 1 % of Li use and is therefore insignificant for overall demand. The remaining end-use categories grew in an average manner ($1.3 \lessapprox demand_{2011}/demand_{2000} \lessapprox 2$) in the period 2000–2011, with the exception of aluminium, which shrunk to ≈ 1/5 of the original level. Therefore, the majority of Li demand did not grow as fast as the demand for LIB and this is why the widespread adoption of LIB did not yet lead to exceptional growth for overall lithium demand.

The demand for tin grew only modestly in the period 1993–2013. This is surprising because, first, the major application of tin is in lead-free solders (for general applications and microelectronics) and the prohibition of lead in solders has increased the weight of tin in solder from about 60 % to 97 % in Europe. Yet, Sn demand for solders remained about constant in the period under consideration.

There are two plausible reasons for this: miniaturization in electronics and material efficiency increase in soldering techniques. Miniaturization in electronics has led to higher performance per chip, thereby reducing the demand for solders. Furthermore, an increasing market share of surface mounted technology (SMT) versus through-hole technology (THT; Marscheider-Weidemann et al. 2016) has also diminished demand for solders. Altogether, tin demand for solders increased little even though applications like consumer electronics experience growth rates above average.

The second reason why the small overall increase in tin demand is initially surprising has to do with displays and, in particular, the dominant use of indium *tin* oxide (ITO) as transparent conductive electrode. This, however, has not significantly influenced demand for tin because the mixed oxide ITO usually comprises about 90 wt% of indium(III)oxide and only 10 wt% of tin(IV)oxide. In addition, total Sn demand is close to 1×10^6 tonnes, whereas total In demand is well below 1×10^4 tonnes (we revisit the issue of market size below).

The demand from other tin applications remained approximately constant.

STEADY INCREASE: ALUMINIUM AND COPPER

The overall demand for Al and Cu developed smoothly between 1993 and 2013, with the only noticeable kink in the curves being tied to the economic and financial crisis in 2009. The ratio of $demand_{2013}/demand_{1993}$ is between 150 and 300 % for all application sectors considered, i.e. there are no application sectors showing particularly strong growth.

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With the high total demand and production of these metals and their distribution over a broad range of applications, demand for these metals for special and emerging applications is generally small in comparison to total demand and therefore not significant for the development of overall demand. This holds true even when considering the widespread adoption of material intensive technologies such as electric vehicles, as illustrated in Figure 4 for Cu and Li, two raw materials associated with the "technology" electric vehicles. Though the raw material demand per vehicle is lower for Li than for Cu, the Cu market is three orders or magnitude larger than the Li market. Consequently, regardless of the market penetration scenario for electric cars and assuming LIB will remain the preferred battery technology in the foreseeable future, the widespread adoption of electric vehicles will more markedly define the Li market. Therefore, it becomes evident that smaller markets are more prone to disruption by the (rapid and) widespread introduction of new technologies by virtue of their market size alone.

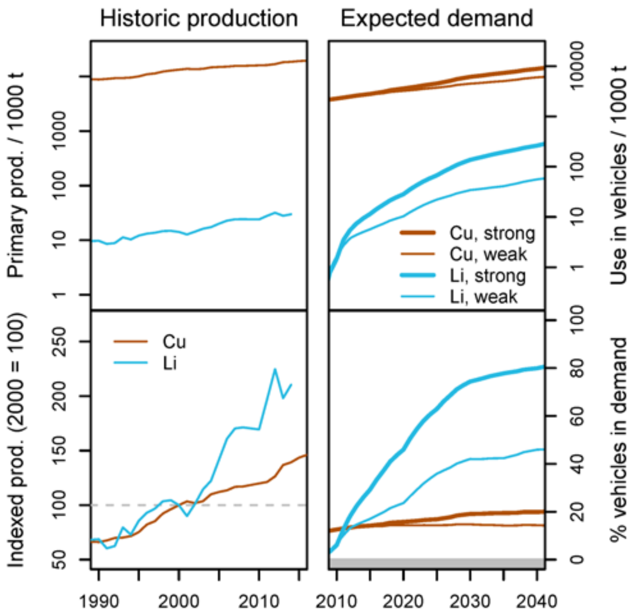

Figure 4: Historic primary supply and expected demand for copper and lithium for (electric) vehicles. Two scenarios for the market penetration of electric vehicles are considered: "strong" and "weak". Figure taken from Langkau & Tercero Espinoza (2018).

EXPLOSIVE GROWTH: INDIUM AND COBALT

Indium and cobalt both experience a more than fivefold growth in (primary) production between 1993 and 2013. In the case of indium, this growth was driven by applications of ITO in displays and thin film solar cells. The requirement of a transparent and conductive material makes ITO difficult to substitute in these applications, and the rapid spread of flat screen TVs and portable electronic devices has been enough to fundamentally change the indium market in a very short period. Notice also that the increase in indium demand depicted in Figure 3 is almost twice the increase in primary production shown in Figure 2. This difference is due to the extensive recycling of the ITO sputtering targets, contributing an estimated 3/4 of the indium used for ITO applications (Licht et al. 2015). In contrast, recycling of indium from post-consumer scrap is currently negligible (UNEP 2011).

Similar to indium demand, the rise in cobalt demand was due to a specific emerging technology: lithium-ion batteries (LIB). LIB using $LiCoO_2$ as cathode material enabled the breakthrough of portable consumer electronics like mobile phones and laptops. This is still the most widespread electrode material in lithium-ion batteries for consumer electronics. The cobalt demand for this technology alone increased to > 1100 % of its

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level in 2000 by 2013. This increase is higher than that for lithium because there is more cobalt than lithium in a LIB (approx. 11 % Co by weight vs. 4 % lithium) while the markets are of similar "size"/tonnage. All other Co-applications have a ratio of $demand_{2013}/demand_{2000}$ of 80–200 %.

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BUILDING UPON PREVIOUS RESULTS FROM WORK PACKAGE 2

The aim of WP2 is to provide an overview of present and future (time horizon: 2035) CRM markets in Europe. The starting point is the CRM list published in 2014, accommodating new CRM from the list published in 2017 as possible in the allotted time and budget. The first building block in this endeavour is a systematic overview of current use of CRM in the EU. This was provided in D2.1 "Report on the current use of critical raw materials" (Deetman et al. 2017a), a summary of which is shown in Figure 5.

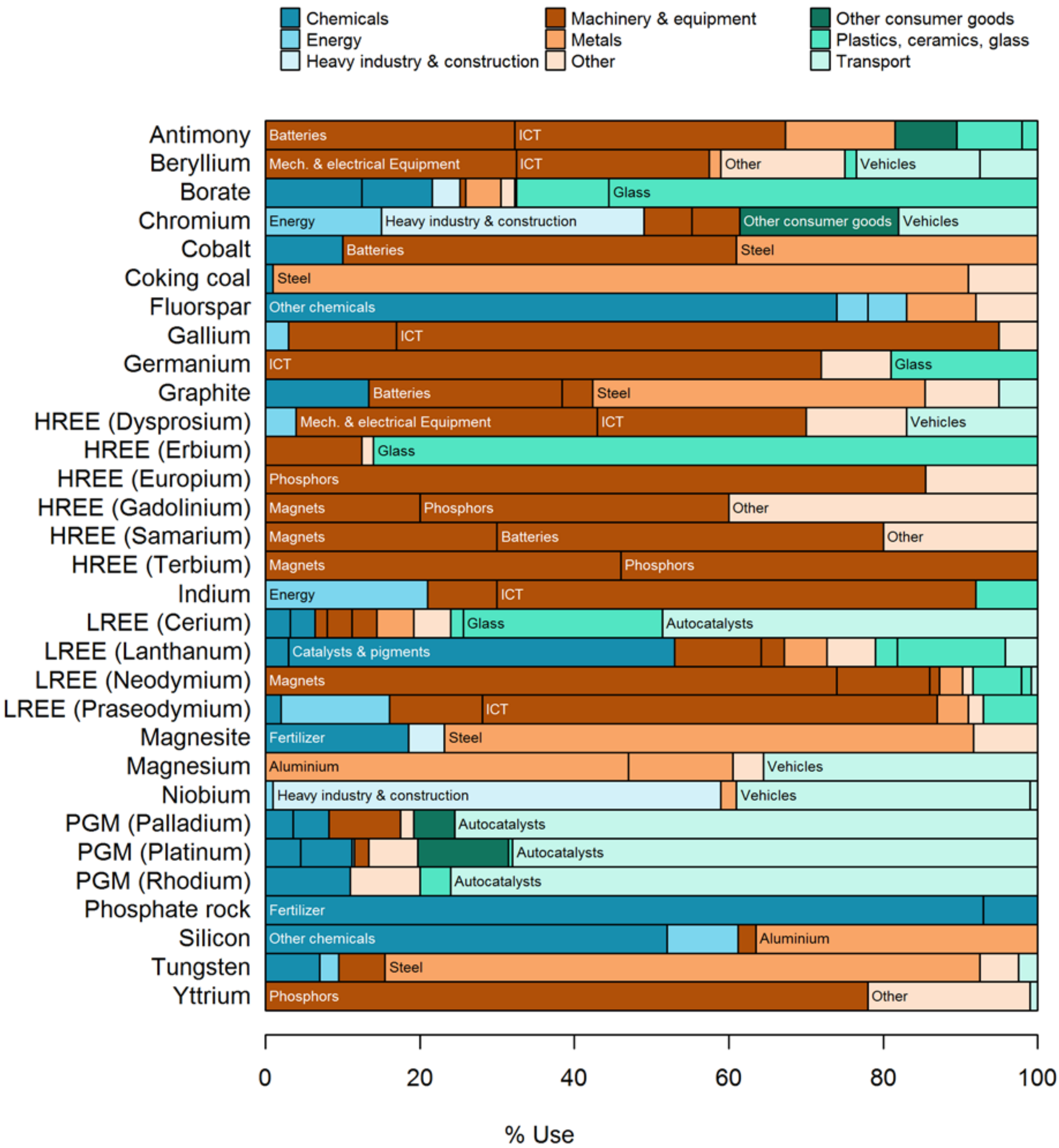

Figure 5: Summary of CRM use in the EU. Data from D2.1 by Deetman et al. (2017a).

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The second building block in WP2 is a systematic overview of trends affecting the future use of CRM in the EU. This is provided in D2.2 "Report on major trends affecting future demand for critical raw materials" by Ait Abderrahim und Monnet (2018). Since such trends are inherently independent of the raw materials they affect, an approach based on industrial applications and sectors was preferred to addressing this topic CRM-by-CRM. The multilevel perspective (MLP; Geels 2002) was chosen as a conceptual framework and the identification of drivers was aided by the use of the PESTEL (**p**olitical, **e**conomic, **s**ocial, **e**nvironmental, **l**egal) framework, as sketched in Figure 6.

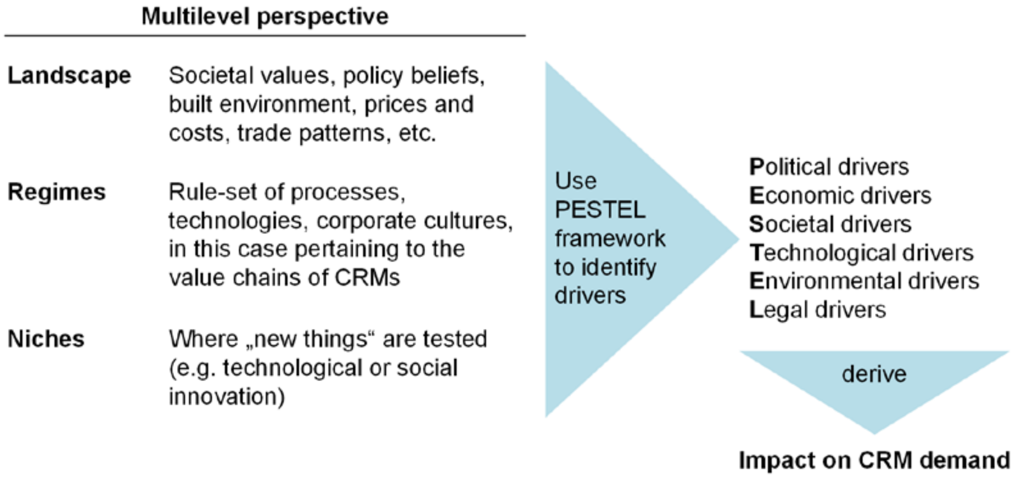

Figure 6: From the multilevel perspective (MLP) through the PESTEL framework to expected impacts on future demand of critical raw materials in Europe.

The selection of technologies to cover attempted to include the majority of CRM use in Europe. In the end, this study covered 12 applications involving 20 CRMs. 5 CRMs have been covered not for their main applications (B, Ba, Hf, W, V) but because they are involved in the main application of other CRMs. As a result, the study covers a low share of their consumption. The coverage rate (percentage of current EU apparent consumption covered in the study) for natural graphite is also low but the reason is different: the applications involving this CRM are emerging and the future requirement for these applications are expected to exceed the total current consumption by 2035. The other 14 CRMs covered have a high average coverage rate. Figure 7 shows a graphical summary of the trends identified for all 12 applications.

Based on literature review, a reference scenario including quantitative data was provided for each application and more than 70 drivers helped to qualify the trends and their potential future evolution. Finally, D2.2 provides a synthesis of these drivers by sector. Briefly:

- Energy: The development of wind power (involving REE) and domestic energy storage (mainly cobalt and natural graphite) are expected to drive up CRM demand in the coming decades. Conversely, the demand related to the deployment of PV panels (mainly silicon, indium and gallium) should become less critical by 2035, especially thanks to improvement in material efficiency. Important drivers to monitor in this sector include policies to further reduce CO_2 emissions, incentives for distributed power generation, power and storage requirements related to the deployment of EVs.

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	P Political	E Economic	S Societal	T Technological	E Environmental	L Legal
Autocatalysts	↕	↓↓↓	↓↓	↑↑	↓↓	↓↓
Displays	↓↓	↕	↓↓ ↑↑	↓↓	↓↓	↓↓
Domestic appliances	↓↓ ↓↓	↓↓	↑↑↑ ↑↑	↑↑	↑	↓↓
Domestic energy storage	↑↑	↑↑	↓↓	↕	↑↑↑	↓↓
Electric vehicles	↑↑↑ ↑↑	↕	↑↑	↕	↑↑	↓↓
Fertilizers	↓↓	↓↓	↑	↓↓ ↕	↓	↓↓
Fibre optics	↕	↑↑↑	↑↑	↓↓		
Jet engines	↕	↑↑↑ ↑↑	↑↑↑	↓ ↓↓↓	↓↓	↓↓
Passenger car bodies	↑↑	↑↑ ↑↑	↓↓	↑↑	↓↓	
Photovoltaic panels	↓↓ ↑↑	↑↑ ↑↑	↑↑	↕	↓↓	↕ ↓↓
Smartphones, laptops, PCs	↓	↓	↑↑↑	↑↑↑		↓↓
Wind tubines	↑↑	↑↑	↓↓	↓↓	↓↓	↓↓

Figure 7: Summary view of trends affecting the use of CRM in Europe in selected applications as identified in D2.2 using the PESTEL framework. The number of arrows denotes the strength of the trend, from weak (one arrow) to strong (three arrows). The colour of the arrows corresponds to their degree of certainty (light colour = low certainty, dark colour = high certainty). Some trends have an unclear effect on CRM use in the selected applications; these are marked with an up/down-arrow (↕).

- Transport: The need to decarbonize mobility and reduce air pollution is closely tied to the emergence of hybrid and electric vehicles and the persistent dependence on autocatalysts for ICE vehicles. The deployment of EVs is expected to drive most of the growth of CRM requirements (mainly REE, cobalt and natural graphite) in this sector by 2035. The search for more performant materials to replace existing ones, especially in terms of weight and performance in extreme conditions (ceramics for jet engines, Al-based alloys for car bodies), should also impacts the sector: Ta, Mg, Nb are the main CRMs concerned. Finally, the increasing demand for mobility, especially in emerging countries, and newer forms of mobility (mobility as a service, MaaS), are not to be overlooked.
- Telecommunication and electronics: The global expansion of digital networks and services implies that more people have access to the internet, thus fuelling the need for connected equipment and fibre optics that Europe could produce and export. Therefore, the demand of CRMs in this sector should either level off (indium for screens) or keep increasing (REE, Ta, Pd for electronic devices & appliances, Ge for optic fibres). Important drivers to monitor in the future include miniaturisation of components, measures against planned obsolescence and restrictions on exports of e-waste. In addition, the search for more performant and cheaper materials or components of electronic appliances fosters substitution, making future demands more unpredictable in the sector.
- Agriculture: Global population growth (moderate in Europe) will foster the need for a more efficient agriculture, thus increasing reliance on fertilisers and potentially encouraging European exports. At the same time, various sources of phosphorous are likely to be considered (animal manure, but also sewage sludge and food waste chain) to reduce dependence on phosphate rocks. At last, the emergence of precision farming, helped by new technologies, might improve the efficiency of the use of fertilisers, in a context where agriculture tries to reduce its environmental footprint.

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FUTURE USE OF CRITICAL RAW MATERIALS IN THE EU

The aim of Work Package 2.3 is the combination of information about historic and current uses of CRMs in the EU (WP 2.1) with the analysis of major trends in their future demand (WP 2.2) to develop projections for future demand in the EU until 2035 across their individual main applications (Deetman et al. 2017a; Ait Abderrahim und Monnet 2018). Intending to show the potential of this method with a broad overview over different materials, applications and trends, a variety of raw materials were chosen according to the following criteria:

- Supply of the raw material is considered critical by the EU and therefore it is part of the CRM list of 2014 or 2017 (European Commission 2014a, 2017b)
- Demand of the raw material is influenced by at least one of the applications analysed in WP 2.2
- Raw materials affected by more than one major trend (WP 2.2) were given priority
- Raw materials with applications that cover a high percentage of their overall demand today and are impacted by a major trend were prioritized for analysis
- Raw materials with applications expected to grow quickly into dominating the overall demand in the near future were prioritized.

Using these criteria, the following raw materials were chosen for further analysis: Barytes, cobalt, gallium, indium, magnesium, niobium, the platinum group metals (PGM) palladium, platinum and rhodium, phosphate rock, the rare earth elements neodymium and dysprosium, tantalum and tungsten.

BARYTES (BARITE)

Applications of barite are spread across multiple industries, with the dominant application being in the oil and gas industry as a lubricant in drilling. The unique properties of barite make it useful in several other applications:

- filler in paint and plastics
- production of lithopone
- getter (scavenger) alloys in vacuum tubes
- deoxidizer for copper
- lubricant for anode rotors in X-ray tubes
- spark-plug alloys
- a high-quality white pigment that is added to paints and some enamels
- finely ground barite is added to synthetic rubber to incorporate the rubber into hot asphalt, typically used in high-traffic areas such as parking lots.
- elemental barium is an additive in optical glass, ceramic glazes

Barite has the unique ability to strongly absorb x-rays and gamma rays (is opaque to ionizing radiation). Consequently, it is used in medical science for special x-ray tests on the intestines and colon. Global barite resources are abundant and distribution is relatively concentrated. To have potential commercial value, barite must meet certain criteria. For example, barite used in drilling fluids must have a minimum specific gravity of 4.2, which limits the amount of contaminants permissible in the concentrate, or the proportion of celestite in solid solution or physical mixtures. There are also government regulatory restrictions imposed on the concentrations of deleterious or toxic elements such as lead (Pb), cadmium (Cd) or mercury (Hg), and these

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limits vary according to jurisdiction. Pharmaceutical and medical applications commonly demand exceptional purity (> 97.5% $BaSO_4$) and low levels of heavy metals and other impurities.

In response to concerns about dwindling global reserves of 4.2-specific gravity barite used by the oil and gas drilling industry, the American Petroleum Institute issued an alternate specification for 4.1-specific gravity barite in 2010. This has likely stimulated exploration and expansion of global barite resources. In 2017, global barite reserves were 290 million tons, of which China, Kazakhstan, Turkey, India, and Iran accounted for 73.4%. Europe has gathered the world's largest paint, polymer, and automakers, so it is likely to continue to be the world's largest non-drilling-level barite consumer zone in the future. In 2017, global barite mining production was 6.38 million tons. When considering barite reserves suitable for use in drilling fluids, there are relatively few major sources with China, India, the US and Morocco, Mexico and Turkey accounting for about 80% of global production. The USA was the largest consumer at around 2.6 million tpa in 2017 - China consumed 1.6Mt and the Middle East 1.4Mt. In the USA over 95% barite output was for the oil industry consumption (Merchant Research & Consulting 2018). Most of China's barites are exported in the form of crude ore and barium salt products. The main target countries are the United States, Saudi Arabia and the Netherlands. Barite's international trade flow has always been China to the Gulf of Mexico; China is the world's largest barite exporter. The United States is the world's leading barite importer (related to the oil & gas drilling industry).

Europe consumption (including Norway and Turkey) was around 0.65 million tpa of which 72% was sourced domestically. Approximately 70% of barite production was into added-value markets so a significant proportion is an export net value, and a higher proportion of the oil-well industry requirement imported. Germany, Bulgaria and UK account for over 90% of the EU-27 output. Approximately 70% European domestic production is for added value in production sectors. For example, overall the chemical and filler industries account for half of the barite consumption.

The increasing of, or slowing of oil and gas production will determine the changes of global barite market. China and India are projected to continue to be the largest suppliers of barite post 2018. Diversification of barite supply is predicted as many new projects (in China and India) are being developed.

Several driving forces influence demand for barite mineral. The bulk of the barite market has been linked to growing demand for oil drilling and filler applications but world recession has hit the automotive industry. Barite demand will not be bullish until there is a strong growth in the need for more drilling in the oil & gas industry. Chemical demand has fallen due to a dramatic switch to LCD/plasma TV and computer screens, which use less barite, but applications in the dielectrics, electro-ceramic and construction industry have risen. It is unclear how these technologies will project into the future.

In geotechnical engineering, drilling fluid is used to aid the drilling of boreholes (liquid drilling fluid is often called drilling mud). This is done for a series of applications like mineral exploration or used while drilling oil and natural gas wells. Drilling fluids are also used for much simpler boreholes, such as water wells. Various kinds of lubricants or drilling muds, such as water-based drilling muds (WBs), oil-based drilling muds (OBs) are used to make the process more efficient and effective. The petroleum industry is, by far, the largest consumer of barite (roughly 85% of global consumption in 2017) and uses it primarily as a weighting agent in drilling muds utilized in drilling for oil and gas. The tight oil (fracking) industry in particular as a much higher rate of drilling is required to maintain production compared to conventional oil and gas operations. Figure 8 shows the consumption of barite globally correlates with the rig count in the oil and gas industry. Thus to understand the barite market, one must understand the oil gas industry needs for drilling. World production is broadly linked to oil-well drilling activity and has increased from 6.0- 6.5Mtpa in the early 2000s to 9.7Mt in 2014 - but fell to

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8Mt in 2015 and to 7.3Mt in 2016 as a result of low oil prices and reduced drilling activity – but recovered to a preliminary estimate of 8.7Mt in 2017.

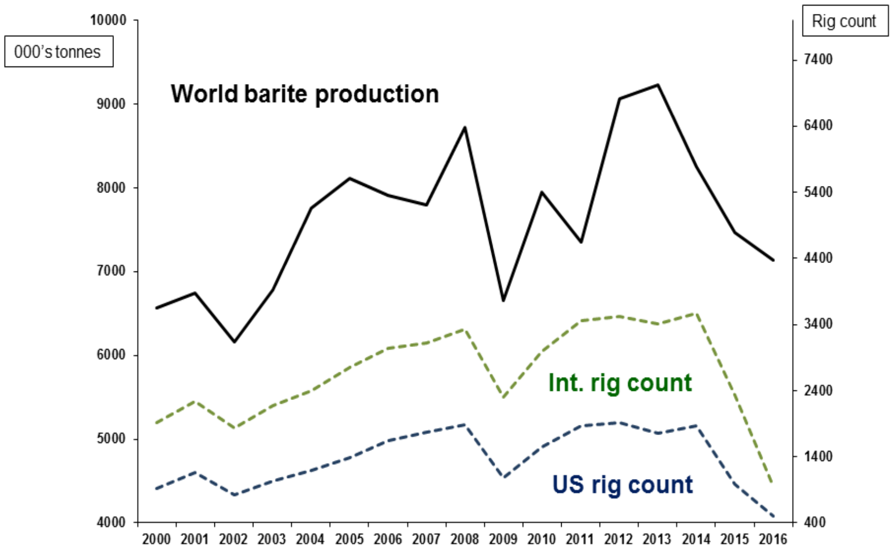

Figure 8: Barite world production, and total drill rig count (Baker Hughes 2017; USGS 2018a).

Barite prices remained relatively steady until approximately 2006/2007 relative to 1995 dollars, after which they increased rapidly until around 2012 and have currently fallen back slightly in 2014, but still some 200% above the inflated 1995-dollar base. The sharp increase of barite market price resulted from a number of factors including rationalisation and consolidation of the Chinese barite mines, in addition to highly intensified US onshore drilling for tight oil and gas, which placed further pressure on suppliers.

The global barite industry share was consolidated in 2016 as leading operators in the barite market accounted for over 55% of the market share in the same year. These operators continue to make heavy investments to upgrade their plant facilities to enhance production capacity and attain competitive advantage in the industrial mineral business. This basic pattern of supply and demand is basically stable and is unlikely to change in the next few years. The major players are adopting key strategy like partnerships and agreements in order to reduce gap between supplier and manufacturer of barite. Apart from that, various key strategies adopted by key players are expansion and acquisition. Advancement in technology and increasing presence of significant players has positively influenced the growth of the barite market. Moreover, market leaders in 2016/2017 expanded their production facility to meet global demand and obtain competitive advantage in the market. Consolidation of market share seems to be the goal ahead of a perceived increase in demand associated with the oil & gas industry.

Grades above 4.3 SG density barite market size is likely to grow at a compound annual growth rate (CAGR) close to 3% owing to rapidly growing rubber, plastic, paints & coatings industry in the near future. In addition, higher-grade barite is attained from deeper earth crust and henceforth is priced higher than lower grade barite and is likely to make prominent contribution to market size in the coming years. Lower grade barite including grade 3.9 SG density to grade 4.2 SG density finds application in oil & gas drilling industry, where grade 4.2 SG density is considered optimum for oil & drilling application as per the American Association of Drilling Engineers. Rapid pace of shale gas production in the U.S. due to reserves availability along with dire need to

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shift industry focus to unconventional energy sources has propelled grade 4.2 SG density demand as weighing agent, which in turn will have positive impact on the barite market size in the coming years.

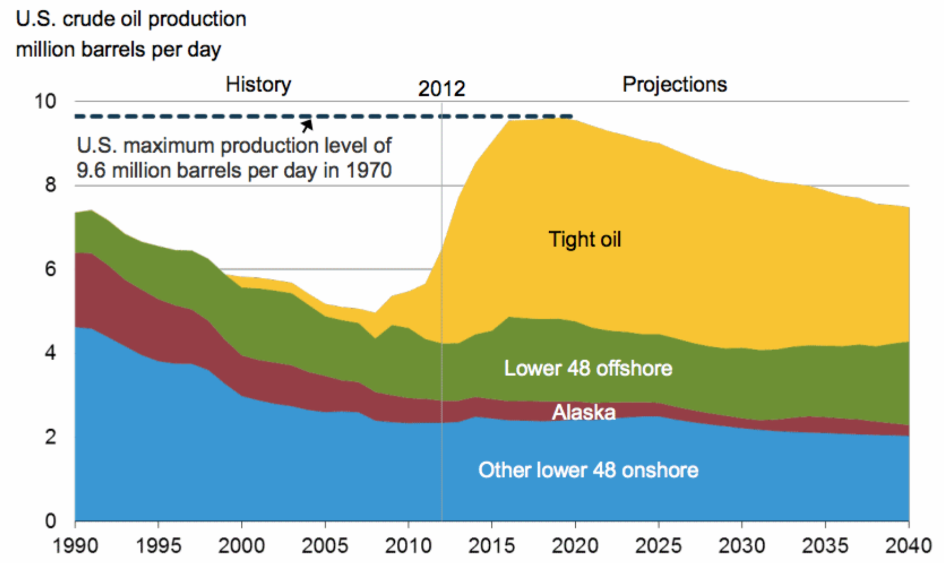

Figure 3: Projection of future U.S. crude oil production (Energy Information Agency 2014, 2018).

Barite market size for oil & drilling is expected to grow at a CAGR close to 4.5% in the coming years. In addition, the product market for pharmaceuticals finds widespread applications as diagnosis materials for stomach & intestine as well as for filling plaster to extend its time limit. Global barite market size for paints & coatings is projected to grow at a CAGR of over 3.5% in the coming years. This is due to rapid pace of paints & coatings industry, which is attributed to strong urbanization and industrialization primarily in the emerging economies. Barite market size for rubber & plastic is anticipated to grow at a CAGR close to 3% owing to positive growth indicators in the automotive industry primarily in the Asia Pacific due to improving socio-economic factors.

The Asia Pacific barite market size is the fastest growing segment and is anticipated to grow at a CAGR of over 7% during the forecast period. This is primarily due to large amount of shale reserves available in China to meet energy demand across various end-user industries including power, automotive, etc. in the region. For instance, China accounts for over 720 billion tons of shale resources, which are likely to be produced in the coming years and henceforth will drive market by 2024. Furthermore, rapid industrialization and urbanization has led to strong growth indicators in the paints & coatings industry, which will further boost the regional barite market size over the projected time spell.

This shifting market focus to use unconventional energy sources to meet demand across various end-user industries including automotive, power, household, etc. has led to rising product global demand by 2024 (Global Market Insights 2016).

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COBALT

CURRENT USE

Cobalt has diverse areas of use: Metallurgical applications such as superalloys for aeronautics, gas turbines or carbon capture and storage, hard metals for tooling and magnetic alloys as well as chemical applications such as catalysts, pigments and other specialty chemicals like tyre adhesives, soaps, paint driers and feedstuffs. Additionally, cobalt is used in rechargeable lithium ion batteries (LIBs) which are commonly used in smartphones, tablets and laptops but also more and more in the emerging technologies of electric vehicles and domestic energy storage. On a global scale, cobalt demand for LIBs has displayed a rapid and massive growth from 3 kt (8% of global cobalt use) in 2000 to 54 kt (46%) in 2017 (Cobalt Institute 2017, 2018b) and is expected to continue this trend in the future. Also for Europe, all three of those LIB application sectors have been identified within WP2.2 as causes for major changes in raw material demand during the next decades. Furthermore, also the sector of jet engine production is expected to undergo major changes which is relevant for the demand of cobalt containing superalloys (Ait Abderrahim und Monnet 2018).

Historic data on cobalt production as well as shares of demand by application sectors is available for 2000-2017 on a global scale (Kühn und Glöser 2013; Cobalt Institute 2018a, 2018b). Information on European cobalt consumption is scarce and significantly less reliable. Total demand for cobalt within the EU is assumed to be between 10-30 kt (Bio by Deloitte 2015; European Commission 2017b). For the distribution of cobalt demand by the European industry on the application sectors, two relatively different data sets were found (Figure 9). An MSA study for 2014 shows a strong emphasis on metallurgical applications in Europe with 44% of cobalt going into superalloys and 31% into hard metals. Chemical applications only play a minor role with 17% for pigments, 5% for catalysts and only 3% for LIBs. Cobalt containing magnetic alloys and specialty chemicals do not significantly contribute to European cobalt demand according to this study. The total European cobalt demand was calculated to have been approximately 13 kt (Bio by Deloitte 2015). On the other hand, a more recent industry survey by the Cobalt Institute (CI, formerly CDI, Cobalt Development Institute) shows with 55% a very strong contribution of specialty chemicals to the overall European cobalt demand. Additionally the other chemical applications of catalysts and pigments contribute with further 8% and 1% each. Metallurgical applications are less significant in Europe with 12% of the total cobalt demand from hard metals, 8% from superalloys and 6% from magnetic alloys according to this CI study (CoRC-CDI 2017). A number on the total amount of European cobalt demand was not known from this survey. For the 2017 criticality assessment of cobalt, the Cobalt Institute made an estimation of 10.5 kt for the apparent cobalt consumption of the EU (European Commission 2017b).

Both datasets can be disputed. The statement in the MSA study of Europe with its strong chemical industry not having a significant contribution to cobalt demand from the specialty chemicals sector should be scrutinized. The CI dataset however, has such a high share of specialty chemicals that the resulting amount of chemicals produced in the EU is higher than the amount produced globally. To the best of our knowledge, this might be attributed to the methodology of the survey. Companies have been asked for the amount of cobalt they process for each application per year and all answers were then summed up. However, some cobalt might go through several steps of processing in different companies, which would lead to double entries distorting the results in this approach. In the following analysis of European cobalt demand, the dataset from the MSA study was used since it was also used within the criticality assessment of cobalt for the EU. Additionally, the logic of

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data analysis in this report does not allow for discrepancies between European and global consumption data as were observed for the CI dataset.

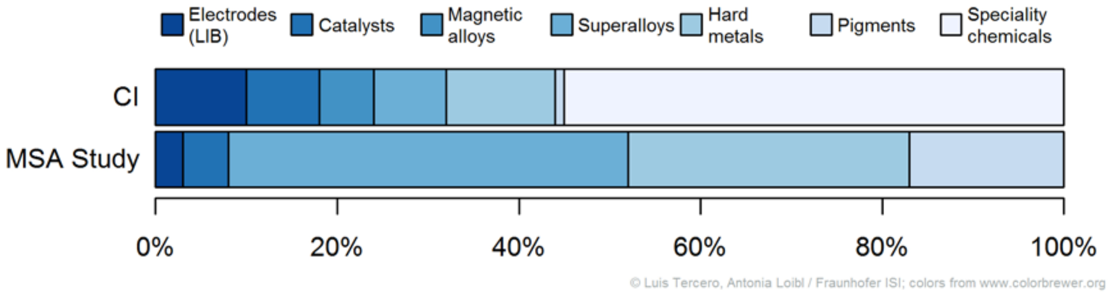

Figure 9 : Comparison of two available datasets for the distribution of cobalt demand on different application sectors within European industry. (Bottom) The MSA study for cobalt flows in the EU was conducted for the year 2012. Shown here are the shares of finished products containing cobalt manufactured in the EU (Bio by Deloitte 2015). (Top) In 2017, the Cobalt Institute (CI) collected data from European industry on cobalt flows within the different application sectors (CoRC-CDI 2017).

With data on European cobalt consumption only available for a single year, two assumptions had to be made. First, the share of European cobalt demand on the global amount was set to be at a constant 17% as it has been in the data year of 2012. Secondly, the application shares for European cobalt consumption were assumed constant. As a result, the historic development of European and global cobalt consumption divided by sectors is derived. Furthermore, we sought to highlight the similarities/differences between Europe and the overall global uses of cobalt so the difference between global and European cobalt demand is shown as demand by the rest of the world (RoW, in Figure 10).

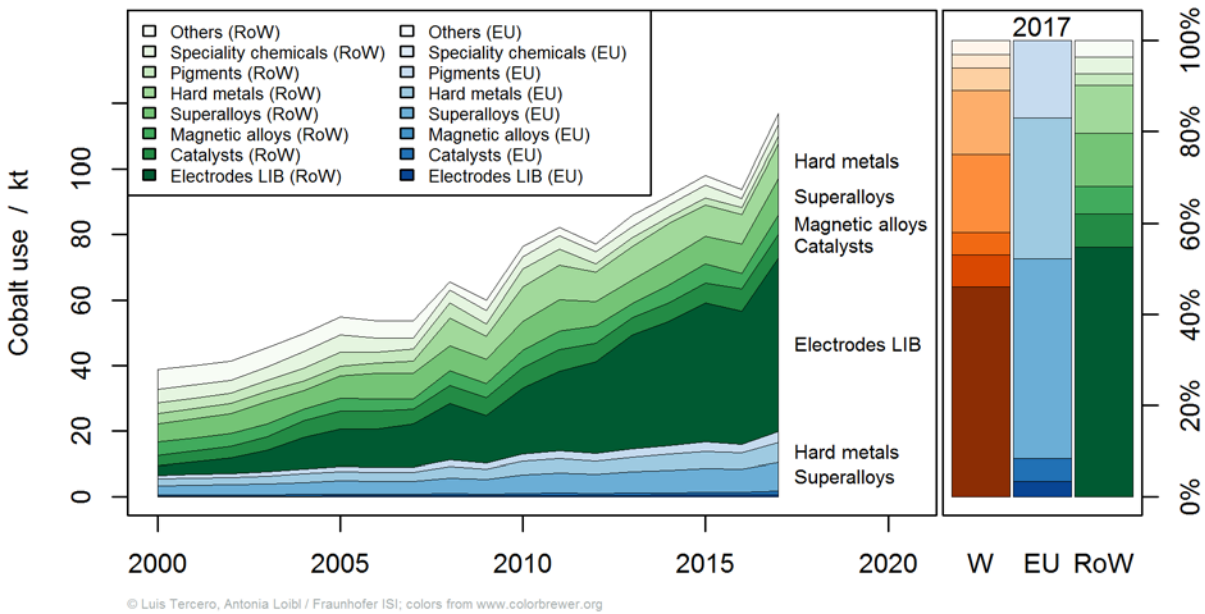

Figure 10 : (Left) Historic cobalt demand 2000-2017 split into its main application sectors and shown for Europe (shades of blue) and the rest of the world (shades of green). (Right) Comparison of shares in total cobalt demand for each application in 2017 (last data year) at the global (orange, "World) and European (blue) levels, and for the Rest of the World (green, "RoW"). Demand estimates for the RoW were constructed by subtracting European demand from global demand for each sector.

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Overall, global cobalt consumption has tripled from 39 kt to 117 kt in the shown timeframe of 2000-2017. Most applications have been growing moderately but consistently. Only cobalt use in pigments has been almost stagnant while the amounts of cobalt contained in specialty chemicals and other uses have been decreasing. The LIB sector on the other hand has displayed a rapid, strong growth from 3 kt of cobalt demand in 2000 to 54 kt in 2017. In 2017, total cobalt demand consisted of 46% from LIBs, 17% from superalloys, 14% from hard metals, 7% from catalysts, 5% for magnetic alloys and pigments each and 3% each for specialty chemicals and other uses.

For Europe, the application sector contributions to cobalt demand are 44% from superalloys, 31% from hard metals, 17% from pigments, 5% from catalysts and 3% from LIBs. Since the share of European cobalt consumption on the global demand had to be assumed as constant for lack of further data, it increased at the same rate as the global consumption from almost 7 kt in 2000 to 20 kt in 2017.

FUTURE USE

In order to develop a projection of cobalt use until 2035, historic data for the sectors of catalysts, magnetic alloys, hard metals, pigments, specialty chemicals and other uses has been extrapolated. Superalloys containing cobalt are used for jet engine production, which is a major driver for material demand in the EU during the next decades according to D2.2. However, the share of cobalt in superalloys going into jet engines was below 1% in 2012 and will stay below 1% until 2035 (Ait Abderrahim und Monnet 2018). Therefore, data for superalloys was also extrapolated without taking into account specific growth rates for jet engine production. For cobalt used in LIBs, the trend analysis for their application in smartphones, tablets and laptops, in domestic energy storage as well as in electric vehicles from D2.2 was taken and their individual growth rates were summed up into one weighted growth rate for LIBs. Resulting is a projection for the future cobalt use until 2035 (Figure 11).

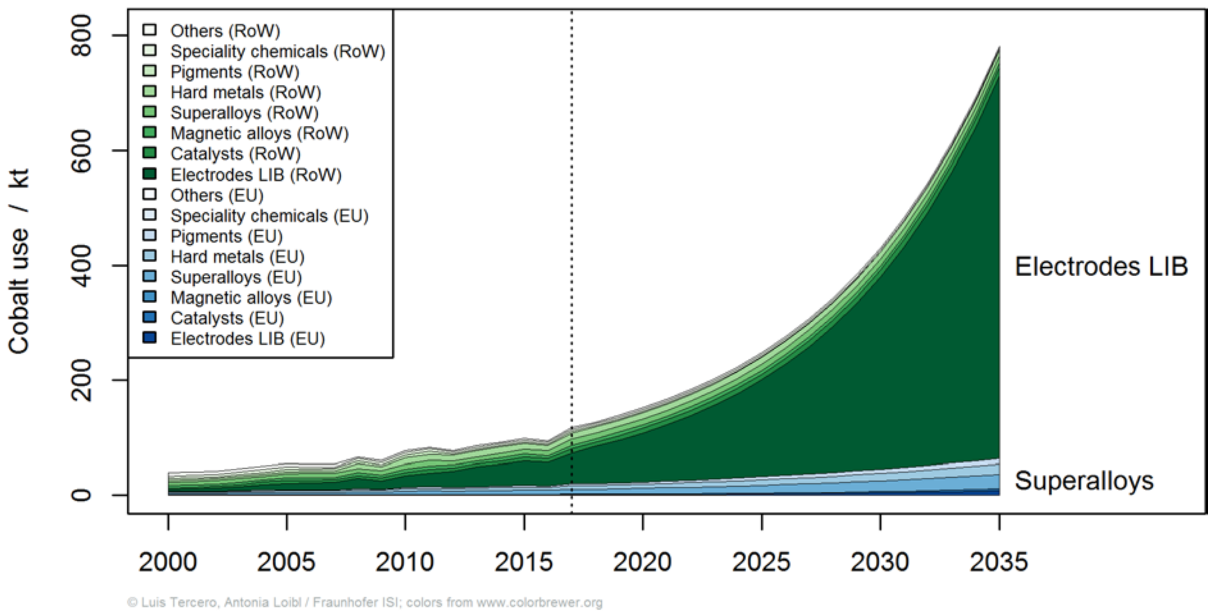

Figure 11 : Cobalt demand for the main application sectors with historical data until 2017 (indicated by the dotted line) and a demand forecast in the timeframe of 2018-2035 shown for Europe (blue) and RoW (green).

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Looking at the projection for the global cobalt consumption, application in LIBs will continue its rapid growth and dominate overall cobalt use with 86% in 2035. All other application sectors apart from specialty chemicals will grow as well but much more moderately. Cobalt use in specialty chemicals will decrease slightly. In 2035, the shares of different end uses are 86% for LIBs, 5% for superalloys, 4% for hard metals, 2% for catalysts, 1% for magnetic alloys, pigments and other uses each and specialty chemicals will fall below 1%. Total cobalt consumption increases from 12 kt in 2017 to 782 kt in 2035 according to this projection.

For Europe, the lack of more historic data than one dataset for 2012 and the consequently necessary assumption of constant application shares in 2000-2017 leads to all sectors apart from LIBs also developing uniformly in the future projections. Consequently, not much information on the development of these sectors in Europe can be drawn from this data. Cobalt use in LIBs was set to grow with a factor of nearly 16 between 2015 and 2035 as was determined in D2.2 (Ait Abderrahim und Monnet 2018). Since LIBs only contributed with 390 t or 3% to the total European cobalt consumption in 2012, even a strong growth rate like this increases the European cobalt demand for LIBs only to 7.7 kt in 2035 or 12% of the total European cobalt demand. Behind this base scenario is the assumption of Europe not gaining any more shares in the market of LIB fabrication during the considered timeframe. In this projection, Europe therefore significantly loses importance in the worldwide cobalt use structure. From 17% in 2012, the European share of the global consumption decreases to 8% in 2035.

When looking at the collective effort currently undertaken by politics and industry to create a competitive and sustainable manufacturing value chain for batteries in Europe, the base scenario with constant market shares in LIB fabrication needs to be complemented with additional scenarios taking this European Battery Alliance and Europe's Strategic Action Plan on Batteries into consideration (European Commission 11.10.2018, 2018b). Currently a "Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1" considering all three application sectors (electric vehicles, energy storage systems as well as portable devices) is being carried out (Neef und Thielmann 2018). Here, the output of a detailed market and stock model for LIB demand in Europe with minimum and maximum sales scenarios is used. Exemplary, the assumed fuel type share in passenger cars sold in the EU until 2035 are shown in Figure 12. Spelling out further assumptions made on commercial vehicles, energy storage systems, cell chemistry and market shares of cell types exceeds the purpose of this report and are therefore only referenced (Fraunhofer ISI 2018, ; Thielmann et al. 2018). Data derived from the model was then combined with an expert assessment on the development of LIB fabrication in Europe. The European share in LIB production for high-tech applications like electric vehicles and energy storage systems was set to 50-80% in 2018 and expected to rise to 70-90% until 2025 (Neef und Thielmann 2019).

Resulting are two additional scenarios for LIB production in Europe and its cobalt demand until 2035. Combined with demand from the other cobalt use sectors, results can be compared to the base scenario from D2.2 (Figure 13).

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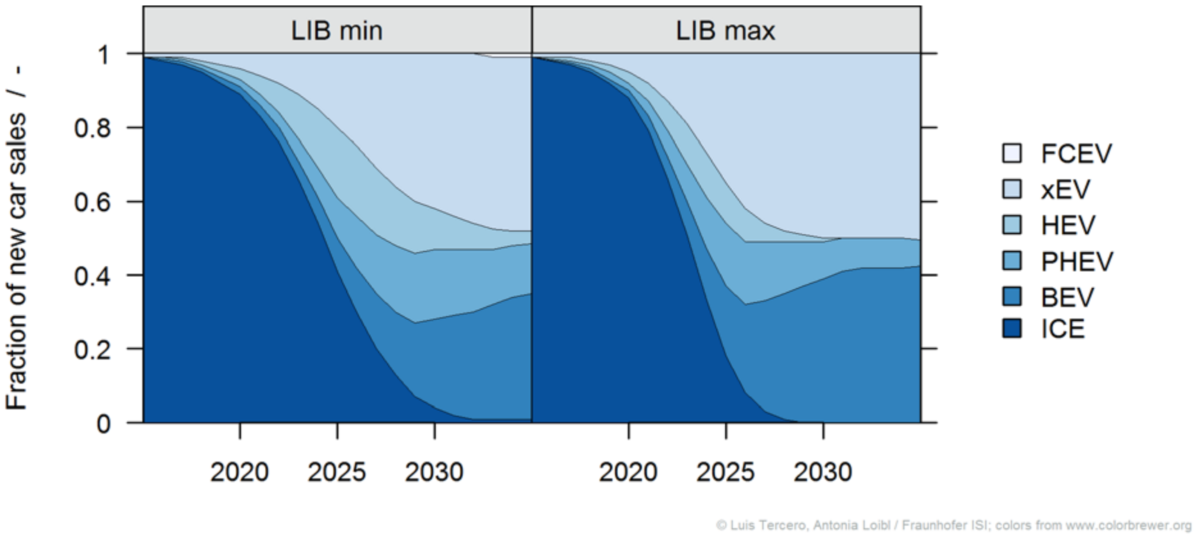

Figure 12: Fuel type shares in passenger cars sold in the EU until 2035 for the minimum and maximum Ecodesign scenarios (Neef und Thielmann 2018). Further assumptions made on commercial vehicles, energy storage systems, cell chemistry and market shares of cell types can be found in the reference.

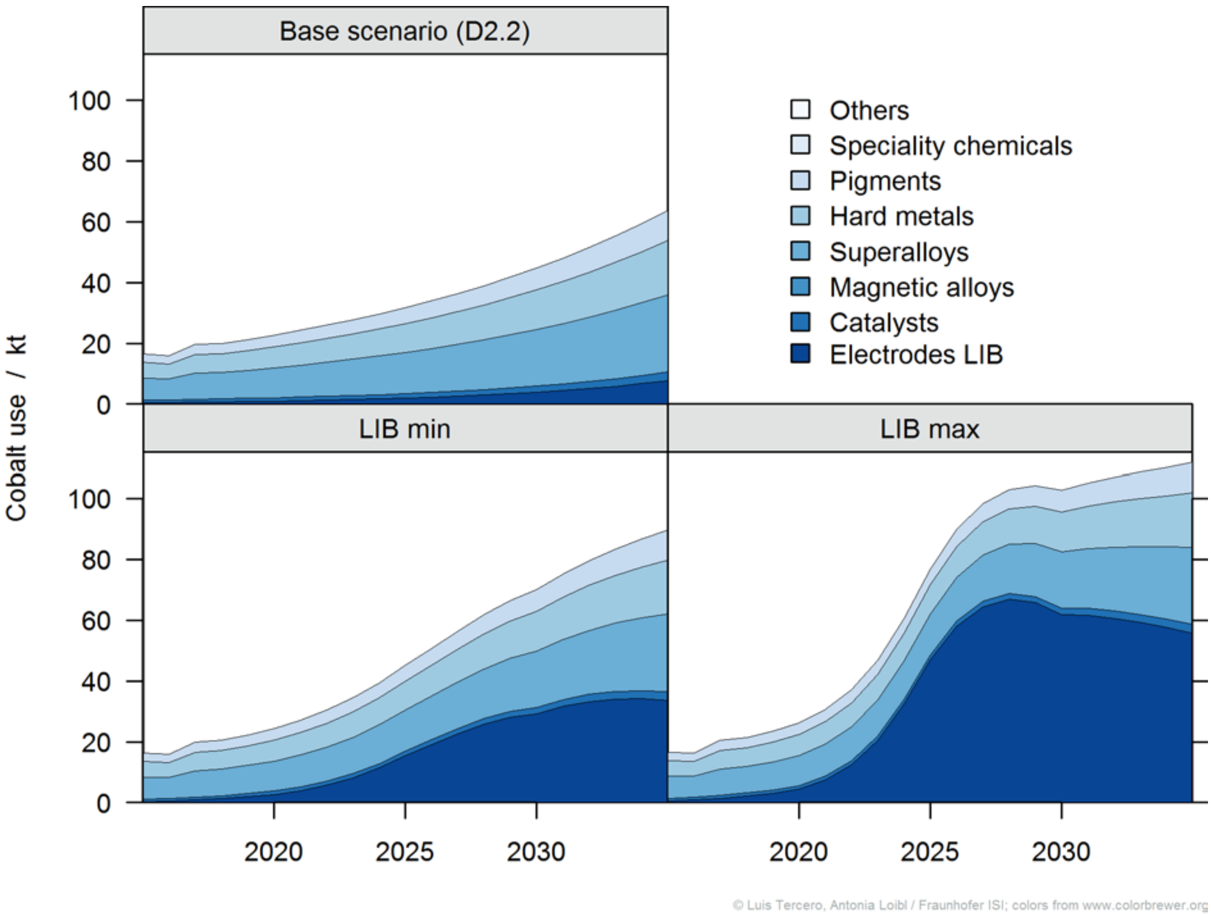

Figure 13 : Comparison between projections for the future European cobalt use with different scenarios for the development of the European LIB fabrication (Neef und Thielmann 2018; Thielmann et al. 2015).

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Since both LIB scenarios include the assumption of a growing share of LIBs being produced in Europe, they both predict a faster growth in European cobalt demand than the base scenario. The base scenario shows an overall cobalt use of 64 kt in Europe in 2035 with only 8 kt going into LIBs. The LIB scenarios on the other hand have a much stronger growth in European cobalt demand for LIBs reaching 34 kt for the minimum and 56 kt for the maximum scenario in 2035, giving an overall demand of 90 kt and 112 kt respectively.

Additionally, the LIB maximum scenario reaches a peak in cobalt demand for LIBs with 67 kt already in 2028. This can be attributed to a very fast market penetration of electric vehicles in this scenario, through which the technological improvement of cathode materials being less demanding in cobalt becomes visible quickly. In the minimum scenario, this change in material composition is hidden for longer by the slower market penetration.

Not considered in this report is the supply side and therefore the amount of material demand that can be covered from secondary sources. For LIBs in electric vehicles, very high collection and recycling rates are expected. Recent calculations show recycled cobalt could cover 10% of global demand for electric vehicles in 2030 and even 40% in 2050 (Buchert et al. 2019).

GALLIUM

CURRENT USE

The element gallium is used in photovoltaic modules, permanent magnets and electronic components. According to Deetman et al. (2017a) in D2.1, about 30 ton of gallium was used in applications in Europe. Estimates of gallium use in Europe range from 10 to 50 tons (Bio by Deloitte 2015) highlighting the large uncertainty in known use of gallium.

The largest fraction of gallium finds its way in electronic components. About 3% can be found in solar cells, which amounts to about 900 kg. A similar value was reported by Blagoeva et al. (2016). The remainder, 14%, is found in permanent magnets where it is a minor alloying element. An overview of gallium use in Europe is given in Table 1. No historic data are available on the use of gallium in Europe.

Table 1: Overview of the use of gallium in 2012 in the EU27.

Application	gallium	fraction
	[t]	[-]
Photovoltaic modules	0.9	0.03
Permanent-magnets	4.2	0.14
Electronics – sensors	5.4	0.18
Electronics – opto electronics (led)	6.0	0.20
Electronics – integrated circuits	12.0	0.40
Others	1.5	0.05
Total	30.0	1.00

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FUTURE DEVELOPMENT OF APPLICATIONS

The use of appliances in which gallium are used are all expected to grow the coming decades. D2.2 (Ait Abderrahim und Monnet 2018) shows an increase of the main application considered, smart phones. More detailed estimates of the use of electronic appliances have been made by Deetman et al. (2018). These estimates are based on a SSP2 scenario (cf. IIASA 2016) and are the same as used for the estimation of the future use of tantalum. The projections on electronic appliances have been used to estimate the amount of gallium in the categories “electronics – sensors”, “electronics – opto-electronics”, and “electronics – integrated circuits” assuming that the amount of gallium per unit electronic device does not change.

The cumulative installed capacity of photovoltaic modules in the future follows the PV EU reference scenario from Blagoeva et al. (2016). We assume that the gallium content per Watt installed capacity does not change from 2015 to 2030.

The amount of gallium in permanent magnets about 14% of the total use of gallium follows the use of permanent magnets in Europe. Little is known about the future applications of permanent magnets. Permanent magnets can be found in many applications. On the one hand, there are many options to make permanent magnets. Materials like ferrite, aluminium-cobalt-nickel, samarium-cobalt, neodymium-iron-boron, and gallium-manganese all exhibit magnetic properties. On the other hand, permanent magnets can partly be replaced by electro-magnets. As a first estimate of the use of gallium in permanent magnets we assume that gallium in permanent magnets follows the cumulative installed wind turbine capacity in Europe. Cumulative installed wind capacity follows the EU reference scenario from Blagoeva et al. (2016).

The category “other” applications of gallium is assumed to be a fixed fraction of 5% of the total uses of gallium.

FUTURE USE

Given the assumptions on the development of the applications in which gallium is used and assuming that the content of gallium per unit of application does not change, a first rough estimate can be made of gallium use in the future in Europe. The results are shown in Figure 14. The rise is in line with D2.2 (Ait Abderrahim und Monnet 2018). Smart phones, the main category pictured there, can be found in our categories “permanent magnets” and “electronics – integrated circuits”.

Gallium recycling from electronic waste has been discussed (Cucchiella et al. 2015). However, it is not known if any gallium is currently being recycled from end-of-life consumer waste.

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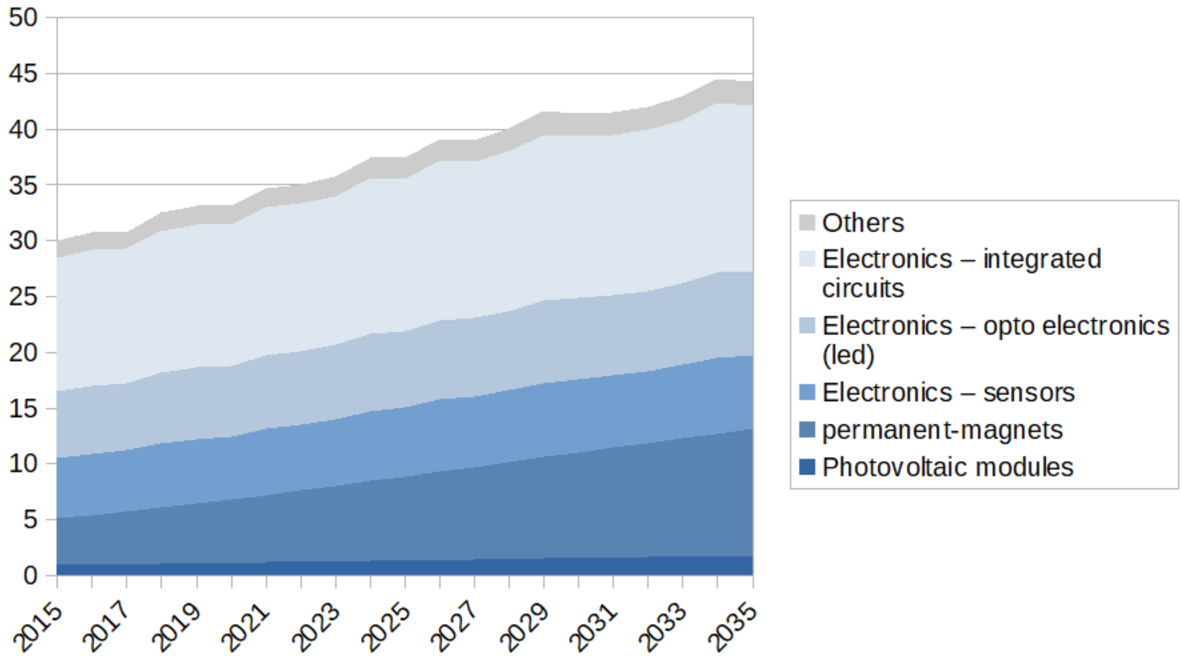

Figure 14: Future use of gallium in Europe. Based on data on about current use of gallium in applications from Deetman et al (2017) and projections on the use of electronic appliances (Deetman et al., 2018) and EU reference scenarios for the development of PV and Wind energy capacity from Blagoeva et al (2016).

INDIUM

CURRENT USE

In 2012, 201 tons of indium were used in final products in Europe (Deetman et al. 2017a). The indium was used in photovoltaic cells (21%), architectural & automotive glass (8%), lead-acid batteries (9%), monitors (27.6%), televisions (20.7%) and computers (13.8%). An overview is given in Table 2.

Table 2: Overview of the use of indium in 2012 in the EU27.

Appliance	indium	fraction
	[t]	[-]
Photovoltaic modules	42.2	0.21
Architectural and Automotive Glass	16.1	0.08
lead-acid batteries	18.1	0.09
Monitors	55.5	0.28
Televisions	41.7	0.21
Computers	27.7	0.14
Total	201	1.00

The use of indium in liquid crystal displays (LCD) in the form of indium tin oxide (ITO) compounds is a major final use category. The LCDs come in the form of standalone monitors, integrated as part of the computer

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(laptop) or as a television. Developments in the use of these appliances and the use of technology in these appliances will drive future final use of indium in Europe. Currently LCDs are mostly used in flat panel displays. The other major flat panel technology in use is organic light-emitting diodes (OLED).

Both in flat panel displays and in photovoltaic modules indium is used in the form of ITO. ITO is used as a transparent conductor coated on glass. Indium is also a major constituent to produce photovoltaic modules based on the semiconductor copper indium gallium selenide (CIGS), also called CIGS solar cells. However, the market share of these thin film solar cells is current very small. Solar cells are currently dominated by mono crystalline and multi-crystalline silicone. We therefore assume that the indium within PV is determined by its use as ITO and not by its use in CIGS.

ITO is probably also used in “architectural and automotive glass”. It can be used for anti-fogging glass as well as windows that darken in the sun.

Based on above assumption we may assume that about 85% of the indium is used as ITO, the remainder being used in lead-acid batteries. In lead-acid batteries, indium is alloyed with the lead anodes. The indium in the lead catalyses the oxidation of Pb (II) to Pb (IV) and facilitates the formation of a more highly conductive corrosion layer on lead.

An application that is not mentioned in Table 2 is it use in control rods in nuclear power plants. Indium has a high neutron-capture cross-section for thermal neutrons. These type of control rods typically contain an alloy of 80% silver, 15% indium, and 5% cadmium. Another application of indium not mention is its use in solder. Indium containing solder wire has a low melting point for soldering heat sensitive components. The indium content of those solders range from 100% to 52%. The use of this solder in Europe is unknown.

All in all, it looks like the use of indium in Europe is not well known. Applications are missing in the inventory and the indium application in PV likely highly uncertain due to the unknown use as ITO versus CIGS.

Global historical use of indium was investigated by Langkau und Tercero Espinoza (2018), and their findings for indium are shown in Figure 15. Scaling their indexed values to the volume of indium used in Europe in 2012, gives a tentative historical time series.

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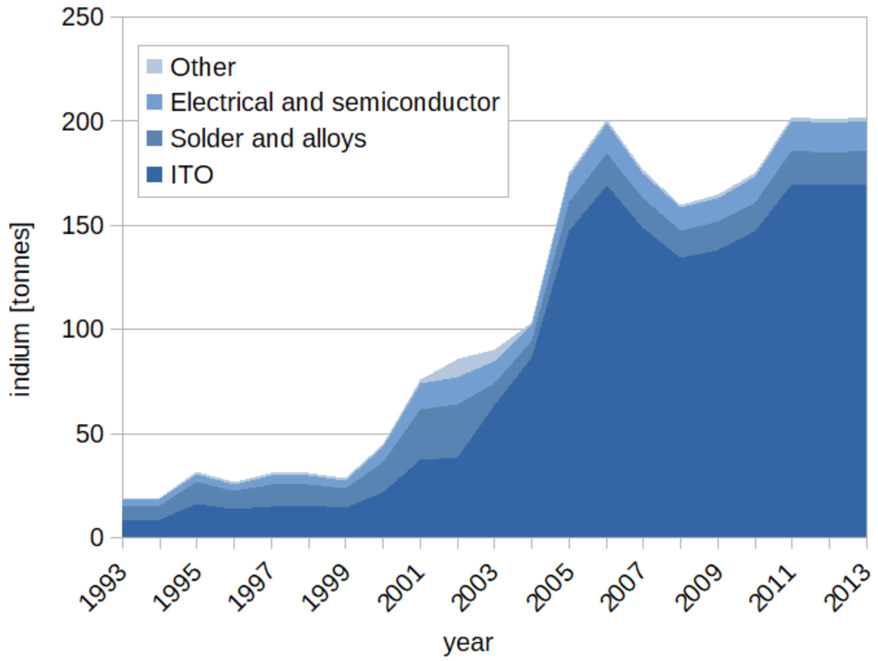

Figure 15: Estimated historical use of indium in Europe. Based on data from by Langkau & Tercero Espinoza (2018) scaled to the total use of indium in Europe in 2012.

Figure 15 is a very tentative figure based on global data. The important message is that use of indium has grown a factor 10 from 1993 to 2013 only due to increased use as ITO. ITO that is used in flat panel displays and solar cells.

FUTURE DEVELOPMENT OF APPLICATIONS

Given that the use of indium is almost completely determined by its use in LCDs and PV as ITO, the growth of these applications and the indium content of those applications that determine future use indium. We assume that CIGS thin film solar cells will remain a small share of the overall PV solar cell market up to 2030.

Growth in the use of flat panel displays is assumed to be 1.6%, a bit higher than the overall growth of TVs, Computers & Laptops and other small appliances as assumed under the SSP2 scenarios which on average sees 1.4% growth per year (Deetman et al. 2018).

FUTURE USE

Based on the growth scenario of ITO using appliances estimated future use of indium in the EU from 2015 until 2030 is shown in Figure 16 together with its estimated historical data. This differs a little from D2.2 (Ait Abderrahim und Monnet 2018). Instead of a slight rise, D2.2 shows a flat development, likely following from the assumption of reducing the indium content of appliances over the years. We were unable to find reasonable estimates for such a reduction, but the difference is not very large.

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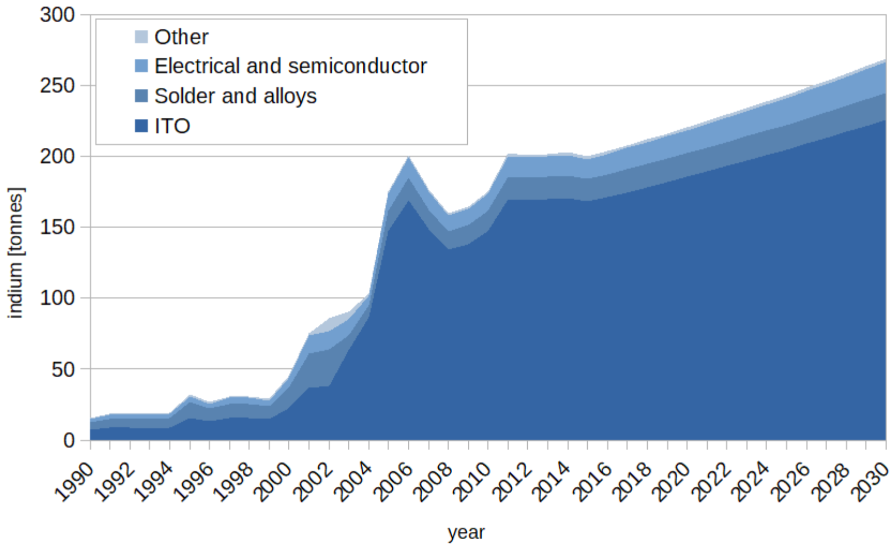

Figure 16: Historical and future use of indium in Europe. Based on data from by Langkau & Tercero Espinoza (2018) scaled to the total use of indium in Europe in 2012.

After the replacement of CRTs with LCDs around 2000, and the associated rapid increase in indium use, the development of the use of indium is expected to steadily increase until 2030 without major surges or decreases in use. Recycling of indium from post-consumer scrap is currently negligible (UNEP 2011) and expected to remain negligible although a stream of discarded LCDs will become available given the short lifetime of electronic appliances.

MAGNESIUM

MAGNESIUM USE AND APPLICATION

Magnesium metal can be used in many different applications and forms. Known as the lightest structural material, it is most advantageous in transport light-weighting applications. There, it is also a possible substitute candidate material for most of the aluminium transport applications. An important, but by far not the only, decision criteria for using magnesium is the Mg/Al price ratio. This has been stable largely stable in the past years both in China and in the EU. The European Mg/Al ratio has not been more than a factor of 1.5, which is at the end off-set by less net material needed for the Mg part (magnesium has a density which is 1/3 less than aluminium).

One third of all magnesium metal is used for alloying aluminium alloys, which are valued for reaching competitive properties, such as strength and processing parameters. There, the addition of small amounts of Mg (typically <5%) increases its strength so it can be used in structural applications such as in transport (e.g. automotive Al sheet), construction, pressurised containers (e.g. beverage cans), and aerospace. Automobile manufacturers use cast magnesium based alloys (Mg-Al) to produce steering wheels, steering columns, support brackets, front and instrument panels, pedals and inlet manifold housings, among numerous other parts. Mg-Al die castings are further used to make transmission and clutch housings. Figure 17 shows the global demand proportion of applications for magnesium metal in 2017.

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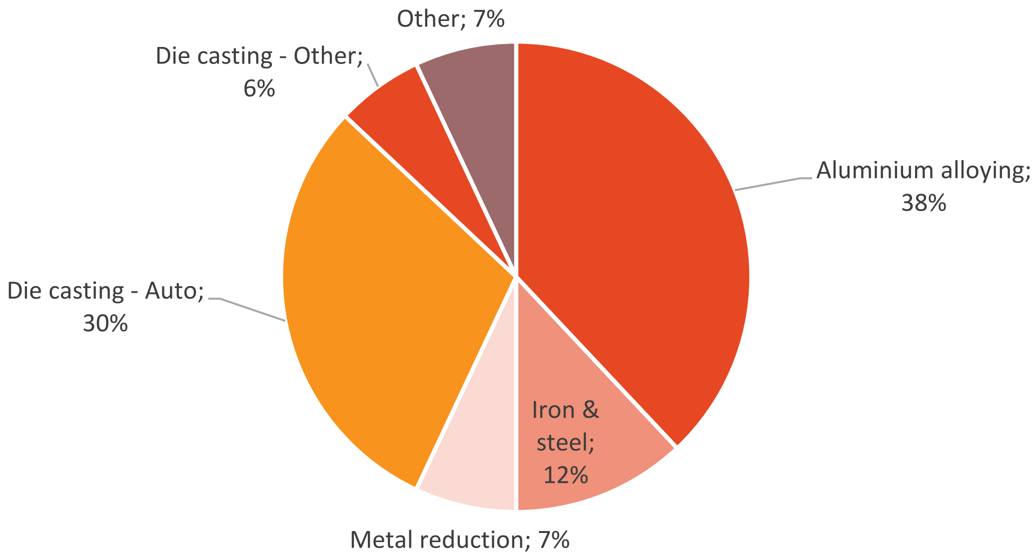

Figure 17: Global magnesium metal engineering applications 2017 (CM Group/Australia 2018).

MAGNESIUM METAL USE IN EUROPE

In a European Union context, magnesium is important to several major industrial economic sectors including road transport, construction materials, metal alloys and the aerospace industry. A study was done by Oakdene Hollins Research and Consulting on behalf of the International Magnesium Association to examine the footprint of magnesium metal material flows through the European economy (Oakdene Hollins 2017). This study used a bottom up approach in a material flows analysis to determine the true volumes of magnesium metal in the European Union economy for the year 2012 (the most recent year where quality data in all relevant sectors was available). As no primary magnesium metal is refined in Europe, all magnesium metal products (primary magnesium ingots) needed for conversion steps after refining were imported. Products examined were everyday products such as aluminium beverage cans, motor and aerospace vehicles, consumer electronics and steel (magnesium granules used as desulphurisation agent).

Below is a high-level Sankey diagram for magnesium metal flowing through the EU. The bottom-up approach applied to developing the material flow analysis, i.e. quantifying each flow per application of Mg individually and then summing them together to get the values presented in Figure 18, meant that it could also be determined how much Mg is used in which applications the EU.

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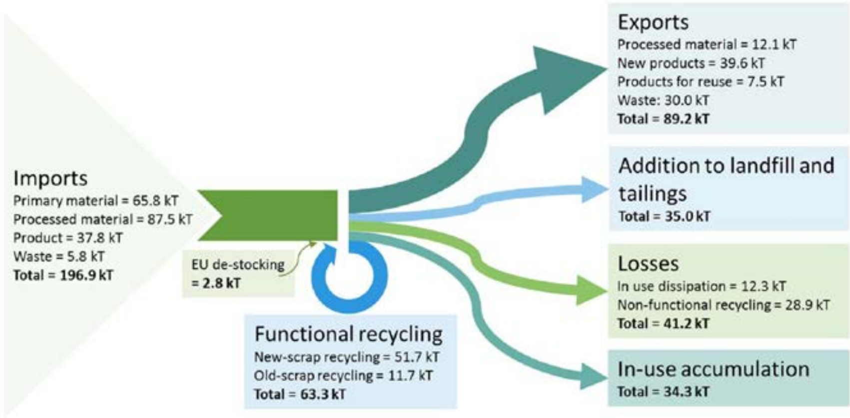

Figure 18: High-level Sankey diagram for magnesium metal produced in 2012 (Oakdene Hollins 2017).

REFINED MAGNESIUM PRODUCTION

China dominates the global supply with well over 80% of the market share. China has been able to dominate the magnesium metal market for a number of reasons. In and/or around the year 2001, the People's Republic of China Government made it a priority to dominate the supply chain of many industrial minerals and metals. The rationale seems to be supply chain dominance ensures control of the price and thus long-term economic security.

The main production method used by Chinese producers is the Pidgeon process, also known as thermal reduction technology (Berry 2015). While this is the cheapest process, it is also environmentally unfriendly and inefficient with coal used as its main energy source. The Pidgeon process is the dominant process to manufacture magnesium metal in China (the dominant producer globally) as the Chinese economy has been comparatively lax on environmental standards, has plentiful labour, and availability of cheap coal. All of this has allowed China to become the dominant global force in magnesium production. As a consequence, production capacity outside China was shut down and new projects have not been realised. As labour costs rise and the Chinese government starts to appropriately deal with environmental challenges, this market dominance may be reduced. In 2018, Qinghai Saltlake Magnesium opened their production, using an electrolytic production process, and claimed the lowest CO_2 footprint for primary production of magnesium (Magontec 2017). This could be seen as a major breakthrough in the future of Chinese magnesium production. It is expected that China will remain the dominant provider in the foreseeable future.

About 15% of the global magnesium supply is produced or exported into protected markets like US and Brazil. There, long-lasting anti-dumping ruling has favoured local production and created unequal regional pricing. Also, outside China, there are several magnesium primary production projects in the pipeline targeting lower CO_2 footprint material and provide customers with an outside China supply source.

CHINESE CHANGE AND ENFORCEMENT OF ENVIRONMENTAL LAWS

In 2017, the Chinese Ministry of Environmental Protection introduced the "special Air Pollution Emission Limits" also known as the "2+26 cities", where maximum pollution exposure limits were drastically reduced (for magnesium and titanium production). Following media announcements, about 22% of production capacity in

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the area of Beijing and Tianjin was closed. The main producing areas of primary Mg - Yulin, Yuncheng, Baotou and Ningxia are outside this target area.

In October 2016, China's MIIT issued its "Non-ferrous Metals Industries Development Plan (2016- 2020)", proposing to focus on the development of high-performance light alloy materials. It rules as well for strictly control of new magnesium smelting projects and capacity expansion, promote magnesium smelting energy-saving and emission-reduction technology, and set out specific targets for reducing comprehensive energy consumption by magnesium smelting. It is expected that a new national environmental standard (following the example of the 2+26 city limits) will be enforced in 2020.

RECYCLING OF MAGNESIUM METAL IN THE EUROPEAN UNION

There is no more primary magnesium metal production in the EU (in 2017, a primary magnesium plant opened in Turkey). While Magnesium is critical to the EU industry, for the foreseeable future it will be imported into Europe. The only source of magnesium metal that may increase is recycling of magnesium waste streams within Europe.

The End of Life - Recycling Input Rate (EoL-RIR) for Mg in the EU was derived from the material flow analysis data (Oakdene Hollins 2017). At 7% the EoL-RIR of Mg is low, lower than that of Al at 12% (global, not EU specific value). This was not unexpected given the dispersive nature of some of Mg's applications, and the collection and recycling inefficiencies.

FUTURE DEMAND FOR MAGNESIUM METAL USE

The greatest opportunity for growth in future demand of magnesium metal could well be in the automotive industry. As time goes on, there is a push to make cars more fuel-efficient (or to increase the range of electrified vehicles). One of the ways to do this is by making cars lighter in weight. To achieve this, the use of magnesium alloys could become more widespread.

Estimates that by 2020, 250 pounds of magnesium will replace 500 pounds of steel and 90 pounds of magnesium will replace 130 pounds of aluminium per vehicle, resulting in an overall 15% weight reduction (S&P Global Platts 2015) appear overly optimistic. However, increasing use of magnesium in automotive applications is expected.

According to the World Steel Association, steel production growth has moderated in 2015 and has been shrinking on a percentage basis in large part due to the economic slowdown in major steel consuming countries such as China. In addition, as the global human society seeks to become more technologically advanced, more complex manufacturing will be required, consuming a range of metals and materials, especially magnesium metal.

The future of the magnesium metal demand looks stable. It will always be needed. Demand is predicted to increase steadily as society becomes larger and more complex. Europe depends on magnesium metal for a number of its mega sectors of manufacture. As there is no primary magnesium plants in the EU, Europe will continue to depend on imports. As China is the dominant supplier at around 85% of the market, the only way the EU can increase its local security of supply will be through advances in the recycling sector.

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NIOBIUM

CURRENT USE

Most of the niobium is used as alloying element in high strengths steel products (Kurylak et al. 2016). The second most important use of niobium is as alloying element in so called super alloys. Super alloys are alloy steels that resist corrosion in high temperature and highly oxidative environments. These super alloys find application in gas turbines and vehicle exhaust systems. According to (Deetman et al. 2017a) in D2.1, about 38% of niobium use in Europe is applied in vehicles. However, it is not known how much of this niobium is used in high strength steel and which part of the niobium is used in super alloys in the exhaust systems. All in all, the use of niobium in high strength steels and super alloys covers about 98% of the uses of niobium. The remaining 2% of niobium is used in superconductors.

Table 3: Overview of the use of niobium in 2012 in the EU27.

Appliance	niobium	Fraction
	[t]	[-]
Superconductors	163	0.02
Vehicles	3088	0.38
Aircraft, ships & trains	81	0.01
Gas turbines	81	0.01
Pipelines	569	0.07
Building construction	4144	0.51
Total	8125	1.00

The amount of niobium in use in superconductors has been estimated at 163 ton in 2012. It is likely that this value is not representative for current use of niobium in Europe. The ongoing building of ITER , the huge nuclear fusion energy plant in France, requires large superconducting electromagnets, that are made from Nb_3Sn and NbTi (Lim et al. 2012). The superconducting alloy used in the magnets weights about 1180 ton (Sborchia 2011). The requirement of ITER alone meant that the global production of Nb_3Sn had to be scaled up from a few tons per year in the past to industrial scale production at about 100 tons/years (Sborchia 2011).

FUTURE DEVELOPMENT OF APPLICATIONS

The use of niobium in superconducting alloys, i.e. NbTi and Nb_3Sn would need a scenario for the development of superconducting magnets. In the short term, demand for superconducting magnets in Europe is likely dominated by the construction of ITER. ITER is planned to be operational by 2025. If no large-scale research facilities are being build such as the Large Hadron Collider (LHC) or ITER after 2025 we may expect that demand for niobium in Europe reduces. Superconducting electro magnets can still be found in MRI scanners.

The use of niobium in vehicles is difficult to foresee because we do not know the amount of niobium going into super alloys or high strength steel applications in those vehicles. When electrical vehicles are replacing the internal combustion engine in vehicles, the super alloys are not necessary anymore but the demand for niobium in high strength steels in vehicles might remain. Overall, the amount of niobium in vehicles might be

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reduced. In D2.2, a different assessment is made, resulting in a slight growth for Nb in vehicles, among others as a result of moving away from ICE mobility. We see no reason for such an increase.

Niobium use in building construction is used in high strength steel. As such, future use of niobium in building construction follows expectations on construction work in Europe, which is expected to remain steady for the coming decades.

Niobium in super alloys in jet turbines and gas turbines are assumed to be the main application in aircraft, ships, trains and gas turbines. As the air transport is expected to increase substantially the coming decades the amount of niobium in aircraft, ships, trains are expected to increase substantially as well (see D2.2, Ait Abderrahim und Monnet 2018). We assume an increase of 1% per year. The use of gas turbines is expected to decrease because in general the use of fossil fuels will decrease under influence of increasingly stringent climate policies in Europe. We assumed a decrease of 2% per year.

Demand for transport in pipelines will determine the amount of niobium used for the construction of pipelines. No European wide scenarios do exist about future developments of the pipeline transport infrastructure. It seems that the use of niobium in high strength steel in pipelines was driven by the development of high pressure gas lines i.e. related to the gas exploration (Gray 2002). Given that the coming decades the use of fossil fuels need to be reduced, we may hypothesize that the use of niobium in pipelines will be reduced in the same way as the use of Nb in gas turbines.

FUTURE USE

Based on above considerations a tentative scenario for the future use of niobium can be drawn up. In Figure 19 the scenario for future developments are shown. The scenario is critically dependent on the assumption that high strength steel based on niobium alloys does not replace other high strength steel alloys. If we assume that there is no substitution between different high strength steel alloys the development of niobium is mostly influenced by a reduction in the use of fossil fuels. This will reduce the amount of niobium in gas turbines, gas pipelines and internal combustion engines. Assuming that the amount of construction work in Europe remains at similar levels as today, the use of niobium in construction work remains constant.

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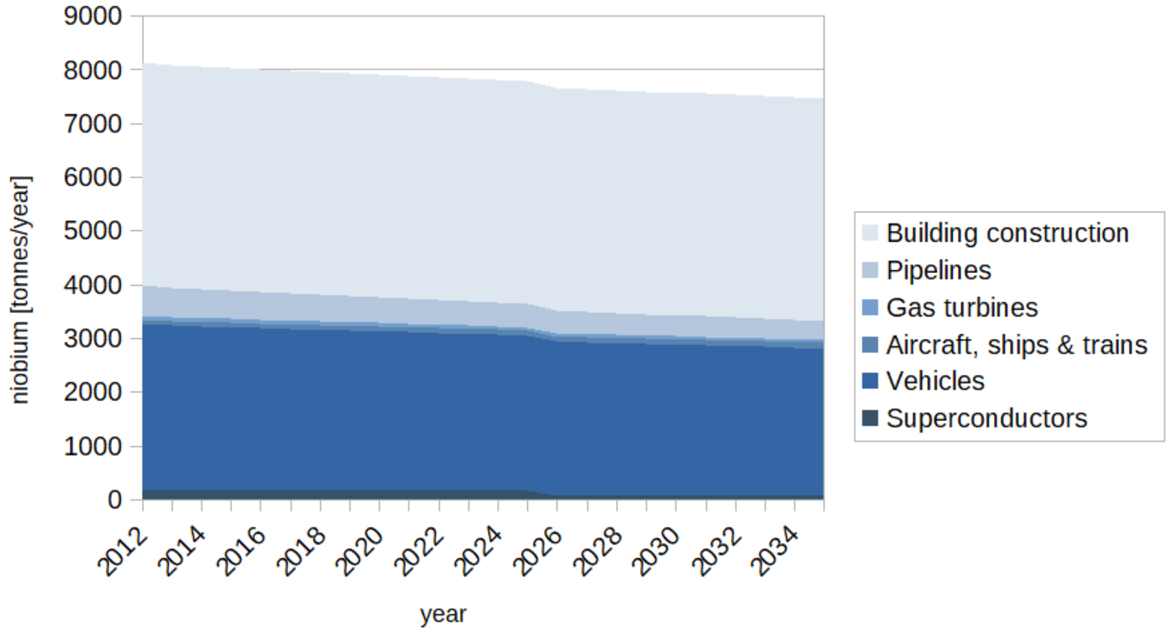

Figure 19: A scenario based on the future use of niobium, which is mostly influenced by a reduction in the use of fossil fuels reducing the amount of niobium in gas turbines, gas pipelines and internal combustion engines and a constant use of niobium in construction work.

PGM: PALLADIUM

CURRENT USE

The mobility sector is expected to change fundamentally during the next decades, turning away from cars with internal combustion engines towards the use of electric vehicles. Since autocatalysts are only needed in cars containing a combustion engine, their production was described as one of the sectors expected to cause major changes in raw material demand in Europe in WP 2.2 (Ait Abderrahim und Monnet 2018). Palladium demand is predominantly driven by its use in autocatalysts. This application was responsible for 80% of the global gross demand of palladium (excluding the influence of investment) and for 84% of the demand at a European level in 2017 (Johnson Matthey 2018b). Therefore, a large part of palladium demand is covered by one of the major trends identified in WP 2.2. Additionally, palladium is also used for printed circuit boards in the electronics sector, which is influenced by two more major trends concerning the material demand of domestic appliances as well as smartphones, laptops and PCs.

Historic supply and demand of palladium is very well documented on a global as well as on a regional scale with a good level of detail concerning applications and a considerably long timeframe from 1980 to 2017 (Figure 20). In our analysis, palladium demand from the investment sector was omitted as being out of scope for the SCRREEN project and the EU Raw Materials Initiative (RMI). Furthermore, we sought to highlight the similarities/differences between Europe and the overall global uses of palladium (the difference between global and European palladium demand is shown as demand by the rest of the world, RoW, in Figure 20).

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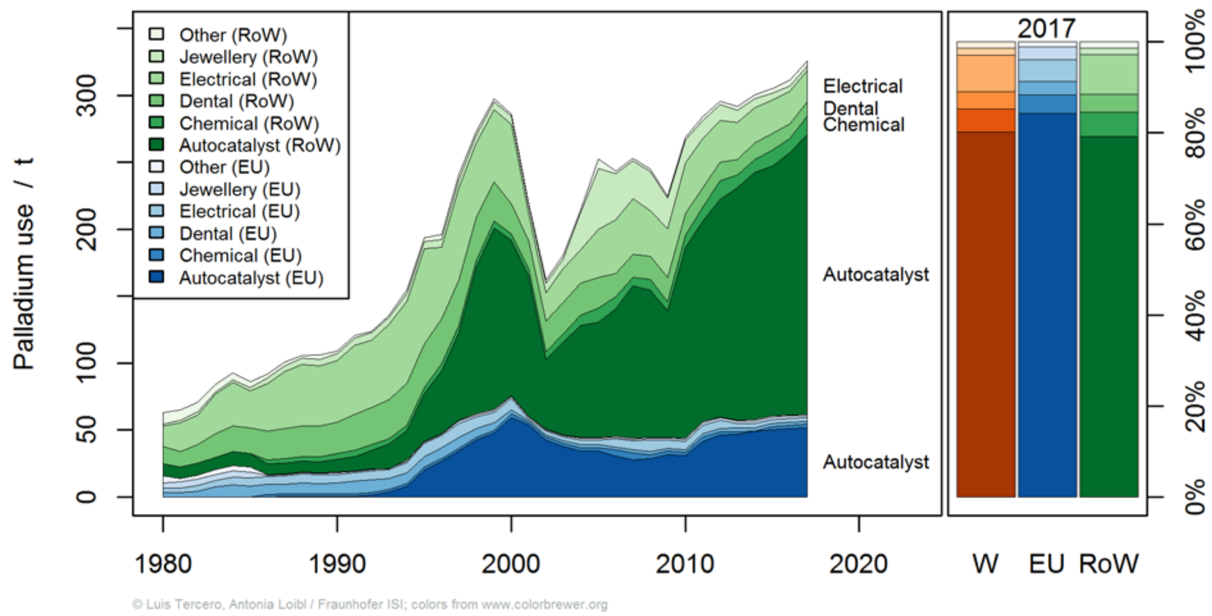

Figure 20: (Left) Historic palladium demand 1980-2017 split into its main application sectors and shown for Europe (shades of blue) and the rest of the world (shades of green). (Right) Comparison of shares in total palladium demand for each application in 2017 (last data year) at the global (orange, "World) and European (blue) levels, and for the Rest of the World (green, "RoW"). Demand for investment is excluded from the illustration (Johnson Matthey 2018a, 2018b). Demand estimates for the RoW were constructed by subtracting European demand from global demand for each sector.

Since the mid-1990s, palladium demand was dominated in Europe as well as in the rest of the world by its use in autocatalysts. With 80% globally and 84% in Europe, very large shares of the total palladium consumption (326 t World, 62 t Europe) went into autocatalysts in 2017. On a global scale the other applications accounted for 8% electrical, 5% chemical, 4% dental, 2% jewellery and 1% other uses in 2017. In Europe, electrical use had a share of 5%, chemical of 4%, dental use and jewellery 4% each and other 1% in 2017 (Figure 20). Overall, European and global demand patterns are very similar.

FUTURE USE

In order to develop scenarios for future palladium use until 2035, the historic data was combined with results from the trend analysis in WP 2.2 (Ait Abderrahim und Monnet 2018). For applications of palladium not covered in WP 2.2 (chemical, dental, jewellery, other), a global as well as a European demand forecast has been developed by extrapolation of the historical data. Future palladium use in autocatalysts and electrical appliances in the form of smartphones, laptops, PCs as well as domestic appliances were discussed in WP 2.2 and scenarios with specific growth rates until 2035 were proposed for each application. Since the data for use in autocatalysts was given for PGMs and not for palladium individually, the assumption of a constant PGM ratio in autocatalysts until 2035 was made to be able to use the given numbers for palladium. The trend analysis for autocatalysts covers the palladium use category of autocatalysts as a whole. Therefore, the growth rate from WP 2.2 was applied as it was to the whole category. On the other hand, the sector for electrical uses includes smartphones, laptops, PCs and domestic appliances as well as other applications. Accordingly, growth rates from WP 2.2 for smartphones, laptops, PCs and domestic appliances were condensed into a growth rate for the whole sector electrical uses. A parallel development of Europe and the World was assumed for the sectors of autocatalysts and electrical uses. The result of these assumptions is shown as palladium demand from the six different application sectors separated into Europe and the rest of the world between 1980 and 2035 (Figure

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21). Over the whole time analysed, Europe has a relatively constant share of about 16-25% of the global palladium consumption. Only in 2000-2003, the European share rose up to 31% since the drop in demand around the turn of the century hit Europe a year later than the rest of the world. During the forecast period of 2018-2035, Europe is responsible for a constant share of 18-19% even though European development of each application differs from the global picture.

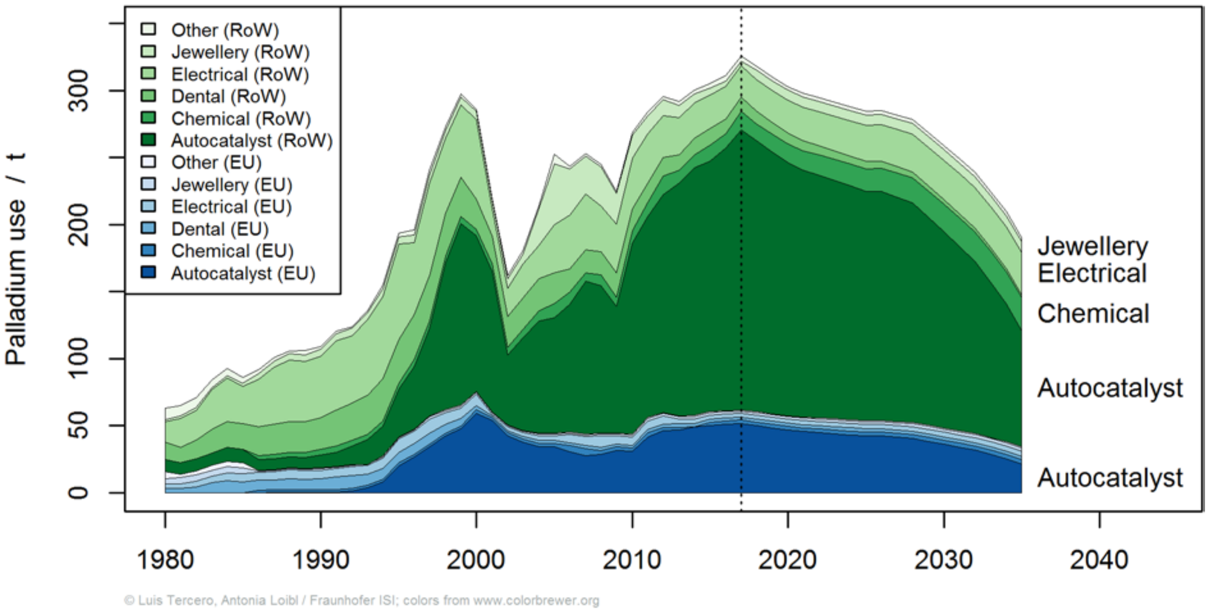

Figure 21: Palladium demand for the main application sectors with historical data until 2017 (indicated by the dotted line) and a demand forecast in the timeframe of 2017-2035 shown for Europe (blue) and RoW (green).

Looking at the forecast until 2035 of these sectors (Figure 21), only chemical use of palladium is expected to grow significantly in absolute demand while dental applications are almost vanishing in the rest of the world. Electrical uses increase slightly in the EU as well as worldwide due to rising demand for smartphones, laptops and PCs as described in WP 2.2 but the overall effect is negligible. Only the demand from the autocatalyst sector is expected to undergo major changes in the next two decades. Using the scenario from WP 2.2 on changes of the mobility sector, a decrease in PGM and therefore palladium demand for autocatalysts by 59% from 2017 to 2035 is considered plausible.

Overall, the forecast results in autocatalysts having a share of 57%, chemical of 15%, dental of 2%, electrical 18%, jewellery 6% and other uses of 2% of the global demand of palladium in 2035. In Europe, 62% of palladium demand is expected to be caused by autocatalyst production, 9% by chemical uses, 8% by dental and 11% by electrical applications, 7% by jewellery and 3% by other uses. The total palladium consumption is assumed to be 191 t globally and 34 t in Europe.

Since palladium demand is expected to undergo major changes in the next two decades and those changes are caused by its use in a single sector going down significantly, it appears sensible to consider different scenarios and to try to establish likely upper and lower boundaries for future palladium demand. Two deployment scenarios for electric vehicles in Europe's transportation sector, which were also used in the project „EU Transport GHG: Routes to 2050", were taken from the JRC Science for Policy Report "Assessment of potential

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bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transportation technologies in the EU" (Blagoeva et al. 2016). Scenario Tech2 assumes a strong market penetration by hybrid electric vehicles (HEVs). It has annual growth rates aligned to the four degrees scenario by the IEA and is considered very conservative (IEA 2013). The Tech3 scenario proposes a rapid breakthrough of the more advanced technologies of plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). Growth rates of Tech3 are close to the Paris Declaration on Electro-Mobility and Climate Change & Call to Action and have to be seen as extreme for the EU (UNFCCC 2015). Further assumptions had to be made for adjustment and updating of the scenarios to this purpose:

- The number of passenger cars produced in the EU 2006-2017 was taken from statistics by the European Automobile Manufacturers Association and the growth rate of the last data year of 0.2% was assumed as constant until 2035 (ACEA 2018c).
- The ratio of fuel types for cars produced in the EU was assumed to be equal to the one of new cars registered in the EU since no regional production data according to fuel type was found.
- The historic share of diesel in new passenger car registrations 1994-2017 for EU-15 was extrapolated into the future (ACEA 2018b).
- Since the shares of HEVs, PHEVs, BEVs and FCEVs were given in five year steps in the JRC report, they were linearly extrapolated in between (Blagoeva et al. 2016). Shares of 2015-2018 were matched with available data for alternative fuel vehicle registrations (ACEA 2017, 2018a).
- The share of petrol cars produced was defined as the difference between 100% and the extrapolated share of diesel cars and the shares of HEVs, PHEVs, BEVs and FCEVs.
- Catalysts in diesel cars were presumed to contain 7.5 g of platinum group metals and autocatalysts in petrol systems 2.5 g (IPA 2013). Hybrid electric cars still have an internal combustion engine and therefore need autocatalysts, which were again assumed to contain 2.5 g of PGMs. Fuel cell vehicles do contain platinum. However, since the focus was on palladium in autocatalysts they were set to zero PGM content as were BEV.

Resulting from these assumptions are two scenarios for passenger cars with different fuel types until 2035 from which likely upper and lower bounds for the palladium demand in Europe can be calculated (Figure 22).

Scenario Tech2 has a slower decrease in market share of petrol-fueled cars and a strong market penetration of HEVs (Figure 22). The share of new cars containing an internal combustion engine and therefore needing an autocatalyst in 2035 is at 72% (Diesel, petrol, HEV, PHEV). The demand for palladium in autocatalysts is nonetheless decreasing significantly from 52 t in 2017 (84%) to 20 t in 2035 (61% of EU consumption) which is very close to the scenario assumed in WP 2.2 (21 t for autocatalysts in Europe in 2035). Total European demand for palladium in 2035 is 33 t in this scenario (Figure 23). Tech2 can be considered a conservative scenario and therefore gives an expected upper boundary for future palladium demand.

In scenario Tech3 HEVs never really break through. Instead, PHEVs reach a strong market penetration and the more advanced technologies of BEVs and FCEVs grow quickly in importance (Figure 22). An autocatalyst is only needed for 49% of new cars in 2035. Hence, palladium demand for autocatalysts drops from 52 t in 2017 (84%) to 14 t in 2035 (52% of EU consumption) with a total European palladium consumption of 27 t (Figure 23). Tech3 assumes a rapid development of advanced technologies on the market and has to be seen as extremely optimistic for the development of Europe over two decades. It gives an expected lower limit for future demand of palladium.

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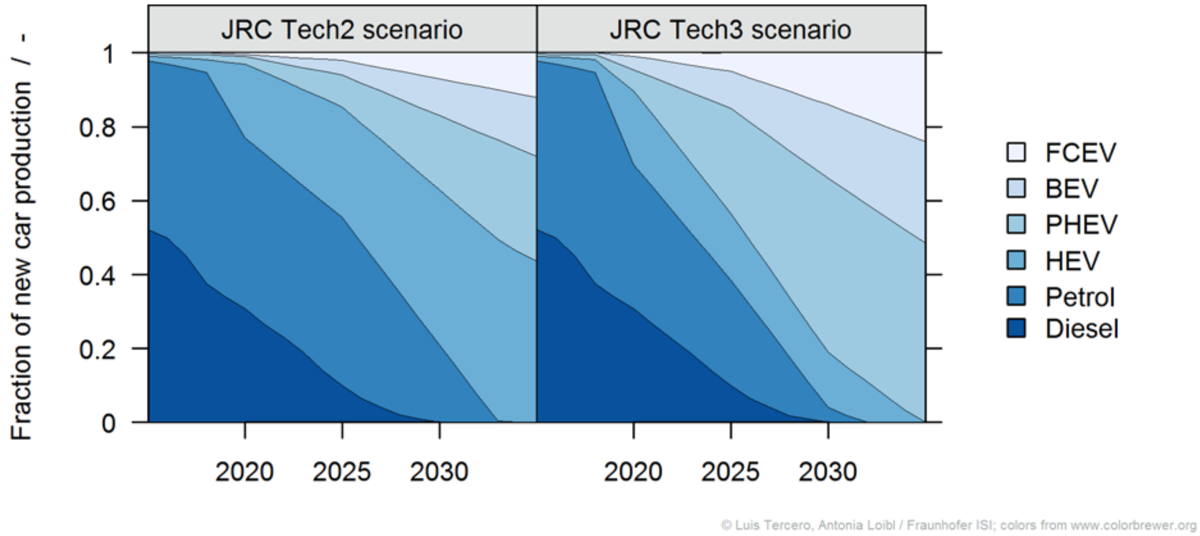

Figure 22: Fuel type shares in passenger cars produced in the EU until 2035 for the conservative scenario Tech2 and the optimistic scenario Tech3 (Blagoeva et al. 2016; ACEA 2017, 2018a).

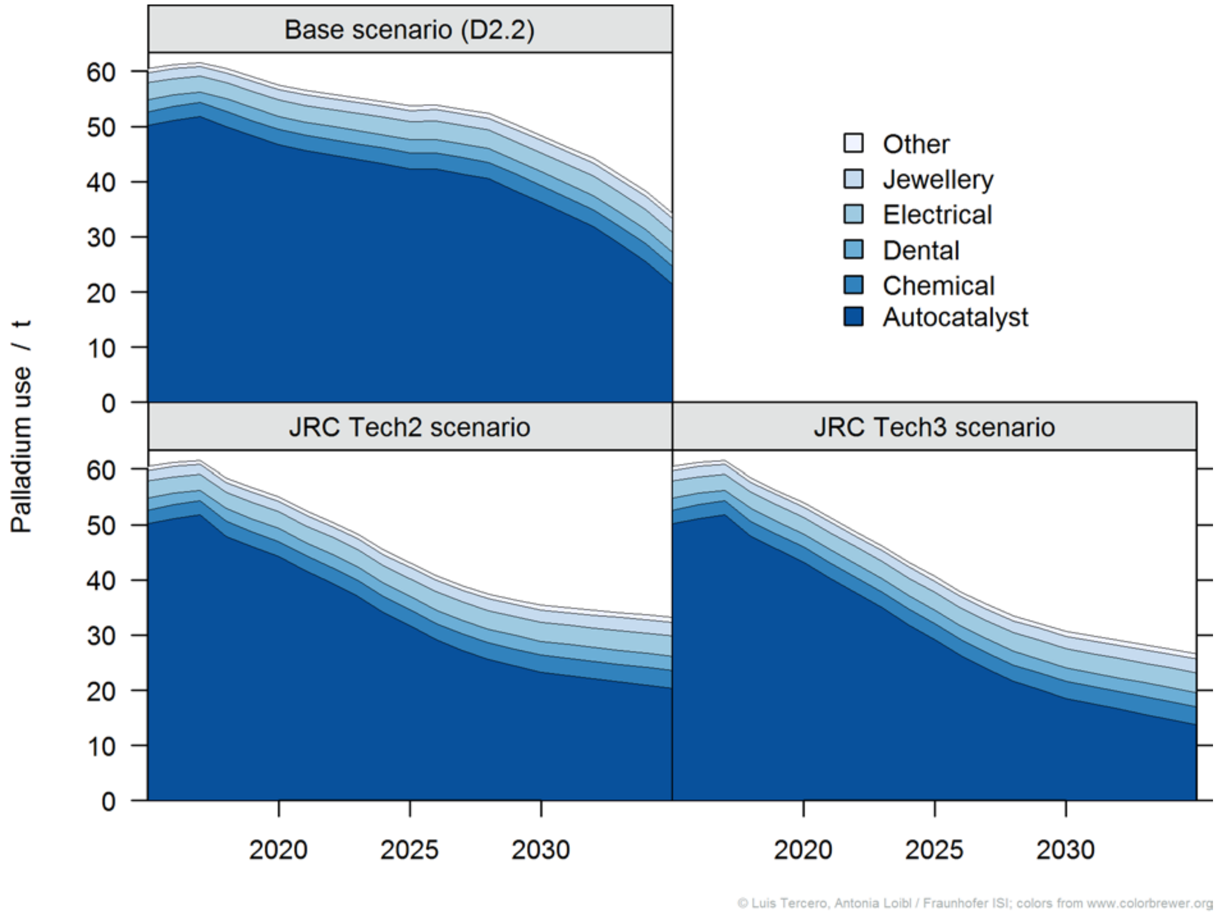

Figure 23: Comparison between projections for the future European palladium use with different scenarios for the development of the transportation sector.

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PGM: PLATINUM

CURRENT USE

Similar to palladium, also interest in platinum is dominated by its use in autocatalysts. In 2017, 43% of the global and even 78% of European demand for platinum was caused by the production of autocatalysts (Johnson Matthey 2018b). With the expected transformation of the transportation sector from a combustion engine-based system towards electric mobility, the overall use of platinum will undergo major changes in the next decades. Since European platinum demand is much more dependent on autocatalysts than demand by the rest of the world is, these changes will be more severe for Europe. Drivers for this trend as well as magnitude and certainty were analysed in WP 2.2 (Ait Abderrahim und Monnet 2018). Besides autocatalysts, other important applications of platinum include its use in jewellery, in the chemical industry and in the production of glass.

Historic supply and demand of platinum is very well documented on a global as well as on a regional scale with a good level of detail concerning applications and a considerably long timeframe from 1975 to 2017 (Figure 24). In our analysis, platinum demand from the investment sector was omitted as being out of scope for the SCRREEN project and the EU Raw Materials Initiative (RMI). Furthermore, we sought to highlight the similarities/differences between Europe and the overall global uses of platinum (the difference between global and European palladium demand is shown as demand by the rest of the world (RoW, Figure 24).

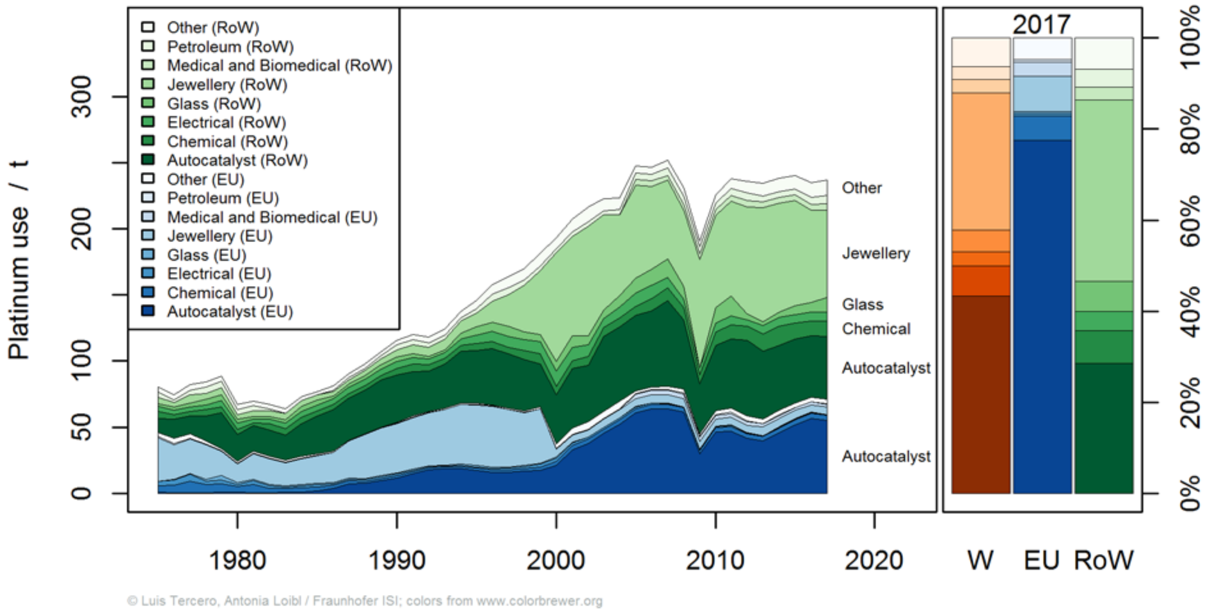

Figure 24: (Left) Historic platinum demand 1975-2017 split into its main application sectors and shown for Europe (shades of blue) and the rest of the world (shades of green). (Right) Comparison of shares in total platinum demand for each application in 2017 (last data year) at the global (orange, "World") and European (blue) levels, and for the Rest of the World (green, "RoW") Demand for investment is excluded from the illustration (Johnson Matthey 2018a, 2018b). Demand estimates for the RoW were constructed by subtracting European demand from global demand for each sector.

Historically, Europe was responsible for a large share of the global platinum consumption of values usually above 40% and even over 50% during the late 1970s and early 1990s. Since 1995, the European contribution

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decreased to 25-30%, which was then constant during the last two decades. The main reason was the contrary development of platinum use in jewellery. In Europe, jewellery was a major application for platinum until a very abrupt decline in 2000 (41 t in 1999, 6 t in 2000). On the other hand, for the rest of the world platinum demand for jewellery production only developed into a significant factor in the 1990s (6 t in 1990, 83 t in 2000) resulting in a quite different structure of current platinum use in Europe and the rest of the world (Figure 24 right).

Today, European platinum demand is strongly dominated by its use in autocatalysts with a share of 78% of the total consumption of 71 t in 2017. The other applications contributed with 8% for jewellery, 5% each for chemical and other uses, 3% in medical and biomedical applications and 1% each for electrical use and the petroleum industry. Platinum use in the glass production does not play a role anymore with a share below 1%. The global demand for platinum of 237 t in 2017 originated mainly from the autocatalyst sector with 43% and the use in jewellery with 30% of the global consumption. Chemical uses had a share of 7%, other of 6%. Glass industry was responsible for 5%, electrical as well as medical and biomedical applications for 3% each and the petroleum industry again for 3%.

FUTURE USE

For the development of a forecast for future platinum demand until 2035, the data for historic platinum use in the world and in Europe was extrapolated separately. Additionally, results from the trend analysis of WP 2.2 were used for the autocatalyst sector (Ait Abderrahim und Monnet 2018). Material demand for autocatalysts and its growth rates until 2035 were given for platinum group metals and not for individual elements. Therefore, the assumption of a constant ratio of palladium, platinum and rhodium in autocatalysts in that timeframe had to be made in order to use the predictions of WP 2.2 for platinum independently. Since the sector of autocatalyst in the trend analysis is congruent with the platinum demand sector of autocatalysts, yearly growth rates were transferred directly and without adjustments. A parallel development of Europe and the World in the autocatalyst sector was assumed. As a result from these assumtions and extrapolations, future platinum demand split into eight different applications can be shown seperately for Europe and the rest of the world until 2035 (Figure 25).

The forecast predicts a decreasing platinum demand for Europe due to the strong decline of the autocatalyst sector from 55 t in 2017 to 23 t in 2035. Platinum use in chemical and other applications is slightly increasing but stays on a low level. Other sectors are stagnant until 2035 resulting in a distribution of European platinum consumption of 51% autocatalysts, 17% chemical uses, 14% each jewellery and other uses, 2% medical and biomedical applications, 1% each petroleum and glass industry and below 1% electrical uses. Overall, a use of 45 t of platinum is projected for Europe in 2035.

Results of the global forecast are similar. However, the growth of chemical and other uses is even stronger, almost balancing the decreasing demand for autocatalysts from 102 t in 2017 to 42 t in 2035. A global platinum consumption of 223 t is predicted for 2035. Application shares are 19% for autocatalysts, 37% for jewellery, 16% for chemical uses, 13% for other applications, 6% for glass production, 4% each for electrical uses and petroleum industry and 2% for medical and biomedical purposes.

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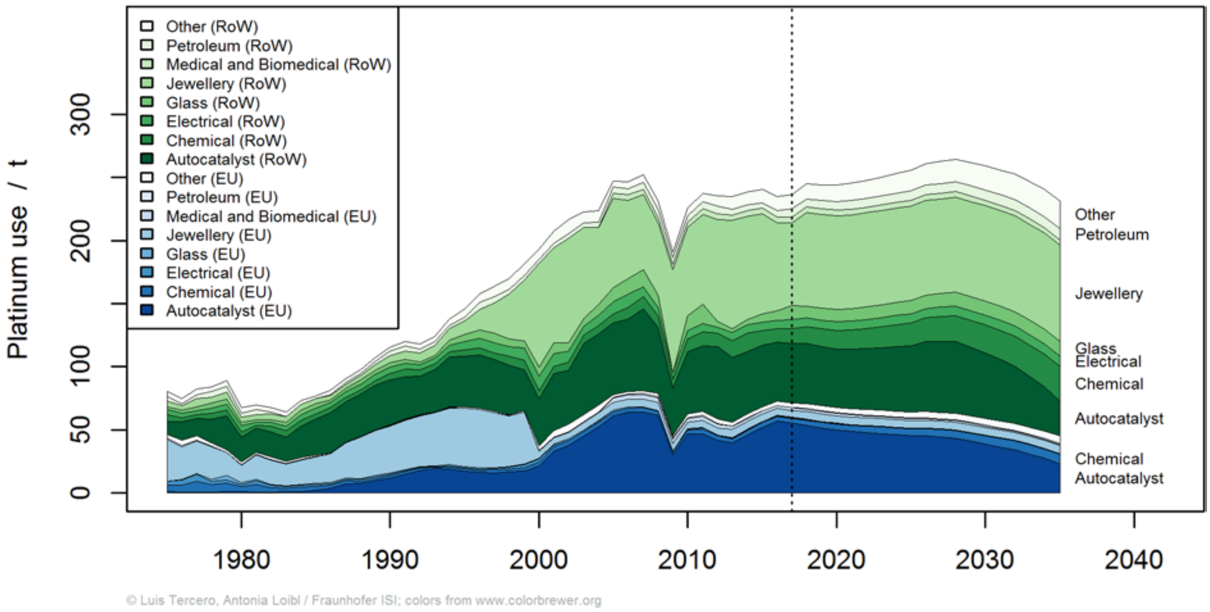

Figure 25: Platinum demand for the main application sectors with historical data until 2017 (indicated by the dotted line) and a demand forecast in the timeframe of 2017-2035 shown for Europe (blue) and RoW (green).

Considering the strong dependence of platinum demand in Europe on a single sector that is expected to undergo major changes in the near future, different scenarios for this transformation were considered. Analogous to the approach for palladium, two scenarios for the penetration of electric vehicles in the European automobile sector were taken from the JRC Science for Policy Report "Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transportation technologies in the EU" (Blagoeva et al. 2016) and adjusted for this purpose. Assumption made and exact specifications for the conservative scenario Tech2 and the optimistic scenario Tech3 are listed in the chapter of palladium (pages 37ff, Figure 22).

One more assumption had to be added when considering platinum use. Fuel cell electric vehicles (FCEVs) do not need an autocatalyst since the combustion of hydrogen only leads to water as a product. They do contain, however, platinum as a catalyst in the fuel cells. With considerable research effort currently going into the reduction of platinum content in fuel cells, assumption of a linear decrease of this value seemed to be sensible (U.S. Department of Energy 2011). Numbers of 0.5 g/kW platinum in 2013 and 0.2 g/kW in 2035 with an average of 75 kW per FCEV were taken from the "Rohstoffe für Zukunftstechnologien" study and combined with the former mentioned JRC scenarios Tech2 and Tech3 (Marscheider-Weidemann et al. 2016; Blagoeva et al. 2016).

Resulting are two scenarios for passenger cars with different fuel types until 2035 from which the European platinum demand can be calculated (Figure 26).

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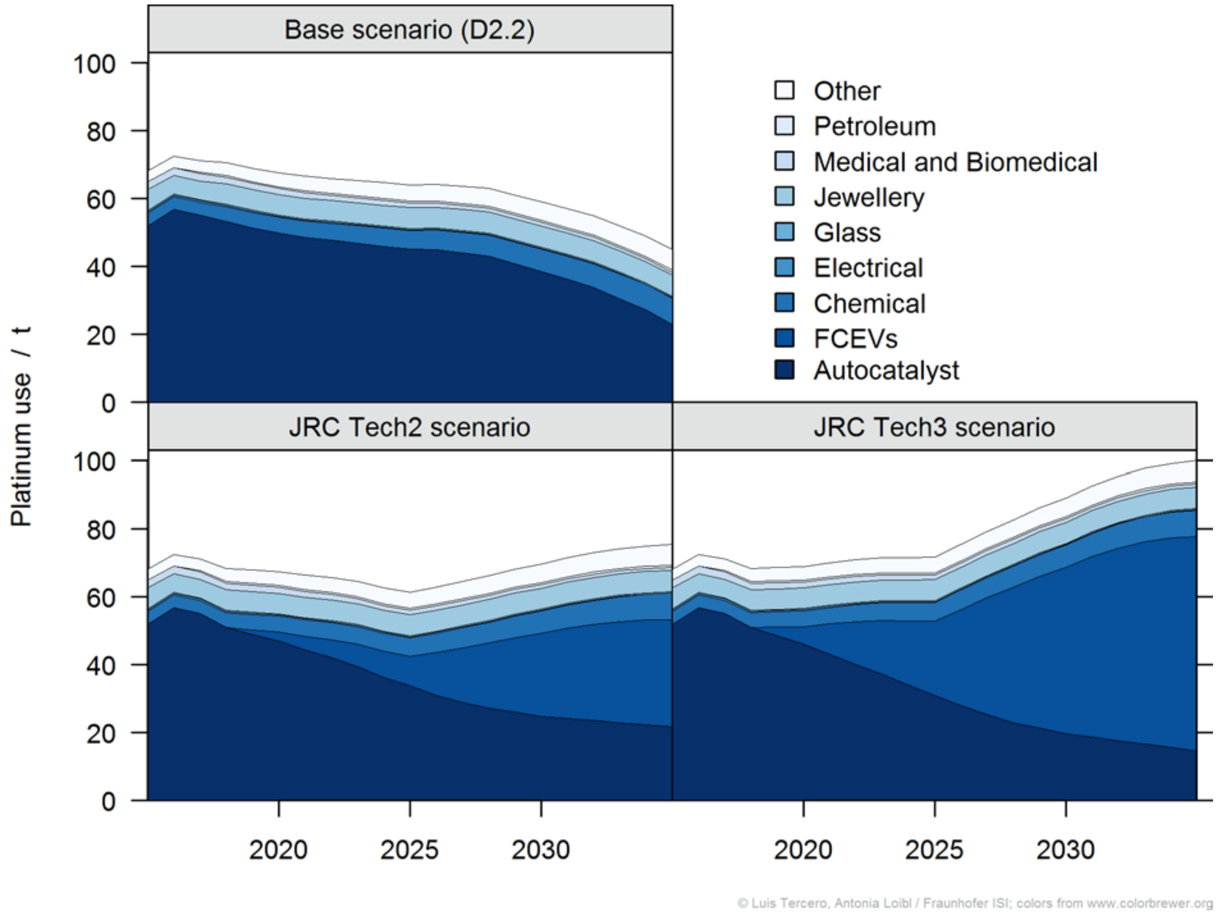

Figure 26: Comparison between projections on the future European platinum use with different scenarios for the development of the transportation sector.

All scenarios show a decrease in platinum demand for the next five years due to a progressing market penetration of electric vehicles and a consequently shrinking need for autocatalysts in vehicles with internal combustion engines (Figure 26). The base scenario of D 2.2 did not take FCEVs into account as a possible alternative to ICE cars in the considered timeframe resulting in a constant decline of platinum use in the forecast period. As a more conservative scenario Tech2 has a strong market penetration of HEVs and only very slowly increasing shares of the more advanced technologies of BEVs and especially FCEVs (Figure 22). Due to the latter, platinum demand starts to increase again in 2025 (71 t in 2017, 75 t in 2035). The more optimistic scenario Tech3 has a faster and stronger market penetration of BEVs and FCEVs (Figure 22) which lets European platinum demand increase again more quickly, surpassing the level of 2017 already in 2023 and rising even further to 100 t in 2035.

PGM: RHODIUM

CURRENT USE

Rhodium is the third of the so-called platinum group metals (PGMs) and like palladium and platinum, it is mainly used in autocatalysts. In 2017, 80% of the global rhodium consumption and approximately the same

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share of the European use was caused by autocatalyst production. Other applications of rhodium are chemical and electrical uses and glass production. The magnitude of rhodium demand, however, is only about one eighth of the ones of palladium and platinum (33 t in 2017, Johnson Matthey 2018b). With the expected transformation of the mobility sector away from internal combustion engines towards electric systems, the production of autocatalysts was identified as one of the causes of major changes in European raw material in this case PGM demand in WP 2.2. Moreover, since the dependence of the rhodium market on autocatalyst production is high, these changes are anticipated to be severe.

The historic demand of rhodium is well documented on a global scale with a good level of detail concerning applications and a considerably long timeframe from 1985 to 2017. For Europe only the total consumption 1985-2013 is available without any splitting into applications (Johnson Matthey 2018a, 2018b). The European Commission funded "Study on Data for a Raw Material Systems Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials" gives rhodium application shares for finished products manufactured in the EU for the year 2012 (Bio by Deloitte 2015). Since these shares for Europe are identical to the data reported for global rhodium use in the same year and no further data was available, shares of the different applications in Europe were assumed to be identical to the global ones during the whole timeframe. Additionally, the European share of the global rhodium consumption between 2013 and 2017 was set to a constant 12% because no newer data was found for Europe. Since we sought to highlight the similarities/differences between Europe and the overall global uses of palladium, the difference between global and European palladium demand is shown as demand by the rest of the world ("RoW", Figure 27).

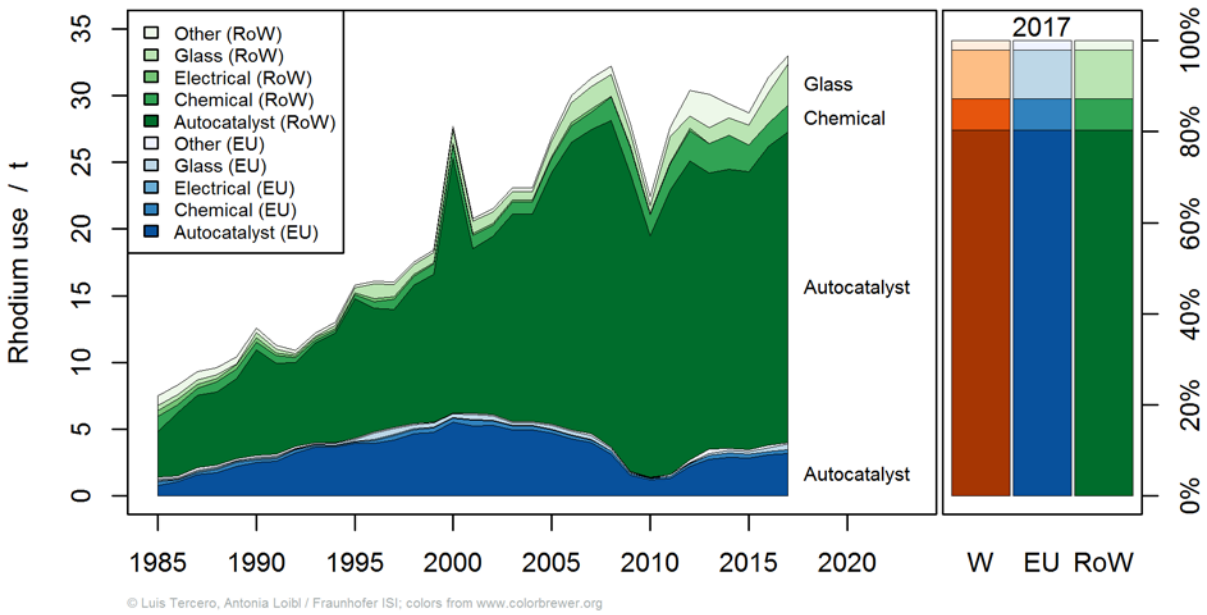

Figure 27: (Left) Historic rhodium demand 1980-2017 split into its main application sectors and shown for Europe (shades of blue) and the rest of the world (shades of green). (Right) Comparison of shares in total rhodium demand for each application in 2017 (last data year) at the global (orange, "World) and European (blue) levels, and for the Rest of the World (green, "RoW"). Demand for investment is excluded from the illustration (Johnson Matthey 2018a, 2018b). Demand estimates for the RoW were constructed by subtracting European demand from global demand for each sector.

While around 30% of global rhodium consumption was generated by Europe in the 1990s, this share decreased since to about 10% in recent years. In 2017 33 t of rhodium were consumed on a global scale and European rhodium use was estimated as 4 t. Autocatalyst production was responsible for relatively constant share of 80-

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90% of the global rhodium consumption since 1990. Rhodium demand for chemical uses and glass production grew slowly but consistently on a small scale. Rhodium use in electrical applications, however, decreased since 1985 and vanished completely after 2010.

In 2017, 80% of the global rhodium consumption of 33 t went into autocatalysts, 11% into glass, 7% into chemical and 2% into other uses. European application shares were assumed to be identical to global values due to a lack of further data.

FUTURE USE

In order to develop a forecast of rhodium demand for different applications, the historic data of European and World consumption was extrapolated until 2035 for each application separately. As mentioned above, less data was available for rhodium use in Europe, which increased uncertainty for the European forecast in comparison to the global projection. For the rhodium application autocatalysts, the analysis of this sector with relating yearly growth rates until 2035 from D 2.2 were used. Material demand was examined for PGMs as a whole without information on separate elements in WP 2.2. Therefore, the assumption of a constant PGM ratio in autocatalysts until 2035 had to be made to use given growth rates for rhodium alone. Otherwise, these growth rates were transferred without further adjustments since trends for autocatalyst production analysed in WP 2.2 are relevant for the whole rhodium demand sector of autocatalysts.

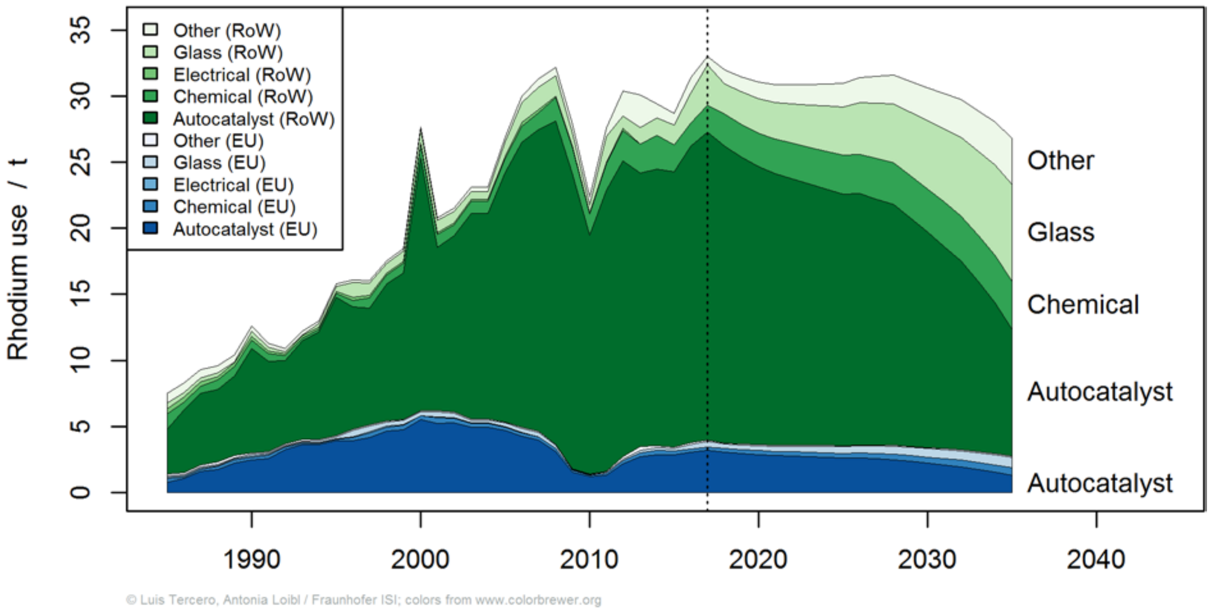

Figure 28: Rhodium demand for the main application sectors with historical data until 2017 (indicated by the dotted line) and a demand forecast in the timeframe of 2017-2035 shown for Europe (blue) and RoW (green).

The global forecast predicts a strong decrease in rhodium demand for autocatalysts while the other sectors of chemical, glass and other uses show an increasing demand for rhodium until 2035. Therefore, the overall rhodium consumption is only diminished by about 18% to 27 t in 2035. The global application shares are foreseen to be 41% autocatalysts, 30% glass industry, 16% chemical and 13% other uses.

The picture of the European projection is similar with a strong decrease in demand for autocatalysts but increasing numbers for the other applications, glass production as well as chemical and other uses. Overall,

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European rhodium demand decreases by 33% to 2.7 t in 2035 which consists of 48% rhodium for autocatalysts, 29% for the glass industry, 20% for chemical and 3% for other uses. For Europe, the forecast for applications other than autocatalysts has to be considered as relatively uncertain since it was made on a small base of data.

Considering the strong dependence of rhodium demand in Europe on a single sector that is expected to undergo major changes in the near future, different scenarios for this transformation were considered. Analogous to the approach for palladium and platinum, two scenarios for the penetration of electric vehicles in the European automobile sector were taken from the JRC Science for Policy Report “Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transportation technologies in the EU” (Blagoeva et al. 2016) and adjusted for this purpose. Assumptions made and exact specifications for the conservative scenario Tech2 and the optimistic scenario Tech3 are described in the chapter for palladium (pages 37ff).

As a result, two scenarios for passenger cars with different fuel types produced in Europe until 2035 are derived from which the European platinum demand was calculated (Figure 29).

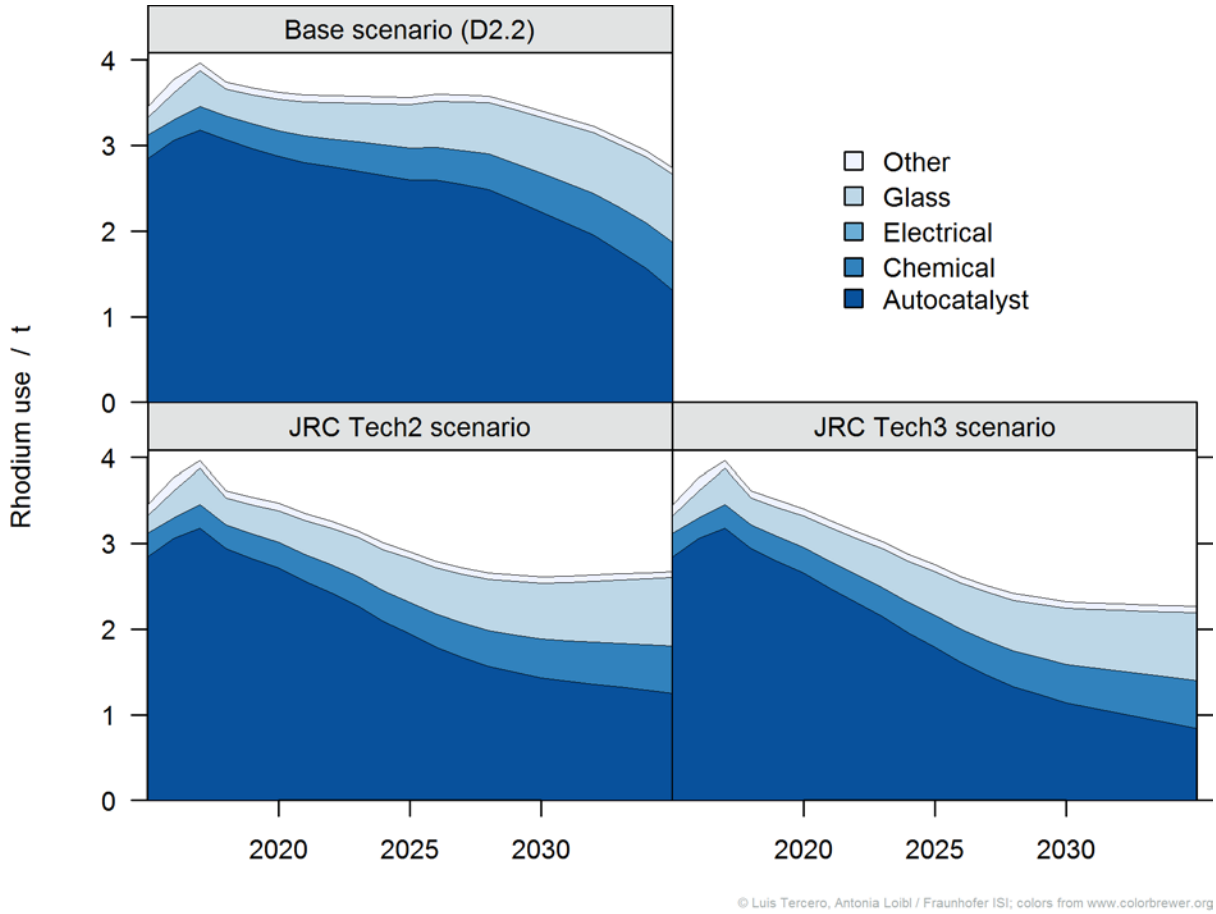

Figure 29: Comparison between projections on the future European rhodium use with different scenarios for the development of the transportation sector.

As a more conservative scenario, Tech2 consists of a slightly slower decreasing market share of petrol-fueled cars and a strong market penetration of HEVs (Figure 22). The share of new cars containing an internal combustion engine and therefore needing an autocatalyst in 2035 is at 72% (Diesel, petrol, HEV, PHEV). The

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demand for rhodium in autocatalysts is nonetheless decreasing significantly from 3.2 t in 2017 (80%) to 1.3 t in 2035 (42% of EU consumption) which is very close to the overall result of the scenario assumed in WP 2.2. Total European demand for rhodium in 2035 is 2.7 t in this scenario (Figure 29).

In scenario Tech3 HEVs never really break through. Instead, PHEVs reach a strong market penetration and the more advanced technologies of BEVs and FCEVs grow more quickly in importance (Figure 22). An autocatalyst is only needed for 49% of new cars in 2035. Hence, rhodium demand for autocatalysts drops from 3.0 t in 2017 (80%) to 0.8 t in 2035 (33% of EU consumption) with a total European palladium consumption of 2.3 t (Figure 29). Tech3 assumes a rapid development of advanced technologies on the market and has to be seen as extremely optimistic for the development of Europe over two decades.

PHOSPHATE ROCK

USE AND APPLICATION OF PHOSPHATE ROCK

Phosphate rock is processed to produce fertilizers, food-grade and feed-grade additives, and detergents. Other marginal applications include metal surface treatment, corrosion inhibition, flame retardants, water treatment, and ceramic production. Despite such widespread use, the latter applications represented only ~3% of the total consumption of various phosphates. Phosphate rock is mined, beneficiated, and either solubilized to produce wet-process phosphoric acid, or smelted to produce elemental phosphorus. Phosphoric acid is reacted with phosphate rock to produce the fertilizer triple superphosphate or with anhydrous ammonia to produce the ammonium phosphate fertilizers.

The element phosphorus underpins our ability to produce food (FAO 2015). It is used as a petrochemical foundation to manufacture fertiliser as part of crop growth and cannot be substituted with another element (at this time). Petrochemical application of phosphorus also manufactures pesticides. Phosphorous is one of the macronutritional elements (as with nitrogen and potassium) and cannot be substituted in its role in manufacturing chemically produced fertiliser use in industrial agriculture (Steiner und Geissler 2018). There is no substitute for the element phosphorus in the growth of all living organisms and this element cannot be manufactured (with current scientific understanding).

While other critical global resources, such as oil, can be replaced with renewable energy sources, such as wind or solar power, no other element can replace phosphorus in food production (Choudhury et al. 2017).

In summary, phosphate fertilisers are needed to ensure a constantly high level of crop yields. These, in turn, are necessary to meet the world's food demand and provide a living for the farmer engaging in planting and harvesting the crops (Cordell und White 2013). Most of the fertilizers consumed have phosphate rock as their primary ingredient. Figure 30 shows the market share for the use of industrial phosphate in 2016.

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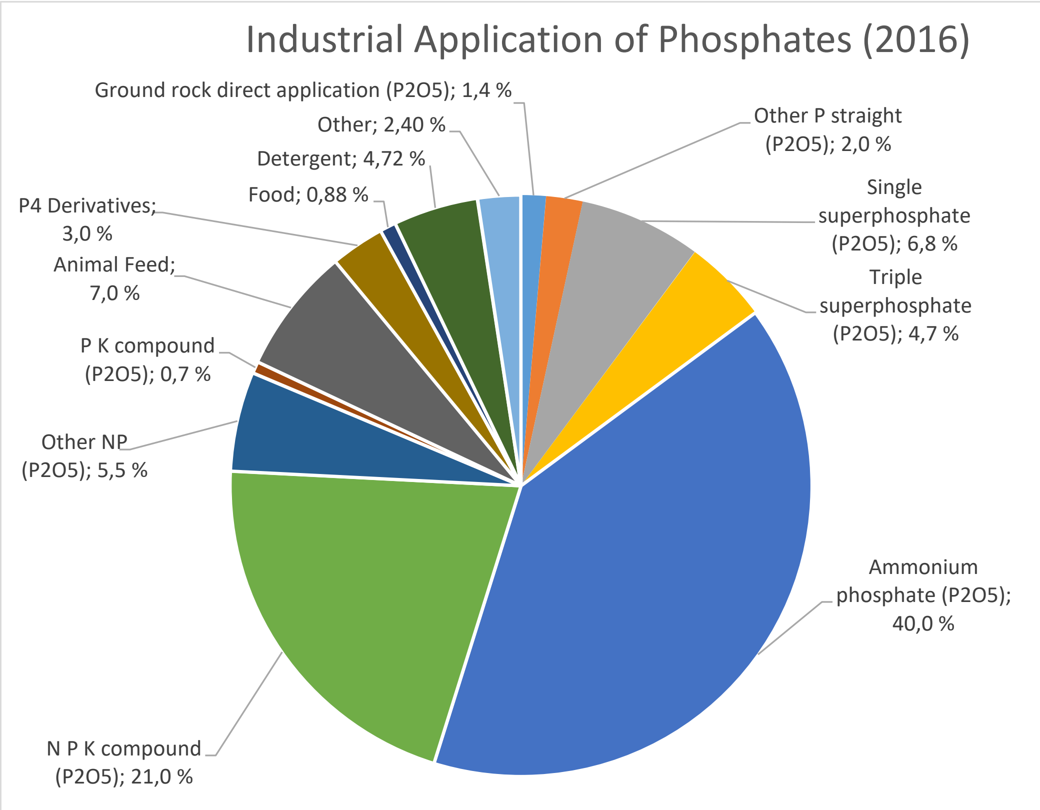

Figure 30: Industrial application and use of phosphate (IFA 2018).

Phosphate rock is considered by the EU Commission report to be subject to "high supply risk" because of concentrated production in three main countries (China, Morocco, USA), with high "corporate concentration" in production (small number of producer companies with large market share). World deposits are considered to be widely distributed, with the biggest deposits stated as being in northern Africa, China, the Middle East and the USA. Additionally, there are large seabed deposits, but these are not considered to be economically accessible at present. Despite predicted growth in world demand of 2%, supply is expected by the Commission report to show a large surplus until the early 2020's.

Currently, the most industrially useful source of phosphorous is phosphate rock, in mineralized deposits of either sedimentary (87%) or igneous (13%) origin (Prud'homme 2016). This mineral is mined, then refined, and manufactured into petrochemical fertiliser. In 2017 there was approximately 200-265 million metric tons of economically viable phosphate rock. Total growth rate for phosphate rock production was 6.3% a year, mainly caused by China (Figure 31). This trend of expansion has been observed since 1968.

European production of phosphate rock is limited to Finland, which started producing 0.36% of global production in 2016. Finland has 1.42% of global reserves of phosphate rock as stated in 2017 (USGS 2018b). Western and Central Europe consumed 17 371 tonnes or 9.3% of global consumption of phosphate based fertilizers (IFA 2018).

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DEMAND FOR AND CONSUMPTION OF PHOSPHATE ROCK

The consumption of phosphate mineral is linked to industrial agriculture manufacture of food and correlates strongly with human population growth (Cordell et al. 2009). Although phosphorus is one of the most abundant elements in the planetary crust, access to industrially useful quantities of phosphorus is now subject to concerns of supply shortage. Mineral fertilizers first were manufactured with the Industrial Revolution. It was not until the development of petrochemical technology that they were applied to food production at an industrial scale. This had an important role in sustaining the growing global population, where now half the population are estimated to be fed with crops grown using synthetic fertilizers (Blanco 2011).

In approximately the year 2000, Chinese consumption of chemically produced fertilizer (derived from among other things phosphate rock) aggressively expanded. The PRC (People's Republic of China) has made a series of long term strategies to ensure long term economic security for the nation of China (JIAO et al. 2018). One of these strategies was to dominate the industrial agriculture manufacture sector and aggressively expand the production of food in China. One of the driving forces behind this was the PRC desire to urbanize 400 million people from a simplistic rural society into a modern industrial society. There was a future perceived food supply gap within China. In the year 2000, the expansion of the industrial agricultural industry was given a new priority as a matter of national security. As can be seen in Figure 3 below, China now far exceeds the rest of the world in not only how much Chinese phosphate rock is produced, but in the consumption of and application of petrochemical fertilizer per unit area of arable land.

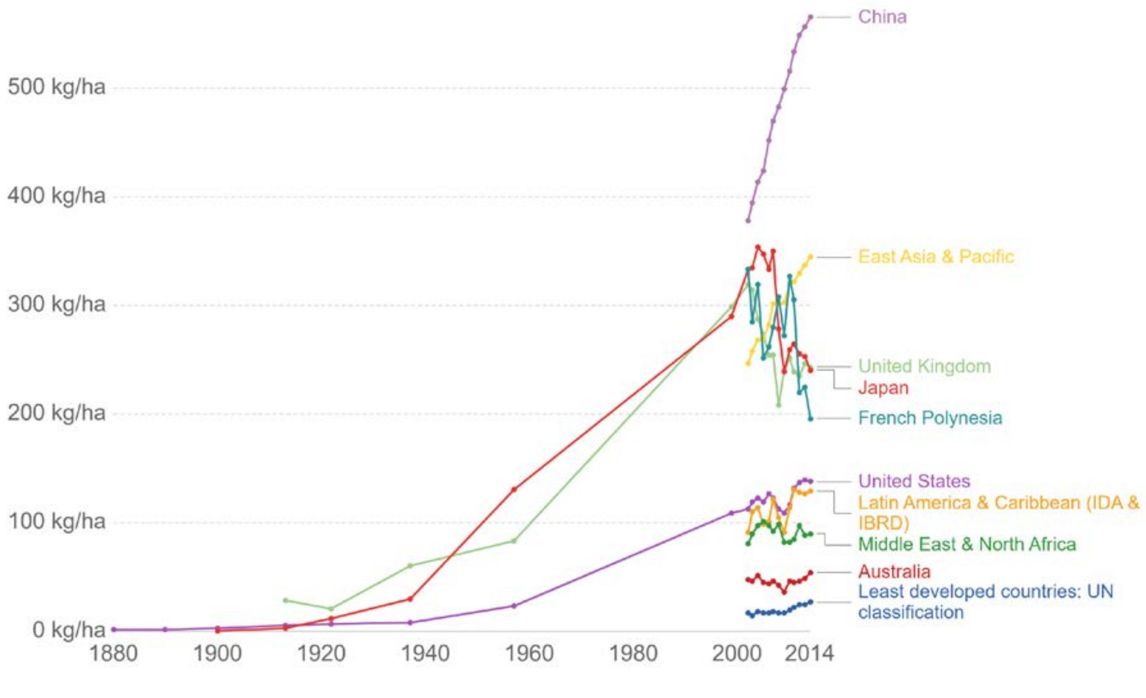

Figure 31: Fertilizer application rates between 1880 and 2014. Average fertilizer application rates for select counties and regions over time. Measured in kilograms of nutrient per hectare of arable land (Roser und Ritchie 2018; World Bank 2018).

China's grain yield increased from 1 t ha^{-1} in 1961 to 6 t ha^{-1} in 2015, while successfully feeding not only its large population but also supplying agricultural products (fertilizers, herbicide and pesticides) all over the world. These achievements were greatly supported by modern technology and distinct governmental policy (Li et al. 2014). In the past 60 years, China's total grain output increased by fivefold, from 113 million tons (Mt) in 1949

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to 571 Mt in 2011, a statistic which provides inspiration to producers in other parts of the world. Grain production per capita doubled, from 209 to 425 kg during the same period. At the national scale, China has succeeded in maintaining a basic self-sufficiency for grain for the past three decades. However, with the increasing population pressure and a growing appetite for animal products, China will need 776 Mt grain by 2030 to feed its own people, a net increase of 35.9% from its best year on record (Li et al. 2014).

While there is little doubt today that phosphorus has played a significant role in feeding the world, humanity is effectively dependent today on phosphorus from mined phosphate rock. Without continual inputs it would not be possible to produce food at current global yields let alone increase them (European Commission 2018a).

Phosphorus is the 11th most abundant element in the earth's crust, yet useful deposits are geographically concentrated in only a few countries. Most of current production is in just three countries (China, Morocco, and USA). One nation state (Morocco) has 71% of global reserves. Those reserves are not available for external audit. This could become geopolitically unreliable and unavailable. Supply to market with existing production in context of growing demand (in context growing population and required increasing tonnes per unit area to meet yield targets), may produce an inelastic supply gap at market in the decade of 2020 to 2030, if measures are not taken by the mining industry to make available adequate capacities on time.

Recycling of phosphorus and a more integrated management approach to the phosphorus cycle could extend reserves viable life by 50 years.

PROJECTION OF FUTURE PRODUCTION OF PHOSPHATE ROCK

Known phosphate reserves are predicted to deplete sometime in the next 100 years (Elser und Bennett 2011). Reserves, however, are not static, but a dynamic concept. For all commodities it can be observed that they grow with consumption due to conversion of resources, which do not yet fulfil the high knowledge requirements of reserves, and discovery from so far undetected geopotentials by changes of technology and exploration (German National Academy of Sciences Leopoldina et al. 2018). The reserve situation of phosphate is more satisfactory than for most of the metals, for example (U.S. Geological Survey 2019).

As phosphate rock supplies a vital mineral resource to a critical function (sustains food supply), and it cannot be substituted with another element, phosphate rock has been classified as a CRM. Even a linear prediction (assuming that demand is linear and not yet exponential), phosphorus demand in 2050 would be 2.7 times the 2012 value. When combined with the 33% increase in population predicted by the UN, total phosphorous rock production is predicted to crease by a factor of 3.6 to 777 Mt/yr (Vaccari 2015).

RARE EARTH ELEMENTS: NEODYMIUM

CURRENT USE

Neodymium as one of the rare earth elements is in Europe mainly used in permanent magnets (74% of products used in the EU) and batteries (12%) as well as to a smaller degree in ceramics (6.25%), phosphors (1.25%), glass industry (1.25%), autocatalysts (1%), hard metals (3%) and other uses (Deetman et al. 2017a; Bio by Deloitte 2015). Neodymium in batteries is really a mixture of several rare earth metals that serves as the negative electrode of nickel-metal-hydride (NiMH) batteries. Those are widely used in electric vehicles at the moment but are expected to be fully replaced by lithium ion batteries due to their improved performance and

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reduced costs in the near future (Blagoeva et al. 2016). Permanent magnets in the form of NdFeB-magnets on the other hand are used in applications such as motors of electronic vehicles, wind turbines and electronics. All three of these sectors were identified in D 2.2 as having the potential of causing major changes in the European raw material demand during the next two decades (Ait Abderrahim und Monnet 2018).

Reliable data on the historic supply and demand of individual rare earth elements is hard to obtain. Rare earth elements are mined together with figures usually published only for the overall amount. Additionally, the rare earth market is highly intransparent with mining mainly taking place in China and a suspected considerable contribution from illegal mining. Therefore, a different approach is necessary for the rare earth element neodymium but also dysprosium in order to analyse their use over time. Using sales figures on appliances containing NdFeB-magnets together with approximations on their neodymium-dysprosium ratio in each application, data on the global neodymium demand from permanent magnet production can be derived (Glöser-Chahoud et al. 2016). Even though this approach disregards other applications of neodymium as well as demand by material losses during production, it has the advantage of being based on relatively reliable data sets. Furthermore, applications of permanent magnets cover approximately 88% of the global demand for neodymium and 79% of the neodymium use in products manufactured in the EU (Deetman et al. 2017a; Bio by Deloitte 2015; European Commission 2014b).

Regional data on the use of rare earth metals is even more difficult to obtain and available data often differs depending on how it was generated. For this study, an available Sankey diagram on European material flows for neodymium in permanent magnet applications in 2010 has been used (Guyonnet et al. 2015). European neodymium demand has been defined as the amount needed for fabrication of alloys, manufacturing of magnets and applications of magnets. Therefore, the import flows of neodymium metal, compounds, alloys and magnets were added together to give a European neodymium demand of 1029 t in 2010. The share different applications had on the European neodymium demand was determined by their distribution in the intra-EU neodymium flow from applications to use of the same Sankey diagram (Guyonnet et al. 2015). Due to a lack of further information, these application shares as well as the share of 5% of the European demand on the global neodymium use has been assumed constant over the whole timeframe of historic data.

Furthermore, we sought to highlight the similarities/differences between Europe and the overall global uses of neodymium so the difference between global and European neodymium demand is shown as demand by the rest of the world (RoW, in Figure 20).

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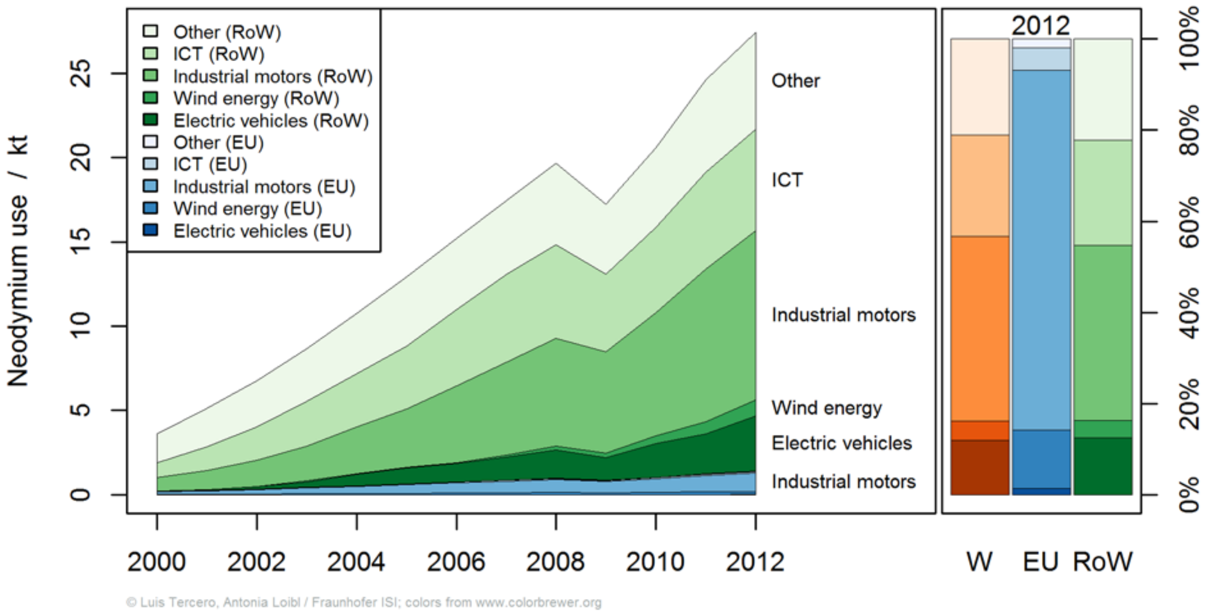

Figure 32: Historic neodymium demand for permanent magnets 2000-2012 split into their main application sectors and shown for Europe (shades of blue) and the rest of the world (shades of green). (Right) Comparison of shares in total neodymium demand for each application of permanent magnets in 2012 (last data year) at the global (orange, "World) and European (blue) levels, and for the Rest of the World (green, "RoW"). Demand estimates for the RoW were constructed by subtracting European demand from global demand for each sector.

As mentioned before, the European share of global neodymium demand is with 5% in 2010 relatively small. Additionally, very different use structures can be observed in Europe and the rest of the world. In the last data year of 2012, global neodymium demand was composed of 41% for industrial motors, 22% for electronics, 21% for other uses, 12% for electronic vehicles and 4% for wind turbines. In Europe on the other hand, 80% of neodymium use was in the production of industrial motors and 13% in the production of wind turbines. Other sectors only had minor contributions in Europe with 5% for ICT, 1% for electric vehicles and 2% for other uses in 2012.

FUTURE USE

For the development of a demand projection until 2035, the historic data for the sectors of industrial motors and other uses were extrapolated. The other sectors of electric vehicles, wind energy and ICT were identified and analysed as causes for major trends in material demand in Europe in that timeframe in D2.2 (Ait Abderrahim und Monnet 2018). In the case of ICT, the suggested growth rates and total amounts of smartphones, laptops and PCs as well as domestic appliances were taken and set off against each other. Wind energy was analysed as its own categories so growth rates were taken and used directly. Significant contributions to neodymium demand in Europe was not observed from the electronic vehicles sector until 2010 (Guyonnet et al. 2015). Therefore, absolute values for the neodymium use in electric vehicles calculated for a scenario between 2015 and 2035 in D 2.2 were used as European demand here and extrapolated until 2010 (Ait Abderrahim und Monnet 2018). Resulting is a projection for the future neodymium use in permanent magnets until 2035 (Figure 33).

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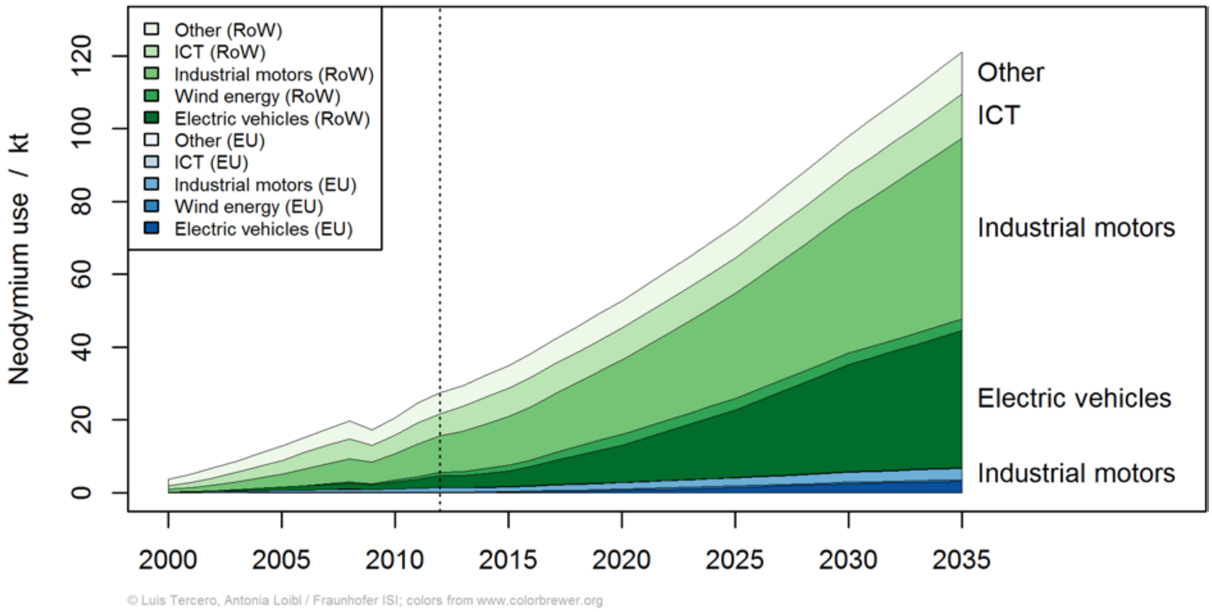

Figure 33: Neodymium demand for the main application sectors of permanent magnets with historical data until 2013 (indicated by the dotted line) and a demand forecast in the timeframe of 2013-2035 shown for Europe (blue) and RoW (green).

The projection shows a significant increase in neodymium demand until 2035 for Europe as well as the rest of the world. While European demand grows by a factor of five, the global development is only slightly less severe with a growth factor of 4.4. Main reason is the predicted change of the transportation sector from cars with internal combustion engines towards electronic vehicles using neodymium magnets in their traction motors. However, all other sectors are projected to grow as well.

In 2035, the projection shows a total global neodymium demand of 121 kt which consists of 44% for industrial motors, 33% for electric vehicles, 10% for electronics and other uses each as well as 3% for wind energy. Europe has a total neodymium demand of almost 7 kt in 2035. Contributing are the sectors of industrial motors with 46%, electric vehicles with 45%, wind turbine production with 6% and ICT and other uses with 2% and 1%, respectively.

In order to investigate the influence of different factors on the projection of future neodymium demand in Europe, different scenarios for its use in electric vehicles and wind energy were developed. Following the approach used for platinum group metals and their use in autocatalysts, two scenarios for the penetration of electric vehicles in the European automobile sector were taken from the JRC Science for Policy Report "Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transportation technologies in the EU" and adjusted as well as updated for this purpose (Blagoeva et al. 2016). Assumption made and exact specifications for the conservative scenario Tech2 and the optimistic scenario Tech3 are listed in the chapter of palladium (pages 37ff, Figure 22).

One more information had to be added for the transfer of these scenarios to the use of neodymium in permanent magnets for electric traction motors. In the former mentioned JRC Science for Policy report, the average neodymium content of different types of electric vehicles were calculated from sales figures of current models as follows: 0.340 kg for PHEVs, 0.153 kg for BEVs and 0.143 kg for HEVs. While permanent magnets used in PHEVs and BEVs usually have the same metal content, the average amount of neodymium in BEVs is considerably diminished by high sales figures of models without a permanent magnet like the Renault ZOE or

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the Tesla Model S (Blagoeva et al. 2016). These average neodymium content values have been used and assumed as constant until 2035. Additionally, FCEVs were set to have the same material demand concerning the electric traction motor as BEVs (Marscheider-Weidemann et al. 2016). Resulting are two projections for neodymium use in cars from European production (Figure 37).

Additionally, neodymium use in wind turbines was examined as well since wind energy was considered to be a sector with the potential of causing major changes in the European material demand in the near future in D2.2 (Ait Abderrahim und Monnet 2018). The low and high scenarios published and updated regularly by WindEurope were used and supplemented with information on the current implementation of new wind power (WindEurope 2017, 2018). The low scenario predicts total wind power installations of 194 GW in 2020 and 256 GW in 2030 with 49 GW offshore and 207 GW onshore. The high scenario has a total installation of 214 GW in 2020 and 397 GW wind power in 2030 with 99 GW offshore and 299 GW onshore. Furthermore, the following assumptions were made:

- Penetration rates for permanent magnet containing turbines were set as 10% onshore DD-PMG turbines in 2014, 29% in 2020 and 44% in 2030, 18% onshore MS/HS-PMG turbines in 2014, 24% in 2020 and 28% in 2030 as well as 21% offshore DD-PMG in 2014, 84% in 2020 and 100% in 2030 (Blagoeva et al. 2016).
- The amount of permanent magnet required was assumed to be 0.675 t/MW for DD-PMG turbines and 0.12 t/MW for MS/HS-PMG turbines (Blagoeva et al. 2016).
- For the neodymium content of the permanent magnet in the wind turbines a value of 22.5% was used (Blagoeva et al. 2016).
- Derived growth rates for the material demand for in Europe newly installed wind power were then transferred to the amount of neodymium currently used for wind turbine production in Europe. In other words, a constant ratio of the deployment of turbines produced in Europe to ones produced elsewhere was assumed.

Results are shown as WindEurope low and WindEurope high (Figure 37).

For the overall neodymium demand for permanent magnets in Europe until 2035, the conservative scenario for the transportation sector Tech2 has been combined with the conservative scenario for the wind energy sector WindEurope low and data for the other sectors from the base scenario in order to produce a lower bound of material demand. On the other hand, the combination of the optimistic scenario Tech3 with the optimistic scenario WindEurope high and the base scenario data of the other sectors gives an upper bound for the European neodymium use in permanent magnets until 2035 (Figure 34).

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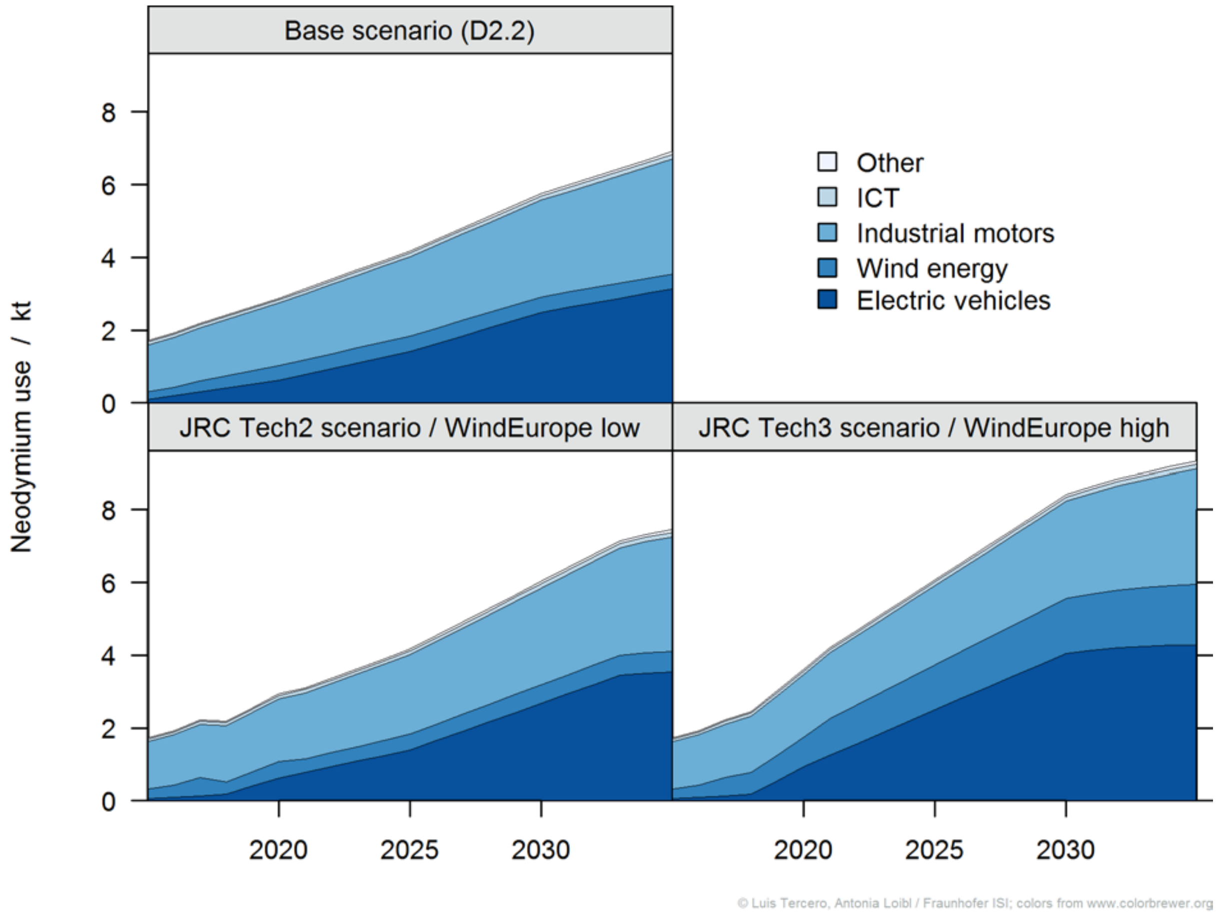

Figure 34: Comparison between projections for the future European neodymium use in permanent magnets with different scenarios for the development of the transportation sector as well as wind energy deployment.

The base scenario with projections for the material demand for wind energy and electric vehicles from D 2.2 predicts a lower neodymium use in 2035 than even the conservative scenario Tech2 / WindEurope low. This can be attributed in part to an assumed partial substitution of neodymium in wind turbines in that timeframe in D2.2 (Ait Abderrahim und Monnet 2018; Pavel et al. 2016). Additionally, even though the base scenario from D2.2 is also based on the Tech2 scenario from the same JRC Science for Policy report, it did not consider a contribution to neodymium demand from FCEVs (Blagoeva et al. 2016). As a result of both, the base scenario predicts a lower neodymium demand for electric vehicles until 2035.

Considering the impact of wind energy on the overall demand of neodymium in Europe, a reduction of the neodymium content in wind turbines was assumed in the base scenario from D2.2. For the evaluation of the maximum impact of the growing wind energy sector on neodymium demand, the WindEurope high scenario with a high amount of yearly installations and without any reduction of material demand of wind turbines was created. However, compared to the immense increase of neodymium use in electric vehicles the impact of wind energy is considerably smaller even under these conditions.

Overall, the conservative scenario Tech2 / WindEurope low projects a rise of the European neodymium demand from 1.4 kt in 2012 to 7.5 kt in 2035. The more optimistic scenario Tech3 / WindEurope high results in an overall neodymium use of 9.3 kt in 2035.

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RARE EARTH ELEMENTS: DYSPROSIUM

CURRENT USE

Even more than neodymium, the heavy rare earth element dysprosium is almost exclusively used in neodymium-based magnets. Only approximately 2% of globally used dysprosium goes into other uses than permanent magnets which are the production of multi-layer ceramic capacitors and Terfenol-D (European Commission 2014b; Hoenderdaal et al. 2013). Therefore, 98% of dysprosium demand is generated by different applications of NdFeB-magnets. In those magnets, neodymium can be partly exchanged for dysprosium in order to achieve a positive effect on the coercivity at higher temperatures (Hoenderdaal et al. 2013). Consequently, dysprosium containing permanent magnets are used in applications demanding good performance at higher temperatures like wind turbines, electric vehicles and industrial motors. Two of these sectors are expected to undergo major changes in the next two decades likely having a strong effect on the overall demand for dysprosium in that timeframe. The sectors of wind energy as well as electric mobility together already cover more than 30% of the global dysprosium use today and will most likely display substantial growth rates in the near future (Ait Abderrahim und Monnet 2018).

As explained for neodymium above, precise information on the historic supply and use of individual rare earth elements is rare. Rare earth elements are mined together and separated afterwards with numbers often only known for the overall amount. Additionally, the rare earth market is highly intransparent with mining mainly taking place in China and a suspected considerable contribution from illegal mining. Therefore, a different approach is necessary for the rare earth elements neodymium and dysprosium in order to analyse their use over time. Using sales figures on appliances containing NdFeB-magnets together with approximations for dysprosium content in each application, data on the global dysprosium demand from permanent magnet production can be derived (Glöser-Chahoud et al. 2016). Since this approach disregards material losses during production as well as the small fraction of dysprosium demand for uses other than permanent magnets, the output should be seen as a lower bound for the overall global dysprosium demand (Figure 35).

Regional data on the use of rare earth metals is even more difficult to obtain and available data often differs depending on how it was generated. For this study, the European neodymium demand for permanent magnets was used together with assumptions on the dysprosium content of those magnets to calculate the European dysprosium demand between 2000 and 2012 (Figure 35).

In the last available data year of 2012, European dysprosium demand made up 6% (140 t) of its global use in permanent magnets (2150 t). The main applications of dysprosium containing NdFeB-magnets in Europe were industrial motors with 69% and the future technologies of electric vehicles and wind energy with 5% and 24%, respectively. The rest went into ICT and other uses of permanent magnets with 1% each in 2013. Globally, the picture was slightly different in 2012 because permanent magnet use in electric vehicles and ICT applications did play a larger role while industrial motors and wind energy are less important than in Europe. The largest contribution to global dysprosium demand again came from the production of industrial motors with 46% followed by electric vehicles with 30% and wind energy with 11%. Other uses had a share of 9% and ICT applications of 4%.

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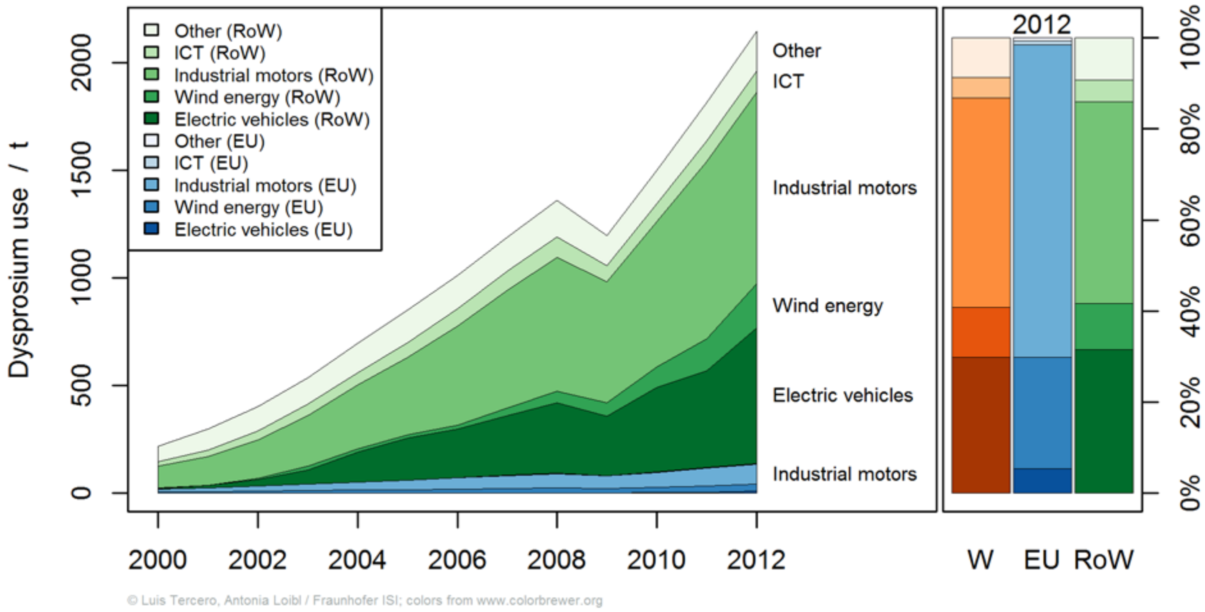

Figure 35: (Left) Historic dysprosium demand 2000-2013 split into its main application sectors and shown for Europe (shades of blue) and the rest of the world (shades of green). (Right) Comparison of shares in total dysprosium demand for each application in 2013 (last data year) at the global (orange, "World) and European (blue) levels, and for the Rest of the World (green, "RoW"). Demand estimates for the RoW were constructed by subtracting European demand from global demand for each sector.

FUTURE USE

For the development of a projection of overall dysprosium use until 2035, historic data for the sectors of industrial motors and other uses was extrapolated. The other sectors of electric vehicles, wind energy and ICT were identified and analysed as causes for major trends in material demand in Europe in that timeframe in D 2.2 (Ait Abderrahim und Monnet 2018). In the case of ICT, the suggested growth rates and total amounts of smartphones, laptops and PCs as well as domestic appliances were taken and set off against each other. Wind energy was analysed as its own category so growth rates were taken and used directly. Significant contributions to the NdFeB-magnet demand in Europe was not observed from the electronic vehicles sector until 2010 (Guyonnet et al. 2015). Therefore, absolute values for the dysprosium use in electric vehicles calculated for a scenario between 2015 and 2035 in D 2.2 were used as European demand here and extrapolated until 2010 (Ait Abderrahim und Monnet 2018). Resulting is a projection for the future dysprosium use in permanent magnets until 2035 (Figure 36).

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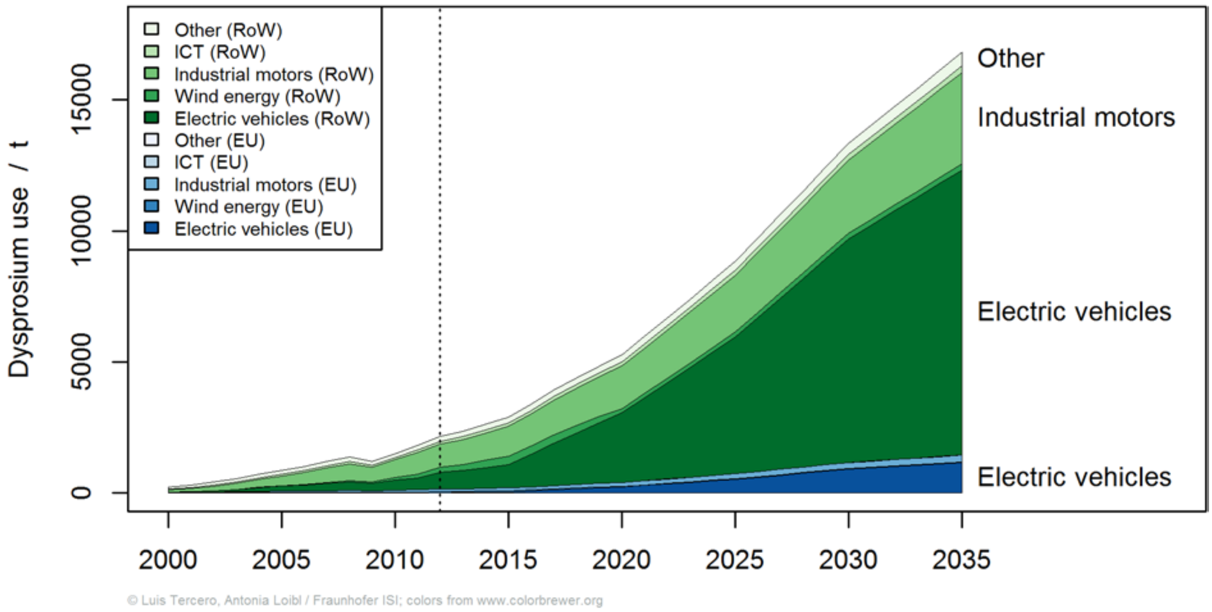

Figure 36: Dysprosium demand for the main application sectors with historical data until 2012 (indicated by the dotted line) and a demand forecast in the timeframe of 2013-2035 shown for Europe (blue) and RoW (green).

Dysprosium demand is expected to grow strongly in the next two decades. While 2,150 t of dysprosium were used globally in 2013, the projection shows a demand for 16,830 t in 2035 which corresponds to a growth factor of almost eight. Most prominent is the strong rise of dysprosium use for permanent magnets in electric vehicles, which contributes 71% to the global demand for dysprosium in 2035. In addition, the amount of dysprosium going into industrial motors is further increasing with a projected share of 22% of the global use in 2035. The rest of global dysprosium demand in 2035 is made up by wind energy and ICT with 2% each and other uses of NdFeB-magnets with 3%. The expected development of wind energy has the potential of causing larger changes in the dysprosium demand than is shown here. However, in D2.2 a strong effort to substitute dysprosium in permanent magnets for wind turbines along the lines of the EC reference scenario has been assumed thereby minimizing the effect the strongly growing market of wind energy has on global dysprosium demand (Ait Abderrahim und Monnet 2018; Pavel et al. 2016; European Commission 2016).

For Europe, the forecast is quite similar with a strong rise in dysprosium demand for electric vehicles to a share of 79% in 2035. A further 19% of dysprosium goes into industrial motors in Europe in 2035. Wind energy still has a share of 2% while ICT applications and other uses do not play a role anymore for dysprosium use in Europe with below 1% of the total demand. Reason for the low impact of the growing wind energy sector is again the assumed substitution of dysprosium in wind turbines in D2.2. In 2035, the European demand for dysprosium is projected to be 9% of its global use with 1440 t.

Seeing the anticipated very large rise in dysprosium use for electric vehicles over the next two decades, consideration of different scenarios for the coming change in the mobility sector seems essential. Following the approach used for platinum group metals and their projected use in autocatalysts, two scenarios for the penetration of electric vehicles in the European automobile sector were taken from the JRC Science for Policy Report "Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transportation technologies in the EU" and adjusted as well as updated for this purpose (Blagoeva et al. 2016). Assumption made and exact specifications for the conservative scenario Tech2 and the optimistic scenario Tech3 are listed in the chapter of palladium (pages 37ff, Figure 22).

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One more information had to be added for the transfer of these scenarios to the use of dysprosium in permanent magnets for electric traction motors. In the former mentioned JRC Science for Policy report, the average dysprosium content of different types of electric vehicles were calculated from sales figures of current models as follows: 0.113 kg for PHEVs, 0.051 kg for BEVs and 0.047 kg for HEVs. Analogous to neodymium, the low average dysprosium content of BEVs compared to PHEVs can be attributed to high sales figures for BEV models without a permanent magnet. Magnet-containing models of PHEVs and BEVs have the same average magnet size and composition (Blagoeva et al. 2016). These values for average dysprosium content per car have been used and assumed as constant until 2035. However, there is a considerable pressure for further substitution of heavy rare earth elements due to availability and prize that might lead to decreasing dysprosium use or even complete substitution of dysprosium in electric vehicles (Pavel et al. 2017; Daido Steel; Honda Motor Co., Ltd. 12.07.2016; Pavel et al. 2016). Additionally to the mentioned average dysprosium contents for PHEVs, BEVs and HEVs from the JRC report, FCEVs were set to have the same material demand concerning the electric traction motor as BEVs (Marscheider-Weidemann et al. 2016). Resulting are two projections for dysprosium use in cars from European production (Figure 37).

Analogous to the approach for neodymium, dysprosium use in wind turbines was examined as well since wind energy is considered to be a sector potentially causing major changes in the European material demand in the near future (Ait Abderrahim und Monnet 2018). The low and high scenarios published and updated regularly by WindEurope were used and supplemented with information on the current implementation of new wind power and assumptions on the material demand of wind turbines (WindEurope 2017, 2018; Blagoeva et al. 2016). Further information can be found in the chapter on neodymium (see pages 52ff). For dysprosium, one more assumption was made:

- For the dysprosium content of the permanent magnet was calculated with 4.5% (Blagoeva et al. 2016). This value has been assumed constant even though there is pressure for technological progress and substitution of heavy rare earth elements similar to what was mentioned above for electric vehicles (Pavel et al. 2016).

Results are shown as WindEurope low and WindEurope high (Figure 37). For the overall dysprosium demand in Europe until 2035, the conservative scenario for the transportation sector Tech2 has been combined with the conservative scenario for the wind energy sector WindEurope low and data for the other sectors from the base scenario in order to produce a lower bound. On the other hand, the combination of the optimistic scenario Tech3 with the optimistic scenario WindEurope high as well as the base scenario data of the other sectors gives an upper bound for the European dysprosium use until 2035.

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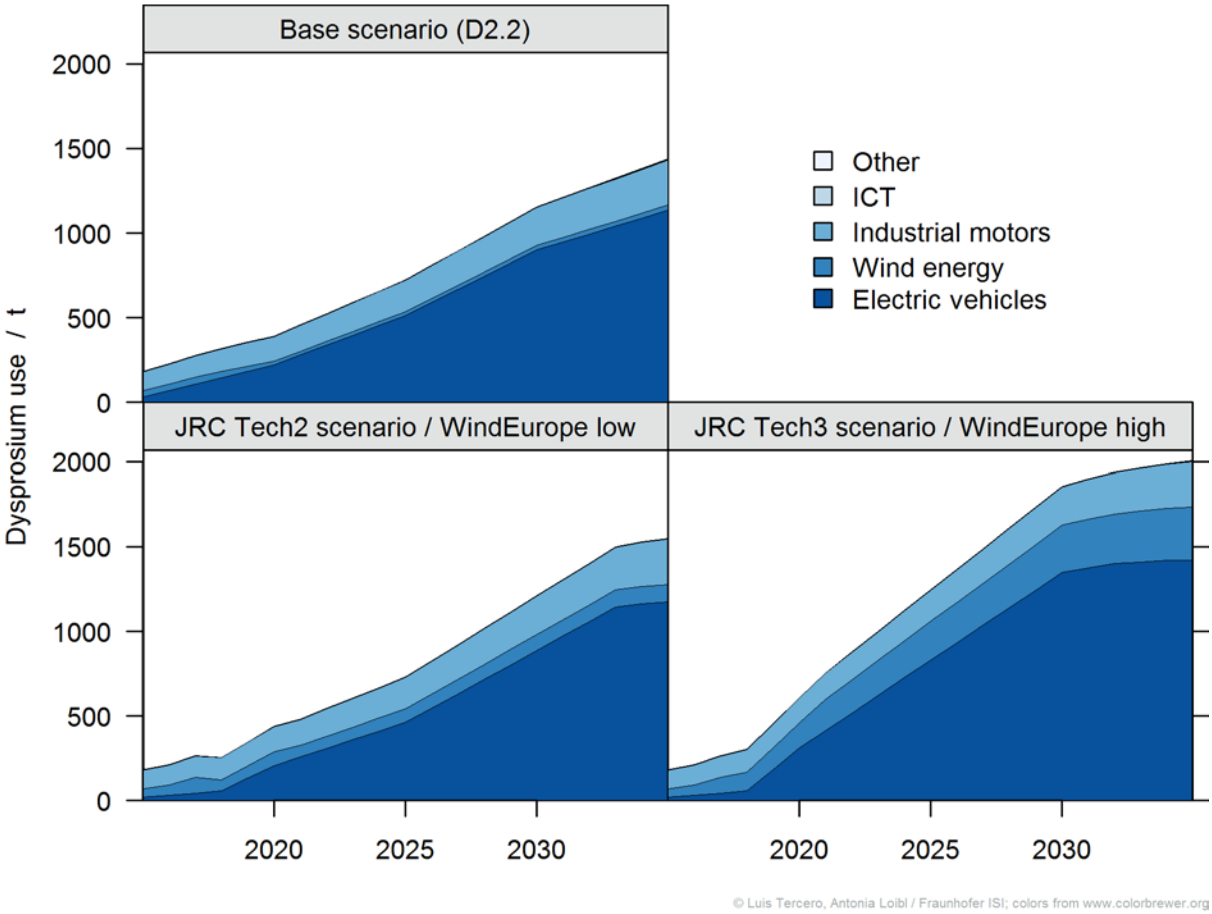

Figure 37: Comparison between projections for the future European dysprosium use with different scenarios for the development of the transportation sector as well as wind energy deployment. Dysprosium demand from ICT and other uses falls below 1% after 2017 and is therefore not visible in these graphs.

The base scenario with projections for the material demand for wind energy and electric vehicles from D 2.2 predicts a lower dysprosium use in 2035 than even the conservative scenario Tech2 / WindEurope low. This can be attributed in part to an assumed partial substitution of dysprosium in wind turbines in that timeframe in D2.2 (Ait Abderrahim und Monnet 2018; Pavel et al. 2016). Additionally, even though the base scenario from D2.2 is also based on the Tech2 scenario from the same JRC Science for Policy report, it did not consider a contribution to dysprosium demand from FCEVs (Blagoeva et al. 2016). As a result of both, the base scenario predicts a lower dysprosium demand for electric vehicles until 2035.

Considering the impact of wind energy on the overall demand of dysprosium in Europe, a severe reduction of the dysprosium content in wind turbines was assumed in the base scenario from D2.2. For the evaluation of the maximum impact of the growing wind energy sector on dysprosium demand, the WindEurope high scenario with a high amount of yearly installations and without any further substitution of dysprosium in wind turbines was created. However, compared to the immense increase of dysprosium use for electric vehicles the impact of wind energy stays very small even under these conditions.

Overall, the conservative scenario Tech2 / WindEurope low projects a rise of the European dysprosium demand from 140 t in 2012 to 1550 t in 2035. The more optimistic scenario Tech3 / WindEurope high results in an overall dysprosium use of 2000 t in 2035.

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TANTALUM

CURRENT USE

In D2.1 of this project (Deetman et al. 2017a), tantalum has not been included (see Figure 5). However, historical and current use of tantalum in Europe has been analysed in depth by Deetman et al. (2017b) using substance flow analysis. Deetman et al. (2017b) used a combination of trade and production statistics together with estimations of the composition of those appliances to obtain an estimate. An overview of the use of tantalum in appliances in Europe for 2007 as found by Deetman et al. (2017b) is shown in Table 4.

Tantalum finds major applications as capacitor and HDD platters and hence is found in all kinds of electronics and computers. A second important application is as alloying element in special (high temperature) steels. Tantalum can therefore be found in artificial joints and furnaces. Tantalum carbides are found in carbide tools.

Table 4: Overview of the use of tantalum in 2007 in the EU27 (Deetman et al, 2017).

Appliance	tantalum	fraction
	[t]	[-]
Vision correction lenses	27	0.02
Hearing aid	42	0.02
Artificial joints	192	0.11
Pacemakers	12	0.007
Carbide tools	37	0.02
Furnaces	9	0.005
Automotive	122	0.07
Aerospace	28	0.02
Mobile phones	307	0.18
Cameras	331	0.20
Desktop PCs	195	0.12
Laptop PCs	189	0.11
External HDD	104	0.06
Central storage	78	0.05
DVD players	2	0.001
GPS	3	0.002
TVs	2	0.001
Lenses	8	0.005

Overall, about 1133 ton of tantalum was in use in (electronic) appliances, 283 ton was in use in industry and 274 tons had a medical use. In total 1688 ton of tantalum was in use in 2007 in the EU27.

The uncertainty in above given values is large. Deetman et al. (2017b) argue that the complexity of products, in terms of the components and materials they contain, has increased rapidly over the last decades, and our understanding of their elemental compositions is lagging behind. For many products, neither consumers nor producers simply have any clue what they contain. This is an observation that pertains to most of the metals in this study. There is a very limited understanding of historical and current use, let alone of those uses in the future.

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Deetman et al. (2017b) also made estimates of the historical use of tantalum in some of the electronic appliances, automotive and energy technologies which comprised about 36% of the tantalum in use in 2007 in the EU27. This historical estimate of tantalum use was based on the elemental compositions determined for 2007 and historical use of appliances and technologies. The estimated historical use of tantalum in these applications is shown in Figure 38.

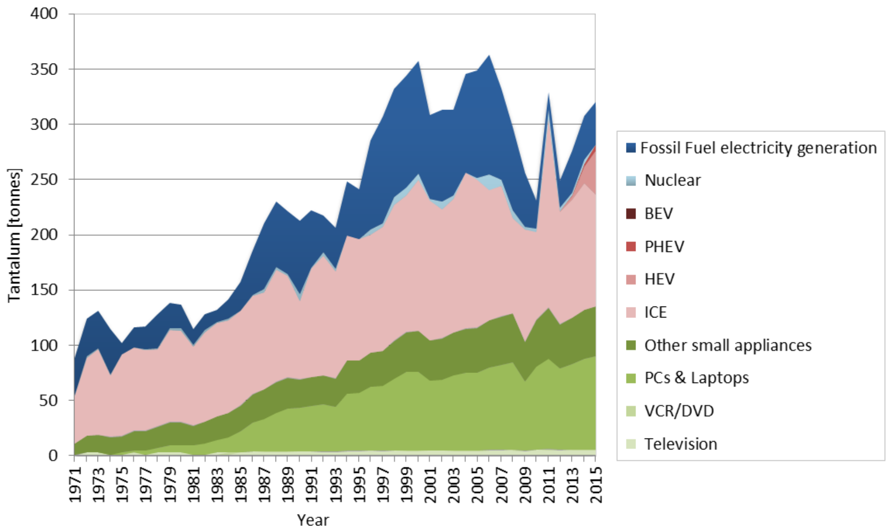

Figure 38: Estimation of historical use of tantalum in the EU27 from 1971 until 2015. It covers about 36% of the total use of tantalum. Data from Deetman et al. (2017b).

The main driver behind the increased use of tantalum is the introduction of PCs and laptops where most of the tantalum can be found in HDD platters. Figure 38 shows about 36% of all the uses of tantalum. Historical use of tantalum in cameras, mobile phones, artificial joints, external HDDs are not shown. Given that mobile phones did not exist in 1971 and are a major contributor to tantalum use and the European population is aging, the total use of tantalum has probably increased much faster from 1971 until 2012 than the factor three shown in Figure 38.

FUTURE DEVELOPMENT OF APPLICATIONS

The use of tantalum is currently determined by a large number of different applications. This is unlike platinum and palladium where the use in autocatalysts is dominant. The future demand for tantalum is therefore a result of the collective use of all these appliances in the future. D2.2 of this project (Ait Abderrahim und Monnet 2018) shows very little detail in Ta applications. For a selective subset of appliances in which tantalum is used scenarios were developed by Deetman et al. (2018), which we used instead for a more detailed picture. Deetman et al. (2018) estimated the use of electricity generation technologies, cars, and electronic appliances based on the shared socioeconomic pathways as implemented by the IMAGE integrated assessment model. The amount of technologies, cars and appliances in use from 2015 until 2035 were estimated under the SSP2 scenario. The SSP2 climate policy scenario leads to a radiative forcing of 2.6 W/m^2 by the end of the century, which keeps global average temperature increases limited to two degrees Celsius. This would entail deep greenhouse gas reductions. The SSP2 is a middle-of-the-road scenario in terms of the main developments; it

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represents moderate population growth and a path in which "social, economic, and technological trends do not shift markedly from historical patterns".

Key data used from IMAGE are the global total person kilometres driven by passenger car annually, the global total number of in use appliances per household, and the newly installed power generation capacity, globally. Deetman et al. (2018) subsequently used these key output data and specified the type of cars used, the electronic appliances in use and the type of power generation technology used.

Having made the scenario on the use of applications, the metal content of the appliances was used to calculate total metal use in these appliances. It was assumed that the metal content of each product is constant over time. This means that the scenario does not account for changes in specific metal requirements that may be a consequence of engineering efficiency or miniaturization trends over time.

FUTURE USE

Based on the estimate on the SSP2 scenario for cars, electrical appliances and power generation technologies, as discussed above, the tantalum use in these can be calculated. The results are shown in Figure 39.

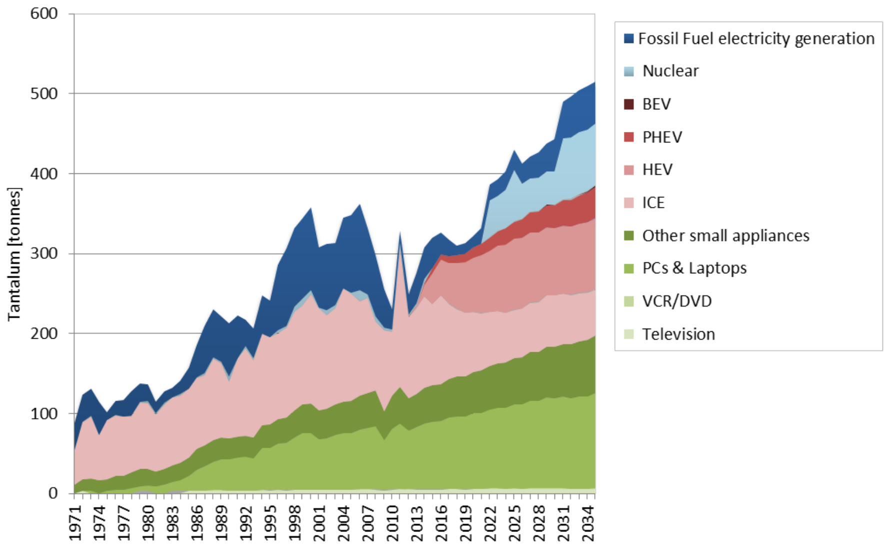

Figure 39: Historical and future use of tantalum in the EU27 from 1971 until 2035. Data combining information from Deetman et al. (2017b) and Deetman et al. (2018).

Notice that the future scenario for tantalum use only covers about 36% of the uses of tantalum in 2007. Other important uses of tantalum can also be found in mobile phones, cameras and artificial joints.

In the scenario the share of tantalum going to internal combustion engines for cars starts to drop being replaced by tantalum going to hybrid electric vehicles, battery electric vehicles and plug-in hybrid electrical vehicles.

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TUNGSTEN

CURRENT USE

Relatively little is known about the final use of tungsten in appliances in Europe. Tungsten use in different appliances in Europe was estimated for 2012 (Bio by Deloitte 2015). In 2012, 69% of the tungsten was used in hard cutting tools in the form of tungsten carbides (in D2.1 categorised under "Steel – hard materials"). Other categories of final use are in super alloys (7%), tungsten alloys as used in turbines (5%) and other uses (18%) such as pigments and electronics. Total final use is estimated to be about 22 kt in 2012. An overview is given in Table 5.

Bio by Deloitte (2015) estimates the use of tungsten in aeronautics & energy applications to be about 1.1 kt. According that study most of the aeronautics & energy applications are airplane engines. Ait Abderrahim und Monnet (2018) estimate in D2.2 the use of tungsten in turbines at about 10 t in 2018. While there might be a difference between the categories jet engines and turbines in general, this likely does not explain the 100-fold difference. The differences between the two reports highlight our lack of knowledge of current final uses of tungsten in Europe. Even though there is a lack of certainty in the use of tungsten in turbines (1.1 kt vs 10 t), the use in tungsten carbides is currently the dominant final use category for tungsten, if we assume that the value reported by Bio by Deloitte (2015) is correct.

Table 5: Overview of estimated current use of tungsten in Europe in 2012.

Group	Application	tungsten [kt]	fraction [-]
Steel and super alloy	Aeronautics & Energy applications	1.10	0.05
	High speed steel	1.32	0.06
	High temp. Steel	0.44	0.02
Cemented carbide	Mill and cutting tools	6.82	0.31
	Mining & construction tools	4.62	0.21
	Other wear tools	3.74	0.17
Tungsten products	Lighting & electronic uses	1.32	0.06
Chemicals and others	Catalysts & pigments	1.54	0.07
	Other (e.g. nuclear fusion)	1.10	0.05
Total	Total	22	1

An historical analysis of tungsten use in Europe based on a material flow analysis was carried out by Mesman (2016). Mesman's data for 2012 are the same as those used in Bio by Deloitte (2015) thus creating a coherent picture of historical uses of tungsten. Mesman (2016) distinguishes five types of applications, i.e. cemented carbide, steel and super alloys, tungsten products, chemicals and others. The total use value found by Mesman for 2012 is 23 kt tungsten. Mesman's estimates and the estimates of Deetman et al. (2017a) are very similar. The largest difference is found in tungsten products – among which tungsten wire in incandescent light bulbs – where Mesman (2016) estimates 1.3 kt tungsten and Deetman et al. (2017a) estimates 2.6 kt of tungsten. This difference does not influence our overall understanding of the uses of tungsten.

According to Mesman (2016), since 1995 tungsten use in Europe has increased about a factor 3. The quantity used in three of the product categories has increased in absolute numbers. In the group of steel and super alloys, the use of tungsten has decreased.

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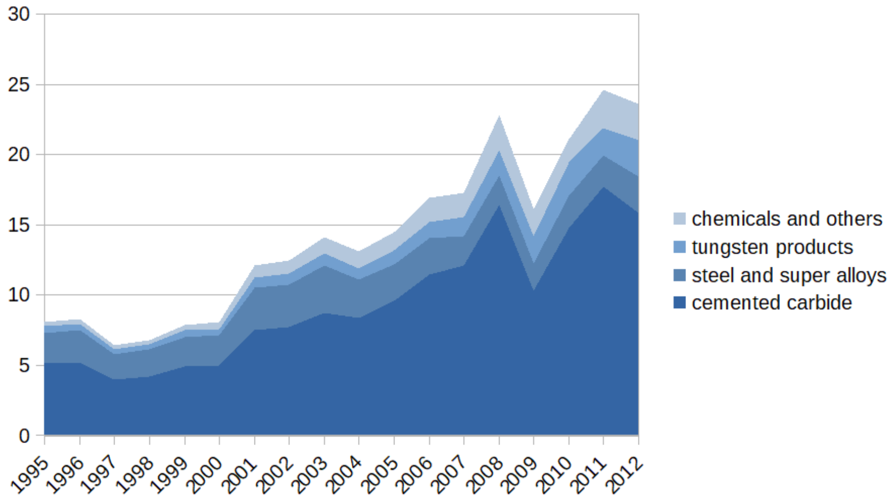

Figure 40: Estimation of historical use of tungsten in Europe from 1995 until 2012. Data from Mesman (2016).

One of the known applications using tungsten is not explicitly mentioned. Its use in armour-piercing ammunition and armour plating. Given the secrecy surrounding any defence activities it is likely difficult to make an explicit estimate how much tungsten is used in these applications. It might be very substantial. A MK211 0.5 calibre (small firearms) armour piercing bullet is estimated to contain about 17 g of tungsten carbide or about 15 g of tungsten. One million of such bullets would already contain 15 tonnes of tungsten. Larger calibre ammunition would likely contain more tungsten. No information is available about the possible amounts of tungsten that may go into armour plating.

FUTURE DEVELOPMENT OF APPLICATIONS

Future demand of tungsten is largely expected to be driven by the need for tungsten carbides, as it is currently the dominant application. The tungsten carbides are used in hard metal cutting tools and in mining tools, specifically rock drill bits.

No information is available about the development of hard metal cutting and milling tools or cemented carbides in general. Hard metal cutting and milling tools are used to create machinery made of iron and steel. The milling and drilling bits are consumables that need frequent replacement. As such, the more machinery is made, the more drilling bits and cutting bits are consumed. Tungsten carbides are also used in mining and construction tools, which are also consumables.

Assuming that tungsten carbides are not replaced by other compounds, the final use of tungsten carbides is determined by the demand for machinery, construction work and mining operations. Given that Europe has a slow growing population and demand for infrastructure is likely not to change below or above current levels our scenario assumes that use of tungsten carbides remains similar to the values found in 2012.

High-speed steel, a steel alloy containing tungsten, is used in cutting tools in the form of drill bits and power-saw blades. Tools that are widely used in construction work. When these tools have become blunt, they cannot be sharpened and are disposed of. Thus, they are typically consumables during construction work. We therefore assume that the amount of tungsten in high speed steel like the use of tungsten carbides remains at the same levels as in 2012.

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FUTURE USE

Combining the information on the current applications of tungsten and the development of those applications as described above gives a scenario for the development of the use of tungsten in Europe as shown in Figure 41.

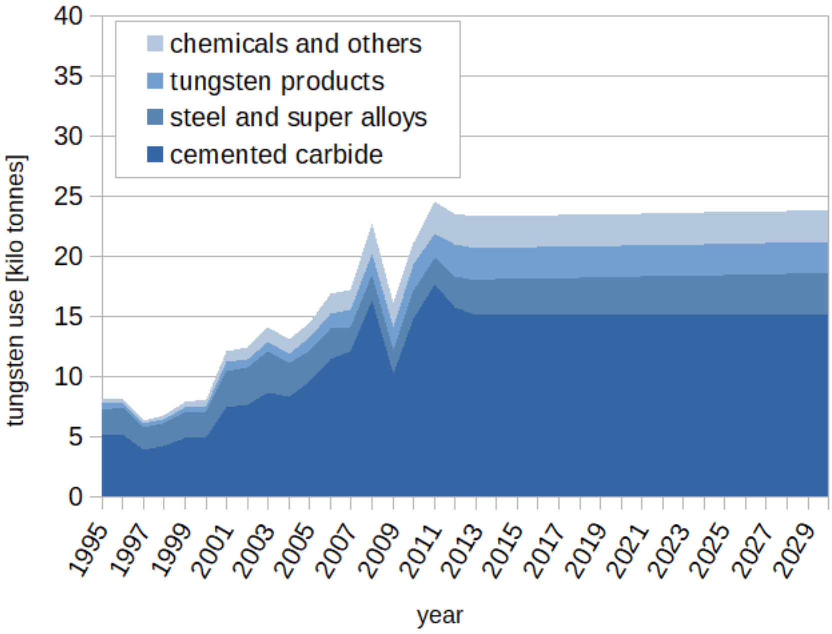

Figure 41: Scenario for the future use of tungsten in Europe. Future use is determined by the assumption of a constant volume of construction work and manufacturing work in Europe the coming decade.

The data presented above relate to tungsten demand. It is likely that a substantial part of tungsten can be supplied from secondary sources. Tungsten carbide bits are easily recycled. In 2012 about 70% of the tungsten carbide tools sold by Sandvik Coromant was already recycled (Sandvik Coromant 2018).

Secondary production in the EU provides on median 47% of the tungsten supply with a low in 1995 of 20% and a maximum of 68% in 2009. These median percentages vary largely between 20% and 68%. The share of secondary production in AT, DE and GR is 50%, 52% and 48% respectively, with major outliers in all three member states and no general trend lines (Mesman 2016).

The scenario of tungsten demand in Europe is highly uncertain. The starting point for the scenario, i.e. current use, is already uncertain. There is conflicting information of the use of tungsten in turbines and tungsten use in army applications is not known but potentially large. The development of the petrochemical industry and the use of high temperature alloys is very uncertain.

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