EPOW European Pathway to Zero Waste
Demonstrating the route to zero landfill

Study into the feasibility of protecting and recovering critical raw materials through infrastructure development in the south east of England.

Summary Report

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wrap Material change for a better environment
SEEDA South East England Development Agency
Working for England's World Class Region
Environment Agency
Life

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1.0 Introduction

Purpose of this Study

The purpose of this study was to examine the applications for the EU's list of 14 critical materials, review existing practices associated with their recovery, and identify the end markets where increased recovery of these materials has the greatest potential for implementation. The issue of critical materials is strongly related to resource efficiency and waste minimisation: these have the possibility to reduce the demand for raw materials. Therefore there are links with the aims of EPOW, which are broader than simply the minimisation of waste, and extend into other related issues such as this.

One of the typical responses to material security issues is to increase the resource efficiency of the use of these materials, such as through improved design to minimise use, to increase longevity or to allow disassembly of the material-containing product. Another response may also be investing in new collection, disassembly and reprocessing methods and infrastructure. The aim of the report is to advise on recovery of these materials and implementation of new schemes or improve existing infrastructure to decrease the demand for these critical materials.

To the knowledge of the authors, this EU Life+ funded project is the first work to look at the issues of resource efficiency in detail for the EC critical materials list. It goes beyond the approach undertaken by other studies which have analysed a different set of metals and had a specific remit on the technologies and products considered. Those studies took a material-focussed approach in considering potential recycling options, whereas this report has taken a product-based approach.

This summary report provides a synopsis of the main sections of the full study; an extensive report and accompanying annexes are available, providing more detail and supporting information.

What are Critical Raw Materials?

There are justifiable concerns about the access of developed countries to raw materials which are critical to high technology or green economy applications. Existing issues around certain resources (for example rare earth elements), and the prospect of further problems led the EC to launch the Raw Materials Initiative, which identified a group of 14 'critical materials' (Table 1).[1]

Table 1: The 14 critical materials identified in the Raw Materials Initiative

Antimony	**Beryllium**	**Cobalt**	**Fluorspar**	**Gallium**	**Germanium**	**Graphite**
Indium	**Magnesium**	**Niobium**	**Platinum Group Metals**	**Rare Earth Elements**	**Tantalum**	**Tungsten**

Source: European Commission

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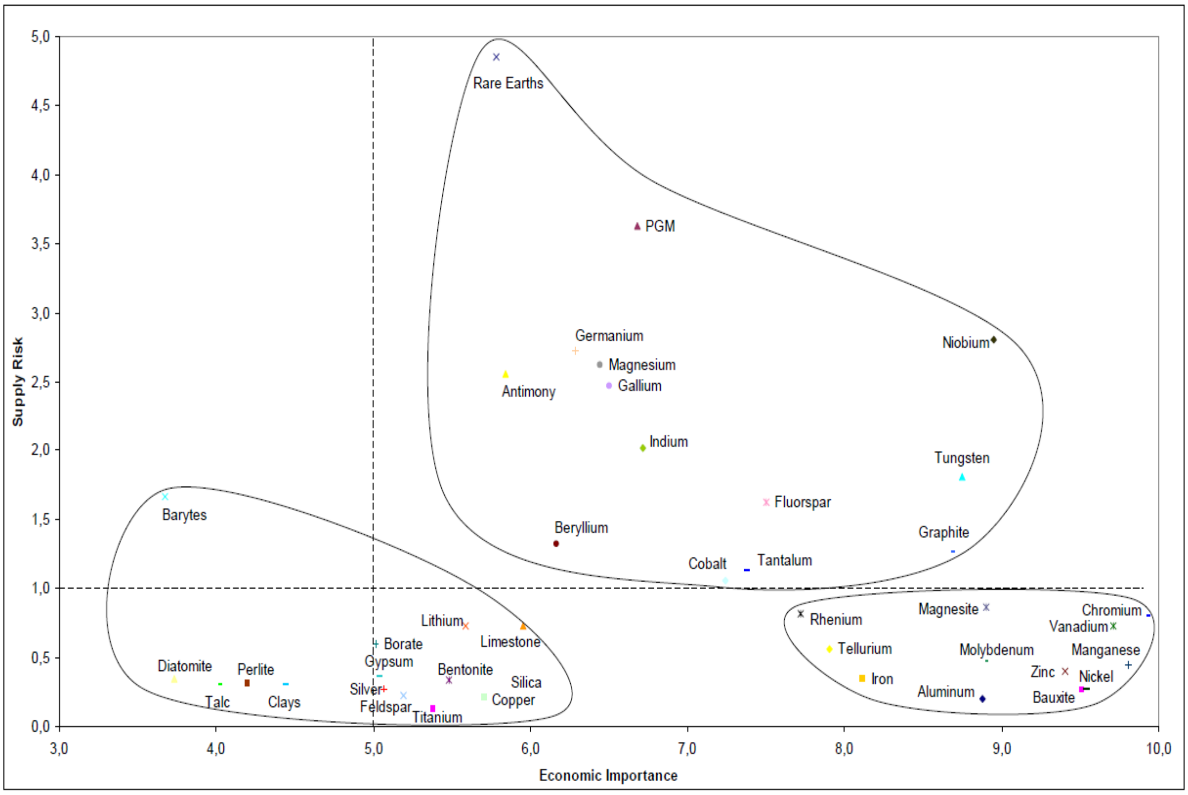
[1] Critical raw materials for the EU, European Commission, July 2010

This group consists of mainly speciality metals which experience a combination of high economic importance to the EU and a high risk of potential disruption to or interference in supply. The EC study quantitatively analysed 41 metals and minerals, and assessed the stability of the producing country, diversity of supply, substitutability and recycling as key factors. Figure 1 gives the overall results of the EC study, with the critical raw materials circled in the top right corner of the chart.

Figure 1: Overall criticality results of the Raw Materials Initiative study



Source: European Commission

A number of different studies have attempted to evaluate the relative criticality of minerals, with different materials identified depending the specific focus and criteria.[2,3,4,5,6,7] This present study differs from these earlier reports in that rather than seeking to identify critical materials, it will identify measures which can be taken to protect and recover them.

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[2] Assessing Metals as Supply Chain Bottlenecks in Priority Energy Technologies, Oakdene Hollins for EC Institute of Energy, 2011

[3] Critical Materials Strategy, US Department for Energy, 2010

[4] Minerals, Critical Minerals, and the US Economy, Committee on Critical Mineral Impacts of the U.S. Economy, 2008

[5] Material Security: Ensuring resource availability for the UK economy, Oakdene Hollins, 2008

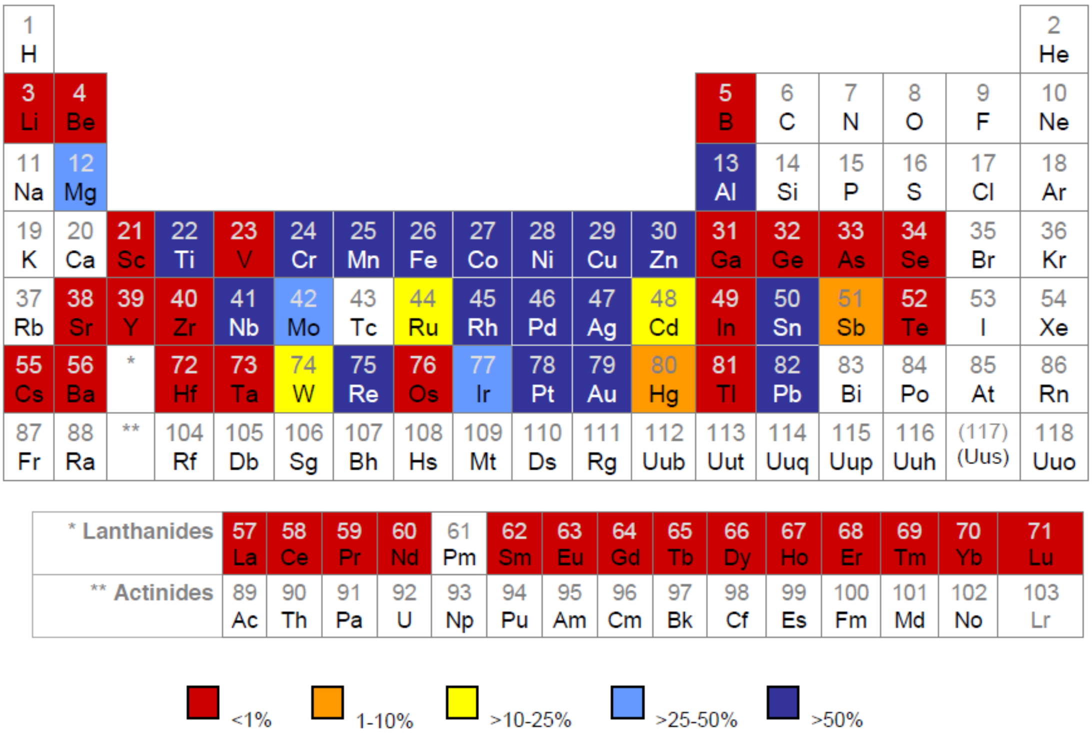
[6] Les nouveaux métaux stratégiques, BRGM, 2008

[7] Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, Defra, 2010

The Recovery of Critical Raw Materials

The rate of recovery and recycling for different metals varies considerably (Figure 2). Amongst the critical raw materials, many have very low recycling rates; beryllium, gallium, germanium, indium, rare earth elements and tantalum all have recycling rates less than 1%. In contrast cobalt, niobium and some of the platinum group metals are all reported to have a recycling rate above 50%. Antimony, magnesium and tungsten have intermediate recycling rates.

Figure 2: Recycling rates of metals



Source: UNEP/EU Working document

There are numerous challenges associated with recovering critical raw materials. Some of these are inherent to recycling in general. The OECD, in their study *Improving Recycling Markets,* identified the main sources of market inefficiency for recycling as:

- transaction costs and information failures between buyers and sellers
- externalities where the actions of individuals or companies affect other organisations, e.g. between the designer and recycler
- the market power in the primary or secondary markets.

The interactions between different actors and the associated market power have been shown to be particularly important within critical metal recycling. For example, for electronic waste in the EU there are 10,000s of different actors involved in collection, 1,000s in dismantling and 100s in pre-processing, but only three major smelters or refiners.[8] Research by the Centre for Remanufacturing and Reuse (CRR) established that

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[8] Opportunities & limits to recycle critical metals for clean energies, Mark Caffarey, Umicore, December 2010

these market inefficiencies also tend to carry over in the remanufacturing and reuse of products. However both government policy and market-led initiatives can be successful in overcoming these inefficiencies and promoting recycling, reuse and remanufacture.[9]

It should be noted that within this report a distinction is drawn between recycling rates and a reduction in the use of virgin raw materials. This is important as a high recycling rate for a critical raw material does not necessarily imply a reduction in the use of virgin raw material. For example, niobium contained within high strength steel grades is commonly recycled along with a larger pool of steel scrap, and is hence much diluted within the secondary steel. The recycled niobium is consequently not available as an alternative to virgin raw material. This use also highlights that the degree of dispersion and value of material is a further key issue of importance for the recycling of critical raw materials. A greater degree of dispersion implies that the cost of collecting, sorting, recycling and refining is likely to be higher than if the raw material were concentrated within a single product or in large piece. For recycling to be economic these costs need to be favourable when compared with value of the material that can be recovered.

Structure and Methodology of this Study

The full study is divided into five main sections with accompanying appendices and conclusions:

- applications, future supply and demand issues for the critical raw materials
- resource efficiency best practice for critical materials
- identification of principal end uses
- resource efficient use of critical raw materials
- conclusions and recommendations.

This summary report broadly follows this structure, however much of detailed discussion has been omitted to provide an outline of this work.

In addition to the main report, annexes have also been produced which include discussion of key applications and potential future substitution of the critical materials, as well as their reserves, output prices; and supply and demand forecasts.

2.0 Applications and Future Supply and Demand Concerns for the Critical Raw Materials

The critical raw materials identified by the EC Raw Materials Initiative are diverse in a number of senses. By way of background, this section provides an overview of the different critical raw materials, summarising the supply, demand and pricing data in Table 2. More information on each critical raw material can be found within the individual material reports located in the main report and Annex A, including summaries of applications, substitution and recycling, and further detailed data for supply, demand and pricing. Some general observations about the supply and demand of the critical materials are made below.

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[9] Market Failures in Remanufacturing, Centre for Remanufacturing and Reuse, 2010

Supply

The critical raw materials fall into three groups in terms of the volumes produced:

- The largest annual production is of fluorspar and graphite (the two minerals), and magnesium, which have world supply at 5,100,000, 1,130,000 and 760,000 tonnes respectively.
- The middle group has a production in the range of 62,000 to 187,000 tonnes, and includes antimony, cobalt, niobium, REEs and tungsten.
- The group with the lowest annual production has a range of 118 to 1,200 tonnes, and includes beryllium, gallium, germanium, indium, platinum group metals (PGMs) and tantalum.

The major primary producing countries are all outside the EU (except Germany for gallium):

- China is the leading producer of nine of the raw materials: antimony (91%), fluorspar (59%), gallium (32%), germanium (71%), graphite (71%), indium (50%), magnesium (77%), REEs (97%) and tungsten (81%), and is in the top three largest producers of two other critical raw materials: beryllium (14%) and cobalt (10%).
- Brazil: niobium (92%), tantalum (16%), graphite (7%) and REEs (1%).
- United States: beryllium (86%), magnesium (7%) and germanium (3%).

Demand

There is a diverse number of applications for these critical raw materials ranging from automotive end-uses to electronics and chemicals to construction. For seven of the critical raw materials, a single application accounts for over half of the consumption. From Table 2 it can be observed that a number of different critical raw materials are contained in the same products. It is this cross-mapping, over different applications, which was used in the screening process to obtain a short list of product groups for resource efficiency review. Demand growth is forecast to be strong for a number of the critical raw materials, with seven having forecast demand growth rate at around 5% or above (significantly above forecast global GDP growth, 3.6%[10]) and three (gallium, niobium and REEs) with growth rates forecast at or around 10% per year. Strong demand growth for particular emerging technologies such as electric vehicles and wind turbines will alter the composition of consumption and could lead to some shortages.

Although there is a broad range in prices, these map relatively closely to production levels In terms of prices for each of the critical raw materials. The most expensive critical raw materials are those among the lowest levels of production: PGMs ($31,847/kg), germanium ($1,151/kg) and indium ($506/kg); the cheapest being those with the largest levels of production: fluorspar ($0.42/kg), graphite ($1.16/kg) and magnesium ($3.29/kg). Assessment of the price trends of these materials highlight the volatility associated with the commodity boom and economic downturn, or government intervention as with REEs.[11]

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10 World Bank World GDP Forecast for 2010-2012, available at URL: http://web.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTDECPROSPECTS/EXTGBLPROSPECTS/0,,contentMDK:20675180~menuPK:615470~pagePK:2904583~piPK:2904598~theSitePK:612501,00.html accessed 02/03/11

11 Graphs are shown are available in the main report and Annex A

Table 2: Summary of supply, applications, price and demand for the critical materials

Critical Raw Material	World Supply 2009 (tonnes)*	Primary Producing Countries (%)	Major Applications (%)	Forecast Demand Growth p.a. (%)	Price – 3yr Ave ($/kg)
Antimony	187,000	China (91%) Bolivia (2%) Russia (2%)	Flame retardants (72%) Batteries (19%) Glass (9%)	4.2%	$6.58
Beryllium	140	United States (86%) China (14%) Mozambique (1%)	Electronics/it (20%) Electric equipment (20%) Final consumer goods (15%)	3.0%	$165#
Cobalt	62,000	Congo Kinshasa (40%) Australia (10%) China (10%)	Batteries (25%) Superalloys (22%) Carbides/tooling (12%)	2.5%	$57.45
Fluorspar	5,100,000	China (59%) Mexico (18%) Mongolia (5%)	Hydrogen fluoride (60%) Steel (20%) Aluminium (12%)	3.4%	$0.42
Gallium	118	China (32%) Germany (19%) Kazakhstan (14%)	Integrated circuits (66%) Laser diodes & led (18%) R&d (14%)	10.2%	$499
Germanium	140	China (71%) Russia (4%) United States (3%)	Fibre optic (30%) Infrared optics (25%) Catalyst polymers (25%)	3.4%	$1,151
Graphite	1,130,000	China (71%) India (12%) Brazil (7%)	Foundries (24%) Steel industry (24%) Crucible production (15%)	3.0%	$1.16
Indium	1,200	China (50%) South Korea (14%) Japan (10%)	Flat panel displays (74%) Other ito (10%) Low melting point alloys (10%)	6.5%	$506
Magnesium	760,000	China (77%) United States (7%) Russia (5%)	Casting alloys (50%) Packaging (16%) Desulfurization (15%)	7.3%	$3.29
Niobium	62,000	Brazil (92%) Canada (7%) Others (1%)	Structural (31%) Automotive (28%) Pipeline (24%)	10.1%	$62.05
Platinum group metals	445	South Africa (61%) Russia (25%) Canada (4%)	Autocatalysts (53%) Jewellery (20%) Electronics/electrics (11%)	2.7%	$31,847
Rare earth elements	124,000	China (97%) India (2%) Brazil (1%)	Catalysts (20%) Magnets (19%) Glass (12%)	9.8%	$29.83
Tantalum	1,160	Australia (48%) Brazil (16%) Congo Kinshasa (9%)	Metal powder (40%) Superalloys (15%) Tantalum carbide (10%)	5.3%	$352
Tungsten	94,009	China (81%) Russia (4%) Canada (3%)	Cemented carbides (60%) Fabricated products (17%) Alloy steels (13%)	4.9%	$41.21

Notes: Supply includes estimates of recycling where available; # Beryllium price is 2 year average of US export prices (not publicly traded)*

Source: Annex A

3.0 Identification of Principal End Use Applications

The ‘EU Critical 14’ minerals and metals are used in a wide variety of products. In addition two of the fourteen are themselves groups of metals: rare earth elements (REEs) and platinum group metals (PGMs). Hence it was not possible to consider the resource efficiency opportunities for each combination of element and end use within the scale of this project. Research on the materials identified 40 end uses. Screening was undertaken to identify the most relevant groups for the purposes of the study, with the aim of identifying around 10 markets or applications for further study of potential resource efficiency measures. Screening criteria were developed based on consumption levels, economic value and carbon impact of the critical materials associated with each group. In total 12 markets were selected using this methodology (Table 3).

Table 3: Final matrix of selected markets and materials

	Antimony	Beryllium	Cobalt	Fluorspar	Gallium	Germanium	Graphite	Indium	Magnesium	Niobium	PGMs	REEs	Tantalum	Tungsten
Automotive/Aerospace		🟦	🟦				🟦		🟦	🟦			🟦	
Batteries			🟦				🟦					🟦		
Catalysts			🟦			🟦					🟦	🟦		
Cemented carbide tools			🟦											🟦
Chemicals				🟦										
Construction									🟦					
Electrical equipment					🟦		🟦	🟦	🟦			🟦		
Electronics/IT	🟦	🟦			🟦	🟦		🟦			🟦	🟦	🟦	
Flame retardants	🟦													
Optics					🟦	🟦								
Packaging									🟦					
Steel & steel alloys				🟦			🟦		🟦			🟦		

Whilst care was taken to ensure that distinct end uses were chosen, the nature of this work and the data available on the use of these materials meant that there was some overlap between them when investigation into the market took place. For example, superalloys were represented as a separate group, but have been discussed within the aerospace sector where appropriate.

4.0 Resource Efficient Use of Critical Raw Materials

Within the study each market was researched, as well as submarkets where appropriate. In total 40 applications of the critical materials were investigated; these are listed in Appendix 1 of this report. Each of these applications were studied in detail to assess existing supply chains, current end of life practice and assess potential for reducing critical raw material demand through improved recovery. Each of these markets and applications is discussed in detail within the main report. Over all the applications, ten were identified as having high potential for recovery, and eleven as having medium potential.

Summary of Opportunities and Recovery of Critical Materials

Table 4 outlines the ten applications identified as having high opportunity to implement critical material recovery.

Table 4: Summary of 'high' opportunities from all markets, with estimated consumption and value associated with each[12]

Market/ Submarket	Application	Raw Material(s)	Current Total Consumption (Tonnes)	Current Total Consumption ($Millions)	Estimated Carbon Impact	Timeframe
Aerospace	Superalloys	Cobalt	10,639	$611	N/A	Short
		Niobium	4,960	$308		Short
		Tantalum	58	$20		Short
	Landing gear	Beryllium	21	$3	N/A	Short
	Aluminium alloys	Magnesium	54,900	$180	Medium	Short
Portable Batteries	Li-Ion	Cobalt	11,594	$666	Medium	Short
		Graphite	39,776	$46		Short
Catalytic Converters (PGMs)	Vehicles	PGMs	232	$7,398	Low	Short
Wind Turbines	Wind Turbines	REEs	6,126	$183	Medium	Long
Screens	Used as ITO in LCD screens	Indium	444	$225	Low	Medium
Hard Disk Drives	80% of ruthenium produced is used in hard disks	PGM (ruthenium)	10	$327	Medium	Short
	Neodymium is used in magnets for HDD	REEs	7,304	$218	Medium	Short
Beverage Cans	Aluminium Alloys	Magnesium	97,600	$321	High	Short

For each of these applications the current consumption in tonnage and value associated with each critical material has been estimated using data from Annex A. It should be

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[12] It was assumed that 5% of tantalum consumption was used for aerospace alloys

noted that these values include material that is already recycled and assume 100% recovery, therefore will likely overestimate the true scale of the opportunity. However, they do provide an indication of the potential materials saving and value associated with each application.

According to these estimates, catalytic converters have the highest potential market value for critical material recovery, even if it is assumed that recovery of half already occurs. Two values are comparatively low: tantalum in aerospace superalloys (however this application includes larger values of cobalt and niobium) and beryllium used in landing gear. The timeframes for implementing the measures discussed in the individual sections have also been estimated, with ‘short’ being 0-5 years, ‘medium’ 5-10 years and ‘long’ 10 years or more. This assessment indicates that most of these opportunities are likely to be feasible in the short term.

Eleven further opportunities were identified as having medium potential for future implementation, (Table 5). These opportunities may still be viable; however, there are greater barriers to implementation, which are discussed within individual market sections.

Table 5: Summary of medium opportunities from all markets, with estimated consumption and value associated for each[13]

Market/ Submarket	Application	Raw Material(s)	Current Total Consumption (Tonnes)	Current Total Consumption ($Millions)	Estimated Carbon Impact	Timeframe
Automotive	Aluminium alloys	Magnesium	259,250	$852	Medium	Medium
Portable Batteries	NiMH	REEs	4,266	$127	Low	Short
		Cobalt	2,046	$118		Short
(H)EV Batteries	Li-Ion/ NiMH	Cobalt	1,860	$107	Low/ Medium	Long
		Graphite	5,424	$6		Long
		REEs	5,654	$169		Long
Catalytic Converters (REEs)	Vehicles	REEs	7,548	$225	Low	Short
Process Catalysts	General	REEs	17,252	$515	Medium	Short
Cemented Carbide Tools	Tooling	Cobalt	7,440	$427	Medium	Short
		Tungsten	34,800	$1,434		Short
Permanent Magnets	(H)EVs	REEs	5,654	$169	Medium	Long
Solar PV	Solar PV	Gallium	4	$2	Low	Long
		Indium	12	$6	Low	Long
Flame Retardants	Flame retardant in plastics	Antimony	134,640	$886	Low	Short
Steel Production (Graphite)	Raise carbon content of steel (recover losses)	Graphite	27,120	$31	Low	Short
Steel Production (Others)	Pickling	Fluorspar	61,200	$25	Low	Short

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[13] It was assumed that 5% of graphite losses could be recovered from steel, and 2% of hydrogen fluoride was used in stainless steel production

Potential Recovery of Critical Materials

To provide an indication of the materials which lack potential recovery opportunities, the consumption and values associated with the high and medium opportunities have been summed together, and an assessment of each material performed (Table 6).

Table 6: Summary of high and medium opportunities associated with each critical material

	Current total consumption of material (tonnes)	Consumption associated with High/Medium opportunities (tonnes)	Proportion attributed to High/Medium opportunities (%)	Value of current consumption ($Millions)	Value associated with High/Medium opportunities ($Millions)
Antimony	187,000	134,640	72%	$1,231	$886
Beryllium	140	21	15%	$23	$3
Cobalt	62,000	33,579	54%	$3,562	$1,929
Fluorspar	5,100,000	61,200	1%	$2,118	$25
Gallium	184	4	2%	$92	$2
Germanium	140	0	0%	$161	$0
Graphite	1,130,000	72,320	6%	$1,307	$84
Indium	600	456	76%	$304	$231
Magnesium	610,000	411,750	68%	$2,004	$1,353
Niobium	62,000	4,960	8%	$3,847	$308
PGMs	445	232	52%	$14,172	$7,398
REEs	124,000	53,804	43%	$3,699	$1,605
Tantalum	1,160	58	5%	$409	$20
Tungsten	58,000	34,800	60%	$2,390	$1,434

From this analysis it is clear that the materials fall into two distinct groups: those which have a large potential for recycling to reduce the demand for raw materials (antimony, cobalt, indium, magnesium, PGMs, REEs and tungsten) and those for which recovery and recycling appear unlikely to significantly reduce the demand for primary production (beryllium, fluorspar, gallium, germanium, graphite, niobium and tantalum). This indicates that whilst recovery and recycling can have an impact on demand for certain materials, other measures such as substitution, reuse or elimination may be necessary to reduce the demand for these raw materials in the future.

5.0 Conclusions and Recommendations

Conclusions

The recycling industry in the UK and EU has been found to be efficient at targeting new opportunities for recovering valuable materials from emerging waste streams, whether they are critical materials or other recyclates. Pre-consumer recycling is efficient for almost of all of the critical materials, and often accounts for a large proportion of the overall supply. By contrast, the levels of post-consumer recycling of the critical materials are more variable as many of the 14 critical materials fall outside more common recycling activities. For example high recycling rates are achieved for magnesium in beverage cans due to its link with aluminium, but almost no recovery occurs for the materials used in electronic equipment. When entering EU-based processing, unrecovered critical materials typically end up in waste slags or landfill or are lost during incineration. However, many end of life products containing critical materials are sent outside the EU, therefore excluding them from EU- or UK-based supply chains. It was also found that not all activities which are considered to be 'recycling' reduce demand for raw materials. For example in steel alloy recycling, the critical material niobium is retained through recycling. However its concentration is diluted due to the presence of different steel grades, and its properties are lost; hence no primary niobium production is avoided. Therefore care is needed when assessing recovery and recycling rates of these materials.

There is technology available for recycling of almost all of the 14 critical materials on at least on a demonstration level (with some uses of REEs and fluorspar being the main exceptions). However, the availability of these technologies does not enable material recovery, and several other factors were found to hinder recovery:

- **Collection:** Recovery of the product does not take place, therefore the materials never enter recycling streams. This is common for batteries, beverage cans, and vehicles.
- **Separation:** The material or component containing the critical material may be difficult to separate or may be contaminated. Therefore extra processing and costs are associated with recycling. This is typical of integral batteries, hard disk drives and flame retardant containing plastics.
- **Dispersion:** The properties of many critical materials mean that they are often found in low concentrations, and large volumes of waste provide only small quantities of material. This is true for niobium-containing steels and metals used in PCBs.
- **Uncertainty:** Implementation of large scale recycling requires significant investment; this is increasingly true for critical materials. Uncertainty about future quantities and qualities of waste streams, legislation and the value of materials can discourage the establishment of recycling activities.

With these factors in mind, and considering existing and future uses of the critical raw materials, ten opportunities for markets with high potential for increased recovery of critical materials were identified, summarised below.

	Market	**Application**
Growth	Catalysts	Catalytic converters
	Packaging	Beverage cans
Implementation	Aerospace	Superalloys
		Landing gear
		Aluminium alloys
	Batteries	Portable Li-Ion
	Electronics and ICT	Hard disk drive magnets and layers
Future Prospect	Electronics and ICT	LCD screens
	Electrical Equipment	Wind turbine magnets

These classifications distinguish between:

- those opportunities which are well established but have potential for **growth** through development of infrastructure
- opportunities which will arise in the short term that will require **implementation** of new infrastructure or technology
- opportunities which are **future prospects.**

A further eleven applications were found as having medium potential for increased recovery. These opportunities may also be viable: however there are greater barriers to their implementation. A gap analysis of all high- and medium-potential opportunities identified two groups within the critical materials: those for which end of life recovery has the potential to reduce demand for raw materials, and those for which this will have little impact.

Critical Raw Materials	
Reduction from recovery	**Low impact from recovery**
Antimony	Beryllium
Cobalt	Fluorspar
Indium	Gallium
Magnesium	Germanium
PGMs	Graphite
REEs	Niobium
Tungsten	Tantalum

Therefore, though recycling presents one option for reducing the demand for raw materials, other activities such as remanufacturing and reuse, substitution or elimination will be necessary to meet projected demands for some critical materials. Some of these activities are already in place; remanufacturing already plays a large role for automotive components and electronic equipment. Substitution, either of material or product, is possible; however, the replacement of many critical materials simply adds to the demand for different critical materials. Care is needed when considering this strategy.

Overall Recommendations

In addition to identifying the ten most promising markets for critical material recovery, the following recommendations, applicable to the UK and EU, are made for increasing the recovery of critical raw materials:

- **Improved collection:** Several of the recycling activities highlighted above are already in place, but their impact is limited by poor recovery. Developing more efficient collections schemes for consumer (e.g. beverage cans) or industrial (e.g. aircraft or cemented carbide tools) waste will increase recycling rates. This may also help enable other end of life options such as remanufacturing and reuse.
- **Advanced sorting techniques:** Existing business models using practices such as ‘shred and sort’ are poor at isolating small, high value items containing critical materials. Therefore, high value materials may be lost or dispersed into large quantities of generic shredded waste. Implementation of more sophisticated sorting, which distinguishes between items containing critical materials, will help encourage the recovery of these raw materials, and produce ‘higher value’ waste streams.
- **Implementation of new technology:** New technologies, such as that for the recovery of magnets from hard disk drives, are becoming available. With the implementation of improved collection and sorting, these will become viable as larger volumes of isolated waste types become available.
- **Linking of agents within the supply chain:** The design and use of many products prevents separation of components such as batteries. Linking together designers, producers and waste management firms will aid understanding of the challenges of separation at end of life.
- **Design for disassembly:** Existing sorting of materials is often held back by product design lowering the ease in which parts can be separated, for instance using epoxy resins or non-standard screw types for connecting components. Adopting design practices which enable disassembly will improve the efficiency of sorting. The EU Ecolabel scheme has already adopted this approach through specification in the electrical equipment criteria. This action will also help remanufacturers and refurbishers extend the life of products.
- **More sophisticated waste recovery targets:** Existing targets are often weight-based, leading to an emphasis on the recovery of materials in bulk whatever their specification; this often causes further dispersion of critical materials. Investigating and implementing measures which would motivate separation based on critical material content would help prevent this occurring.
- **Alignment and enforcement of regulations:** Implementation and enforcement of headline policy to specific market regulations will provide recyclers with greater certainty over future waste streams.

- **Remanufacturing and reuse:** Remanufacturing and reuse activities can help resource efficiency through product life extension. These activities are already established with the aerospace and automotive industries, however wider implementation would increase their impact.

Recommendations for the South East of England

The recommendations and opportunities described above on a wider scale also apply to the South East of England. However, the existing infrastructure and regional scale should be borne in mind; for certain materials there may only be enough material arising in Europe to reasonably supply one refiner.

At present the infrastructure in the South East of England is mainly focussed around collection, sorting and processing with companies such as Light Brothers acting as focus for these activities. Once products are processed the recycling of the materials typically happens outside the region for example at Johnson Matthey's plant in Royston, Hertfordshire, and a few other large sites in the EU; alternatively they are sent to outside the EU. No refiners of these materials were identified within the region.

The most likely short term opportunities of improving the recovery of critical materials in the South East of England through infrastructure development lie within the improvement of existing collecting and sorting infrastructure, through the recommended measures above. Opportunities for implementing new recycling technologies for potential future waste streams also exist, however the lack of smelters may inhibit the extent to which these can be implemented.

Therefore, providing the availability and concerns over these critical raw materials continue, and prices remain high, conclusions about changes required to the South East's infrastructure can be made, particularly for those opportunities identified above:

Post-Consumer Waste:

- WEEE - More sophisticated WEEE recycling facilities, including
    - Greater disassembly prior to shredding
    - Greater segregation of a larger number of material streams.

This would enable the recovery of critical material containing components within many of the uses described above. For example, Hitachi has developed technology to isolate and recover the REE magnets used in hard disk drives. Technologies are also available for the recovery if indium from LCD screens, antimony from plastics and both Li-Ion and NiMH batteries.

- Packaging – Improved collection of "on-the-go" recycling for beverage, for example through increased numbers of recycling facilities in public spaces, are required as recycling technology is well established

Post-Industrial Waste:

- A larger number of distributed post-industrial collections schemes (or expansion of existing) will lower critical material demand. For example, collections systems for cemented carbide tools, though actual recycling taking place outside the South East.
- The recovery of aerospace components is a growing theme, as manufacturers and organisations are increasingly seeking to investigate this end of life option. Locations for strip down facilities will be required, although given space requirements it is likely that expansion will occur outside the South East.
- Recovery of wind turbine magnets is a long term prospect, likely to be most viable near large wind farms. Development of dismantling and recovery specific to wind turbines will be necessary, as well as recycling technology and substantial investment in infrastructure.

6.0 Appendix 1 – Summary of Markets and Applications

Market	Submarket	Application		
Aerospace and Automotive	Aerospace	Aluminium alloy parts	Landing gear	Super alloys
	Automotive	Aluminium alloy parts	Steel alloy parts	Brake linings
Batteries	Portable Batteries	Lithium-Ion	Nickel Metal Hydride	
	Electric Vehicle Batteries	Lithium-Ion	Nickel Metal Hydride	
Catalysts	Vehicles	Catalytic Converters		
	Process Catalysts	Plastic	General	Petrochemical
Cemented Carbide	Tooling	Tooling		
Chemical	Fluorocarbons	Refrigerants	Blowing Agents	Fluoropolymers
	Aluminium fluoride	Flux agent		
Construction	Aluminium alloys	Wrought Products		
	Low alloyed steel	Pipelines	Structural	
Electrical Equipment	Permanent Magnets	Electric Vehicles	Wind Turbines	Small Domestic Appliances
	Solar Panels	CIGS type	CdTe type	
Electronics and ICT	---	Circuit Boards	Flat Panel Displays	Hard Disk Drives
Flame Retardants	Antimony Trioxide	Plastics		
Optical Equipment	---	Fibre optics	Lenses	LED lighting
Packaging	Aluminium alloys	Beverage Cans		
Steel and Steel Alloys	Steel Production (Graphite)	Carbon content	Electrodes	
	Steel Production (Others)	Flux agent/pickling	Desulfurization	Stainless Steel

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Study into the feasibility of protecting and recovering critical raw materials through infrastructure development in the south east of England.

Annexes

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Glossary

AlNiCo	Aluminium Nickel Cobalt (battery)
BGS	British Geological Survey
CFCS	Chlorofluorocarbons
CIGS	Copper Indium Gallium Selenide (photovoltaic)
CIS	Commonwealth of Independent States
CRT	Cathode Ray Tube
EC	European Commission
EEE	Electronic and Electrical Equipment
EV	Electric Vehicle
FCC	Fluid Cracking Catalyst
HDD	Hard Disk Drive
HEV	Hybrid Electric Vehicle
HSS	High Speed Steel
IMCOA	Presentation?
ITIA	International Tungsten Industries Association
ITO	Indium Tin Oxide
LCD	Liquid Crystal Display
LED	Light Emitting Diode
MBM	Metals Bulletin Monthly
MLCC	Multi-Layer Ceramic Capacitor
MRI	Magnetic Resonance Imaging
NdFeB	Neodymium Iron Boron (magnet)
NiMH	Nickel Metal Hydride (battery)
PGM(s)	Platinum Group Metal(s)
PHEV	Plug-in Hybrid Vehicle
REE	Rare Earth Elements
RRF	Resource Recovery Forum
SAW	Surface Acoustic Wave
SEEDA	South East of England Development Agency
SmCo	Samarium Cobalt (magnet)
UNEP	United Nations Environmental Programme
USGS	United States Geological Survey
WEEE	Waste Electronic and Electrical Items

Units Conventional SI units and prefixes used throughout: {k, kilo, 1000} {M, mega, 1,000,000} {G, giga, 10^9} {kg, kilogramme, unit mass} {t, metric tonne, 1000 kg}

Contents

1 Annex A – Summary of Critical Materials

This section provides a summary of each of the 14 critical raw materials highlighted by the EC's report on critical raw material. For each material the key applications, supply, demand and prices forecasts are provided.

1.1 *Antimony*

Antimony (Sb) is a silvery-white shining, soft and brittle metal. It is a semiconductor, and has thermal conductivity lower than most metals' conductivities. Due to its poor mechanical properties, pure antimony is only used in very small quantities; larger amounts are used for alloys and in antimony compounds[a]. Antimony is toxic and immediately dangerous to life or health at 50 mg m-3 or above.

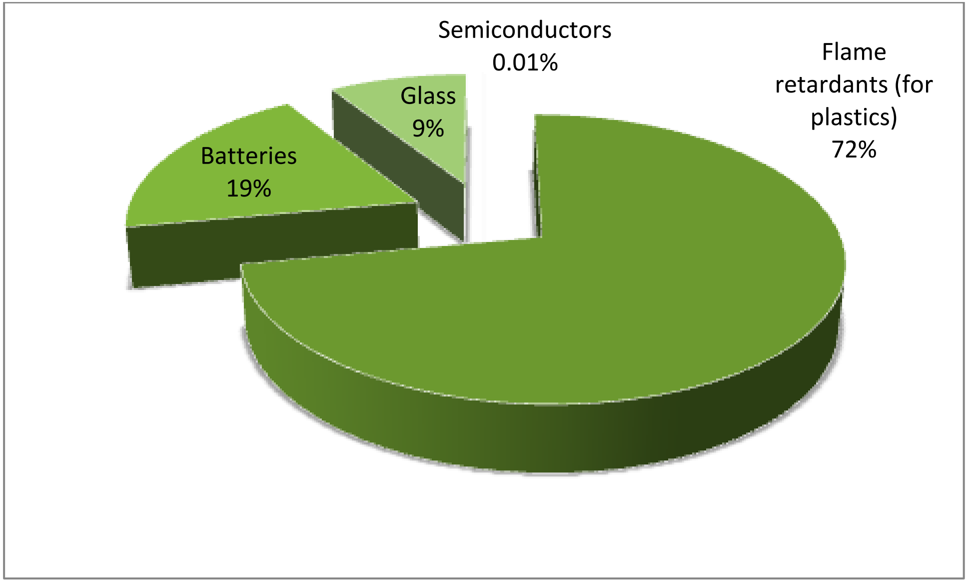
Antimony's abundance in the earth's crust is 0.2 ppm. There are more than 100 known antimony containing minerals, the most important of which is black stibnite (Sb_2S_3).[b] The element also occurs in white valentinite (Sb_2O_3) and as antimonides and sulphoantimonides of metals like lead, copper and silver. Stibnite is the only source for metallic antimony to be commercially mined.

Antimony ores are mined and then beneficiated and processed into antimony metal or oxide, a white powder. To obtain antimony metal, stibnite is reduced with iron, and the iron sulphide is then removed as slag. The metal can also be produced by roasting stibnite to the oxide, which is then reduced with carbon in the presence of a carbonate flux. As antimony is often to be found as a trace element in gold, copper, lead and silver ores; the metal is also extracted from these. China dominates the world antimony market.

1.1.1 Key Applications and Potential Future Substitution

Antimony is a very brittle metal and difficult to shape, therefore pure antimony has no direct applications, but it is extensively used as an alloying element and in other compounds, Figure 1.

Figure 1: Applications of Antimony by value



Source: Critical raw materials for the EU (2010)

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a Römpp Online: Antimon. Georg Thieme Verlag, Stuttgart, 2004
b Ullmann's Encyclopedia of Chemical Technology: Antimony and Antimony Compounds. Wiley-VCH Verlag, Weinheim, 2006

Globally the principle use of antimony is in flame retardants as antimony trioxide, which consumes 72% (134,640 tonnes) of its supply. In this use antimony trioxide is most commonly used as a synergist to improve the performance of other flame retardants such aluminium hydroxide, magnesium hydroxide and halogenated compounds. This enhanced performance minimises the amount of flame retardant required to achieve the desired or legislated level of performance. Antimony trioxide is used in this way in many products including plastics, textiles, rubber, adhesives, toys, and in seat covers of aircrafts and automobiles.

The second most common use of antimony is as a hardener for lead electrodes in lead acid batteries. This use is in decline as the antimony content of typical automotive battery alloys has fallen to 0.6% or lower, and the use of antimony in batteries will reduce further as calcium, aluminium and tin alloys are expected to replace it completely by 2020.[a]

Antimony, in the form of sodium antimonite, is also used in the glass production as a decolourising and fining agent[b] mainly for CRT glass, optical glass used for cameras, photocopiers, binoculars and spectacles, and in fluorescent light glass tubing. Antimony additions generally comprise 0.1 to 0.2% of the glass batch.

Antimony is also used in low quantities for the following:

- Catalyst in the production of polyethylene and the vulcanization of rubber
- Pigments and enamels for plastics as well as metal and ceramics
- Intermetallic components in electronics such as “phase-change” computer chips
- Brake linings
- Ammunition primers
- Fireworks.

In general the global demand of antimony is experiencing a decline, especially in the battery industry. However, the use of antimony in flame retardants is expected to remain consistent unless regulations change.

Substitutes

Currently, only a few substitutes for antimony oxide in flame retardants are available, particularly as a synergist. Minimisation of antimony use can be achieved by simply not using it and increasing the amount of primary flame retardant present. However this is often undesirable, particularly if the level of halogenated flame retardants is increased.

Combinations of cadmium, calcium, copper, selenium, strontium, sulphur and tin can be used as substitutes for hardening lead; these are already replacing antimony in lead acid batteries[c]

Compounds of chromium, tin, titanium, zinc and zirconium can be used as a substitute for antimony chemicals in paint, pigments, and enamels.

Recycling

No recovery of antimony from flame retardants takes place as it is a dissipative use; antinomy is present in low concentrations in high volumes of plastics. However, some uncontrolled and often unintentional reclamation takes place through normal plastic recycling routes as it is retained in the plastic.

Traditionally most secondary antimony has been recovered by recycling used lead acid batteries, but new battery technologies lead to a declining amount of recycled antimony. The trend to low-maintenance

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[a] Antimony, Metals Bulletin Monthly, May 2007

[b] Fining agents aid the removal of microscopic bubbles in these glasses

[c] Critical raw materials for the EU. European Commission, 2010

batteries has tilted the balance of consumption away from antimony and towards calcium as an additive.[a] In 2000, an estimated 95% of the U.S. secondary antimony supply resulted from used lead acid batteries.[b] The recovered antimonial lead is generally generated and consumed by the battery industry in a closed loop process.

In the UK an estimated 140,000 tonnes of lead acid batteries are recycled every year: 90-95% are automotive batteries and the remaining 5-10% are portable batteries.[c] However, the overall recycling rate of antimony from old scrap is estimated to be somewhere between 3 and 20%.

1.1.2 Current European and Global Output and Reserves

World mine production of antimony was 187,000 tonnes in 2009 of which 91% came from China, Table 1. The Chinese production however is not concentrated within a single company. Following a number of fatal mining accidents in Guangxi province mines, many smaller and illegal mines have been closed[d]. The largest antimony mining company is thought to be the state owned Hsikwangshan Twinkling Star Company in Hunan Province, which is reported to have an annual capacity of 12,000 tonnes on antimony metal according to one estimate[e], although other estimates put production at 50,000 tonnes of antimony metal and trioxide combined[f].

The other 9% of world production is split between a number of countries, although no European countries have significant production levels (approximately 1% of world production is located in Turkey and Hungary is believed to produce antimony[g]). World reserves are more geographically distributed than mine production – China accounts for 38% of world reserves, with Thailand, Russia and Bolivia all with large deposits.

Table 1: World Antimony Production and Reserves – 2009 (tonnes of antimony content)

Country	Mine production	Reserves
China	170,000	790,000
Bolivia	4,500	310,000
Russia	3,000	350,000
South Africa	3,000	44,000
Tajikistan	2,000	50,000
Thailand	—	420,000
Other countries	4,000	150,000
World total (rounded)	**187,000**	**2,100,000**

Source: USGS Mineral Commodity Summaries (2010)

Global Demand and Supply, and Price Forecasts until 2020

Future supply growth is forecasted to keep pace even with strong growth in demand (Figure 2). The market is expected to remain broadly in balance until 2015. Significant surpluses are possible towards the end of the decade as a result of increased exploration interest outside of China driven by the impetus of much increased prices following China's efforts to control its own production in 2000-2001. Roskill

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[a] USGS, Mineral Commodity Summaries, 2010

[b] James F. Carlin, Jr. *Antimony Recycling in the United States in 2000*. U.S. Geological Survey, 2000

[c] *Battery Recycling Market Research Study*. Valpak consulting, March 2010

[d] MBM (May 2007), Antimony

[e] HAI (2009), Antimony: A Metal?

[f] MBM (May 2007), Antimony

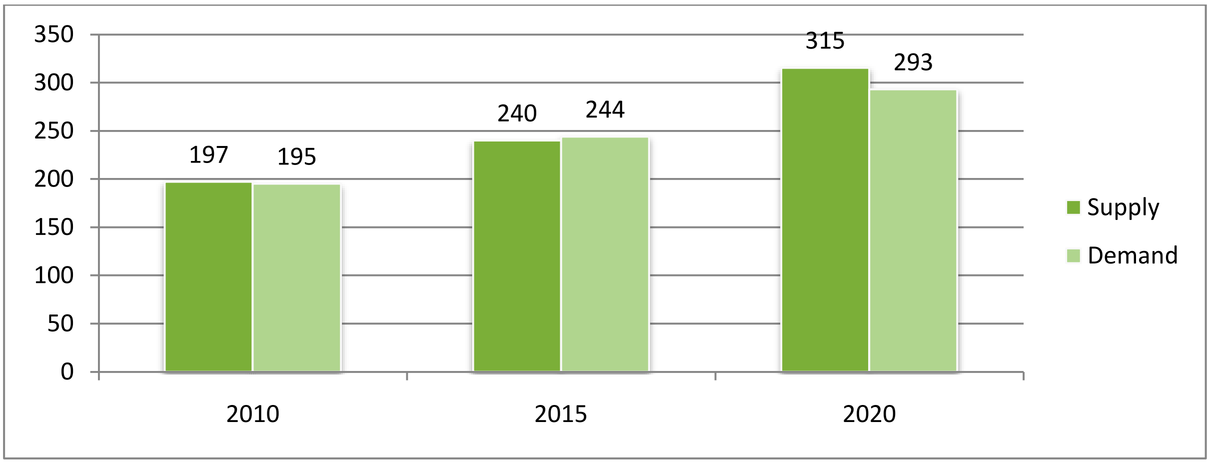
[g] BGS (2010), World Mineral Production 2004-2008

note that such was the degree of oversupply in the market, prices took around four years to respond to China's industrial interventions[a].

The assumptions underlying the forecast are:

- Antimony mine production in 2010 recovers to 2008 levels and China's long run growth in production is modest at 2% per year, as a result of the measures it has undertaken to curb its domestic production.
- For the rest of the world production, Roskill (2007) identified 96,000 tonnes of Project Antimony Supply Capability that would come on stream by 2011 under the assumption that prices remained above $5,000 per tonne[b]. It seems likely that some of these projects will have been delayed by the economic climate; but it has been assumed that they are completed by 2020, with some of this capacity available in 2015.
- On the demand side, for the largest market of flame retardants, Freedonia produced a long term forecast for the period 1994-2014. This forecast had demand for antimony based flame retardants to grow at 7% per year until 2014, slowing from 7.5% per year. This strong growth above the rate of demand growth for flame retardants as a whole is explained in part by a shift towards antimony based flame retardants. However Roskill (2007) note that whilst the forecasts were broadly on target till 2006, such a forecast did not envisage the large price rises that have occurred for antimony. Accordingly Roskill determined a rate of 5.5% to 2015 being more realistic[c]. Thereafter a further slowing to 4% growth per year has been used.
- For the other smaller markets, a 4.8% growth rate has been used for batteries, with the increase mostly driven by emerging markets[d] and a 5% a year decline in demand for glass for CRT use has been assumed.

Figure 2: Antimony Supply and Demand Forecasts (kt)



Source: Oakdene Hollins Calculations from Roskill (2007) and Freedonia (2010)

The price developments for antimony are shown in Figure 3. Prices were at a painfully low level below $1,500 per tonne for much of 2001, but have risen steadily in the years subsequent to China's reforms. Aside from a dip in late 2008 and the first half of 2009, prices have remained above the key price floor of $5,000 per tonne identified by Roskill as being able to support non-Chinese producers; in 2010 prices have surged to a current high of $12,000 per tonne. Given the fundamentals in the market it is not likely that prices will return to lows previously seen, with support above $5,000-6,000 per tonne expected.

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[a] Roskill (2007), The Economics of Antimony, 10th Edition

[b] Roskill (2007), The Economics of Antimony, 10th Edition

[c] Roskill (2007), The Economics of Antimony, 10th Edition

[d] Freedonia (2010), World Batteries to 2014

Figure 3: Antimony Regulus Prices min 99.65% Grade II (EU) ($/t)

Source: Metal Pages

1.2 Beryllium

Beryllium (Be) is a silvery-white shining, hard, brittle and light metal. Its mechanical and thermal properties relative to its low density is superior to those of all other materials, and has the highest melting point of the light metals, melting at 1278°C. Beryllium and its salts are both highly toxic and carcinogenic.

Beryllium's abundance in the earth's crust is 2.8 ppm. The mineral beryl, [$Be_3Al_2(SiO_3)_6$] is the most important source of beryllium, which is the mineral name of several well-known gemstones like emerald and aquamarine.

There are different methods of extracting beryllium, depending on the type of ore processed[a]. In general, to extract Beryllium, Beryl ore is heated, with or without fluxes, and is then leached to give an aqueous solution of beryllium fluoride or sulphate.[a] Other beryllium ores can yield their beryllium upon leaching with sulphuric acid without pre-treatment.

1.2.1 Key Applications and Potential Future Substitution

Beryllium is ideally suited for a number of specialized applications where low weight and high rigidity are important qualities, whether in the form of an alloy as a pure metal, as a chemical compound, or as an oxide in ceramics, Figure 4.[b] Due to its high price and its toxicity, beryllium is only used in small quantities in the civilian sector, however it is used in a vast array of different sectors and applications.

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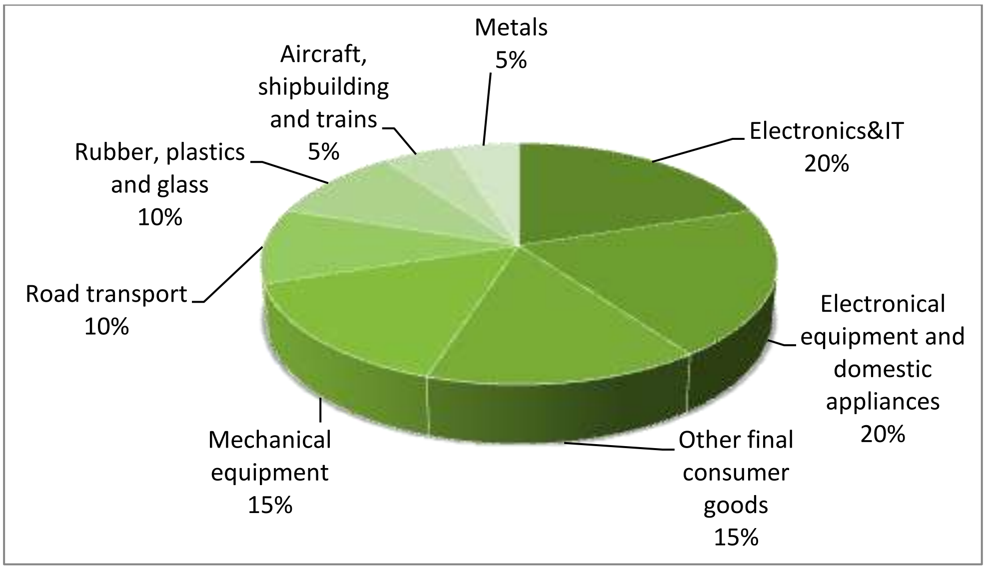
[a] USGS, Minerals Yearbook, Beryllium, 2008

[b] Tom Vulcan, Beryllium: Bombs And More (Much More), Hard assets, December 2008

Figure 4: Applications of Beryllium, shown by value.



Source: Critical raw materials for the EU (2010)

Electronics and electrical components, combined, represent berylliums main end-use corresponding to 40% of the value. In these applications beryllium is mainly used in the form of beryllium copper alloys which are divided into high-strength alloys (typically containing 1.6-2% Be), used for applications like telecommunications, and high-conductivity alloys (containing around 0.3% Be) which are used in markets such as the automotive sector.[a] Other applications in which these alloys are found include:

- electrical contacts and connectors in mobile phones and computers
- spot-welding electrodes
- underwater fibre optic cable systems
- cable and HD TV
- hi-fi loudspeakers
- springs
- plastics moulds.

Beryllium copper is also used in drilling equipment and tools (oil and gas industry) due to its non-sparking properties as well as in aircraft landing gear, particularly the brakes. Brakes used in military aircrafts are often 100% beryllium, whereas those used in commercial aircraft will use the metal in an alloy form as operating conditions are less extreme.[b]

Beryllium can be used in a variety of different compounds. For example, beryllium oxide ceramics are used extensively in electronics particularly in the computer and telecom industries and as heat sinks.[b] AlBeMet - aluminium-beryllium materials – have a beryllium content of up to 65% by weight and are primarily used as a lightweight metal in the aerospace industry in the construction of jet fighters, helicopters, spacecraft and satellites. Further applications include hard disc drives, brakes, speaker tweeters, woofers, and medical and industrial x-ray applications.[c]

Other applications in which beryllium is used are:[d]

- thermostats
- bellows
- sockets

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[a] David McNeil, *Beryllium*, The Mineral Journal, 2005

[b] Tom Vulcan, Beryllium: Bombs And More (Much More), Hard assets, December 2008

c David McNeil, Beryllium, The Mineral Journal, 2005

d Critical raw materials for the EU. European Commission, 2010

- CT scanners and X-ray machines: Beryllium metal is used for x-ray transparent windows
- physical instruments: Beryllium has properties that make it interesting for a variety of physical instruments (e.g. neutron monochromators)
- nuclear reactors.

Substitutes:
Because the cost of beryllium is high compared with that of other materials, it is used in applications in which its properties are crucial. In some applications, certain metal matrix or organic composites, high-strength grades of aluminium, pyrolytic graphite, silicon carbide, steel, or titanium may be substituted for beryllium metal or beryllium composites. Copper alloys containing nickel and silicon, tin, titanium, or other alloying elements or phosphor bronze alloys (copper-tin-phosphorus) may be substituted for beryllium-copper alloys, but these substitutions can result in substantially reduced performance. Aluminium nitride or boron nitride may be substituted for beryllium oxide in some applications.[a]

Recycling:
According to the USGS, detailed data on the quantities of recycled beryllium are not available, but may be as much as 10% of apparent consumption. Most of the beryllium is recycled from new scrap generated during the manufacture of beryllium products.[b] Beryllium alloys and beryllium metal have been reclaimed at manufacturing plants that produce beryllium-related components. According to an EU report only an estimated 50% of possible new scrap material is recovered and recycled; 90% of this is then reused in the beryllium industry.[d]

The beryllium contained in post consumer scrap is not recovered specifically, but is contained in the slag produced by copper recycling processes.[c] Most beryllium-copper-alloys are used in electrical and electronic components. However, little beryllium is recovered from these used applications owing to their small size, difficulty in separation, and the low beryllium content in the alloys (2 to 2.7% depending on the intended application). Furthermore the beryllium copper alloy is often recycled to reclaim the copper, and the contained beryllium is lost to the beryllium industry.

1.2.2 Current European and Global Output and Reserves

World mine production of Beryllium was 140 tonnes in 2009 of which 86% originated from the United States, with China being the only other significant producing country, Table 2; a similar pattern exists for the extraction of the main ore of beryl. As for European production, it is noted that Portugal produces 0.1% of world supply of Beryl[d]. The world beryllium markets are dominated by a single company, Brush Wellmann, which is a subsidiary of Brush Engineered Materials. Brush Wellmann closed its primary beryllium production facility in 2000, with a new facility due to open in 2010. In the meantime it has been sourcing material from stockpiles and from contracts with Ulba Metallurgical Plant in Kazakhstan[e].

World beryllium reserves are not sufficiently well quantified to provide accurate country-by-country estimates due to its usage in military applications, although world resources are estimated at 80,000 tonnes of which 65% are in the United States[f].

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[a] USGS, Mineral Commodity Summaries, 2010
[b] USGS, Minerals Yearbook, Beryllium, 2008
[c] Critical raw materials for the EU. European Commission, 2010
[d] USGS, Minerals Yearbook, Beryllium, 2008
[e] Metals Bulletin Monthly, Beryllium, 2007
[f] USGS, Mineral Commodity Summaries, 2010

Table 2: World Beryllium Production 2009 (tonnes of beryllium content)

Country	Mine production
United States	120
China	20
Mozambique	1
Other countries	Negligible
World total (rounded)	**140**

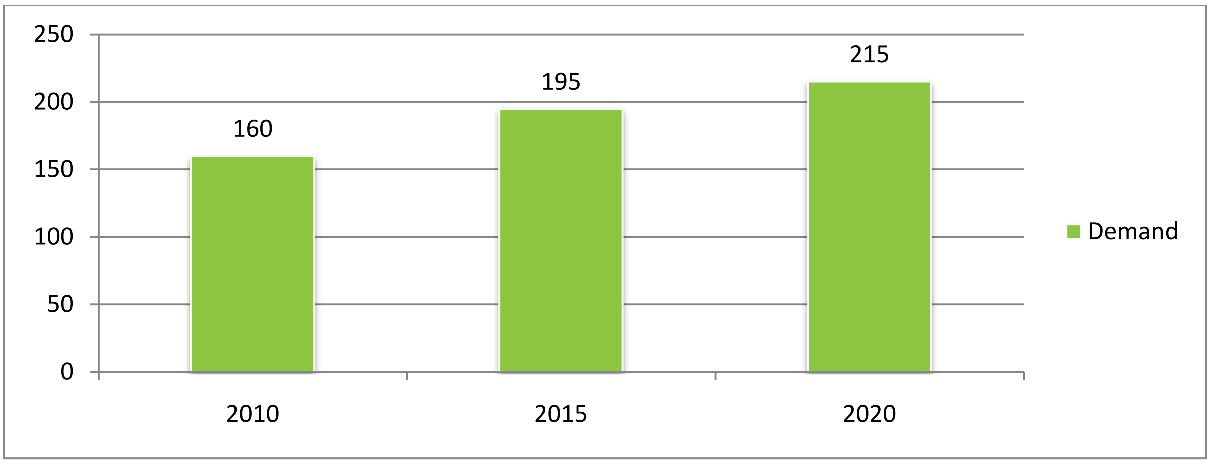
Source: USGS Mineral Commodity Summaries (2010)

Global Demand and Supply, and Price Forecasts Until 2020

Given the dominance of a single company in the Beryllium market, Brush Wellmann, a supply forecast was not deemed appropriate. It is noted that historical US mine production has considerably exceeded the 120 tonnes supplied in 2009 (176 tonnes were mined in 2008). Roskill (2001) report global capacity figures of 534 tonnes for 2000[a], so it has been assumed that supply will be able to increase accordingly with demand. On the demand side a modest growth rate of 2% per year is quoted in the literature as being reasonable as a result of declining uses in military applications, although this figure is now relatively old[b]. In terms of the demand forecast shown in Figure 5, some recovery from the 2009 lows has been assumed for 2010 and 2011, with the 2% growth rate applied thereafter. This would take Beryllium demand to 215 tonnes in 2020.

Regular price data for Beryllium is not available, although given the dominance of the United States in its production, some price data can be inferred from US export data. This shows that Beryllium prices have risen steadily from $60/kg in 2002 to around $140/kg in 2008.

Figure 5: Beryllium Demand Forecast (t)



Source: Oakdene Hollins based on Roskill (2001)

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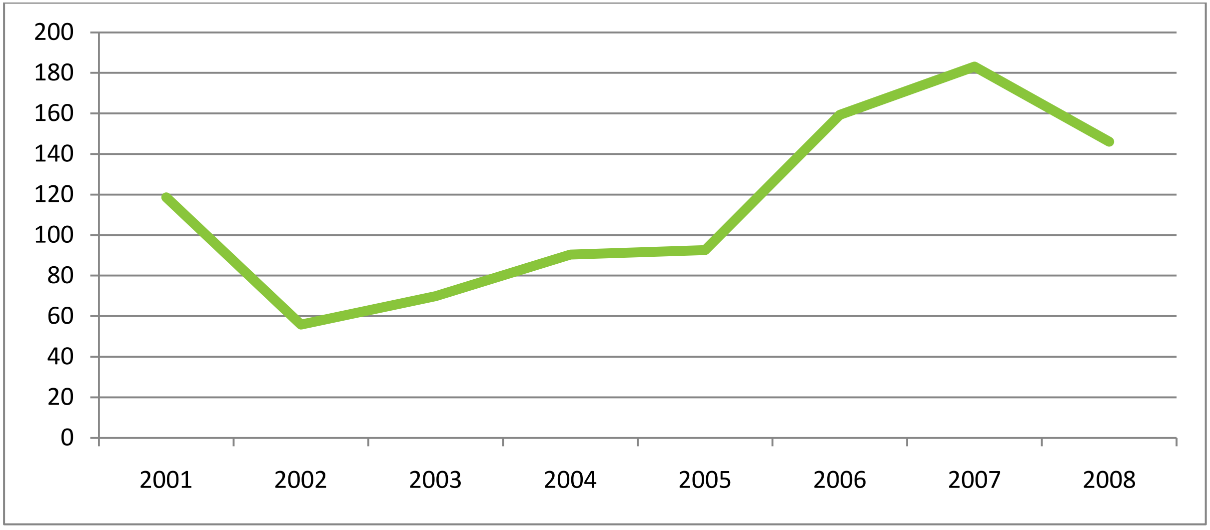
[a] Roskill, The Economics of Beryllium, 6th Edition, 2001

[b] Roskill Mineral Services, Beryllium, 2005

Figure 6: Average US Beryllium Export Prices ($/kg)



Source: Oakdene Hollins calculations, based on USGS Data

1.3 Cobalt

Cobalt (Co) is a bluish-white, lustrous, hard and brittle metal. It has fairly low thermal and electrical conductivity, is ferromagnetic and is very active chemically. Cobalt and its compounds are considered to be slightly toxic.

Cobalt's abundance in the earth's crust is 25 ppm, and it can be found in several common ores (cobaltite, erythrite, glaucodot and skutterudite). It can also be found in economic concentrations in olivine, spinel and chlorite, in lateric and hydrothermal deposits. Generally, production of cobalt is as a by product of copper metallurgy and as a by product of nickel production.

Because cobalt is extracted from a wide variety of ores, there is an equally extensive variety of mining, extraction and refining methods. For example, the process of purifying cobalt bearing copper sulphide ore involves crushing and separating the ore, to subsequently roast and leach the concentrate with sulphuric acid. The cobalt can then be separated from the pulp as cobalt hydroxide. After the other metals have been removed the hydroxide is re-dissolved in acid.[a]

The world's cobalt reserves are concentrated in Central Africa. Interestingly, about 36% of refined cobalt production is based on imported material processed by countries that have no cobalt mining production.

1.3.1 Key Applications and Potential Future Substitution

Cobalt has few applications in its pure form, and it is most commonly used as an alloy constituent or chemical compound where it can provide chemical resistance and high temperature strength. The main commercial applications of cobalt are in portable rechargeable batteries (27%) and super-alloys for jet turbine parts and other types of turbines (22%), Figure 7.

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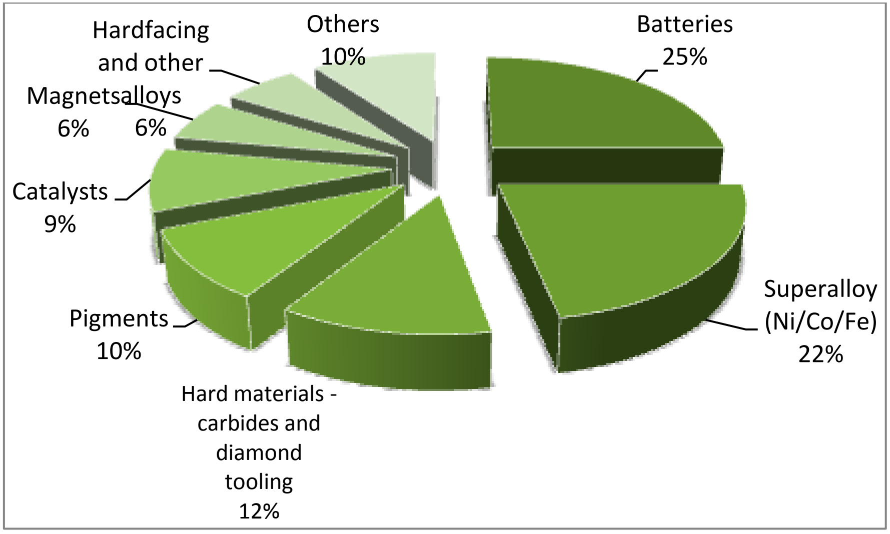
[a] BGS, World Mineral Production 2004-2008, 2010

Figure 7: Global end use of primary cobalt



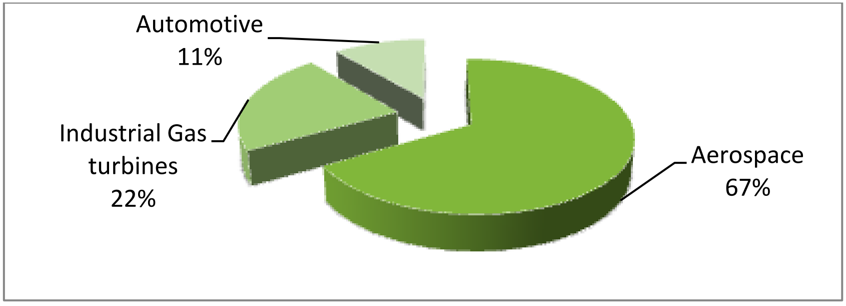
Source: British Geological Survey (August 2009)

Batteries
Cobalt is an important component in the three main rechargeable battery technologies in portable electronic devices such as digital cameras, mobile phones, laptops or power tools. Lithium-ion batteries contain up to 60% of cobalt as lithium cobalt oxide and have dominated the market over the last 10 years by value[a]. Nickel-metal hybrid batteries contain up to 15% cobalt and these form an important component of current hybrid electric vehicles (HEVs) as well as other uses. A fine cobalt oxide or hydroxide powder is used in nickel-cadmium batteries accounting for 1 to 5% of its composition.[b]

The demand for rechargeable batteries for portable electronic devices should remain healthy and is expected to grow. The use of rechargeable batteries in automotive applications (HEV, EV and PHEV) is likely to be a potential growth market. However, the demand for cobalt will strongly depend on the battery technology which will be adopted in this market. Industry forecasts suggest that in 2015, NiMH batteries will account for 70% of the battery systems in hybrids[c] and cobalt, used in the more powerful lithium-ion cells, might be substituted by cheaper metals like manganese and nickel.[d]

Superalloys and Magnet Alloys
Cobalt is widely used as an alloying metal in superalloys and magnets. Superalloys are primarily used in jet engines and turbines, and to a smaller amount in automotive and chemical applications.

Figure 8: Industrial superalloy markets



Source: Hard Assets/ Roskill

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[a] Tom Vulcan, Cobalt: More Than Just Blue, Hard Assets, October 2008

[b] BGS, Cobalt, August 2009

[c] Darton Commodities Ltd, Cobalt Market Review, 2009

[d] Metal Bulletin, Cobalt, August 2005

Other cobalt alloys are: high speed steels, hard facing materials, prosthetic limbs, low expansion alloys, maraging steel.

Cobalt is used in magnetic alloys either in high strength samarium cobalt magnets and lower powered AlNiCo magnets. These magnets are used in a variety of applications including high performance electrical equipment such as those below, Table 3.

Table 3: Historical uses of cobalt based magnets in electrical equipment

Electric Motors	Generators	Telephones
Microphones	Automotive Sensors	Loudspeakers
Travelling Wave Tubes	Computer hard disk drives	

However, neodymium based magnets have and are replacing these magnets in many applications, though applications are retained in certain niche uses, such as in high temperature conditions.

Catalysts

Catalytic processes account for 9% of all cobalt consumption. One of the primary uses is to increase polymerization/oxidization rates in the manufacture plastic resins, which are critical to the plastics industry. Cobalt is also used in gas-liquid technologies where natural gas is processed to produce synthetic diesel fuel. It is also used in the petrochemical industry in the form of cobalt-oxide to remove sulphur from crude oil in the refinery process. Both these sectors are likely to increase their cobalt use in the future.

Other applications

Cobalt is used in a variety of other applications; the most important of these include:

- A binder material in hard materials such as cemented carbide and diamond tool applications (12%).
- Pigments in glass, enamels, pottery and china (10%).
- In medicine as part of cancer treatment, as well as in the alloy vitallium (Co-Cr-Mo-C) which is fully compatible with human tissues and bones and used in prostheses systems and dentistry.
- Electronic connectors on integrated circuits (containing up to 15% of Co).

Substitution

Cobalt content in lithium-ion cells might be reduced or even replaced by cheaper metals like manganese and nickel; this switch may also help to ease futures demand in the battery sector. These technologies are in development and may reduce the cobalt composition from 60% to 10%, or even completely remove its use[a] The use of existing cobalt cathode materials for Li-ion batteries will drop to approximately 45% by 2013 from forming almost all the market. The use of alternatives based on nickel, manganese and aluminium with grow steadily in this time.[b]

Nickel shares similar properties to cobalt, and can be used as a substituent in alloys in certain circumstances. Substitution is possible in applications such as cutting and wear resistance materials, jet engines, nickel-iron magnets, petroleum catalysts and batteries; however this will almost always result in a loss of performance, therefore cobalt is generally preferred. Barium and strontium can replace cobalt in high-hardness alloys and high performance ceramics can be used as a substitute in applications where high temp-resistant and high-hardness materials are required.

Some substitution is possible for cobalt in pigments, where cerium, iron, lead, manganese and vanadium are feasible alternatives.

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[a] Darton Commodities Ltd (2009), Cobalt Market Review

[b] European Commission (2010), Critical raw materials for the EU

Recycling
According to the EU material report cobalt's end of life recycling rate is estimated to be 68% (higher than for most other metals), with a recycling content rate of 32% (lower than most other metals). In the USA, cobalt contained in purchased scrap represented an estimated 24% of cobalt reported consumption.[a] In general it can be said that end-of-life products are an increasingly important source of cobalt supply especially for the EU cobalt industry.

A significant proportion of cobalt has been recovered from cathode materials and batteries due to cost benefits (compared to cobalt extraction from ore) and to prevent potential environmental damage cause by batteries ending up on landfills. The recycling of batteries is carried out by the cobalt industry and takes place in a closed loop system so that no material is lost. In addition to the shift towards lower or no cobalt cathode materials, increased recycling efforts (the EU target is to recycle 40% of batteries by 2016) will ultimately reduce the demand for primary cobalt. Politically, recycling cobalt has also become more important in order to become less dependent on cobalt main suppliers historically located in central Africa.

According to the EU mineral report, the "recycling of alloy and hard metal scrap is generally operated by and within the super alloy and metal carbide sectors and cobalt is recovered, in fact, in alloyed or mixed form."[b] Some hard metal materials are being recycled through the cobalt industry route. It is not possible to recycle cobalt from applications in pigments, paints, glass, etc as these usages are dissipative.

1.3.2 Current European and Global Output and Reserves

World mine production of cobalt was 62,000 tonnes in 2009, of which Congo (Kinshasa) accounted for 40%, Table 4. The remaining 60% is split between a number of countries including Australia, China, Russia and Canada. As for European production, Finland mined 105 tonnes of cobalt in 2008 and additionally Poland, Spain and Turkey are known to produce cobalt containing ores[c]; similarly it is noted that New Caledonia, which is a French overseas territory, is listed as mining 1,300 tonnes in 2009. Reserves of cobalt are geographically more concentrated, with Congo (Kinshasa) having over half of the world's reserves, and Australia accounting for a further 23%.

Table 4: World Cobalt Production and Reserves 2009 (tonnes of cobalt content)

Country	Mine production	Reserves
Congo (Kinshasa)	25,000	3,400,000
Australia	6,300	1,500,000
China	6,200	72,000
Russia	6,200	250,000
Canada	5,000	120,000
Cuba	3,500	500,000
Zambia	2,500	270,000
Morocco	1,600	20,000
New Caledonia	1,300	230,000
Brazil	1,000	29,000
United States	—	33,000
Other countries	3,200	180,000
World total (rounded)	**62,000**	**6,600,000**

Source: USGS Mineral Commodity Summaries (2010)

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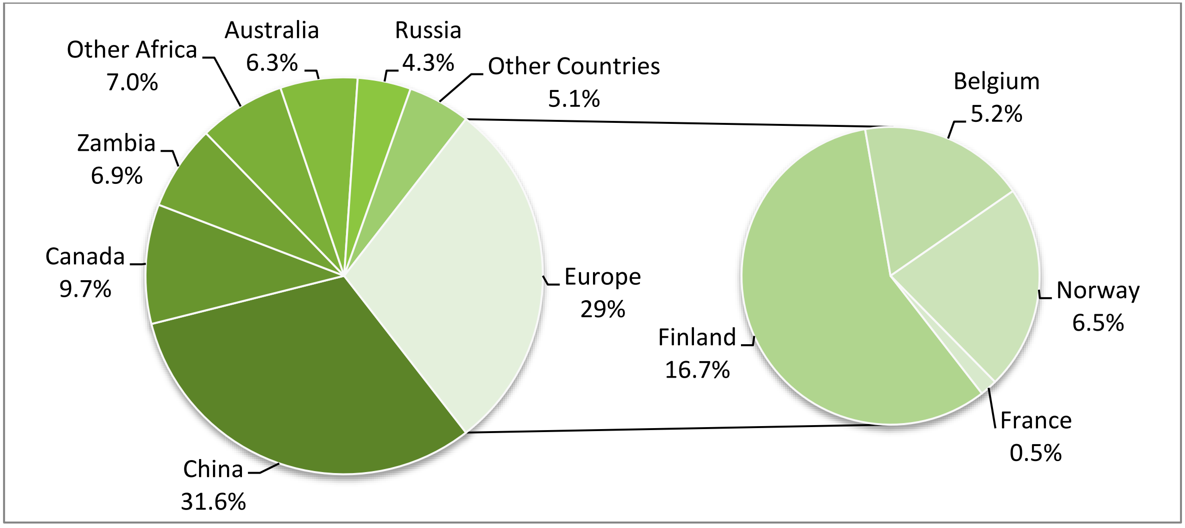
[a] USGS (2010), Mineral Commodity Summaries,

[b] European Commission (2010), Critical raw materials for the EU

[c] USGS (2010), Cobalt 2008 Minerals Yearbook

A different geographic picture however emerges from statistics of cobalt refinery production, Figure 9. Whilst China is the world's largest cobalt refiner accounting for 32% of global cobalt metal production, Europe accounts for 29% of the global total. Major European refiners include Finland, Norway, Belgium and France, with the UK and Poland listed as other known European refiners[a]. Data is available on the major cobalt refining companies. Around 41% of refined production is by members of the Cobalt Development Institute (CDI), with OMG in Finland representing the largest single producing company accounting for around 15% of world supply according to CDI figures[b]. In all 20 separate cobalt refining companies are listed, although it is noted that for the largest refining country, China, no company breakdown is presented. Nevertheless, this data does suggest a relative lack of concentration for cobalt refining.

Figure 9: World Cobalt Refinery Production 2008 (tonnes of cobalt content)



Source: USGS (2010), Cobalt 2008 Minerals Yearbook

1.3.3 Global Demand and Supply, and Price Forecasts Until 2020

Cobalt supply and demand forecasts are given in Figure 10, which shows the cobalt market will remain roughly in balance for the coming decade. The demand forecast comes from CRU and predicts a growth rate of 2.5% per year[c], which lies in between the high and low growth rates modelled by Öko-Institut of 2.8% and 1.7%[d]. The strongest growth in cobalt demand is expected for super alloys and batteries. On the supply side there is a considerable degree of uncertainty over the opening of new mine over the next few years. The USGS list over 80,000 tonnes of potential new mine capacity that is scheduled for completion by 2013[e]. Some of this new capacity will replace existing capacity (output from existing capacity is forecasted to fall by some 15,000 tonnes or 25% between 2009 and 2013 according to one source[f]); however some is unlikely to open or be fully utilised. Nonetheless the existence of this potential mining capacity alleviates scarcity concerns for cobalt even where demand growth is higher than predicted.

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[a] USGS (2010), Cobalt 2008 Minerals Yearbook & BGS (2010), World Mineral Production 2004-2008

[b] CDI (2010), Cobalt Facts: Supply and Demand

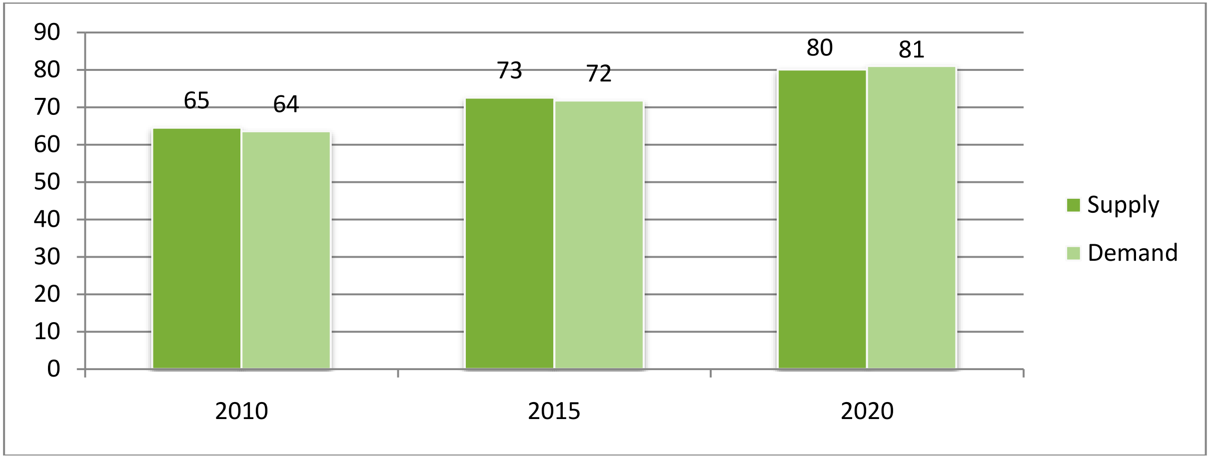
[c] CRU in Hard Assets Investor (2008), Cobalt: More than just blue

[d] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

[e] USGS (2010), Cobalt 2008 Minerals Yearbook

[f] Geovic website: Cobalt Mining & Cobalt Demand, http://www.geovic.net/cobalt_mining.php [accessed 07/01/2011]

Figure 10: Cobalt Supply and Demand Forecasts (kt)



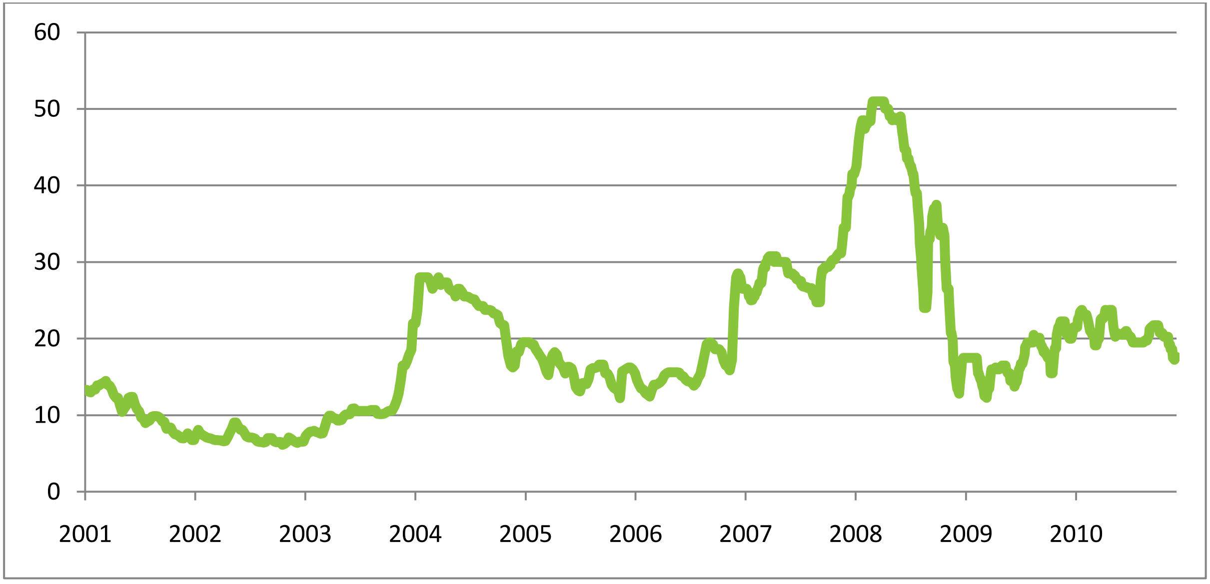
Sources: CRU in Hard Assets Investor (2008), Own Calculations based on Economist Intelligence Unit

With this uncertainty in mind with regards to new cobalt mining capacity the following assumptions have been used for the supply forecast. The approach that has been used has been to investigate the by-product relationships, rather than to attempt to predict which mines will open:

- The production cobalt in 2009 was 62,000 tonnes, of which 50% from Nickel, 35% from Copper & other and 15% from primary cobalt operations[a]
- The supply of by-product sources track the growth rates forecasted by the Economist Intelligence Unit for 2010 and 2011 for Nickel and Copper, reverting thereafter to long run average growth rates (1.8% and 2.2% per year respectively)
- Supply from primary cobalt mines grows at 2% per year.

Prices for cobalt peaked at $50/lb at the beginning of 2008, but for much of the past decade have moved within range between $10/lb and $30/lb. It seems probable that this pattern of prices will continue into the forthcoming decade, although some volatility is likely depending on the timing of the opening of new mine capacity relative to mine closures and the pace of demand growth.

Figure 11: Cobalt Price Developments min 99.8% Purity - aerospace application (US$/lb)



Source: Metal Pages

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[a] CDI website, Cobalt Supply & Demand 2009, http://www.thecdi.com/cobaltfacts.php [accessed 07/01/2011]

1.4 Fluorspar

Fluorspar is the commercial name of the mineral Fluorite (CaF_2). Fluorspar is primarily in demand for its fluorine content; fluorine is the most electronegative and most reactive of the elements and has many uses because of this.[a] Though fluorine itself is toxic and difficult to handle safely, the toxicity of fluorspar is regarded as low because of the relative insolubility of the compound.

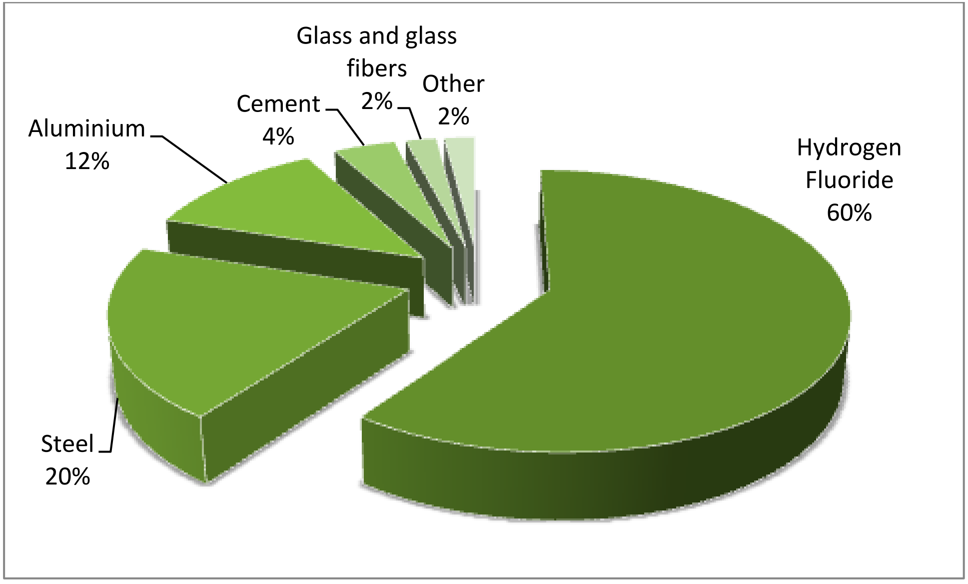
The element fluorine represents an average of 0.06 to 0.09% of the earth's crust. The mineral fluorite may occur as a vein deposit, especially with metallic minerals. It is also a common minor constituent of dolostone and limestone.

Fluorspar ore varies significantly in its physical character and grade. For this reason, it requires blending to realise an optimal feed to the plant. Processing involves crushing, washing and heavy media separation, and finally froths flotation to produce a high purity acid-grade fluorspar (CaF_2) product[b]. The largest identified Fluorspar reserves are in South Africa; however the largest current producer of fluorspar is China.

1.4.1 Key Applications and Potential Future Substitution

Industrially fluorspar has two main uses: as a source of fluorine and as the mineral itself which has useful properties for metal production. A more specific breakdown of this uses is given in Figure 12.

Figure 12: Applications of Fluorspar



Source: Critical raw materials for the EU (2010)

There are three main grades of fluorspar available based on purity: acid grade (>97% CaF_2), ceramic grade and the lowest purity, metallurgical grade. Each of these grades has different uses related to their purity.

Acid-grade fluorspar is a raw material for the fluorochemicals industry where it is used as a source of hydrofluoric acid (HF). HF is a precursor in the synthesis of almost all fluorochemicals, most notably fluorocarbons.[c] These fluorine containing chemicals are used as refrigerants (replacing CFCS), non-stick coatings, medical propellants, anaesthetics, and in the production process of electronics, computer chips, printed circuit boards, and thermal insulation.

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[a] http://mineral.eng.usm.my/web%20halaman%20mineral/FLUORSPAR.pdf

[b] BGS, post 2008

[c] BGS, Mineral Planning Factsheet - Fluorspar, 2010

HF is also required in smaller quantities for the processing of metals, including aluminium, stainless steel and uranium for nuclear fuel. It is used in the process for the refining of crude oil. Other, minor uses of HF include:

- foam blowing - improving insulation properties of plastics
- waterproofed textiles
- insecticides and herbicides
- cleaning products
- glass etching.

One third of the total fluorspar output is consumed as the mineral itself by the aluminium and steel industry (a separate use to the need for HF in these industries). Metallurgical grade fluorspar is used as a fluxing agent to lower the melting point and to increase the fluidity of the slag.

Ceramic grade fluorspar is the least in demand of the three fluorspar grades, and is typically used in the manufacture of specialist glasses, enamels and cookery equipment.

Over the past 25 years fluorspar usage in the steel and glass industry has declined due to product substitutions or changes in industry practices away from the use of this mineral.[a] However, fluorine used in the plastic and electronic industries becomes more and more important. A second rapidly growing market is nitrogen trifluoride (NF_3), which is widely used as a cleaning gas in the manufacture of semi-conductors and LCD screens.

Substitutes

Industrially there are two major sources of HF: fluorspar as described above, and as a by-product from fertilizer production (where small quantities of fluorine are present in the mineral apatite). The second of these sources is the main supply of HF at the present time, therefore a viable source of HF is available for the chemical and other dependent industries. However, it is unclear if the fertiliser industry is or would be able to completely supply the demand for HF if required.

In certain applications replacement of fluorine based chemicals is possible, therefore reducing the demand for HF. For example, fluorochemicals used for cooling purposes might be replaced with hydrocarbon-based refrigerants such as butane and propane. However, this substitution often needs to be balanced against a change in performance such as increased flammability and lower efficiency.[b] In certain circumstances fluorocarbons can be replaced by hydrocarbons in the production of some foamed plastics.

In the steel and aluminium industry fluorspar can be substituted by a variety of other minerals. Alternative fluxing agents have been used, for example, aluminium smelting dross, borax, calcium chloride, iron oxides, manganese ore, silica sand, and titanium dioxide are already used as substitutes for fluorspar fluxes.[c] These may provide suitable larger scale substitutions in the future, and substitution is already occurring.

Recycling

As fluorspar is typically used as a source of fluorine and a precursor to a variety of chemicals, there is little opportunity of directly recycling the mineral. Some recovery from existing processes does occur, but this is mainly due to wastages during processes. In 2009, a few thousand tons of fluorspar was recovered in the United States. The primary sources of this were uranium enrichment as well as petroleum alkylation and stainless steel finishing.[d] However, compared to the total amount used, this is

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[a] USGS, Minerals Yearbook – Fluorspar, 2008

[b] BGS, Mineral Profile: Fluorspar, November 2005

[c] USGS, Mineral Commodity Summaries, 2010

[d] USGS, Mineral Commodity Summaries, 2010

a very low percentage. In the European Union, less than 1% of fluorspar is recycled, and there is believed to be little potential for increasing this rate.[a]

A further possible route to reduce demand is through the recycling or recovery of materials containing fluorine such as fluorocarbons, as this is likely to reduce the overall demand for the precursors such as fluorspar. However, these uses are often dissipative or in decline, and at present no large scale recycling activity of this type is known to occur.

Within the aluminium smelting industry the AlF_3 is recycled to a certain extent by the capture of gaseous HF, which is formed from AlF_3 during processing. HF is then used to produce AlF_3

1.4.2 Current European and Global Output and Reserves

World mine production of Fluorspar was 5.1 million tonnes in 2009 of which China 59% originated in China, Table 5. Mexico was the second most important producing country (18% of world supply). Collectively European producers accounted for 4.3% of world supply in 2008, with Spain, Germany and Romania being producing countries (Figure 13); additionally Bulgaria is believed to produce fluorspar[b]. On fluorspar mining companies, Mexichem (a Mexican multinational chemicals company) appears to be have the greatest market share, with reported mine capacity of over 1m tonnes per year (representing 17% of world production)[c], although it is noted that very little data is available on Chinese companies.

Reserves of fluorspar are geographically dispersed with ‘Other countries’ representing nearly half of estimated reserves. Individual countries with significant reserves include South Africa (18%), Mexico (14%) and China (9%).

Table 5: World Fluorspar Production and Reserves – 2009 (thousand tonnes of fluorspar)

Country	Mine production	Reserves
China	3,000	21,000
Mexico	925	32,000
Mongolia	280	12,000
Russia	210	NA
South Africa	180	41,000
Spain	110	6,000
Namibia	60	3,000
Kenya	45	2,000
Morocco	40	NA
Other countries	250	110,000
World total (rounded)	**5,100**	**230,000**

Source: USGS Mineral Commodity Summaries (2010)

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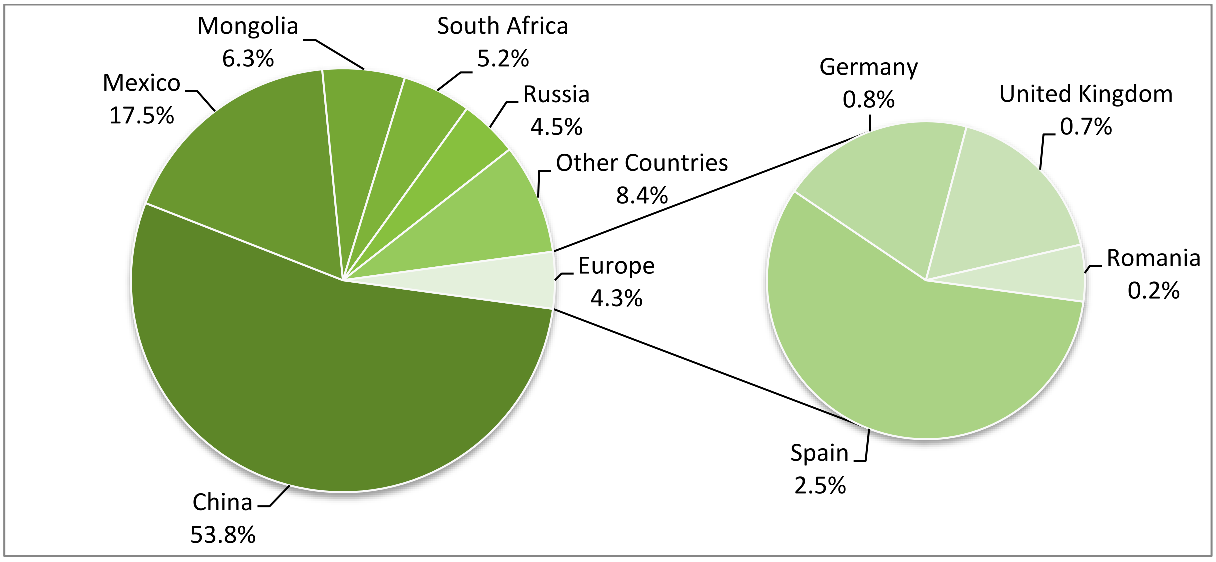
[a] Critical raw materials for the EU. European Commission, 2010

[b] BGS (2010), World Mineral Production 2004-2008

[c] IM (march 2010), Fluorspar Forging Ahead

Figure 13: World Fluorspar Mine Production 2008 (thousand tonnes of fluorspar)



Source: USGS (2010), Fluorspar 2008 Minerals Yearbook

Global Demand and Supply, and Price Forecasts Until 2020

Future supply of Fluorspar is forecasted to be just ahead of demand for the coming decade, resulting in a small surplus for the market, based upon demand forecasts and reasonable assumptions on the addition of fluorspar mining capacity.

The assumptions underlying the forecast are:

- Half of the fluorspar capacity idled between 2008 and 2009 (where there was 16% fall in world supply) and will return into production in 2010.
- On future supply, Roskill (2009) report that proposed mining operations have a total identified potential output of 1.4Mt of which 0.7Mt have acquired significant funding[a]. It is likely that the economic climate will have put back the openings of some of these mines, but it has been assumed that 70% of the capacity comes on stream in 2015, with supply continuing at the rate of growth implied by these opening to 2020.
- For demand, a recovery to 2008 levels is expected to occur only by 2013[b].
- As for longer term growth, it has been forecast that aluminium will consume 2.25Mt acidspar in 2030 (versus 1.2Mt in 2008) and steel making will require 3.45Mt of metspar (versus 1.68Mt in 2008)[c]. These represent annual growth rates of 2.9% and 3.3% respectively, which have been applied to 2014 to 2020. No forecast was found for non-aluminium uses of fluorspar, so the 2.9% growth estimate has been used.

Price developments for Acidspar are shown in Figure 15. Currently prices for Chinese dry basis at US Gulf Ports are around $370 per tonne having risen from $140 per tonne at the start of 2003 and peaked above $500 per tonne in 2008-2009.

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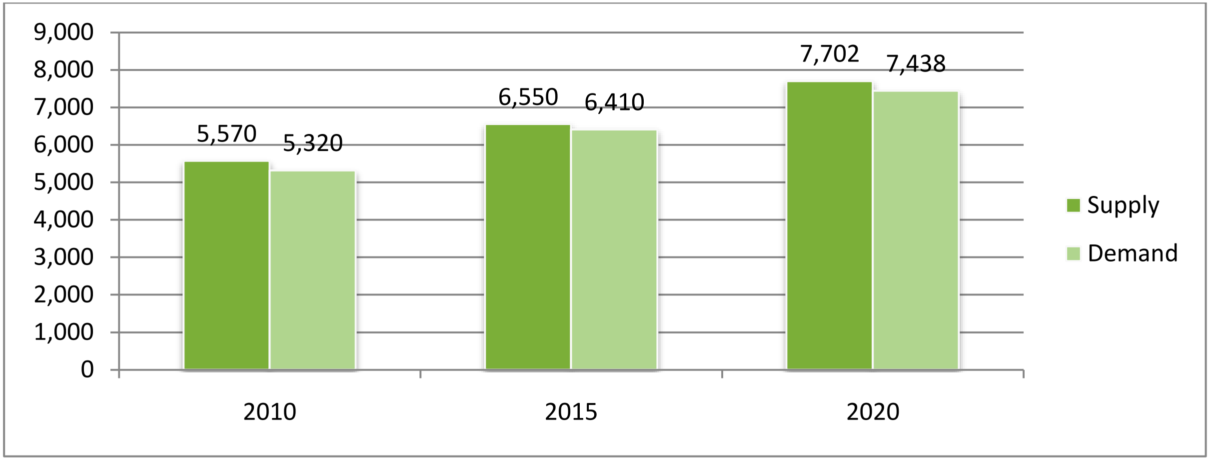
[a] Roskill (2009), The Economics of Fluorspar, 10th Edition

[b] IM (November 2009), Fluorspar post-2009

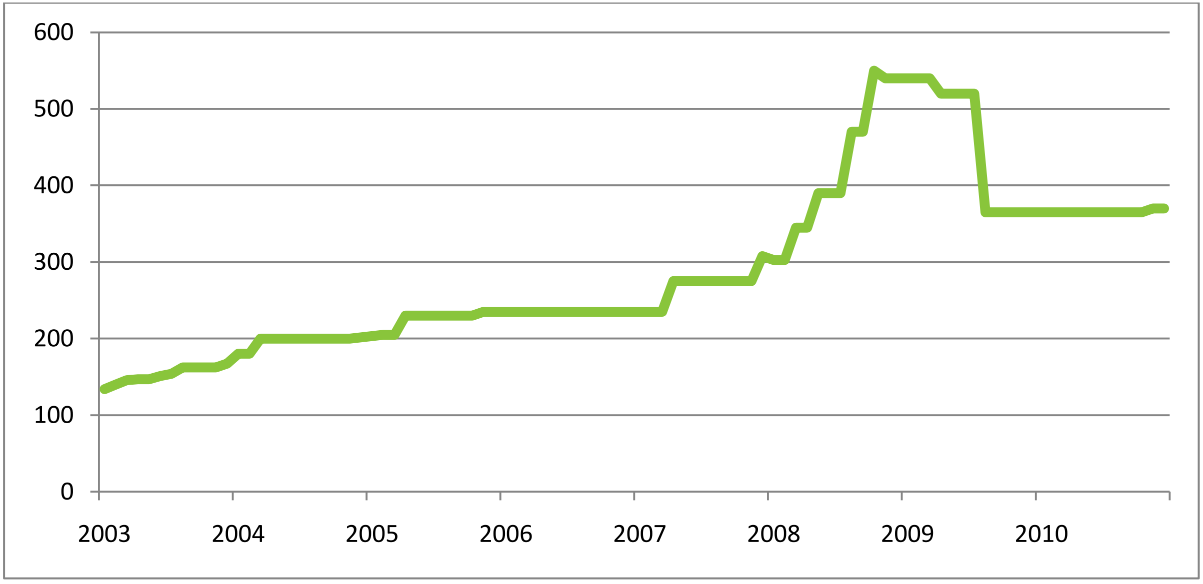
[c] IM (December 2010), Metals fortify fluorspar & IM (March 2010), Fluorspar Forging Ahead

Figure 14: *Fluorspar Supply and Demand Forecasts (kt)*



Source: Oakdene Hollins Calculations

Figure 15: Fluorspar Prices, acidspar filtercake bulk, Chinese dry basis, CIF US Gulf Port ($/tonne)



Source: Industrial Minerals Magazine

1.5 Gallium

The soft silvery metal gallium (Ga) has the longest liquid range of all elements with a melting point slightly above room temperature (29.76˚C) and a boiling point of 2,204˚C[a]. Gallium is chemically similar to aluminium and nearly as dense as iron. It has a low vapour pressure at high temperatures and can easily be supercooled. Even though gallium is a relatively common metallic element it only occurs in trace amounts in bauxite and zinc ore. Its primary use is in semiconductors used in electronic devices.

Overview of Processing Routes
Even though gallium can be found in aluminium and zinc ores and to a very small extent in coal, diaspore and germanite, economic deposits of gallium rarely occur, therefore production is almost entirely as a by-product of alumina production. The concentration of gallium in bauxite ranges between 0.003 and 0.008%[b]. During the production of aluminium, gallium is extracted in an impure form from the crude aluminium hydroxide solution resulting from the Bayer process.[c] The impure gallium is further refined to

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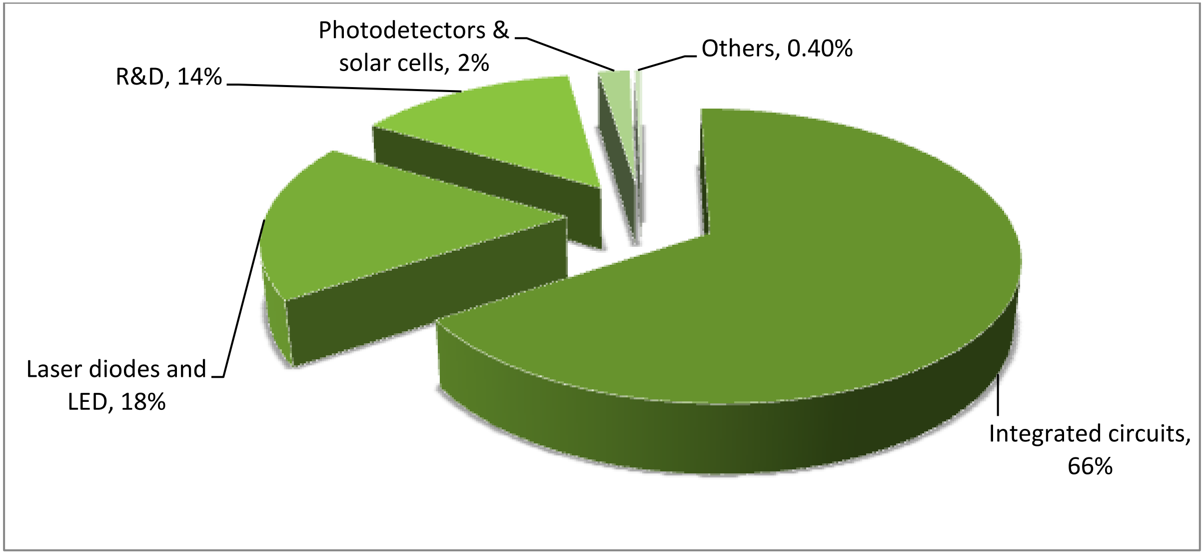
[a] Vulcan T. Gallium: A Slippery Metal. Hard Assets, 2009
[b] Critical raw materials for the EU. European Commission, 2010
[c] Gallium, Minor Metals Trade Association

high purity gallium. The production capacity of gallium is highest in Australia, followed by China and Germany.

1.5.1 Key Applications and Potential Future Substitution

An estimated 196 tonnes of gallium were used in 2009. In terms of products the major use arises in integrated circuits, particularly mobile phones, which consumed two thirds of the overall gallium supply predominantly as gallium arsenide (GaAs), Figure 16. Of the remainder, around 20% is used for optoelectronic devices such as laser diodes and LEDs and 2% in photo detectors and solar cells which again use GaAs based semiconductors. The remaining 15% were mainly used in research and development. Other uses for gallium include high-temperature thermometers, in the production of high-quality mirrors, and in certain dental applications, often as a substitute for mercury.

Figure 16: Applications of Gallium, by value.



Source: Critical raw materials for the EU, 2010

The primary use for gallium across these applications is in semiconductors, with the vast majority consumed in GaAs which is estimated to constitute around 95% of all commercial gallium use.

In the future the demand for integrated circuits in mobile telephones is predicted to remain the primary growth market for the GaAs industry, accounting for 70% of GaAs use until 2012. Additionally the Wi-Fi market is expected to grow by 20% *per annum* until 2010, representing GaAs second largest use[a].

Alternative types of gallium based semi conductor, particularly gallium nitride (GaN), are also expected to become more important in future applications such as blue, green and white high-brightness LEDs. The market for blue-violet laser GaN diodes for high-density optical storage is also expected to grow rapidly over the next years.[b] Overall the GaN market is expected to grow at a rapid rate, with some predictions estimating growth rates of 98% *per annum* from 2009 to 2012. At present 55% of GaN is used for military and defence applications; GaN's primary existing commercial application will be the wireless infrastructure market (in addition to GaAs).[c]

The previously growing LED market is still very strong but has recently seen changes. Existing LED market segments including automotive lighting, mobile phones, and outdoor video screens has seen a decline. By comparison, emerging LED market segments, such as backlights for liquid crystal displays in televisions

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[a] USGS, Minerals Yearbook – Gallium, 2008

[b] The Mineral Journal, Gallium, 2005

[c] USGS, Minerals Yearbook – Gallium, 2008

and notebook computers, are still showing growth.[a] However, in the future the demand for gallium from the LED sector is expected to be surpassed by growing demand from the CIGS industry (thin-film solar cells based on copper indium gallium selenide) as the solar power generation increases.[b]

Substitutes

Substitutes are available or are being developed for gallium in a number of applications, however the complete replacement of GaAs in all semiconductor applications looks unlikely at present. For example, GaAs-based integrated circuits are used in many defence-related applications because of their unique properties, and there are no effective substitutes for GaAs in these applications. Replacement by different materials is possible is certain cases, however this typically relies on another scarce material such as the germanium based materials in certain mobile phone applications and indium compounds as an alternative to GaAs based infrared laser diodes.

Liquid crystals made from organic compounds are used in visual displays as substitutes for LEDs. Researchers also are working to develop organic-based LEDs that may compete with GaAs in the future, and are beginning to be seen on the market on a larger scale.

Recycling

Significant amounts of gallium are being recycled, however this is almost entirely from new gallium arsenide scrap (produced both in wafer manufacturing and from old electronics). This accounts for up to half the gallium supply into the world market.[c] According to the Mineral Journal only 15% of GaAs is actually used during electronics manufacture and the remaining 85% can be recycled. The USGS estimates that 78 tonness of gallium are recycled form new scrap each year; this processing is dominated by Germany, Japan, the UK and the US.

However, at present gallium is not recycled from old scrap, partly because of the small quantities available in existing waste streams.[d] According to a recent industry presentation on gallium the recycling quantities of gallium are difficult to implement due to the value of gallium and the toxicity of arsenide, and as processes have already been optimized.[e] However, there are indications that it will be necessary to retain and recycle gallium containing scrap in the future on an EU level, if future demands are to be met.

Current European and Global Output and Reserves

Estimating the world production and reserves of gallium is very difficult because it is produced as a by-product of treating bauxite, an aluminium ore, and to a lesser extent from zinc-processing residues. There is considerable primary production capacity for gallium available globally, with China, Germany, Kazakhstan, Japan and Russia having the largest capacities, Table 6. The respective companies are Aluminium Corporation of China, Recapture Metals/Mining & Chemical Products (Germany) and Dowa Holdings (Japan)[f].

Additionally, a significant proportion of supply arises from new scrap, with global capacity being estimated at 78 tonnes annually by the USGS[g]. Actual production however is estimated to be considerably lower. Total output is estimated at 194t for 2009, which includes 74t from recycling processes[h]. Details per country are not available, but China is considered to be the largest supplier of virgin material, accounting for about half of global output, with Japan and the US being other important

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[a] USGS, Mineral Commodity Summaries, 2010

[b] Strategic Metal Report, Gallium Market Report, August 2010

[c] Tom Vulcan, Gallium: A Slippery Metal, Hard assets, January 2009

[d] Critical raw materials for the EU. European Commission, 2010

[e] Tom Vulcan, Gallium: A Slippery Metal, Hard assets, January 2009

[f] Tom Vulcan, Gallium: A Slippery Metal, Hard assets, January 2009

g U.S. Geological Survey, Mineral Commodity Summaries, 2010

h Indium Corporation, Presentation Indium, Gallium & Germanium, Supply and Outlook producers. Concerning Europe, the BGR reported that in 2006 Germany, Hungary and Slovakia refined from bauxite 12, 5.5, and 0.5 tonnes of gallium respectively.

Table 6: World Primary Gallium Production Capacity – 2008 (tonnes of gallium content)

Country	Production Capacity
China	59
Germany	35
Kazakhstan	25
Japan	20
Russia	19
Ukraine	10
Hungary	8
Slovakia	8
Total	184

Source: USGS Mineral Yearbook, Gallium

The USGS estimates gallium's world resources in bauxite alone to be 1 billion kilograms. However, only parts of the very large global bauxite reserves are going to be mined over the next decades, so the gallium content of much of the bauxite reserves cannot be treated as recoverable in the near term[a]. In Table 7, we nonetheless provide an estimate of European gallium reserves based on European bauxite reserves. They were calculated by assuming an average content of 50ppm of gallium in bauxite and an average recovery rate of 40%.

Table 7: European Gallium Reserves Based on Identified European Bauxite Deposits

Country	European Bauxite Reserves (kmt)	European Gallium Reserves (Mt)
Greece	600,000	12,000
Hungary	300,000	6,000
Turkey	80,000	1,600
Romania	50,000	1,000
France	30,000	600
Italy	5,000	100
Spain	5,000	100

USGS 2010 – (Based on a conversation with Mr. Bray, bauxite expert at USGS)

Global Demand and Supply, and Price Forecasts Until 2020

Gallium supply and demand forecasts are given in Figure 17. Gallium is forecast to move from a small supply surplus indicated in 2010 to a significant deficit in 2015 representing 13% of supply due to strong growth in solar photo-voltaics before returning to a balance. The demand forecast comes from Umicore[b]; although it is noted that it does not materially differ from the 10% per year growth rate, as modelled by Öko-Institut[c].

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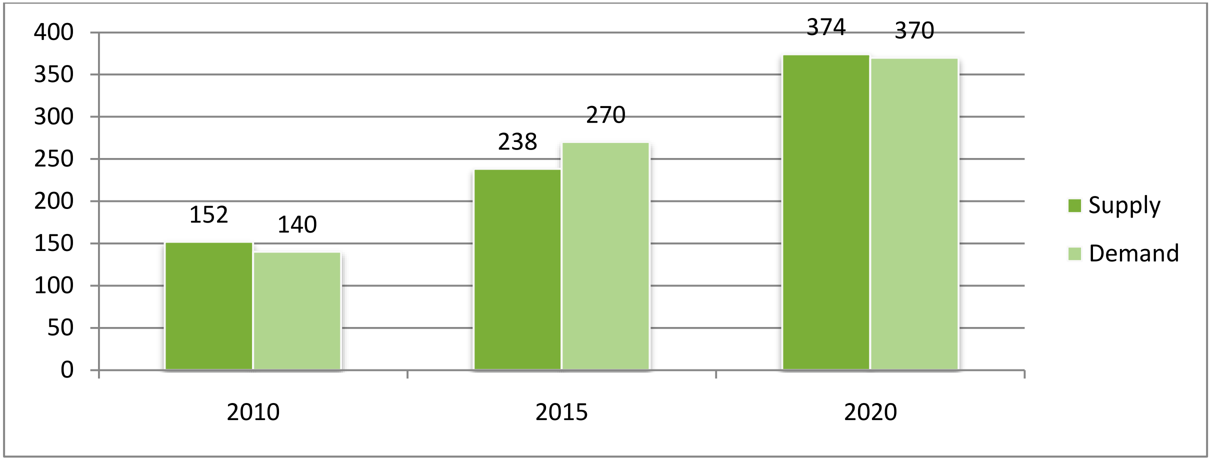
[a] U.S. Geological Survey, Mineral Commodity Summaries, 2010

[b] Umicore (2010) in EC (2010), Annex V to the Report of the Ad-hoc Working Group on defining critical raw materials

[c] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

Figure 17: Gallium Supply and Demand Forecasts (t)



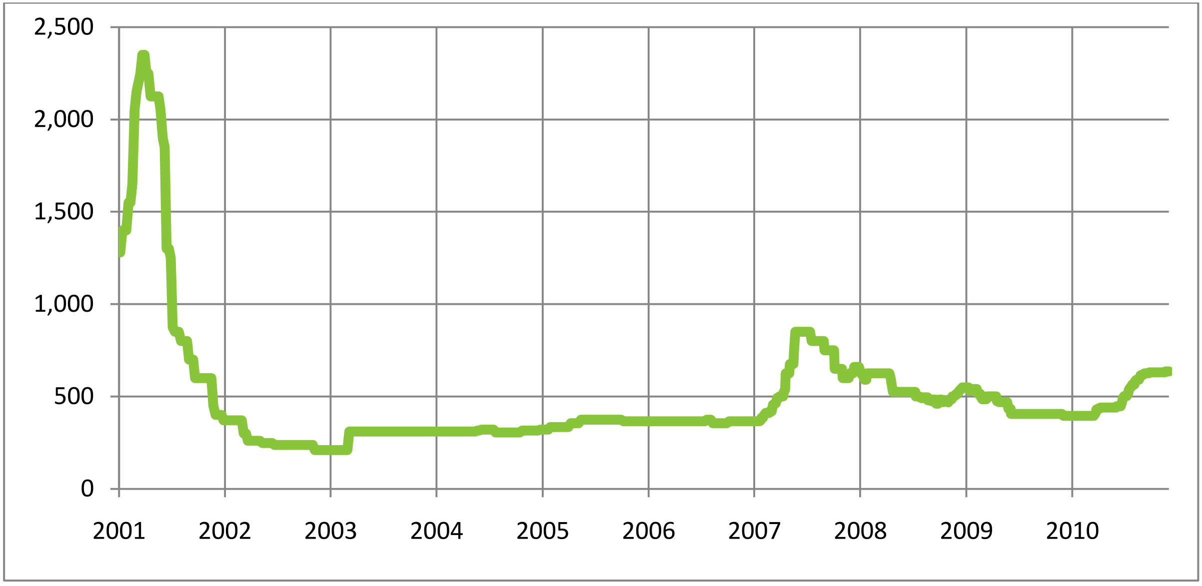
Sources: Umicore; Own Calculations based on USGS, Öko-Institut, US Dept of Energy

The assumptions underlying the supply forecast are:

- Primary gallium production of 111t in 2008 and 78t in 2009, with secondary gallium production of 40 tonnes (both years).
- Gallium refining increases at a rate of 9% in year in response to increases in demand (as calculated by the US Dept of Energy[a].

Prices for gallium peaked at over US$2,000 per kg in 2001 and have subsequently remained below US$1,000 per kg in the intervening period, Figure 18. Given sharply increasing demand, upward pressure on prices is to be expected over the coming years and might induce additional capacity to come on stream.

Figure 18: Gallium Metal Prices, CIF Main Airport, 99.99% Purity (US$/kg)



Source: Metal Pages

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[a] US Dept. of Energy (2010), Critical Materials Strategy

1.6 Germanium

Germanium (Ge) is a gray-white, lustrous, hard, crystalline and brittle metal. It is a semiconductor, and unusually expands as it solidifies like water.

Germanium's abundance in the earth's crust is 1.5 ppm. The main ore in which germanium is found is germanite. However, germanite is only a minor source of germanium in existing production, as germanium is mainly derived from the processing of the zinc sulfide mineral sphalerite.

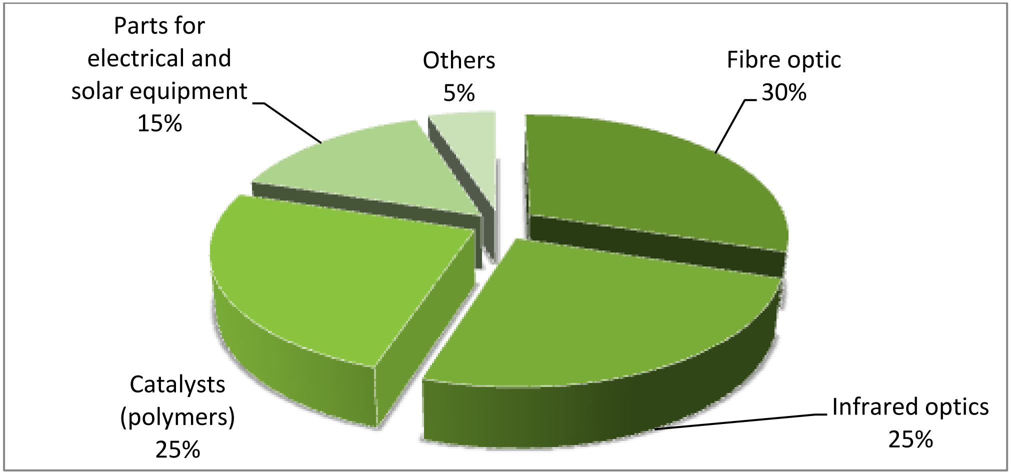
In the latter extraction process, zinc concentrates are treated in roasters or pressure-leach facilities to extract germanium and other by-products. Zinc sulphide is roasted and the resulting germanites are leached together with the zinc using sulphuric acid. After neutralization only the zinc stays in solution, the precipitate contains the germanium and other metals. Like gallium, germanium is also extracted from fly-ash.

China is the largest producer of Germanium, and a relatively high percentage of global demand is met by recycled germanium.

1.6.1 Key Applications and Potential Future Substitution

Germanium has a key role many hi-tech applications, Figure 19, and its use has grown in the recent future with an estimated 140 tonnes produced in 2009. Germanium has three major uses which currently have similar economic value; fibre optics, infrared optics and catalysts for polymer production.

Figure 19: Applications of Germanium, based on value



Source: Critical raw materials for the EU, 2010

The largest use of germanium is in optical materials which consist of fibre optic accounting for 30% of value, and infrared optics accounting for 25% of value. Germanium dioxide is used extensively as an additive (usually < 4% by weight) to the silicon dioxide in the core of optical fibres.[a]

The second major category of use is as a catalyst in the industrial production of polymers (mainly Polyethylene terephthalate) in the form of germanium dioxide. This use accounts for about 25% of the world germanium consumption.

Electrical and solar applications represent a smaller use of germanium, where it is used for in semiconductors (silicon-germanium), and in modern solar panels. These uses represent fast growing end-use markets, shifting from high end applications such as use in space to more commercial uses such

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[a] Tom Vulcan, Germanium: Winkler's Metal, Hard assets, March 2009

as mobile phones. This also represents a shift back to germanium based semiconductors, which were historically a large market for germanium but declined as they were almost entirely replaced by cheaper silicon semiconductors. Changing priorities mean that germanium is once again in consideration, as germanium containing chips provide the opportunity to miniaturize electronics products.

The military demand for germanium is especially high where the metal is used in various infrared applications such as lenses and window blanks as well as thermal imaging technology. Commercially, germanium is also used in high-brightness, light-emitting diodes for backlighting liquid crystal display screens and in vehicle headlights and to a very small amount in jewellery in a tarnish resistant silver alloy known as argentium.

Other future growth markets include the automotive industry as it is predicated adopt technologies such as infra-red based security and surveillance equipment.

Substitutes

As mentioned above, less expensive silicon has replaced germanium in transistors and might do so in other electronic applications in the future. However, there has recently been a shift back to the use of germanium, albeit in materials with silicon, as this allow the miniaturization of electronics. Some metallic compounds that contain gallium, indium, selenium, and tellurium can be substituted for germanium. However, germanium is more reliable than these materials in many high-frequency electronics applications and is a more economical substrate for some light-emitting-diode applications. In addition, there are also issues around the supply of these alternative materials which may limit their use in the future.

In other uses, zinc selenide has been used as substitute in infrared applications, but this also results in a loss in performance therefore it is often not optimal. In the case of polymerisation catalysts antimony and titanium based alternatives are already in use.

Recycling

About 30% of the total germanium consumed worldwide is produced from recycled new scrap materials. During the manufacture of most optical devices, more than 60% of the germanium metal used is routinely recycled as new scrap.[a] Pre-consumer recycling of solar cells, fibre optics and infrared devices is likely to increase due to increasing production.

Only very small amounts of germanium are being recovered from post-consumer goods. Most germanium products and devices contain very small amounts of the metal which is often finely dispersed, therefore it is technical and economical difficult and complex to recover secondary germanium from this type of scrap. Recycling rates of old scrap might increase though due to the implementation of the EU Directives on Waste Electrical and Electronic Equipment (WEEE). By contract no germanium is recovered from polymers at present.

Current European and Global Output and Reserves

World production of germanium was 140 tonnes in 2009 of which 71% originated in China, Table 8. There are six major chinese germanium producers, with a collective annual capacity of 115 tonnes. The largest two companies are Yunnan Lincang Xinyuan Germanium Industrial and Nanjing Germanium Factory (both 30 tonnes of capacity)[b].

Other significant producing countries are Russia and United States. Known European producers are France, Germany, Italy, Spain and the UK[c]. Reserve estimates are available only for the United States (450 tonnes), although Chinese reserve base is estimated at 3,055 tonnes[d].

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[a] USGS, Mineral Commodity Summaries, 2010

[b] Tom Vulcan, Germanium: Winkler's Metal, Hard assets, March 2009

[c] BGS (2010), World Mineral Production 2004-2008 & USGS (2010), Germanium 2008 Minerals Yearbook

[d] Tom Vulcan, Germanium: Winkler's Metal, Hard assets, March 2009

Table 8: World Germanium Production and Reserves – 2009 (tonnes of germanium content)

Country	Refinery production	Reserves
China	100	NA
Russia	5	NA
United States	4.6	450
Other countries	30	NA
World total (rounded)	**140**	**NA**

Source: USGS Mineral Commodity Summaries (2010)

Global Demand and Supply, and Price Forecasts Until 2020

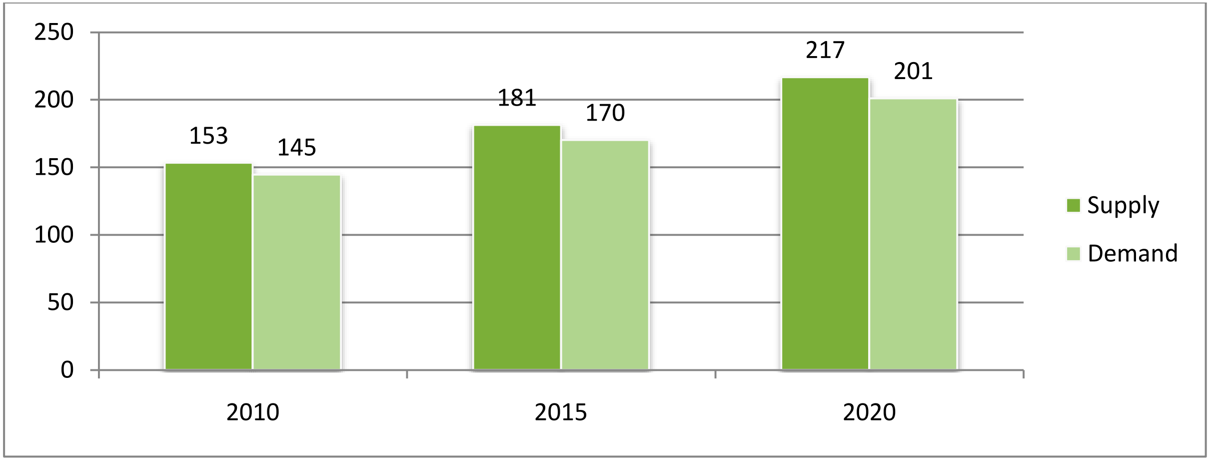
Germanium supply and demand forecasts are given in Figure 20. The small market surplus in 2010 is forecasted to widen somewhat over the period to around 20% of world supply. This is because the growth rate in supply of zinc, the main metal from which germanium is extracted from, exceeds the overall growth rate in demand.

The assumptions underlying the forecast are:

- Market for Germanium is in balance in 2009 at 140t[a]
- Germanium supply growth matches zinc supply growth as forecasted by Economist Intelligence Unit and tracking the long run trend for zinc thereafter (3.6% per year)
- Demand growth for fibre optic markets increases at 4.4% per year[b] and at 1.9% for year for other applications as modelled by Öko-Institut[c].

Prices for Germanium dioxide peaked at around US$1,000 per kg during 2008 before falling back below $600 per kg thereafter. Given the surpluses forecasted, germanium prices may remain relatively weak over the coming decade.

Figure 20: Germanium Supply and Demand Forecasts (t)



Sources: Own Calculations based on Economist Intelligence Unit, USGS, Öko-Institut, Global Industry Analysts

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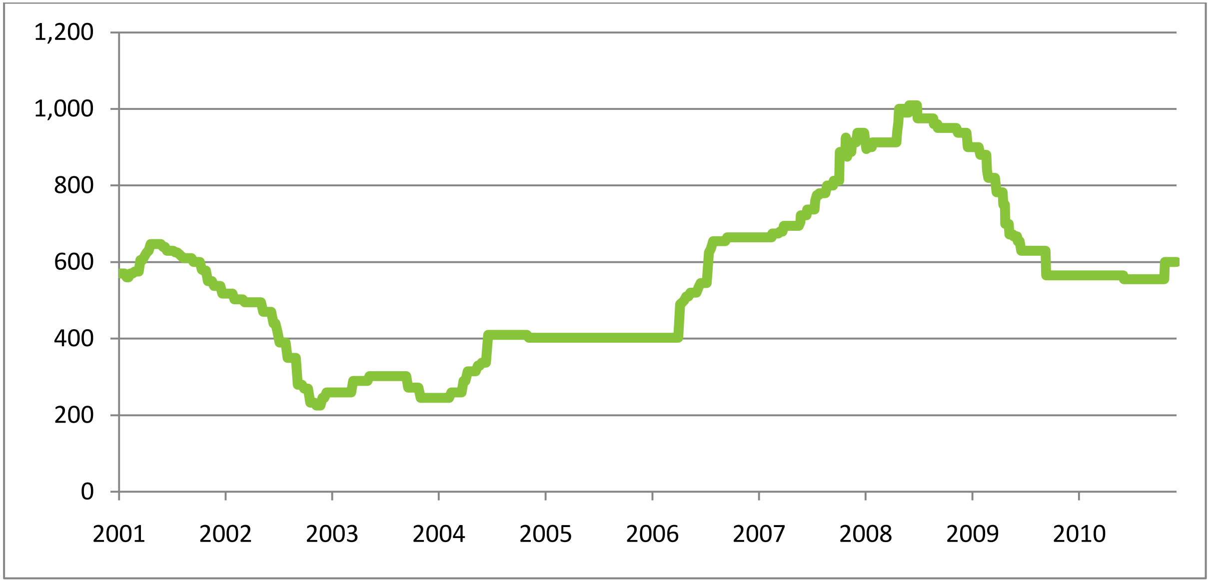
[a] Öko-Institut reported demand levels of 120-130t in 2006-2008, which moderately outstripped supply at the time

[b] Global Industry Analysts (2008), http://www.prweb.com/releases/germanium_zinc/infrared_optics/prweb869094.htm#

[c] Öko-Institut reported demand levels of 120-130t in 2006-2008, which moderately outstripped supply at the time

Figure 21: Germanium dioxide, min 99.99% Purity (US$/kg)



Source: Metal Pages

1.7 Graphite

Graphite (C) is a black, soft, flexible but not elastic, allotrope of the element carbon and has properties of both metals and non-metals. Graphite is the most electrically and thermally conductive of the non-metals and is also chemically inert[a]. Other properties include high thermal resistance and lubricity[b]. Pure carbon has very low toxicity, however inhalation of large quantities of carbon black dust can cause irritation and damage to the lungs.

Beneficiation processes (i.e. extraction of the pure mineral) for graphite may vary from a complex four-stage flotation to simple hand sorting and screening of high-grade ore[c], depending on the ore it is extracted from. For example, some soft graphite ores need no primary crushing and grinding, others types of ore do. In general, the ore undergoes desliming and is subjected to a rough flotation to produce 60% to 70% carbon concentrate. This concentrate is ground and through flotation a concentration of 85% carbon reached. It is then screened to produce a variety of products that contain 75% to 90% carbon. Graphite can also be produced synthetically.

Graphite is found in almost every country and is relatively common. Large producers of natural graphite are China India Brazil, North Korea, and Canada[d]

1.7.1 Key Applications and Potential Future Substitution

The majority of graphite used is found naturally, however modern technologies have produced graphite synthetically from oil based feedstocks. Natural graphite exists in three varieties: vein graphite (1% market share), flake graphite (38% market share) and microcrystalline or amorphous graphite (61 % market share). For industrial purposes flake graphite is the most prized, due to the large volumes required in the metallurgical industry.

Figure 22 shows the major applications of graphite by value. Natural graphite is mostly consumed in refractory applications mainly in steel production in the form of graphite electrodes to raise the carbon

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[a] USGS (2008), Minerals Yearbook

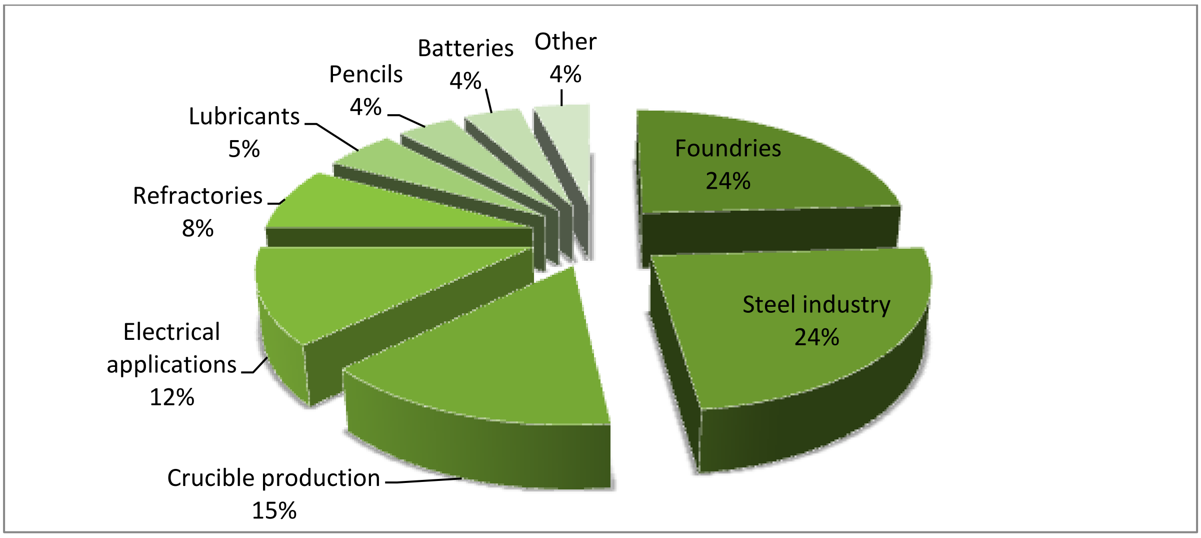
[b] European Commission (2010), Critical raw materials for the EU

[c] USGS (2007) Minerals Yearbook

[d] USGS (2008), Minerals Yearbook

content of molten steel (32%), foundry facings (24%) and crucible production (15%). Together, these three applications account for 802,300 tonnes of world graphite use.

Figure 22: Applications of Graphite by value



Source: Critical raw materials for the EU (2010)

Further uses are in electrical applications such as electrical arc lamp electrodes, dry lubricants, pencils, coatings and brake linings for heavier (non-automotive) vehicles.

The demand of graphite for use in batteries is rapidly increasing, partly due to the increased availability of high-purity, high-carbon grades of graphite, and partly because of increased demand for lithium-ion batteries, which use graphite in the anode. Graphite demand for this use is expected to increase in the hybrid and electric vehicles industry; in the long term using high-purity graphite in fuel cell and battery applications could consume as much graphite as the whole market does today.[a]

Expanded graphite is used as a sealing material, for example, as fire stops fitted around a fire door; this is now one of the fastest growing end-use sectors for flake graphite.[b.] Graphite foil, made from expanded graphite, is made into heat sinks for laptop computers keeping them cool while saving weight. Laminated foil can also be used in valve packing or made into gaskets.

Future uses for graphite are predicted in heat storage in solar systems, building climatisation and high purity powders in nuclear reactors.

Substitutes

The production of synthetic graphite is already carried out on a large scale, particularly in the US where it is conducted on the multi thousand tonne scale, and forms the majority of the US's market.[c] The graphite produced by this processing is suitable for most uses, including high purity anodes. However, this process relies on supplies of petroleum tar from crude oil based feedstock, and requires large amounts of energy, therefore it may become a less appealing route in the future for large scale production.

According to the USGS mineral survey manufactured graphite powder, scrap from discarded machined shapes, and calcined petroleum coke can be used in iron and steel production. Finely ground coke with olivine is a potential competitor in foundry facing applications. Molybdenum disulfide competes as a dry lubricant but is more sensitive to oxidizing conditions. Graphite refractory products are used in all

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[a] USGS, Mineral Commodity Summaries, 2010

[b] Roskill, The Economics of Natural Graphite, 2009

[c] USGS, Minerals Yearbook, 2008

industrial high-temperature processes in the basic industries, and substitution with other materials if difficult at this time.

Recycling

At present the recycling of graphite occurs on a small scale, but is feasible from a practical standpoint, particularly for the recovery of high-quality flake graphite from steelmaking. Information on the quantity and value of recycled graphite is not available.[a] It is also believed that the relative abundance of graphite available on the world market inhibits large scale implementation of recycling.

Despite these factors, the market for recycled refractory graphite material is growing with material being recycled into products such as brake linings and thermal insulation.[b] Within the metal production industry, graphite-containing refractories are recycled on occasion, but not due to their graphite content. High volume items, such as carbon-magnesite bricks, contain only 15–25% graphite, which is generally too little graphite for viable recycling. However, recycled carbon-magnesite bricks can be used as the basis for furnace repair materials, or may also be crushed to be used in slag conditioners. Crucibles have high graphite content therefore recycling is more attractive, however the volume of crucibles used and then recycled is very small.

1.7.2 Current European and Global Output and Reserves

World graphite production is estimated at 1.13 million tonnes by the USGS of which 71% originates in China, Table 9. Other significant graphite producing countries are India and Brazil. (It is worth noting that the BGS estimated 2008 world production at 2.1 million tonnes, with the estimate for Chinese production put at 1.8 million tonnes[c]). European production of graphite is very limited at approximately 0.5% of world supply (Czech Republic, Norway and Sweden). China also dominates the reserves for graphite, although it is noted that proven reserves of 5 million tonnes exist in Europe[d].

In terms of the graphite producing companies, the top 12 producers account for around 50% of world supply (total capacity of around 598,000 tonnes per year). The largest of these in terms of annual capacity are Jixi Liumao Graphite Resource at 80,000-90,000t, Heilongjiang Aoyu Graphite at 80,000t, Chenzhou Luteng Crystalline Graphite at 70,000t (all China) and Nacional de Grafite at 70,000t (Brazil)[e]. Supplies of synthetic graphite are significant and do compete with natural sources, with US production estimated at 196,000 tonnes in 2008[f].

Table 9: World Natural Graphite Production and Reserves 2009 (thousand tonnes of graphite)

Country	Mine production	Reserves
China	800	55,000
India	140	5,200
Brazil	77	360
Mexico	10	3,100
Other countries	100	7,340
World total (rounded)	**1,130**	**71,000**

Source: USGS Mineral Commodity Summaries (2010)

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[a] Critical raw materials for the EU. European Commission, 2010

[b] USGS, Mineral Commodity Summaries, 2010

[c] BGS (2010), World Mineral Production 2004-2008

[d] EU (2010), Annex V to the Report of the Ad-hoc Working Group on defining critical raw materials

[e] Roskill (2009) in IM (July 2010), The Bright Side of Graphite

[f] USGS, Minerals Yearbook, 2008

Global Demand and Supply, and Price Forecasts Until 2020

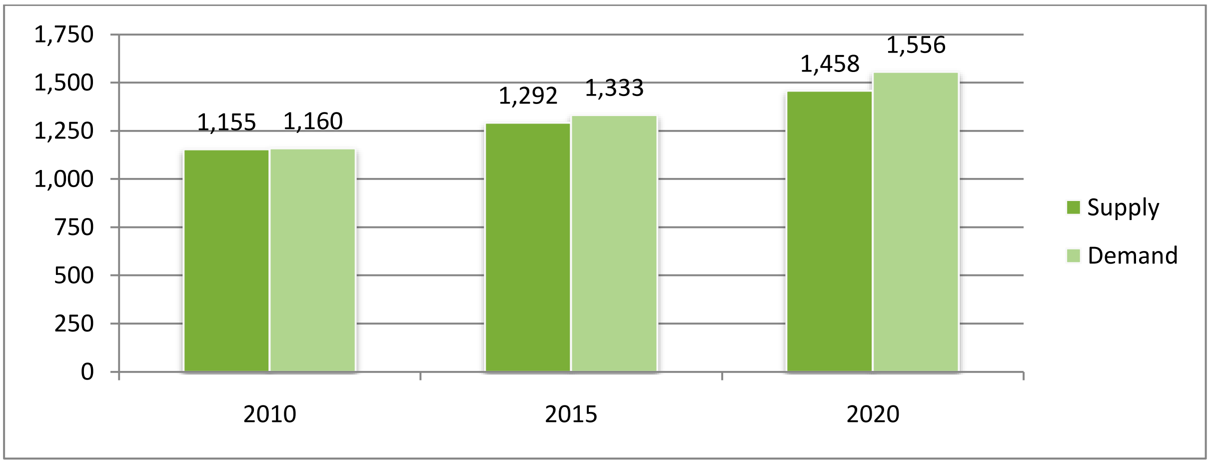
Supply and demand forecasts for natural graphite indicate that the market may move from being broadly in balance to having a significant and widening deficit by the end of the next decade (Figure 23). This is because strong growth has been forecast for graphite usage in Li-ion batteries, at 12.6% per annum; albeit from a low base[a]. It is noted that the 1Mt of graphite per year for batteries remains controversial within the industry as this estimate appears to be based on optimistic uptake scenarios for electric vehicles, low material efficiency in processing and a reliance on natural rather than synthetic graphite for this purpose.

The assumptions underlying the forecasts are:

- Supply from Chinese production grows slowly at the 1.6% per year that has been exhibited since 2001[b]. This slow growth reflects government measures to control mine production.
- Roskill report that increasing demand has encouraged potential developments outside of China that could add 70,000 tonnes per year to supply[c]. These are assumed to come on stream in 2015 and the rate of growth in rest of the world supply implied by their opening has been applied to 2020.
- For the demand for steel related applications (foundries, refractories etc.) a rate of growth of 2% per year has been assumed on the basis that demand is unlikely to track steel production due to a declining amount of graphite used per tonne of production.
- Demand from batteries has been forecasted at 1Mt per year in 2035, or growth of 12.6% per year[d]
- A demand growth of 3% per year has been assumed for other applications (pencils, lubricants, electrical)

Price developments for natural graphite are shown in Figure 24. This shows a rising trend in prices from $600 per tonne in 2003 to 2005, to present highs of $1,600 per tonne (Figure 24). Further prices rises are possible if the graphite usage in batteries does fulfil the high rates of growth anticipated by some. There will of course be limits to the price rises because of the competition from synthetic sources.

Figure 23: Natural Graphite Supply and Demand Forecasts (kt)



Source: Oakdene Hollins Calculations based on Roskill (2009) & IM Magazine

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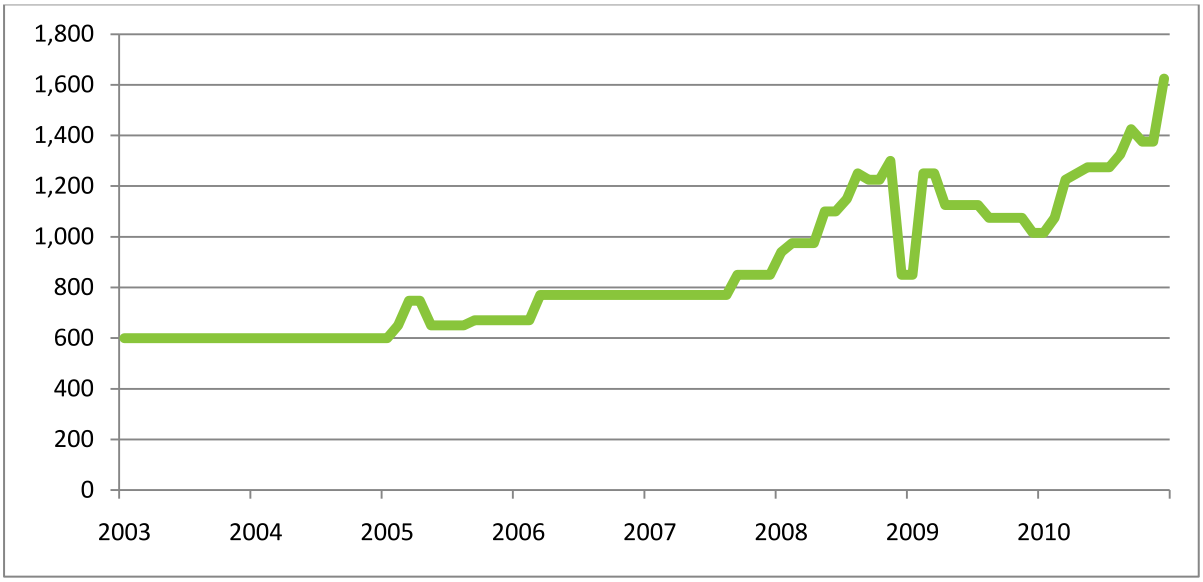
[a] IM (February 2010), Concern over battery grade graphite supplies

[b] Roskill (2009), The Economics of Natural Graphite, 7th Edition

[c] Roskill (2009), The Economics of Natural Graphite, 7th Edition

[d] IM (February 2010), Concern over battery grade graphite supplies

Figure 24: Graphite Prices, crystalline medium flake, 94-97% C, +100 mesh-80 mesh, FCL, CIF European Port ($/tonne)



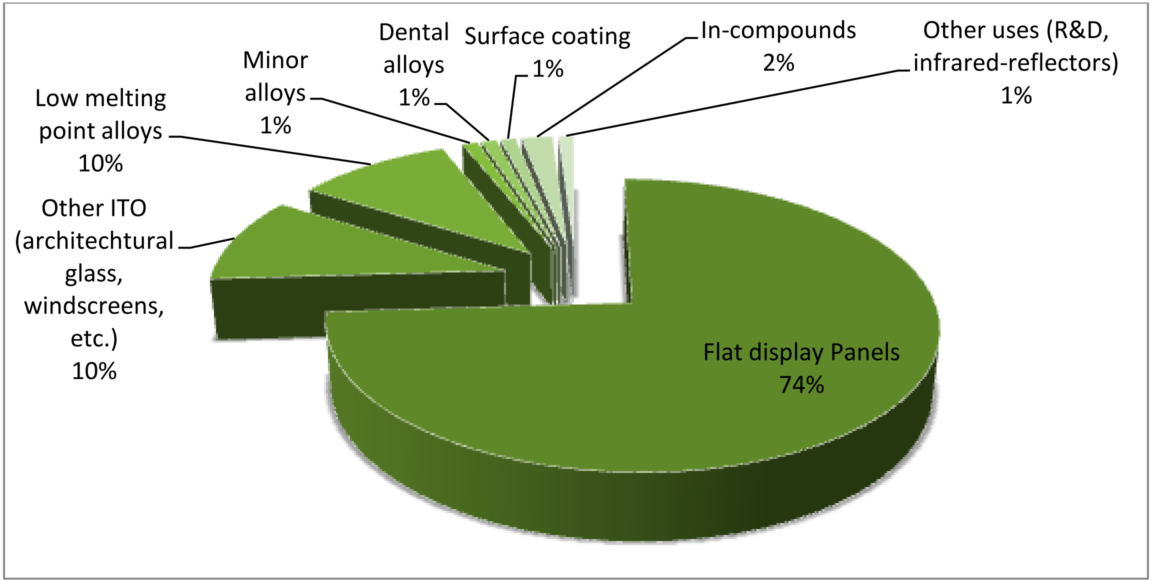
Source: IM Magazine

1.8 Indium

Indium (In) is a very soft metal with a shiny silver colour; its main contemporary use is in flat displays in an optically transparent, conducting layer. Indium's abundance in the continental crust is about three times greater than silver or mercury[a], however no significant deposits are known which contain high concentrations of indium ores. Instead indium is recovered as a by-product of the production of other metals, most commonly the refining of zinc ores. Indium is obtained through processing slag and zinc dust waste, then further purified by electrolysis.

1.8.1 Key Applications and Potential Future Substitution

Figure 25: Applications of Indium



Source: Critical raw materials for the EU. European Commission (2010)

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[a] USGS, Mineral Commodity Summaries, 2004

Indiums primary use is in indium-tin-oxide (ITO), which typically comprises of 90% indium oxide and 10% tin oxide by weight. When ITO is deposited as a thin film onto either clear glass or plastic, it becomes a transparent electrical conductor. These ITO thin-film coatings are primarily used in flat-panel displays and, in particular, liquid crystal displays (LCD) used in TVs, mobile phones, notebooks, computers and other electronic devices. These uses consume over 50% of the world virgin output of indium and about 80% of the total availability including reclaimed indium.[a] ITO is also used in touch screen cathode ray tubes and applied to car and aircraft windshields where it is used as a de-icing and de-misting material. The remaining 16% are used in various purposes, including:

Solders	Temperature sensors	Laser diodes
Sodium vapour lamps	Dental alloys	Surface coating of bearings
Nuclear control rods	Corrosion-inhibitors	Bonding materials

The market for LCD applications is still dominating indium use and is expected to grow by 24% between 2007 and 2012, according to the Öko-Institut. ITO demand is also driven through the tendency towards bigger screen sizes which causes the need for more ITO per unit.

CIGS (copper indium gallium selenide) thin-film solar cells are a relatively new application with strong growth potential. Indium consumption in this area is expected to increase to 300 tonnes per year by 2013 (currently 30-35 tonnes per year).[b] The demand for Indium used in InGaN-applications (indium-gallium-nitrite), used for white LEDs and Blue-ray discs, is expected to increase by a factor of eight until 2030.[c]

Recycling

Indium is most commonly recovered from ITO. 'Sputtering', the process of putting ITO as a thin-film coating onto glass panels, is highly inefficient. Less than 30% of the material from the target is deposited onto the glass, and estimates place this figure as low as 15%.[d] The unused material consists of the spent ITO target material, the grinding sludge, and the after-processing residue left on the walls of the sputtering chamber.[e] However, according to the Indium Corporation, the indium supply has been bolstered by continued improvement in recycling programs. In the rapidly growing LCD market, greater than 85% of non-deposited indium is reclaimed and returned to the supply chain.[f] The ITO recycling loop - from collection of scrap to production of secondary materials - now takes less than 30 days with most of the ITO recycling taking place in China, Japan, and the Republic of Korea - the same countries where ITO production and sputtering take place.[g]

Indium recycling from old scrap is only partly installed and initiated. The EU report on critical materials indicates that less than 1% of indium is recycled from old scrap, mainly from indium tin oxide (ITO) products such as scrap LCD panels.[h] The reason for low recycling rates is the lack of focused collection and reconditioning of indium-containing products and the dissipative use of indium in EEE and solar cells. From a technical point of view the post-consumer recycling of indium from mixed scraps is less difficult compared with tantalum, for instance.[i]

Reclaiming indium from tailings and slags is more difficult and thus more expensive. However, these materials can be treated if demand and price for indium increase. According to the Indium Corporation,

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[a] Indium Corporation, Availability of Indium and Gallium, September 2009

[b] Defra, Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, December 2010

[c] Critical raw materials for the EU. European Commission, 2010

[d] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

[e] USGS, Mineral Commodity Summaries, 2010

[f] Indium Corporation, http://www.indium.com/supply.php, accessed 14/01/2011

[g] USGS, Mineral Commodity Summaries, 2010

[h] Critical raw materials for the EU. European Commission, 2010

[i] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

total residue reserves worldwide amount to over 15,000mt of indium and another 500mt of indium is generated every year in residue form.[a]

Within Europe, LCDs are the fastest growing waste source in the EU. It is estimated that 9 tons of liquid crystals, 900kg of indium and 8,000 tons of glass could be recovered every year from UK WEEE; these are comparable quantities to consumption figures. However, little or none is recovered at present as recovery and recycling processes are not viable.

Substitutes

Indium's recent price volatilities and supply concerns have led to a search for replacements, particularly for ITO. Some of these alternatives are outlined below.

Perhaps the most advanced work is in the use of zinc oxides, which have been developed to be suitably adhesive for coatings through the production of zinc oxide nanopowders. These can replace ITO in LCDs and solar panels, and its use is likely to become more widespread in the future. Antimony tin oxides (ATO), which are deposited by an ink-jetting process, have also been developed as an alternative to ITO coatings in LCDs and have been successfully annealed to LCD glass. Carbon nanotube coatings, applied by wet-processing techniques, have been developed as an alternative to ITO coatings in flexible displays, solar cells, and touch screens. Poly (3,4-ethylene dioxythiophene) (PEDOT) has also been developed as a substitute for ITO in flexible displays and organic light-emitting diodes. Graphene quantum dots have been developed to replace ITO electrodes in solar cells and also have been explored as a replacement for ITO in LCDs. However, development is at an early stage in most of these technologies, and it is unclear if they will displace ITO in the long term.

Elsewhere, indium phosphide can be substituted by gallium arsenide in solar cells and in many semiconductor applications. Hafnium can replace indium in nuclear reactor control rod alloys.[b]

1.8.2 Current European and Global Output and Reserves

The majority of indium production occurs in Asia and is dominated by China, with a production of 300 metric tonnes in 2009, accounting for half the world's total production of 600 tonnes of primary indium (Table 10). In terms of the Chinese companies, it is possible to get an impression of the degree of concentration based upon export quota data. 18 separate companies are listed with export quotas totalling 140 tonnes for 2011. Zhuzhou Keneng New Material has the largest quota at 24.5 tonnes (17.5% of the total quotas), with a further 4 companies accounting for 66.5 tonnes between them[c]. As for European indium producing countries, Belgium represented 5% of the indium world supply, with Germany, Netherlands, Italy and UK collectively accounting for a further 5% of world production (Figure 26).

Because indium is extracted as a by-product of zinc refining, up to date numbers in indium reserves are hardly available. However, in 2007 the US Geological Survey published their last estimates on world indium reserves. According to that data 8,000t of economic indium deposits are located in China and the world total accounted for 11,000t with an estimated 16,000t of indium resources worldwide. Latest estimates are significantly higher due to newly identified resources which can be economically mined. According to the Indium Corporation, 50,000t of indium resources have been identified[d].

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[a] Indium Corporation, Availability of Indium and Gallium, September 2009

[b] USGS, Mineral Commodity Summaries, 2010

[c] Metal Pages (29 December 2010), China allocates first batch of indium export quotas

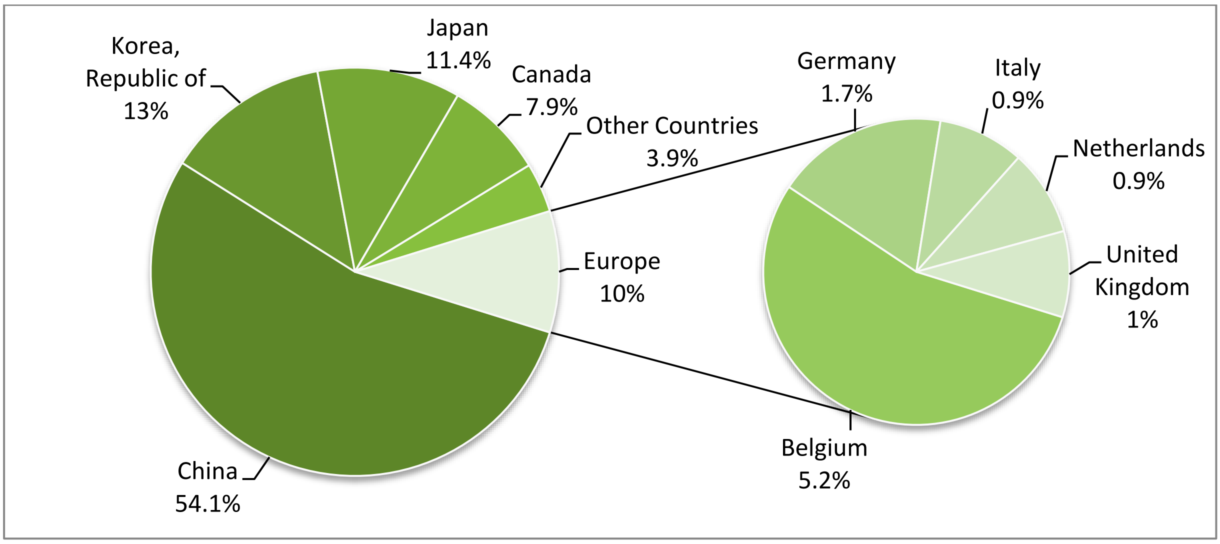
d Critical raw materials for the EU. European Commission, 2010

Table 10: World Primary Indium Refinery Production (2009), Reserves (2007) – (tonnes of indium content)

Country	Refinery production	Reserves
United States	—	280
China	300	8,000
Korea, Republic of	85	—
Japan	60	—
Canada	50	150
Belgium	30	*
Peru	20	360
Russia	12	80
Brazil	10	—
Other countries	30	1,800
World total (rounded)	**600**	**11,000**

**Reserves for this country are included with "Other countries." Note: Reserve estimates based on the indium content of zinc ores*
Source: USGS Mineral Commodity Summaries (2007, 2010)

Figure 26: World Indium Refinery Production 2008 (tonnes of indium content)



Source: USGS (2010), Cobalt 2008 Minerals Yearbook

Global Demand and Supply, and Price Forecasts Until 2020

Future demand from the electronics industry will put severe pressure on supply. Indium supply and demand forecasts are given in Figure 27. The market is forecast to move from a small surplus in 2010 to a significant deficit in 2020, representing 21% of forecast supply because of strong growth in Solar PV. The demand forecast comes from Umicore[a], although it is noted that it does not substantially differ from the 5% per year growth rate, as modelled by Öko-Institut[b].

The assumptions underlying the supply forecast are:

- Primary indium production of 600 in 2009, with secondary production of 600 tonnes
- The parts per million of indium extracted from zinc remaining constant at 50ppm, modelled using supply forecasts for zinc from the Economist Intelligence Unit
- Secondary production matches primary production.

Prices for Indium hovered around US$1,000 per kg during 2005 and 2006, although at the time this was the limit to the price rises. Upward potential for prices is expected particularly for the second half of the decade, when strong demand growth is likely to create significant pressure on prices.

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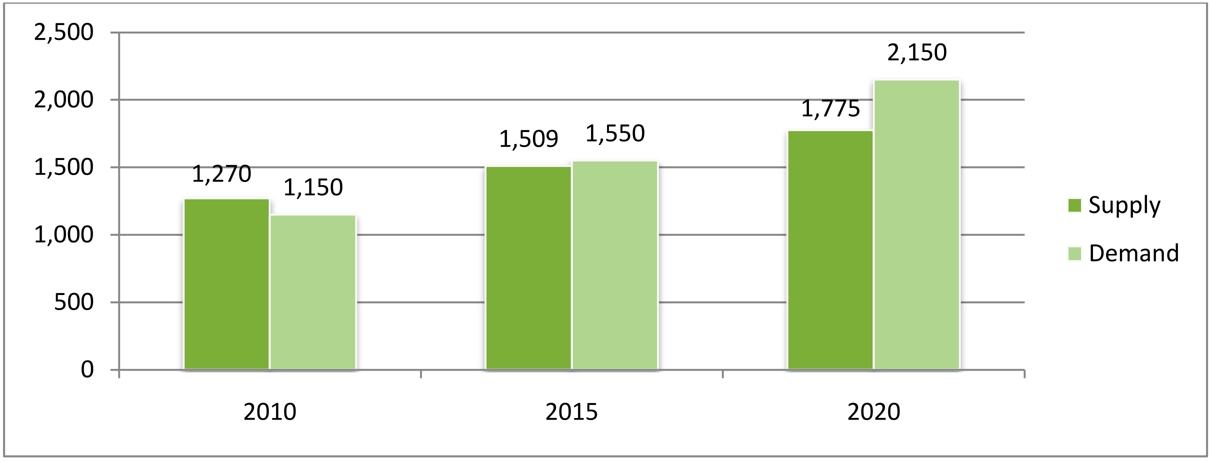
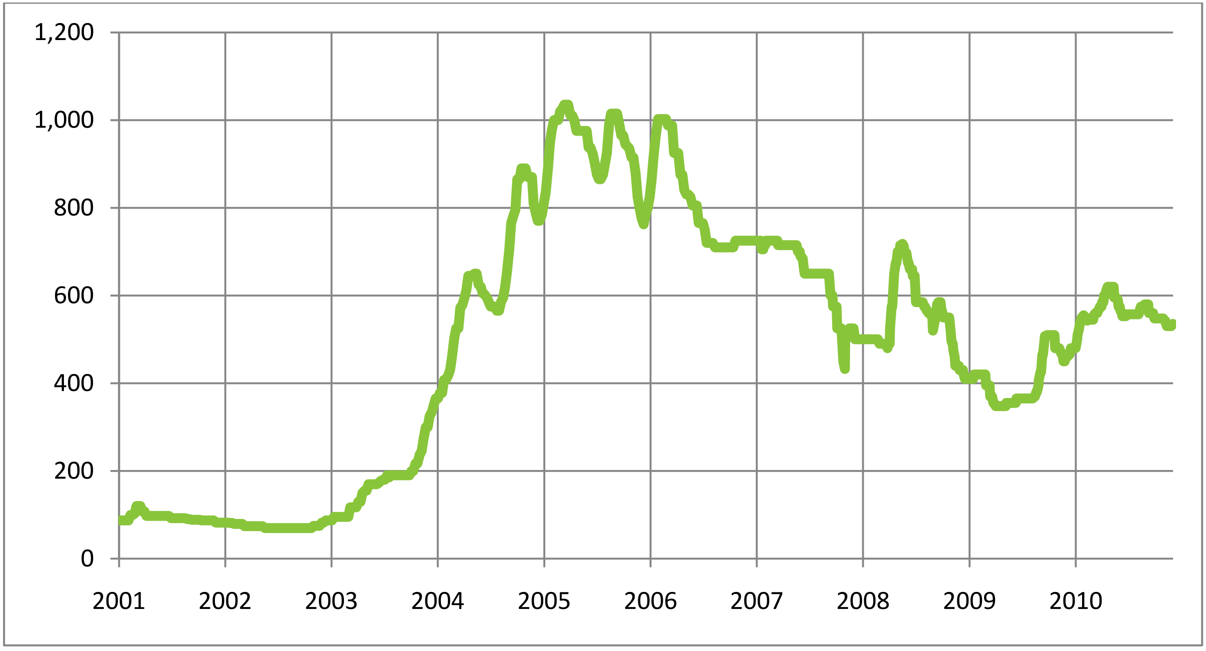
[a] Umicore (2009) in EC (2010), Annex V to the Report of the Ad-hoc Working Group on defining critical raw materials
[b] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

Figure 27: Indium Supply and Demand Forecasts (t)



Sources: Umicore; Own Calculations based on Economist Intelligence Unit, USGS, Öko-Institut

Figure 28: Indium Metal Prices, min. 99.99% Purity (US$/kg)



Source: Metal Pages

1.9 *Magnesium*

Magnesium (Mg) is a silvery-white shiny, low density, moderately strong metal and in its purest form it can be compared with aluminium. Magnesium is the eighth most abundant element in the Earth's crust and the sixth most abundant metal. Magnesium is found in many types of mineral, however only dolomite, magnesite, brucite, carnallite, and olivine are of commercial importance[a]. Magnesium and other magnesium compounds are also produced from seawater, well and lake brines and bitterns.

Magnesium is obtained commercially by the 'Pidgeon' process, where under high temperature silicon is used as a reducing agent to extract magnesium from minerals as dolomite, magnesite or saltwater. Magnesium can also be obtained using an electrolytic process, but the economics of this process are less favourable[b]. China is the largest producer of Magnesium.

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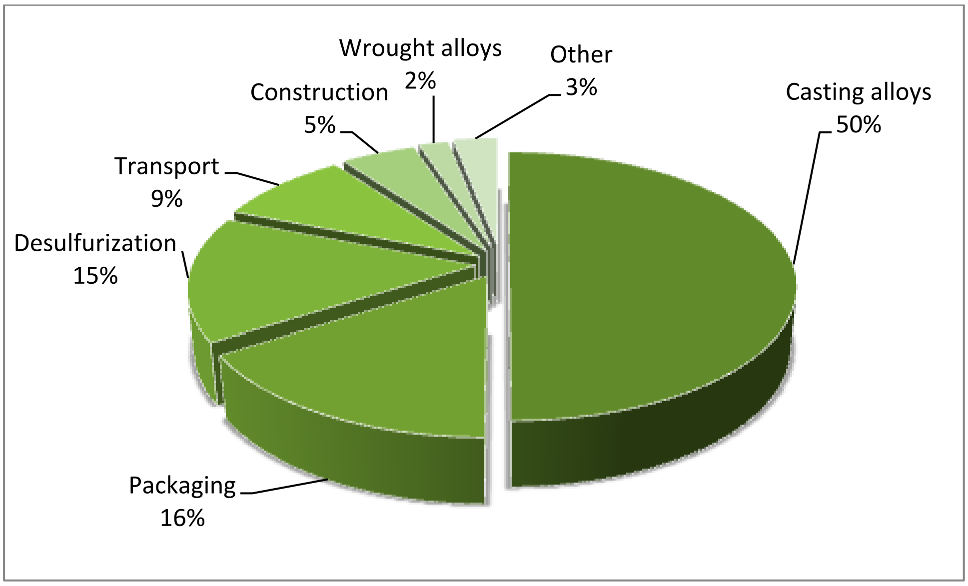
[a] Annex V

[b] MBM 2005

1.9.1 Key Applications and Potential Future Substitution

Due to difficulties associated with using the pure metal, the primary applications for magnesium are mostly associated with its alloys. In these uses magnesium imparts useful mechanical properties, and also helps with light weighting of metal products due to its low density. Over all sectors, magnesium's primary application is in aluminium alloys which account for the majority of magnesium use in casting alloys, wrought alloys, packaging and construction markets, Figure 29. The main consumers of these aluminium alloys are within the aerospace, which currently consumes the vast majority of these alloys, and the packaging industry. In the latter the material is used for beverage cans which contain 1.1% and 4.5% of magnesium for the body and lid respectively.

Figure 29:Applications of Aluminium by value



Source: Critical raw materials for the EU. European Commission (2010)

In the transport industry magnesium is used as both a metal and alloy, and used to produce die cast, wrought and sand cast parts for the automotive and aerospace industries. The aerospace industry uses magnesium in helicopter air intakes, speed brakes, engine frames, gearboxes and wheels. In other vehicles, magnesium is used in chassis, driveline and powertrain components; use in this sector is growing as manufacturers seek new, light weight and high performance materials to use in vehicles. Within the construction sector, aluminium/magnesium alloys are used as lightweight structural components.

Magnesium's desulfurization properties are used in iron and steel making accounting for 15% of the primary magnesium market.[a] Low-sulphur materials are produced to make high-strength, low-alloy steel grades. When magnesium is added to molten iron, it reacts to form magnesium sulphide, which floats to the surface as a readily separated phase. In combination with ferro-silicon, magnesium is also used in the production of nodular iron used to make ductile iron castings.

Other uses of magnesium metal include:

- As a reducing agent in the production of beryllium, hafnium, uranium and zirconium.
- As anodes to prevent steel corrosion in storage tanks and buried pipelines.
- In fireworks and marine flares, in which it burns with a white bright shining light.
- Light weight sports equipment and power tools.

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[a] MBM, Magnesium, October 2006

Recycling
Magnesium recycling is very energy efficient when compared to the primary production, as it uses twenty times less energy. Industrially, magnesium scrap from die casting processes can be directly recycled by the die-caster or by magnesium recyclers and then sold back into the die-casting industry. A closed loop system for recycling scrap from the die casting process is a key element in magnesium economics,

Magnesium alloys are also very suitable for recycling, and are estimated to have a recycling rate of 33% across all uses at end of life. When used in alloys magnesium is not recovered individually; instead the alloy is recycled without separation.

The USGS estimates, that in 2009, the equivalent of 22,000 tonnes of secondary magnesium were produced through scrap recycling in the US, accounting for 40 to 50% of total magnesium supply in the country.[a]. That the world's largest magnesium recycling facility, Advanced Magnesium Alloys Corporation (AMACOR) is american, is indicative of the developed nature of this industry in the US.

There is no primary production of magnesium metal in the UK but Magnesium Elektron Ltd., a division of Luxfer, process scrap and primary metal in Manchester to produce magnesium metal and alloys in a variety of forms. Capacity of plant was estimated to be 11,400 tonnes/year in 2005.

Substitutes
Aluminium and zinc may substitute for magnesium in castings and wrought products in certain circumstances, however these do not provide the same light weight options. Iron and steel desulfurization may also be performed using calcium carbide. b

Certain uses, particularly packaging, allow substitution through replacement of the material. For example aluminium based drinks cans can be replaced by plastic alternatives.

1.9.2 Current European and Global Output and Reserves

World production of primary magnesium metal according to the USGS was estimated at 610,000 tonnes in 2009, of which China was the dominant producer accounting for 77% of world production, Table 11. (The BGS estimate for primary magnesium production is higher at almost 800,000 tonnes[c]). In terms of the distribution of production, there are 66 separate magnesium smelters. Production does not appear to be concentrated within just a few companies, as Taiyuan Yiwei Magnesium Industry, which is one of China's leading producers, had a capacity of 80,000 tonnes per year in 2008 (12.6% of Chinese output that year)[d]. Within Europe, Serbia produces around 2,000 tonnes of magnesium metal per year.

The major feedstock for magnesium metal production is the mineral magnesite, which can be mined or extracted from brines or seawater. Global production of magnesite was estimated by the USGS at 19 million tonnes, of which 5 million tonnes was mine production[e]. China is the largest producer of magnesite accounting for over half global production, Figure 30. European countries (Austria, Slovakia, Spain, Greece, Poland and Serbia) however produce 13% of world magnesite supply, with Turkey accounting for a further 10.5%. (Alternatively the BGS estimate world magnesite production at 24 million tonnes). Mineral reserves for magnesite are estimated at 2.3 billion tonnes, excluding brines and seawater, of which 36 million tonnes are within Europe. The USGS report that "to a limited degree the existing natural brines may be considered to a renewable resource"[f].

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[a] Tom Vulcan, Magnesium: Behind The Bright Shining Light, Hard Assets, May 2010

[b] USGS, Mineral Commodity Summaries, 2010

[c] BGS (2010), World Mineral Production 2004-2008

[d] USGS (2010), Magnesium Metal 2008 Minerals Yearbook

[e] USGS Mineral Commodity Summaries (2010) & USGS (2010), Magnesium Compounds 2008 Minerals Yearbook

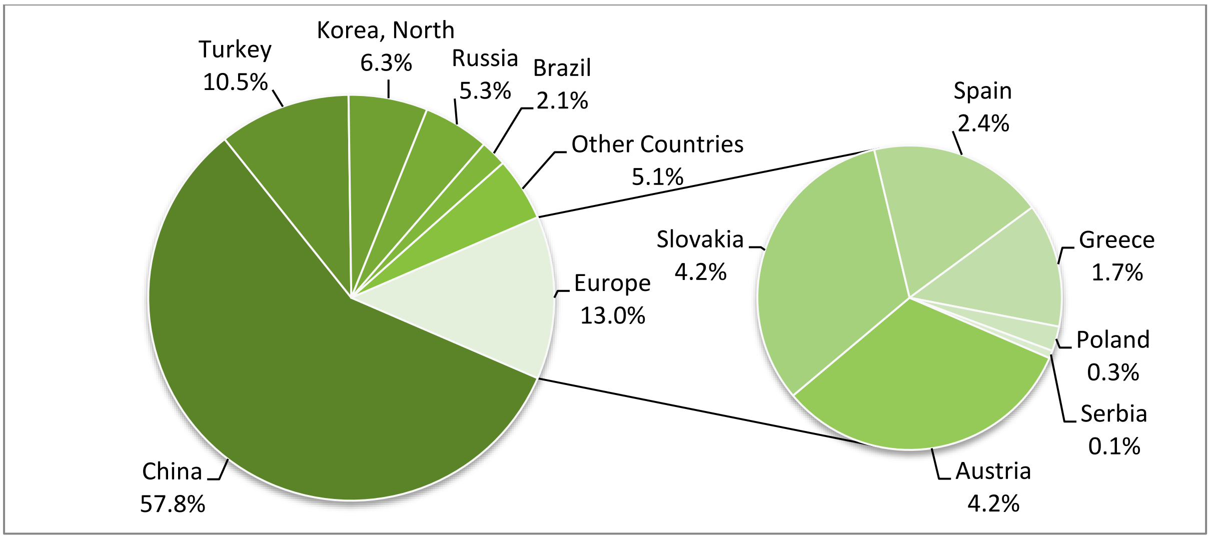
[f] USGS Mineral Commodity Summaries (2010)

Table 11: World Magnesium Metal Production 2009 (thousand tonnes of magnesium metal)

Country	Primary production
China	470
United States	40*
Israel	30
Russia	30
Kazakhstan	20
Brazil	15
Ukraine	3
Serbia	2
World total (rounded)	**610**

Source: USGS Mineral Commodity Summaries (2010)
** Withheld in USGS data, but available from BGS*

Figure 30: World Magnesite Production 2009 (thousands tonnes of magnesite)



Source: USGS (2010), Magnesium Compounds 2008 Minerals Yearbook

Global Demand and Supply, and Price Forecasts Until 2020

Supply and demand forecasts for magnesium metal in Figure 31 show that the surplus in global production will narrow towards the end of the next decade due to strong growth in demand. However with global magnesium capacity currently at 1.4Mt in 2009[a], with much of it currently idle, there is little need for further expansion of capacity in order to meet the growth in demand.

The assumptions underlying the forecasts are:

- Demand for magnesium and magnesium alloy grow at an average of 6% and 8% per year respectively as forecast by Roskill for 2009-2013[b]
- On the supply side, growth has been modelled at 7% per year for primary magnesium production to keep pace with demand. For secondary production (150,000 tonnes per year in 2008), which mostly comprises the recycling of aluminium packaging, a slower growth rate of 3.5% per year has been modelled.

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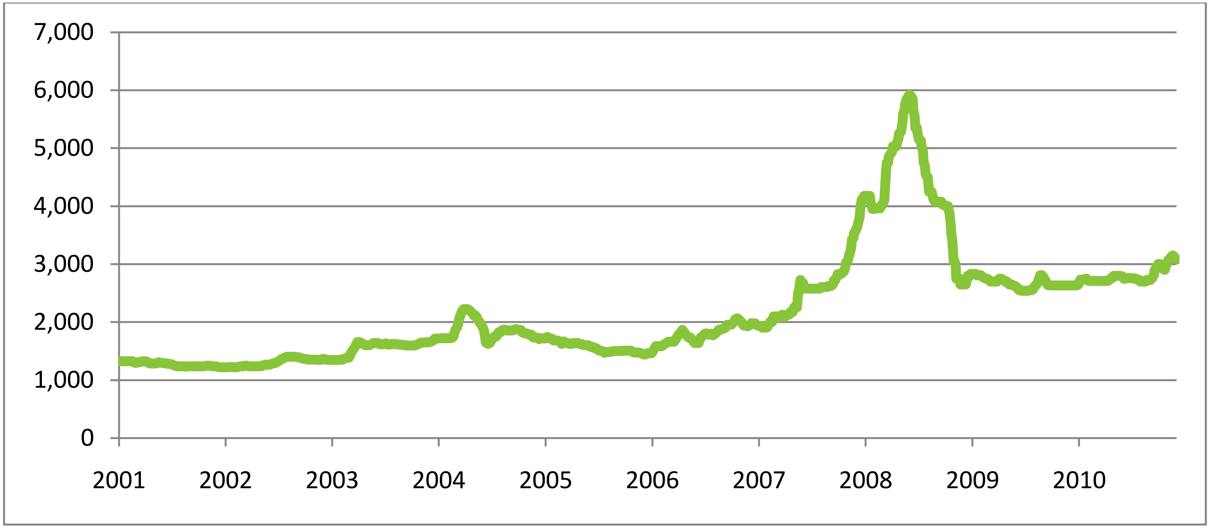
[a] Roskill (2008), The Economics of Magnesium Metal, 10th Edition
[b] Roskill (2008), The Economics of Magnesium Metal, 10th Edition

Figure 31: Magnesium Metal Supply and Demand Forecasts (kt)

Sources: Oakdene Hollins calculations based on Roskill (2008).

Price developments for magnesium are shown in Figure 32. Except for the price spike in mid 2008 to $6,000 per tonne, there has generally been a steady trend rate of prices increases from around $1,300 per tonne at the start of the decade, to their present levels of around $3,000 per tonne. On prices, resource investment research company, Seismic Research, expect there to be upward pressure to prices despite the significant levels of idle capacity. Their prediction is for prices to stabilise above $3,500 per tonne[a].

Figure 32: Magnesium Price Developments min 99.9% FOB P.R.C. ($/tonne)



Source: Metal Pages

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[a] Seismic Research (2010), The Magnesium Market in China Magnesium Corporation Research Note

1.10 Niobium

Niobium (Nb), also called Columbium, is a grey, shiny, soft and ductile metal. At cryogenic temperatures, niobium is a superconductor. Niobium is one of the major refractory metals materials with very high resistance to heat and corrosion.

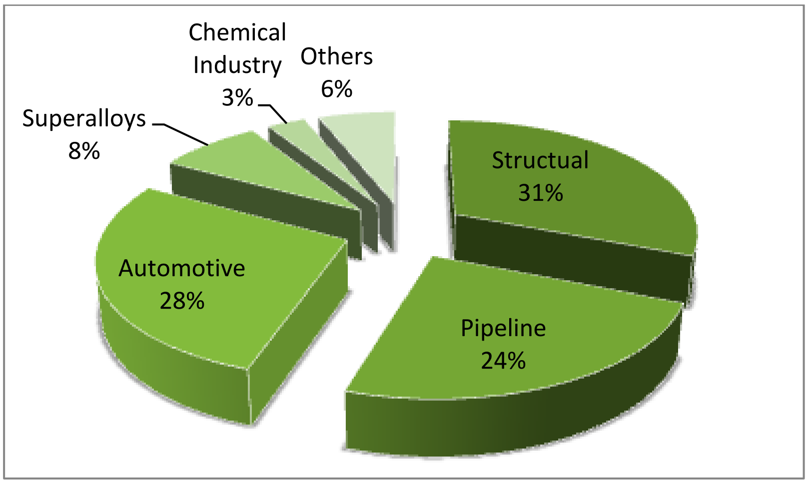
Niobium's abundance in the earth's crust is on average 20 ppm. It is primarily obtained from the mineral pyrochlore, which provides the largest supply of niobium. However it can also be obtained from columbite and other tantalum-bearing ores. Niobium is also found in small quantities in slags resulting from smelting of some tin ores, tantalites, struverite and loparite.

Naturally niobium is present in ores as its oxide, typically mixed with oxides of other metals; therefore the first step in the production of niobium is the isolation of pure niobium oxide through chemical processing. For steel production, niobium is produced as an alloy of iron known as ferroniobium, which is directly used in the steel industry. A similar process is used for the production of high purity niobium, however only aluminium is used and further purification steps are required, with techniques such as electron beam melting used to produce the highest grades.[a]

1.10.1 Key Applications and Potential Future Substitution

Niobium is used primarily steel production in high-strength low-alloy (HSLA) steel (also called micro-alloyed steels). The addition of small quantities of niobium (around 0.05%) to carbon steel produces marked increases in strength, toughness characteristics, and temperature resistance; these properties are advantageous for many applications. Approximately 83% of niobium is used in HSLA steels, with these alloys corresponding to around 10% of total steel production. In 2004 the US and Europe consumed about 73% of the total HSLA production containing niobium.[b] This trend has continued, and in 2008 there remained a large disparity between niobium use in developed countries and other steel producing countries. However, this indicates that the demand for HSLA steel could grow significantly in the future if demand from developing countries increases.[c]

Figure 33: Uses of Niobium by value



Source: Heraeus Presentation April 2010 - Minor Metals

Figure 33 shows the common uses of niobium by broad application. About 31% of all niobium is used for structural purposes including bridges, buildings, railroad tracks, and in ship building. Another 24% is used

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[a] Niobium - Raw Materials and Processing, Tantalum-Niobium International Study Center (TIC)

[b] William A. Serjak, The Mineral Journal, Niobium, 2005

[c] Mark Sumich (Global Metals & Mining), Global Mining Investment Conference, September 2010

in oil and gas pipelines and 28% is used in the automotive sector for car bodies, wheels and structural members for automobiles and trucks.

In the aerospace and aircraft industry vacuum-grade ferro- and nickel-niobium are used in the production of nickel-based superalloys. When compared with HSLA steels, the concentration of niobium in superalloys is much higher, typically between1% and 5%. These alloys are highly heat and corrosion resistant and are used when reliability in extreme conditions is required, for example, turbine blades in rocket and jet engines and land-based turbines.

Minor uses of niobium include uses in the nuclear industry for fuel cells and core elements as an alloy with zirconium. Niobium-titanium-tin alloy is used in medical applications in the construction of the magnetic coils for magnetic resonance imagery (MRI) equipment. Pure niobium metal is used in corrosion resistant equipment, sputtering targets, and cathodic protection systems.

Other, nice uses of niobium containing materials include:

- Camera lenses
- Lithium niobate based SAW (surface acoustic wave) filters. Application of these devices is electronic circuitry, for example, in mobile phones.
- The manufacture of cutting tools and in wear-resistant applications
- Ceramic capacitors, which may replace tantalum based for specific circuitry requirements, though development work is still required.
- The catalytic conversion of palm oil into biodiesel fuels.
- Jewellery

These uses are expected to grow in the future, however use will continue to be dominated by the steel industry. In 2030, the demand for niobium in the production of micro capacitors is predicted to be six times higher than today. Nevertheless that will be only 3% of total niobium consumption.[a] Similarly, new niobium end-uses, such as converting palm oil to bio-diesel, will not significantly affect the global demand.

Recycling

A recent EU report estimated that greater than 50% of niobium is recycled,[b] and, according to the USGS a large proportion of apparent consumption may come from recycled sources. However, this recycling mainly occurs through the recycling of steel, and little niobium is specifically recovered from products just for the niobium content. Therefore, at end of use the niobium is dispersed into other, less particular grades of steel. Specific data on recycling processes are not available due to industrial secrecy.

Substitutes

Though substitution of niobium is possible, it may involve higher costs and/or a loss in performance. Substitutes are:

- molybdenum and vanadium, as alloying elements in high-strength low-alloy steels
- tantalum and titanium, as alloying elements in stainless and high-strength steels
- ceramics, molybdenum, tantalum and tungsten in high-temperature applications.[c]

1.10.2 Current European and Global Output and Reserves

Brazil is by far the leading producer of niobium. In 2009, Brazil produced 57,000 tonnes from the two world's largest deposits of pyrochlore or 92% of the world's production, which the USGS puts at 62,000 tonnes. Most of the remaining 8% comes from the third biggest niobium mine located in Canada. Smaller quantities are being mined in Africa.

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[a] Critical raw materials for the EU. European Commission, 2010

[b] Thematic Strategy on the Prevention and Recycling of Waste, EC Working Document, 2011

[c] Critical raw materials for the EU. European Commission, 2010

In terms of companies, the niobium market is highly concentrated with just 3 mines accounting for 99% of world niobium production. CBMM owns the largest mine at Araxá in Brazil, which currently has niobium capacity of 56,000 tonnes per year (85,000 tonnes of standard grade ferro-niobium at 66% Niobium content)[a]. The other two significant mines are Catalão, Brazil owned by Anglo American with an output of 4,600 tonnes and Iamgold's Niobec mine in Canada with an output of 4,300 tonnes.

The USGS estimates that Brazil's economic reserves of niobium stand at 2,900,000 tonnes and Canada's are 4,300 tons. However, according to the Tantalum-Niobium International Study Center, "the reserves [of niobium] are enough to supply current world demand for about 500 years; about 460 million tons"[b]. Currently, there is no Niobium production in Europe and no economic deposits appear to be present in the European territory[c].

Table 12: World Niobium Production and Reserves – 2009 (tonnes of niobium content)

Country	Mine production	Reserves
Brazil	57,000	2,900,000
Canada	4,300	46,000
Other countries	400	NA
World total (rounded)	62,000	2,900,000

Source: USGS Mineral Commodity Summaries (2010)

Global Demand and Supply, and Price Forecasts Until 2020

Demand and supply forecasts for niobium are shown in Figure 34. Because of the very high degree of concentration in the mining of niobium a capacity forecast is more appropriate for gauging future supply. Forecasts for the ferro-niobium market are available from the Canadian miner until 2014, Iamgold, which have been used as the basis of the forecast[d] (displayed as the niobium content). The forecasts show that excess capacity in the niobium market is likely to narrow over the period considerably as demand grows rapidly, but capacity does not expand between 2012 and 2015 by which point the planned capacity increases by CBMM and Niobec will have been completed.

The assumptions underlying the longer term forecasts are:

- Long term demand for niobium increases at 8% per year, in line with forecasted growth rates for high strength steel[e]. This represents a slowing from the 14% per growth rates predicted by Iamgold for 2009-2014, which allows stronger growth as the global economy recovers.
- Long term supply growth has been modelled at 8% growth per year for 2015-2020, although Iamgold note that future investments by CBMM will be expensive and require higher niobium prices[f].

Initiated by the major supplier CBMM, prices for niobium rose to a new level during 2007, from $19 per kg at the beginning of 2007 to around $40 per kg (Figure 35). Further price rises are likely over the coming decade in response to high growth rates in demand and the need for expensive investments to boost capacity.

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[a] Mining Technology (14 January 2010), The Future of Tantalum and Niobium

b T. Vulcan Niobium or Columbium? Hard Assets, 2010

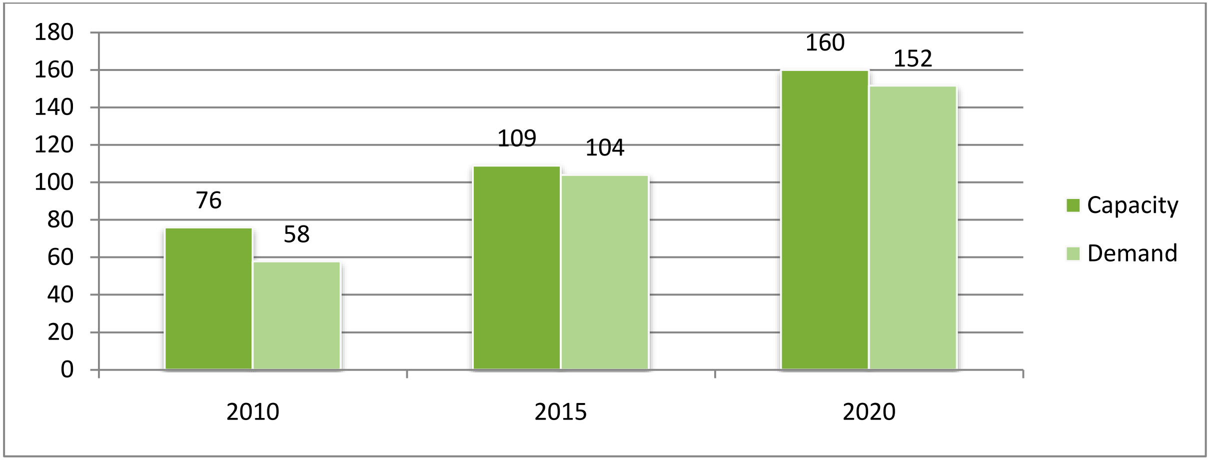
c Annex V of the EU report, "Critical raw materials for the EU"

[d] Iamgold (2009), Niobec Tour Presentation

[e] Byron Capital Markets Presentation

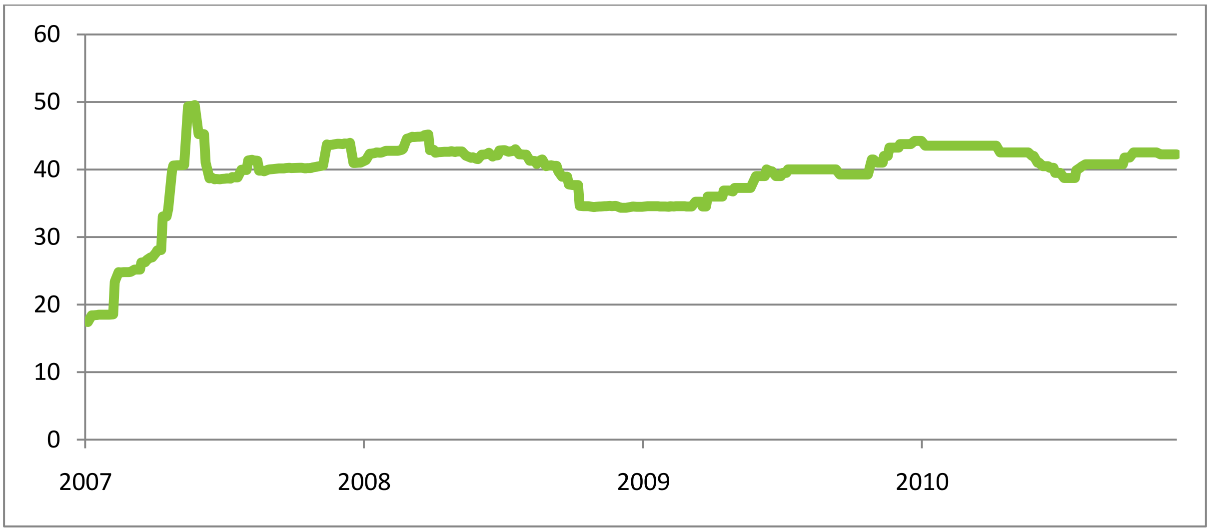
[f] Iamgold (2009), Niobec Tour Presentation

Figure 34: Niobium Capacity and Demand Forecasts (kt)



Sources: Iamgold Presentation and own calculations from Byron Capital Markets

Figure 35: Ferro-niobium prices, 65% purity (US$/kg)



Source: Metal Pages, note: prices before 10/03/09 have been converted from Chinese Ferro-niobium 66% purity, denominated in Rmb, into US$ using Oanda historical interbank exchange rates (applying a 10% premium to account for transaction costs and slight purity difference)

1.11 Platinum Group Metals

Platinum Group Metals (PGM) is a collective term for six metals with similar chemical and physical properties: ruthenium (Ru), rhodium (Rh) and palladium (Pd) (sometimes categorised as light platinum metals) and osmium (Os), iridium (Ir) and platinum (Pt) (sometimes categorised as heavy platinum metals).

All PGMs have many useful properties such as high melting points, high resistance to corrosion, good electrical properties and most do not oxidize in air even at high temperatures. [a] They are also excellent catalysts for a host of chemical reactions. In general PGMs and their compounds are considered non-toxic. However, certain chemical compounds such as osmium tetroxide, which forms when osmium comes into contact with air, are considered hazardous.

The PGMs are very rare in the earth's crust, where the abundance of platinum and palladium in the crust are similar, approximately 5 ppb, and several tonnes of ore are required to yield 1 gram of metal[b]. In nature, platinum group elements are primarily held either in base metal sulphide minerals, such as

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[a] Annex V of the EU report, "Critical raw materials for the EU"

[b] (BGS, 2009)

pyrrhotite, chalcopyrite, and pentlandite, or in platinum group bearing accessory minerals[a]. They occur most commonly as a wide variety of alloys with other metals like iron, tin copper lead, mercury and silver. Enrichment of PGMs occurs in a wide variety of geological setting and accordingly PGMs are derived from deposits of several types, commonly associated with nickel and copper.

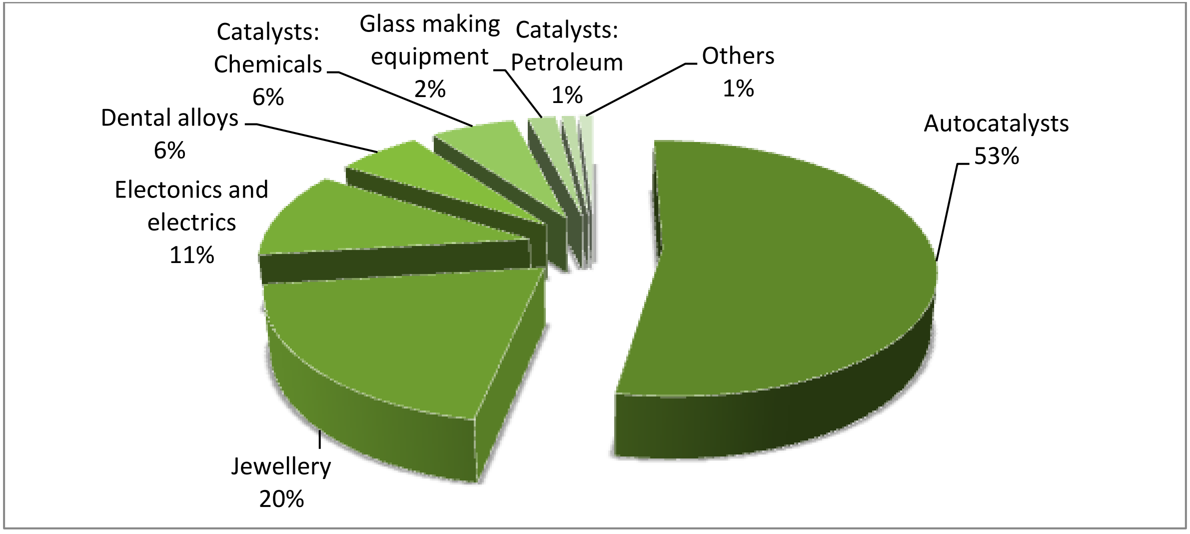
In PGM dominant ores the PGMs are collected by a sulphide liquid, with minor by-products nickel and copper. Platinum is also produced commercially as a by-product of nickel refining from copper-nickel ores.

The largest known reserves are in South Africa, which is also the largest producer of platinum.

1.11.1 Key Applications and Potential Future Substitution

PGMs have many unique properties; as such they find use in a wide variety of different applications, Figure 36.

Figure 36: Value of Platinum Group Metal applications



Source: Critical raw materials for the EU (2010)

The leading use of PGMs is in catalytic converters (Pt, Pd, Rh) for air-pollution abatement in both light- and heavy-duty vehicles. Around 20% of all PGMs are used in jewellery; this is mainly platinum and palladium. The electronics industry consumes around 11% of PGM production where they are mainly used in hard disks (Pt, Ru), multilayer ceramic capacitors (Pd) and hybridized integrated circuits (Pd).

PGMs are critical for various processes in the chemical using industries; by the glass manufacturing sector in the production of fibreglass, liquid crystal displays, and flat-panel displays; in the petroleum refining sector and in the fabrication of laboratory equipment. Platinum, palladium, and a variety of complex gold-silver-copper alloys are also used in dental alloys.

Platinum

In 2008 the total production of platinum was estimated to be 178 tonnes.[b] The major applications included autocatalysts (52%) and jewellery (19%), with the remainder utilised in a selection of smaller uses including chemical catalysts, petrochemical production, electronics, glass and investment, each using between 3 and 6%. The technical uses for platinum are described below.

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[a] BGS 2009

[b] USGS, Mineral Commodity Summaries, 2010

Platinum's main end-use is as a constituent in diesel catalytic converters and to a lesser extent with palladium petrol catalytic converters. This use is likely to remain high due to automotive emissions legislation, and lack of alternatives. Platinum is crucial in many chemical processes, perhaps most importantly in the manufacture of fertilisers and explosives where platinum is used as a catalyst in the conversion of ammonia to nitric acid. Platinum is also critical to the refining of petroleum and the production of plastics, synthetic rubber and polyester fibre. In glass manufacture platinum-based equipment is used in the manufacture of a large range of glass products, the most important of which are flat panel screens and fibreglass. Within the electronics industry platinum is primarily used in computer hard disks to increase storage capacity. Other uses include:

- dental alloys used in inlays, bridges and crowns
- non-catalytic automotive (e.g. electrodes of spark plugs in gasoline engines and oxygen sensors in engine management systems)
- biomedical (e.g. anti-cancer drugs and pacemakers)

Non technical uses for platinum include jewellery and investment, which together account for a significant proportion of use.

Palladium

The annual production of palladium is estimated to be 195 tonnes; the majority of this is used in autocatalysts (55%), with other uses including electronics (16%), jewellery (11%), dental (8%), investment (5%) and chemical (4%).

The use of palladium in catalytic converters is mainly for petrol-powered vehicles and a smaller amount for the diesel sector. Historically palladium has been significantly cheaper than platinum, therefore it is the preferred material used by autocatalysts manufacturers.[a]

The electronic industry is the second largest consumer of palladium accounting for 16% of worldwide demand. It is mainly used in multi-layer ceramic capacitors (MLCC), widely used in mobile phones, and to a smaller amount in hybrid integrated circuits (HIC). It is estimated that each mobile phone handset contains 0.015g of palladium.

Palladium is also used in jewellery, either as a component of white gold or as palladium jewellery itself, representing its third most substantial use.

Rhodium, Ruthenium, Iridium and Osmium

Rhodium is a critical component of autocatalysts which account for more than 80% of its use. Other uses of rhodium were, in descending order of use, LCD glass manufacturing (1,700 kg in 2006), chemicals, electrical applications, and jewellery.[b]

Global consumption of ruthenium is fuelled by the electronics industry where over 80%[c] of it is used in hard disks and other applications such as chip resistors and flat screen displays plasma display panels . Some of the other uses for ruthenium are conductive paste used in resistor components, plasma display panels, jewellery, and chemical processors. Future uses of ruthenium are in fuel cells (as a catalyst) and turbine blades (alloy).

Iridium is used in process catalysts; spark plug tips, and iridium crucibles to produce high-quality crystals for electronics. Osmium is used in small amounts in an alloy with platinum and iridium, which is used in pen tips, electrical contacts, filaments in light bulbs and in medical implants.[d]

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[a] T. Steinweg and E. de Haan, Capacitating Electronics, November 2007

[b] T. Steinweg and E. de Haan, Capacitating Electronics, November 2007

[c] Critical raw materials for the EU. European Commission, 2010

[d] British Geological Survey, Platinum, September 2009

Recycling

The value of these metals means that when recycling practices are implemented they are typically efficient. This is particularly apparent from chemical catalysts and equipment used in optical manufacture. Indeed, pre-consumer recycling of PGMs (closed loop approach) is efficient, and industrial users typically only need to purchase PGMs to cover lifecycle losses or market growth (expansion or new applications).[a] To a certain extent this hides the actual scale of usage in these industries, as from the outside the demand appears small, however over 90% of the PGMs are believed to be recovered in these industries for further use.

Recycling is important but less pervasive in the automotive catalyst industry. According to the BGS and Johnson Matthey in 2008, just over 28 tonnes of platinum and 36 tonnes of palldium were recycled from autocatalysts. Elsewhere it is estimated that between 50-60% of PGMs used in automotive catalysts are recovered worldwide. In Europe this figure is below 50%, mainly due to the export of older vehicles to outside the EU. Recovery of the catalyst after use is the largest challenge associated with this processes, as when implemented, metal recycling processes for PGMs from catalytic converters are highly efficient and can obtain recovery rates of well over 95%.[b]

Currently, no universal techniques for recovering PGMs from post-consumer scrap, such as electronic items or end of life vehicles, are in place.[c] At present it is estimated that only 10% of PGMs used in electronic equipment are being recycled.[d] However, the low recovery rate in this, and similar applications is not just due to technical recycling problems, but also because of difficulties in the collection systems for dissipative applications like EEE and used vehicles. This is a consequence of a large share of these products ending up in developing countries, which lack the infrastructure and know-how to recover these precious metals.[e]

A further reason for low recovery rates in electronics is the dissipative use of the metals which puts economic and technical challenges on recycling. Examples are Ru and Pt in hard disks, Pt in silicones, Pt and Ir in spark plugs, platinum in sensors, and PGMs in medical applications or galvanoplating.[f]

Substitutes

Generally PGMs can substitute for each other though often at a performance cost, for example, palladium can replace platinum in autocatalysts and vice versa. The main factor which influences substitution is the current price ratio. However, as Pt and Pd are mined at similar locations and in similar quantities, substituting the materials with one another does not necessarily solve the problems with scarcity associated with PGMs.

Substitution by other materials is difficult due to the unique properties of these metals. The price of PGMs has meant that cheaper replacements have been extensively in demand, however few successes have been achieved.

Current European and Global Output and Reserves

World production of platinum group metals amounted to 445 tonnes in 2009 of which South Africa (61%) and Russia (25%) accounted for the majority of world supply, Table 13. European production of platinum group metals is limited at around 850kg per year, most of which comes from Finland[g]. World reserves of PGMs are put at 71 million tonnes of which close to 90% are located in South Africa.

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[a] Critical raw materials for the EU. European Commission, 2010

[b] Critical raw materials for the EU. European Commission, 2010

[c] Critical raw materials for the EU. European Commission, 2010

[d] Critical raw materials for the EU. European Commission, 2010

[e] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

[f] Critical raw materials for the EU. European Commission, 2010

[g] USGS (2010), Platinum Group Metals 2008 Minerals Yearbook

There is a relatively high degree of concentration of production amongst a few companies. Anglo Platinum (South Africa) is the world's largest producer of PGMs and in 2008 it produced 123 tonnes of PGMs or around 26% of global PGM supply that year, but notably it produced close to 40% of the global platinum supply[a]. The second most significant PGM producer is MMC Norilsk Nickel in Russia, which produced 104 tonnes of PGM is 2008, 22% of global PGM supply that year, but notably it produced 43% of the global palladium supply[b]. Other significant producers include Impala Platinum Holdings and Lonmin (both in South Africa).

Table 13: World Production of Platinum Group Metals (tonnes of PGM)

Country	**Mine production**				**PGM Reserves**
	Platinum	Palladium	Other PGM*	Total PGM	
South Africa	140	79	54	273	63,000
Russia	20	80	13	113	6,200
Canada	5	9	4	18	310
United States	4	13		16	900
Zimbabwe	6	5	2	13	#
Other countries	3	10		13	800
World total (rounded)	178	195	72	445	71,000

Source: USGS Mineral Commodity Summaries (2010) & USGS (2010), Platinum Group Metals 2008 Minerals Yearbook
** 2008 data*
 # included in 'Other Countries'

Global Demand and Supply, and Price Forecasts Until 2020

Future demand growth for platinum group metals for auto catalysts as a result of increasing global demand for cars and the trend towards more stringent emission levels could put pressure on supply[c]. Platinum group metal supply and demand forecasts are given in Figure 37. These suggest that the market will move from a small surplus in 2010 to a deficit in 2020, although it is worth noting that the rates of demand growth used for the forecast do considerably exceed long run demand growth rates implied by market data.

The assumptions underlying the forecasts are:

- Supply of Platinum of 178t and Palladium of 195t in 2009, with 72t of other PGMs in 2008 (Table 13).
- Demand growth of 2.7% per year for PGMs (middle rate of growth suggested by Öko-Institut).
- Supply growth from South Africa for Platinum and Palladium tracking long run growth rates (1% and 2% respectively[d)], with supply other PGMs growing at 2% per year.
- Supply growth in Russia, tracking forecasted growth rates for nickel supply for former Soviet Union nickel production from the Economist Intelligence Unit, with which it is co-mined; and tracking long run growth rates thereafter.
- Supply growth for other countries at 2% per year.
- A 3% overall PGM surplus in 2010, as implied by Johnson Matthey's figures.

Composite prices of a platinum group metals peaked at beginning of 2008 at nearly $1,800 per troy ounce before falling sharply by around two thirds to below $600 in the wake of the financial crisis at the end of that year. Prices have now recovered to above $1,000 per troy ounce as investors have sought

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[a] USGS (2010), Platinum Group Metals 2008 Minerals Yearbook

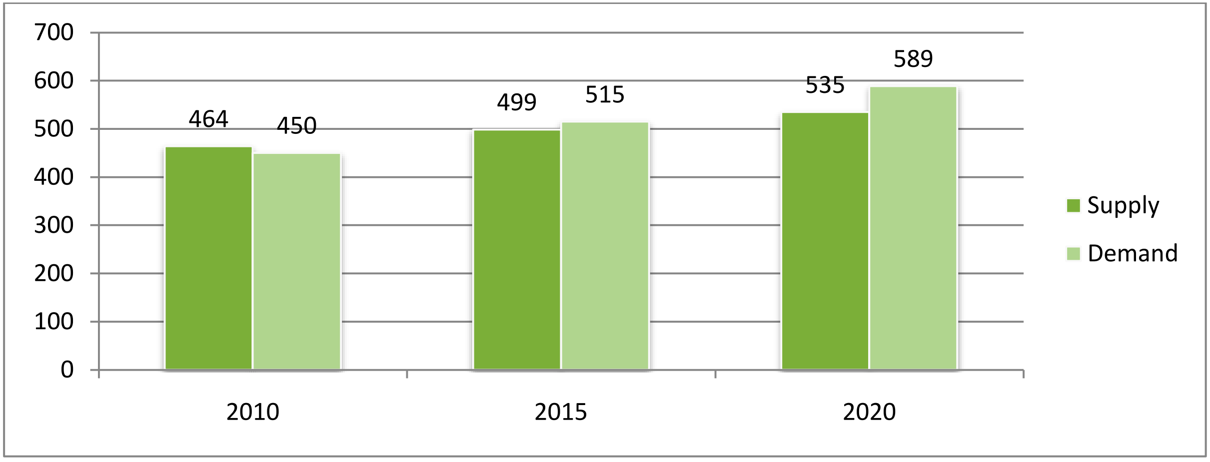
[b] USGS (2010), Platinum Group Metals 2008 Minerals Yearbook

[c] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

[d] Johnson Matthey Market Data Tables, available: http://www.platinum.matthey.com/publications/market-data-tables/ [accessed 06/01/2011]

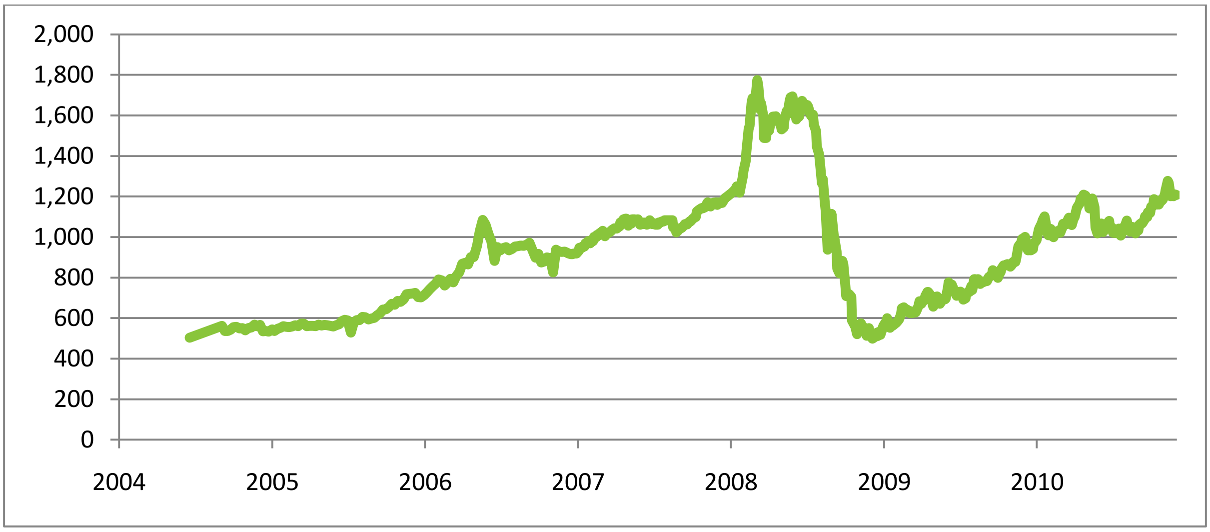
safe havens with the continuing sovereign debt crises in Europe and the threat of inflation as a result of quantitative easing policies[a]. Further upward pressure on prices is possible over the longer term should the strong demand growth, as forecasted by some, be realised.

Figure 37: Platinum Group Metals Supply and Demand Forecasts (t)



Sources: Own Calculations based on USGS, Johnson Matthey, Öko-Institut, Economist Intelligence Unit

Figure 38: Platinum Group Metals Composite Price, EU Prices[b] ($/troy oz)



Source: Metal Pages

1.12 Rare Earth Elements

Within this report the rare earth elements are defined as a group of fifteen metallic elements, specifically yttrium, lanthanum and the lanthanides (excluding promethium). These elements are typically discussed together due to their similar chemical and physical properties, and because they are often obtained from ore deposits. Two other elements, promethium and scandium, are sometimes included within this group, however they are not included for the purposes of this report.

Rare earth elements are all metallic in nature, and are chemically and physically very similar. However, slight differences in their properties mean that each has unique uses, and substitution of one for another is often not possible. Despite their name, rare earth elements are not particularly uncommon, with cerium the most abundant having a similar abundance in the earth's crust to copper. Examples of ores

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[a] Johnson Matthey (2010), Platinum 2010

[b] 45% weighting to Platinum (99.95% AM/PM fixes); 50% weighting to Palladium (99.95% AM/PM fixes) & 5% weighting to Rhodium (min 99.9%); weighting comes from Roskill (2005), "The Economics of Platinum Group Metals", 7th Edition

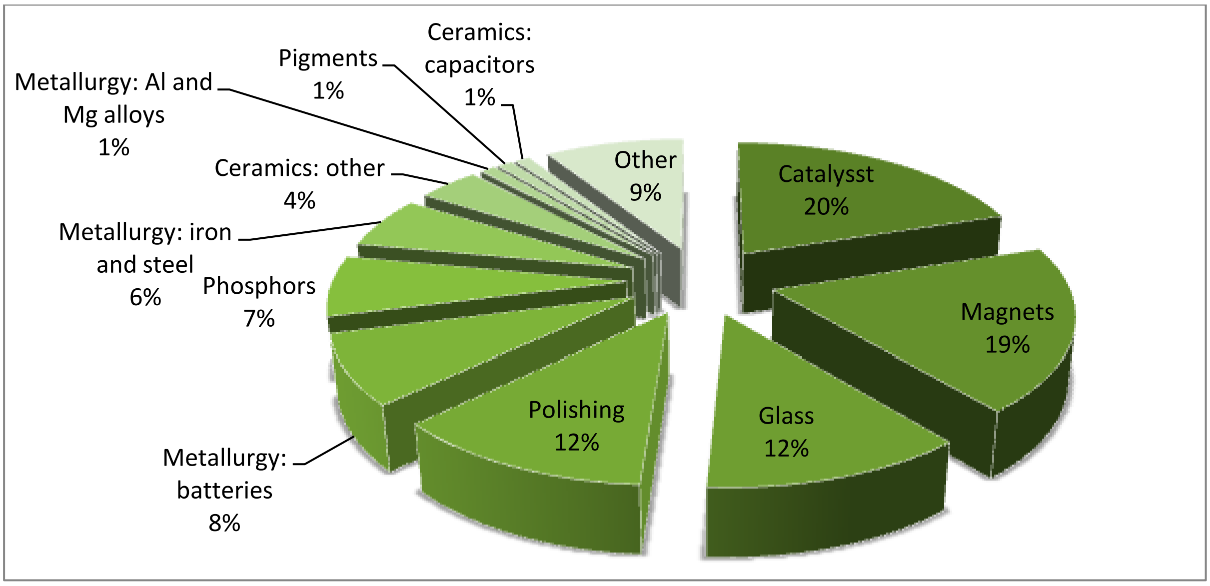
containing rare earth elements include bastnaesite and monazite. Different deposits contain different proportions of each element, with those containing higher proportions of the heavier metals (such as neodymium and dysprosium) currently being the most desirable.

Extraction and refining of rare earths from ore is complex due to the similar properties of the metals. Extraction can occur through typical mining processes, however other techniques are also used which use acid leeching to extract the rare earth ores in situ, causing environmental concern over the production of these metals. Additional complexity is added where other metals are present, for example, some deposits also contain the radioactive element thorium, which needs to be safely separated and stored as part of the extraction process. Once the rare earth containing ore is obtained, a complex multistage process is required, which uses small differences in solubility to isolate each metal as its oxide, and rare earths are typically supplied as an oxide.

1.12.1 Key Applications and Potential Future Substitution

Rare Earth elements are a fundamental constituent of many of today's hi-tech materials. These materials find key applications in catalytic converters, magnets and many other uses, Figure 39.

Figure 39: Overall end uses of rare earth elements, by economic value



Source: EU

Catalysts
Approximately 20% of the rare earth metals are used in catalysts. According to Lynas Corporation Ltd, around two thirds are used for fluid catalytic cracking (FCC) conversion processes, used in petroleum refining catalysts. Lanthanum and cerium used in FCC processes account for 90% and 10% respectively of the rare earth use in this application.[a] Automotive catalytic converters account for most of the remainder of rare earth usage in this sector. Cerium is primarily used in catalytic converters, where it is present as an oxide to aid conversion of harmful exhaust gases and to improve the stability of the catalytic converter.

Magnets
Rare earth metal based magnets are by far the strongest known permanent magnetic materials, therefore rare earth magnets find a large number of uses. Two types of rare earth based magnet have been developed: neodymium iron boron (NdFeB), reliant on the rare earth neodymium, and samarium cobalt magnets (SmCo), reliant on samarium. Neodymium magnets are the more powerful of these two

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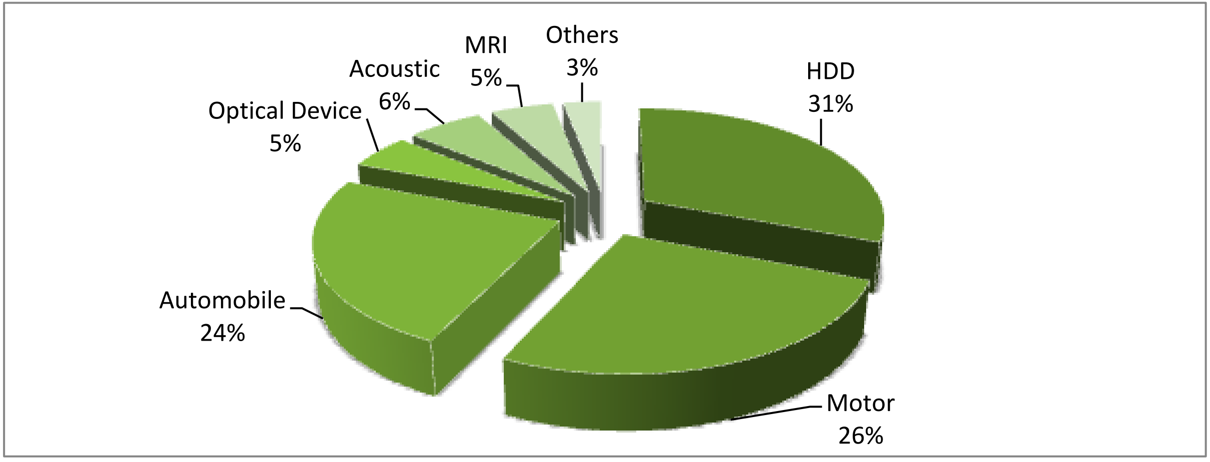
[a] Lynas Corporation Ltd., International Metals Conference, April 2010 - Percentages represent estimated average consumption distribution by application

and therefore are more widely use. The use of SmCo magnets has declined since the discovery of neodymium based magnets, and they now mainly find use in niche applications, for example, in high temperatures applications or corrosive environments.

Pure NdFeB magnets consist of 66% iron, 32% neodymium and 1% boron.[a] However, other rare earth elements are often substituted in place of neodymium to provide different properties, and allowing magnets to be tuned for a specific application. Therefore the actual overall average rare earth content of a NdFeB magnet is estimated to be 69% neodymium, 5% dysprosium, 23.4% praseodymium, 2% gadolinium, 0.2% terbium.[b] Dysprosium is particularly important as it enhances the temperature performance of these magnets, and almost all dysprosium production is used in these magnets. *Figure 40* shows the uses of neodymium magnets, which includes applications such as generators in wind turbines and electric motors for hybrid cars. Smaller magnets are used in computer hard disk drives (HDD), microphones, loudspeakers or in-ear headphones.

Figure 40: Applications of Neodymium Magnet by weight



Source: Shin Etsu presentation at 5th International Rare Earths Conference in 2009

Glass and Polishing

Cerium (65%), lanthanum (31.5%) and praseodymium (3.5%) are used, amongst others, in polishing agents for equipment such as LCD screens, plasma screens, CRT screens, optical lenses and other precision optical and electronic components.[c]

Historically, cerium (66%), lanthanum (24%), neodymium (3%), yttrium (2%) and praseodymium (1%) were widely used as additives for CRT screens, to protect the glass from the cathode ray, however this use is clearly diminishing. Nowadays, this application is typically used on to small, high performance optical lenses.[d]

Batteries

Approximately 8% of the rare earth elements are used as an alloy in rechargeable nickel-metal hydride (NiMH). To minimise costs associated with separation a mixture of metals is often used know as mischmetal, which exhibits similar performance to purer mixtures. Mischmetal used for this purpose typically consists of lanthanum (50%), cerium (33.4%), neodymium (10%), praseodymium (3.3%) and samarium (3.3%). [e,f] NiMH batteries are widely used in hybrid electric vehicles (HEV), representing more than half the usage, other applications include portable tools, cordless phones and games, Figure 41.

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[a] Oakdene Hollins, Lanthanide Resources and Alternatives, May 2010

[b] Lynas Corporation Ltd., International Metals Conference, April 2010 - Percentages represent estimated average consumption distribution by application

[c] Lynas Corporation Ltd., International Metals Conference, April 2010 - Percentages represent estimated average consumption distribution by application

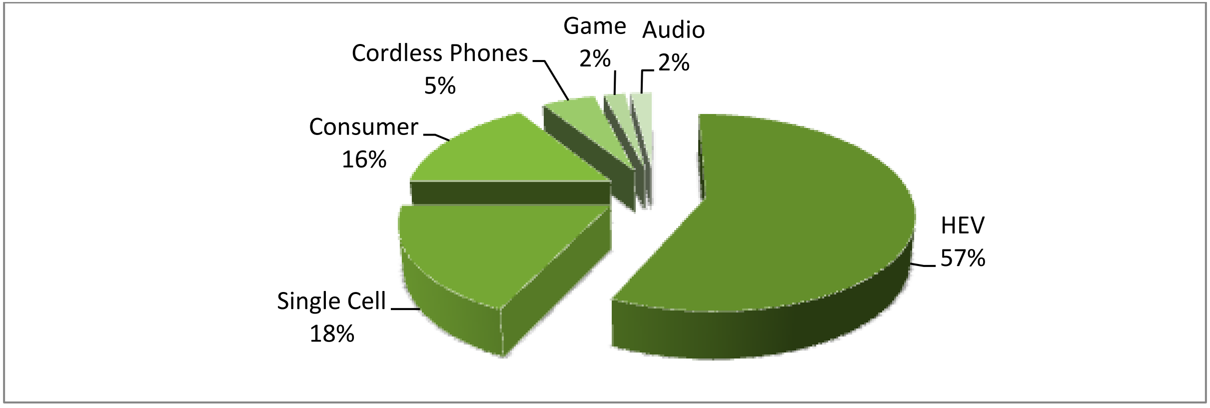
[d] Lynas Corporation Ltd., International Metals Conference, April 2010 - Percentages represent estimated average consumption distribution by application

[e] Lynas Corporation Ltd., International Metals Conference, April 2010 - Percentages represent estimated average consumption distribution by application

[f] Lynas Corporation Ltd., International Metals Conference, April 2010

However, many of these applications are beginning to switch to lithium based batteries which offer better performance.

Figure 41: Breakdown of NiMH batteries by end use, 2007



Source: Roskill presentation

Further uses of rare earths include[a]:

Applications of REEs	Percentage	Rare Earth Elements
Phosphors	7%	Y, Ce, La, Eu, Gd, Tb
Metallurgy (iron and steel/ Al and Mg alloys)	7%	Ce, La, Pr, Nd
Ceramics (e.g. capacitors)	5%	Y, La, Ce, Pr, Nd
Pigments	1%	Ce, Pr, Nd

Potential Future Applications

Extensive research activities are ongoing in the application of rare earth based materials, and it is predicted that there will be new applications for magnetic devices, catalysts, batteries, electronics, fibre optics and medical applications. One promising technology is the magnetic refrigeration, which could eventually substitute conventional gas-compression refrigeration, as it is more efficient and requires no refrigerant.[b] Additionally the use of rare earth magnets in offshore wind farms is expected to place large demands on the supply of rare earths, particularly neodymium and dysprosium. The gearless turbines which use these motors are expected to be more reliable than others, making them attractive for offshore use.

Recycling

To date, only very small quantities of rare earth elements (estimated 1%[c]) have been recycled from pre-consumer scrap, mainly permanent magnet scrap despite certain magnet manufacturing processes wasting 50% of material. There is no information or evidence of any current activities in the post-consumer recycling.

Two very active research themes exist in this area, these are looking at minimisation of rare earth usage (such as the quantity of dysprosium in magnets) and the recovery and recycling of rare earths. These are addressed in more detail in the best practices section of this report. Other work has investigated possible alternative sources of rare earth ores, such as from titanium oxide minerals.

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[a] Lynas Corporation Ltd., International Metals Conference, April 2010

[b] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

[c] Critical raw materials for the EU. European Commission, 2010

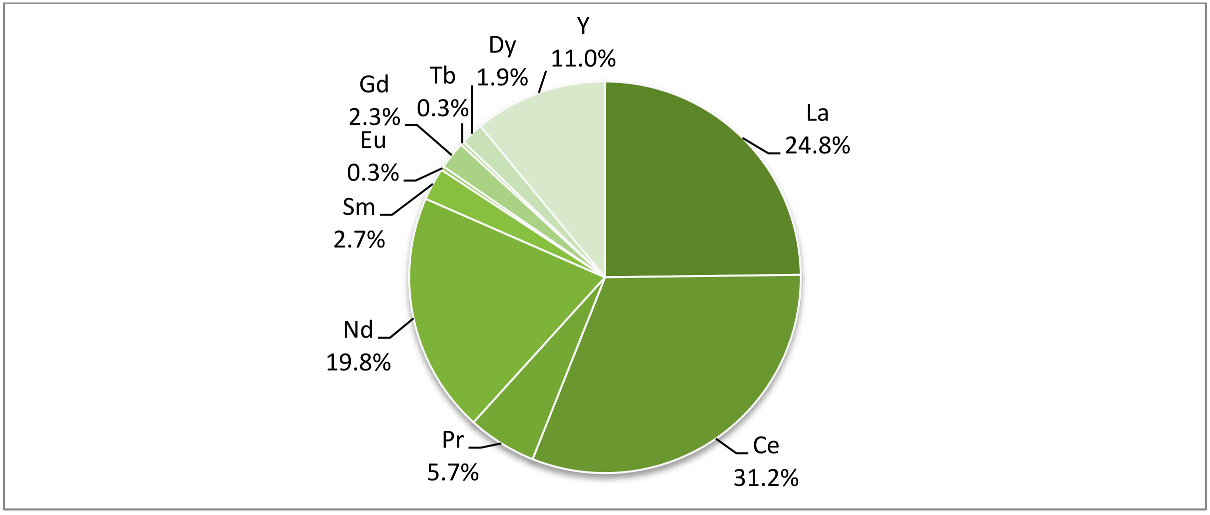
Substitutes

Substitutes are available for many applications, but they are generally less effective, less suitable or more expensive. [a] For example, lithium-ion batteries can be used in hybrid vehicles instead of NiMH batteries.

Current European and global Output and Reserves

World mine production for rare earths was 124,000 tonnes in 2009. The composition of rare earth supply is shown in Figure 42. Four elements (Lanthanum, Cerium, Neodymium and Yttrium) comprise 85% of total rare earth supply.

Figure 42: Composition of Global Rare Earth Supply, 2010



Source: Lynas Presentation (April 2010), International Minor Metals Conference

China dominates world production of rare earths with 97% of world production in 2009, Table 14. The rare earth producing company is Inner Mongolia Baotou Steel Rare-Earth Hi-Tech, which in 2008 had a production of 60-70,000 tonnes of rare earth concentrate at its Bayan Obo Bastnasite mine[b] (just over 50% of world production of rare earths). Production from ion adsorption clays in Southern China accounted for around 50,000 tonnes of rare earth production in 2008, although these are typically small and sometimes illegal mining operations.

As for the geographic distribution of rare earth reserves, China's position is much less dominant than it is for production, accounting for 36% of world reserves. The CIS, United States and Australia also have large reserve deposits for rare earths. It is notable that 'Other countries' represent a large fraction of rare earth reserves at 22% of the total. These 'Other countries' include reserves in Greenland and Turkey, which are of interest from a European perspective[c].

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[a] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

[b] IMCOA Presentation (2010), The Challenges of Meeting Rare Earths Demand in 2015

[c] See USGS (2010), "The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective" for more information on rare earth resources.

Table 14: World Rare Earths Production and Reserves 2009 (tonnes of rare earth oxide content)

Country	Mine production	Reserves
China	120,000	36,000,000
India	2,700	3,100,000
Brazil	650	48,000
Malaysia	380	30,000
Commonwealth of Independent States	NA	19,000,000
United States	—	13,000,000
Australia	—	5,400,000
Other countries	NA	22,000,000
World total (rounded)	**124,000**	**99,000,000**

Source: USGS Mineral Commodity Summaries (2010)

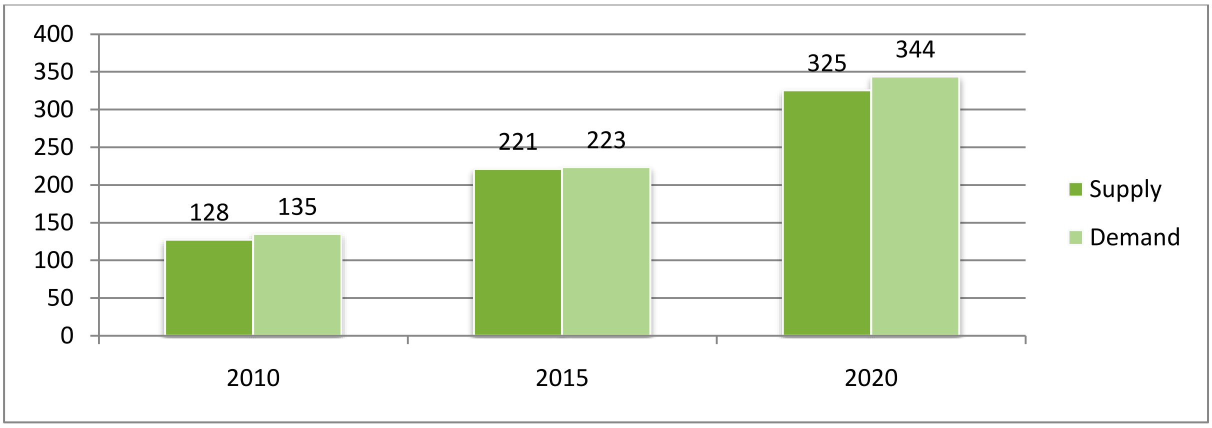
Global Demand and Supply, and Price Forecasts Until 2020

Rare Earth supply and demand forecasts are given in Figure 43; both of which are set to more than double over ten years. The supply shortage that currently exists for Rare Earths (6% of supply) is expected to continue, although the severity is forecast to lessen somewhat to around 1% of supply in 2014-2015, before worsening out to 6% by 2020. However it should be noted that this is the pattern for rare earths as a whole and masks variation between elements e.g. large surpluses forecasted for cerium and sizeable deficits for elements such as neodymium and dysprosium[a].

The assumptions underlying the supply and demand forecasts are:

- Global supply and demand for rare earth oxides were 124kt in 2008.
- IMCOA[b] forecasts for demand and supply until 2014.
- Longer term supply assumes growth slowing to 3% per year for Chinese supply, but remaining at 20% per year for supply in the rest of the world[c] .
- Longer term demand assumes a 9% per year global growth rate, as modelled by Öko-Institut[d].

Figure 43: Rare Earth Supply and Demand Forecasts (kt)



Sources: Own Calculations based on IMCOA, Öko-Institut

Prices for Rare Earths have increased substantially over the past years and escalated sharply in 2010, reaching nearly $80/kg for a composite price late in 2009 on the back of strong demand, aggressive tightening of export restrictions in China, and ongoing uncertainty about the further development of

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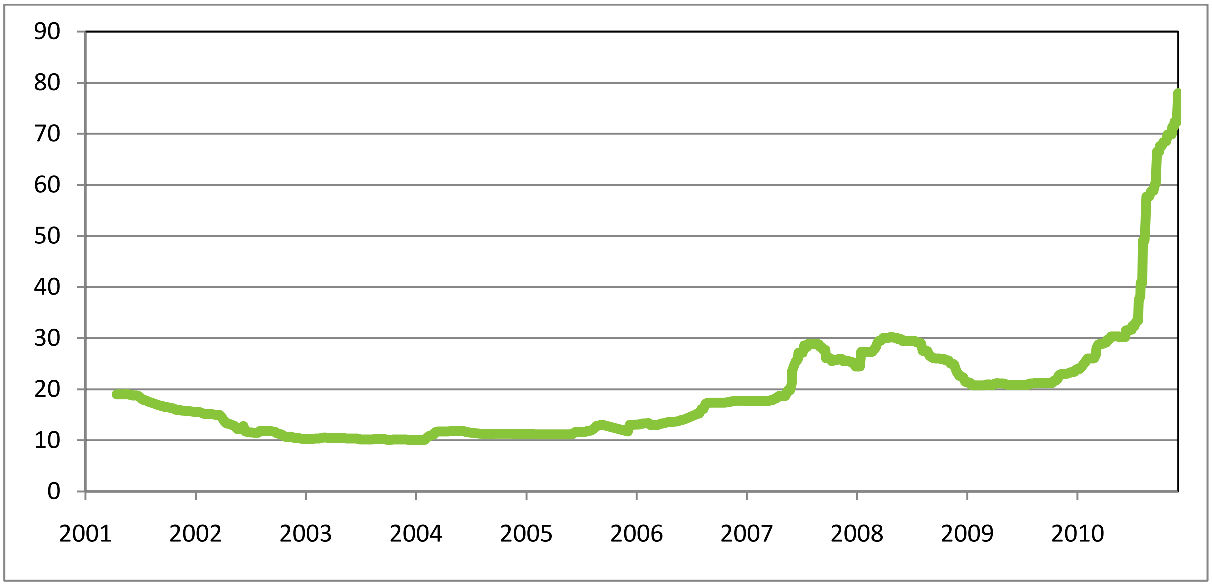
[a] IMCOA presentation at 5th International Rare Earths Conference in 2009
[b] IMCOA presentation at 5th International Rare Earths Conference in 2009
[c] Oakdene Hollins for DfT, (2010), Lanthanide Resources and Alternatives – Scenario 2
[d] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

Chinese policy (Figure 44). It should be noted that rare earths tend to represent a very small proportion of the final price of a product and are not readily substitutable. Despite several new projects outside of China that are due to come online over the coming years, expected strong demand growth is likely to sustain a supply deficit, resulting in continuing upward pressure over the coming decade.

Figure 44: Rare Earth Oxide Prices Developments (composite of 9 metals[a]), min. 99% Purity[b] on an FOB China Basis (US$/kg)



Source: Metal Pages

1.13 Tantalum

Tantalum (Ta) is a shiny, gray, highly ductile metal. Tantalum is an excellent conductor of heat and electricity, and in comparison to other metals it has melting point exceeded only by tungsten and rhenium. Like Niobium, tantalum is a major refractory metal and has a very high resistance to heat and wear. It is considered to be non-toxic in its elemental form.

The abundance of tantalum in the earth's crust is 1.7 ppm. As with most metals it is not found free in nature, and it is often found in co-deposited with niobium. Common tantalum containing minerals are called tantalites or columbites, depending on the proportion of tantalum or niobium present. Tantalum is also present in the tin slags and the tailings produced in South East Asia.

Extraction of tantalum is generally produced by treating ores with a mixture of hydrofluoric and sulphuric acids at high temperatures. The resulting tantalum compounds can then be separated from the impurities. Tantalum metal powder is produced by the reduction of the purified tantalum compound with sodium at high temperature. An alternative method tantalum production method has also been developed. This involved the reduction of the metal oxide within the ore with carbon or aluminium, or the reduction of the chloride with hydrogen or an alkaline earth metal. The metal powder is then compacted and sintered at over 2,500°C and the resulting rods are purified by either vacuum arc or electron beam melting[c].

The Democratic Republic of Congo is home to the world's largest tantalum reserves.

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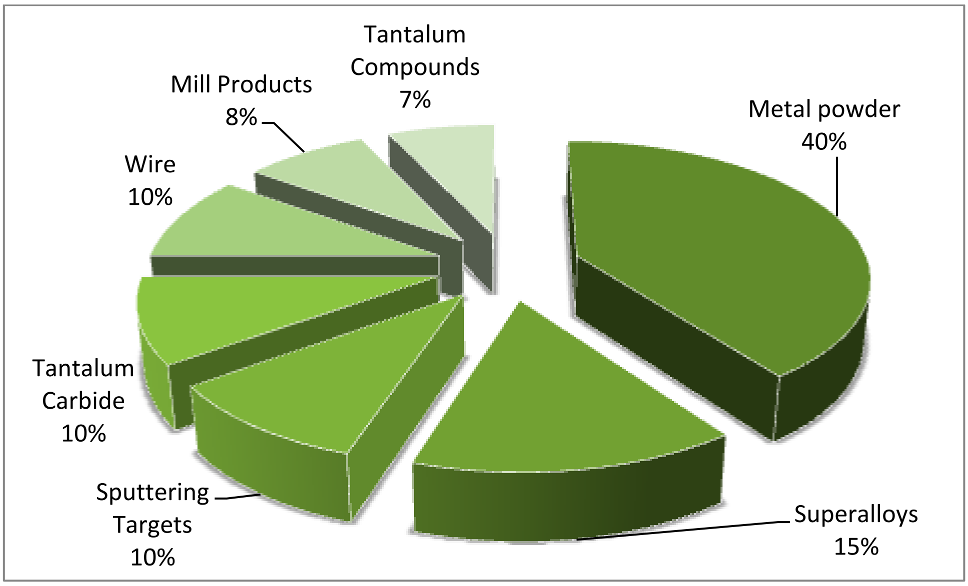
[a] Based on the composition shown in Figure 42, only with Gadolinium excluded due to a lack of long term price data

[b] Yttrium with a min 99.9% purity

[c] MBM, Tantalum, February 2008

Key Applications and Potential Future Substitution

Figure 45: Applications of Tantalum, 2007 by value.



Source: Hard Assets

The primary use of tantalum is in capacitors used in electronics where both tantalum powder and wire is used. Tantalum capacitors have become the standard in many electronic applications such as laptops, smart phones, video and digital cameras, and games consoles. Mobile phones with cameras contain around 23 separate tantalum capacitors. In automotive control systems tantalum capacitors are used in ignition, engine emission, airbags, and automatic braking (ABS) systems. They are also used in medical appliances such as hearing aids and pacemakers, structural implants as well as military uses where high reliability is essential. Tantalum capacitors account for an estimated 50% of tantalum consumption, and account for between 2-5% of the capacitor market.[a] However, this is likely to increase, and the EU report on critical materials estimates that the future demand for tantalum in capacitors will triple in the next two decades, mainly due to the increased production of electrical devices.

Superalloys are the second highest consumer of tantalum. These specialist and high performance alloys are required where operational conditions, such as temperature, are extreme. The most common use is as an additive to nickel-based superalloys used in turbine blades, both for jet engines and stationary gas and steam turbines, as well as for the construction of industrial chemical equipment. Typically these alloys contain 3-11% tantalum, however some turbine components with tantalum-containing coatings contain up to 15% of tantalum.[b]

Further uses of tantalum include:

- Tantalum carbide - used to make hard metals for drill bits and cutting blades. The largest consumer of these is the automotive industry.

- Sputtering targets – used in the production of semiconductors and glass.

- Mill Products, in the form of plates, rods, sheets and tubes; tantalum is used in:
    - furnace parts
    - artificial hip joints and suture clips
    - corrosion-resistant nuts and bolts
    - military applications (e.g. gun barrel coatings)

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[a] MBM, Tantalum, February 2006

[b] Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

- Tantalum chemical compounds - mainly tantalum oxide, are used in such things as camera lenses, ink jet printers and X-ray film. Tantalum oxide is also used in surface acoustic wafers for infra-red devices, in mobile phones, hi-fi stereos and television.

Recycling

Table 15 shows a breakdown of the historical supplies of tantalum.

Table 15: Historical sources of tantalum

Source	Percentage
Primary concentrates	60%
Secondary concentrates	10%
Tin slag	10%
Scrap recycling, synthetic concentrates	20%

Source: Tantalum-Niobium International Study Centre

Rather than being recovered at tend of lift, tantalum is recycled mainly from new scrap, generated during the manufacture of tantalum-containing electronic components, and from tantalum-containing cemented carbide and superalloy scrap. Tantalum scrap recycling, within the various segments of the tantalum industry, accounts for about 20% of the total input each year. Old low tantalum grade tin slags also contribute a significant proportion of supply. These waste deposits are either hydrometallurgically processed to chemical intermediates (China) or pyrometallurgically upgraded to synthetic concentrates (Germany).

Recycling from capacitors, the main use of tantalum is difficult and insufficiently developed due to the dissipative used of tantalum in this application. Some post consumer recycling takes place in the form of tantalum bearing cemented carbide and super alloys. Information about recycled content from old scrap differs from less than 1% to 9%.[a]

Substitutes

In certain applications tantalum can be substituted by other materials with a loss in effectiveness. Niobium can replace tantalum in carbides. Niobium, platinum, titanium, and zirconium can be used as a substitute in corrosion resistant equipment. Hafnium, iridium, molybdenum, niobium, rhenium, and tungsten are possible substitutes in high-temperature applications. [b]

Competitive capacitor materials are now in development, such as materials derived from aluminium, ceramics, and niobium. This might become strong competition for tantalum based capacitors in the future. New technologies are also being developed to significantly increase tantalum powder capacitance to well beyond the present limits of current technology; this will help reduced the quantity of tantalum required in each capacitor.[c]

Current European and Global Output and Reserves

World mine production of tantalum was 1,160 tonnes in 2009 of which Australia accounted for around half of global production, Table 16. Most of this production originated from a single mine, Wodgina owned by Talison Minerals, although production from this mine was suspended during 2009. African countries (Congo, Rwanda and others) accounted for 35% of world supply. Significant individual mines exist in Mozambique and Ethiopia (77 tonnes each in 2008), but much of the other African Tantalum mining is small and artisanal. Brazilian production comes from two separate mines. No tantalum mining is known to have taken place in Europe.

Estimates of tantalum reserves are only available for Brazil and Australia.

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[a] Critical raw materials for the EU. European Commission, 2010

[b] USGS, Mineral Commodity Summaries, 2010

[c] D. Henderson (Rittenhouse International Resources), Tantalum, 2010

Table 16: World Tantalum Production and Reserves 2009 (tonnes of tantalum content)

Country	Mine production	Reserves
Australia	560	40,000
Brazil	180	65,000
Congo (Kinshasa)	100	NA
Rwanda	100	NA
Canada	40	NA
Other countries	180	NA
World total (rounded)	**1,160**	**110,000**

Source: USGS Mineral Commodity Summaries (2010)

Global Demand and Supply, and Price Forecasts Until 2020

The market situation for Tantalum is one of considerable uncertainty, with some commentators fearing there may be serious shortages for tantalum in the coming years[a]. On the demand side, the Öko-Institut models growth rates of 5.3% being reasonable (Figure 46) with a 3.4% growth rate being a more conservative alternative possibility[b]. A higher growth rate of 9.2% per year has been forecasted by another organisation[c]. A figure of 1,400 tonnes has been selected for 2010 to take account of the recovery in demand to earlier levels following a period of weak demand after the financial crisis[d].

The supply situation for tantalum is not one that can be forecasted with much degree of accuracy. In 2008 in a matter of months, 40% of global primary production capacity was closed in response to low prices and demand and it is unclear when or if it will return to production[e]. A key issue regards the supply of low cost and illegally mined coltan (a tantalum ore) in Central Africa where much of the funds are used to fund rebel militias. In the meantime inventories are being run down, with the US Strategic stockpile having already been exhausted. There are prospects for the opening of tantalum mines in Mozambique and Egypt, which have the potential, but their openings have been delayed by a number of years by red tape and other issues[f]. With these issues in mind the outlook for tantalum supply must be considered highly uncertain. In the near term there could be severe shortages if new mine capacity is further delayed, but in the long term excess capacity is also possible in response to rising prices. For the purposes of the forecasts in Figure 46, it has been assumed that the mines due for opening in Egypt and Mozambique are open by 2015 and the reopening of mines in Australia occurs by 2020, adding to current supply.

Tantalum metal is not publicly traded so prices on the metal are not available. Price developments can however be assessed from price movements of tantalite concentrate, at 30% purity of Ta_2O_5, Figure 47. Prices for tantalite crashed from above $300/lb following the bursting of the dotcom bubble in 2000-2001. For most of the last decade prices have ranged between $30/lb and $45/lb, although in the last year they have risen considerably as concerns over supply have mounted. Further price rises are probable in the short term until new mining capacity comes on-stream.

---

[a] For example Roskill (2009), The Economics of Tantalum, 10th Edition

b Öko-Institut for UNEP (2009), Critical Metals for Future Sustainable Technologies and their Recycling Potential

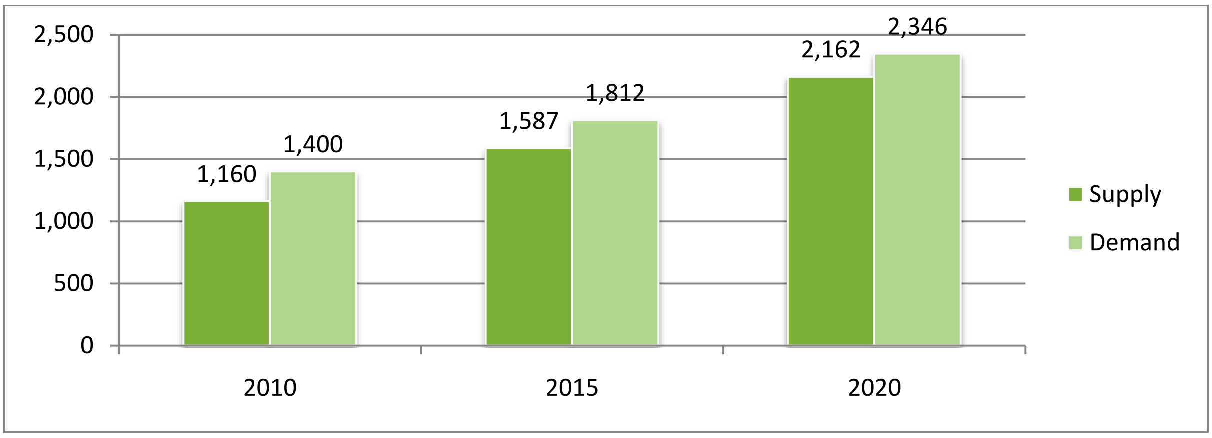
[c] Paumanok (2010), Tantalum Capacitors: World Markets, Technologies & Opportunities: 2010-2015

[d] Hendreson of Rittenhouse International Resources (2010), Tantalum

[e] Roskill (2009), The Economics of Tantalum, 10th Edition

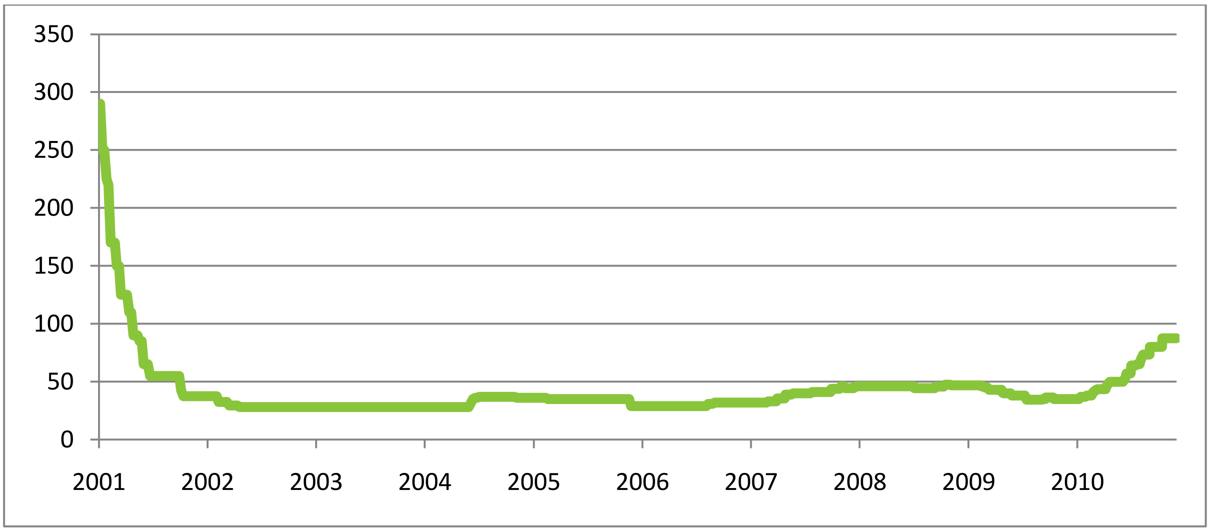
[f] E&MJ (September 2008), Africa remains key to future tantalum supply

Figure 46: *Tantalum Demand and Supply Forecasts (t)*



Sources: Own Calculations based on Öko-Institut & E&MJ

Figure 47: Tantalum Price Developments, Tantalite basis 30% Ta_2O_5 *(US$/lb)*



Source: Metal Pages

1.14 Tungsten

Tungsten has the highest melting point of any metal, and has an extremely high density (1.7 times that of lead) and low vapor pressure; it also retains its strength at high temperatures. Tungsten's properties, particularly as a carbide, make it highly valued in hard metal alloys which are used for applications such as cutting tools, carpentry tools and rolling mills. The alloys used for these applications combine the high hardness and strength of the tungsten carbide with the toughness and plasticity of a metallic binder (e.g. Co, Ni, Fe).

Tungsten's abundance in the earth's crust is 1.25 ppm. As with the majority of metals it is not found free in nature, and although more than thirty tungsten bearing minerals are known, the only ores of tungsten important for industrial use are wolframite (an iron manganese tungstate) and scheelite (calcium tungstate).[a]

Tungsten is extracted from its ores in several stages. One common method initially concentrates the ore by using tungsten's magnetic properties.[b] Tungsten is then extracted from this concentrated ore with hydrochloric acid yielding a precipitate of tungsten trichloride. This precipitate is then dissolved in

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[a] Critical raw materials for the EU. European Commission, 2010

[b] Tungsten is not strongly magnetic like iron, but retain a small amount magnetism

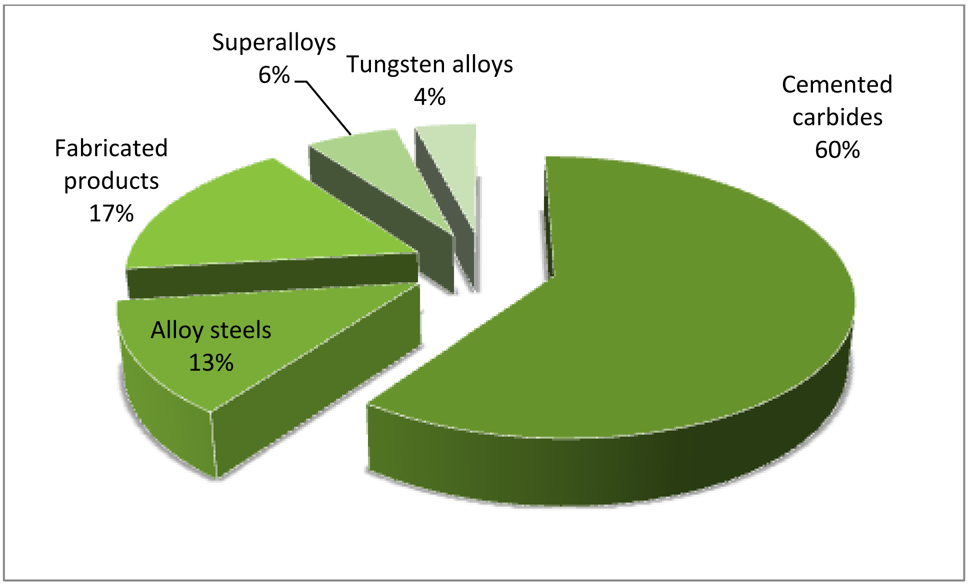
ammonia and the tungstate formed though this process is crystallised[a]. This tungsten oxide is heated with hydrogen or carbon to produce powdered tungsten.

China has about 60 % of the world tungsten reserves.

1.14.1 Key Applications and Potential Future Substitution

About 60 % of the tungsten production worldwide is consumed by hard metals (cemented carbides).[b] Hard metals are used for cutting and wear-resistant materials, primarily in the construction, metalworking, mining, and oil- and gas-drilling industries. For example, cemented carbide is used for: micro drills circuit board production, general manufacturing, large equipment manufacturing, mining, and oil and gas drilling.

Figure 48: Application of Tungsten by value.



Source: Critical raw materials for the EU (2010)

13% of all tungsten is used in steel alloys where it improves the performance for each use. These highly alloyed steels are used primarily in working, cutting and forming of metal components, and fall into three categories: tool steels, high speed steels (HSS) and heat resisting steel. Tool steels contain between 0.5 and 9% of tungsten and are used for most types of tool. High speed steels (HSS) are a more specific variety of tool steel which are used where higher performance is necessary such as for cutting tools: drills, taps, milling cutters, gear cutters, saw blades, etc. HSS contain between 1.5 and 18% of tungsten depending on grade. However, the use of tungsten in HSS is declining due to new coating techniques and the increasing switch-over to higher performance cemented carbide tools, which also contain tungsten.

Tungsten is also used in superalloys which can contain up to 6% tungsten. The main use is in alloys for combustion engines valves, such as the outlet valves; these can contain around 2% tungsten. Such alloys are necessary as the red-hot hardness of the component has to be combined with high temperature corrosion resistance.[c]

The remaining tungsten is used in:

- tungsten heavy metal alloys used for applications requiring high density such as:
    - armaments, heat sinks, and weights and counterweights
    - wear-resistant alloy parts and coatings

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[a] http://www.ucc.ie/academic/chem/dolchem/html/elem/elem074.html
[b] International Tungsten Industry Association, http://www.itia.info/, accessed 21/12/2010
[c] International Tungsten Industry Association, http://www.itia.info/, accessed 21/12/2010

- electrodes, filaments, wires, and other components for electrical, electronic, heating, lighting, and welding applications
- chemicals for various applications such as catalysts, corrosion-resistant coatings, dyes and pigments, fire-resistant compounds, lubricants, phosphors, and semiconductors
- high tech applications in nuclear and fusion applications
- light bulbs, television sets, magnetrons for microwave ovens and other electrical consumer products.

The future demand for tungsten used in cemented carbides, its main end-use, strongly depends on developments in the automotive and aircraft production, construction and electronics manufacturing industries. Tungsten use is also influenced by Government spending for defence applications. [a]

Recycling

35 to 40% of all tungsten consumed by industry in general comes from scrap; this corresponds to about 34,000 tonnes. The high tungsten content in scrap, compared to ore, makes it a very important factor in the world's tungsten supply. According to the International Tungsten Industry Association (ITIA) the tungsten processing industry is able to treat almost every kind of tungsten-containing scrap and waste to recover tungsten, and, if present, other valuable constituents.

However, recycling in many applications is at a low level. For example, the recycling of lamp filaments does not take place at all due to the very small amount of tungsten used in such applications (average coil weight: 30 mg). The recycling of welding electrodes and chemicals is low.

Substitutes

Cemented tungsten carbides can be substituted by cemented carbides based on molybdenum carbide and titanium carbide, ceramics, ceramic-metallic composites (cermets), diamond tools, and tool steels.

Potential substitutes for other applications are as follows:

- Molybdenum for certain tungsten mill products
- Molybdenum steels for tungsten steels
- Lighting based on carbon nanotube filaments, induction technology, and LEDs for lighting based on tungsten electrodes or filaments
- Depleted uranium for tungsten alloys or unalloyed tungsten in weights and counterweights
- Depleted uranium alloys for cemented tungsten carbides or tungsten alloys in armor-piercing projectiles.

In some applications, substitution would result in increased cost or a loss in product performance. [b]

1.14.2 Current European and global Output and Reserves

World mine production of tungsten was 58,000 tonnes in 2009 of which around 80% originated in China, Table 17. Data for production for specific Chinese companies is scarce, but insights are available from the distribution of export quotas. For the first half of 2011, export quotas for tungsten (APT, acid, oxides, powders) are nearly 12,000 tonnes, split between 14 companies. Three companies account for over half the total: Minmetals Nonferrous Metals (26%), Xiamen Tungsten (15%) and Jiangxi Rare Earth and Metal Tungsten (14%)[c].

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[a] USGS, Mineral Yearbook – Tungsten, 2008

[b] USGS, Mineral Commodity Summaries, 2010

[c] Metal Pages (29 December 2010), Chinese Export Quotas for tungsten in H1, 2011

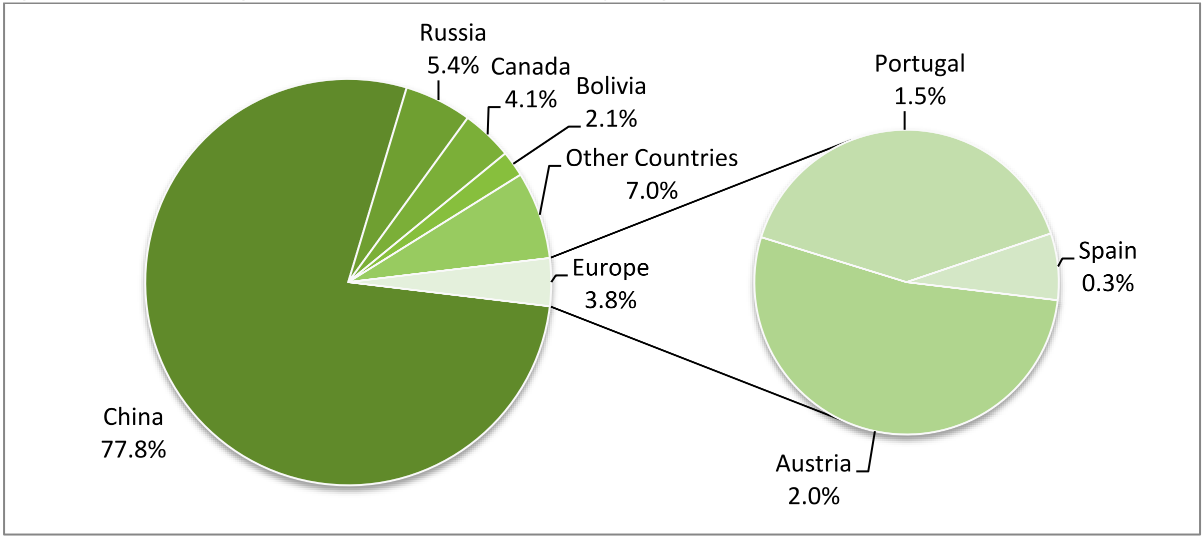
A small amount of tungsten, roughly 4% of global supply, was produced in Europe in 2008 in Austria, Portugal and Spain (Figure 49). Large reserves exist for tungsten – around two of which is located in China, but significant deposits exist in Russia, United States and Canada.

Table 17: World Tungsten Production and Reserves 2009 (tonnes of tungsten content)

Country	Mine production	Reserves
China	47,000	1,800,000
Russia	2,400	250,000
Canada	2,000	110,000
Austria	1,000	10,000
Bolivia	900	53,000
Portugal	850	4,200
United States	0*	140,000
Other countries	3,700	400,000
World total (rounded)	**58,000**	**2,800,000**

Source: USGS Mineral Commodity Summaries (2010)
** Withheld in USGS data, but not listed as a producer by BGS*

Figure 49: World Tungsten Production 2008 (tonnes of tungsten content)



Source: USGS (2010), Tungsten 2008 Minerals Yearbook

Global Demand and Supply, and Price Forecasts Until 2020
Tungsten demand and supply forecasts show that a significant shortage for tungsten is likely to open up in the early part of the coming decade based upon forecasts from CRU. This shortage is due to China implementing measures to control its tungsten resources, high growth rates in demand and the time that it will take for non-Chinese supplies to become established.

The main assumptions underlying the forecasts are:

- Demand growth for tungsten is as strong as the global economy recovers, but slows to a long run rate of growth of 3.8% per year whilst growth in supply from China is modest, at around 2.8% per year[a].
- Supply from the rest of the world is strong at 13% per year to 2020 with a number of mines opening, identified by Roskill (2007) in Australia, and Vietnam[a], and also South Korea by 2015[b], which had been held up a few years due to weak demand.

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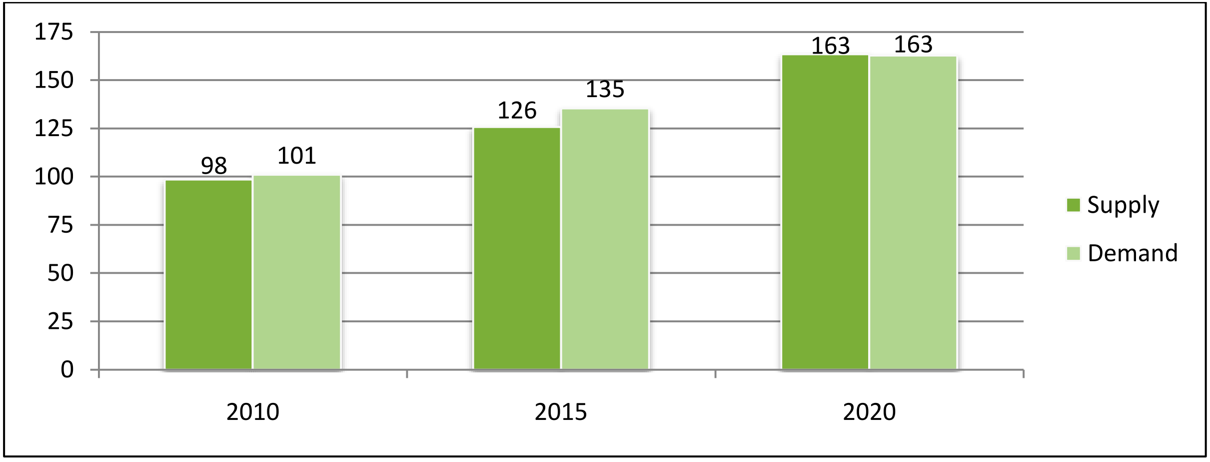
[a] CRU (2009) in Ormonde Mining Presentation (2010), Tungsten Market Overview

- Secondary production is 34,000 tonnes in 2009 and grows at a rate of 5% per year[c].

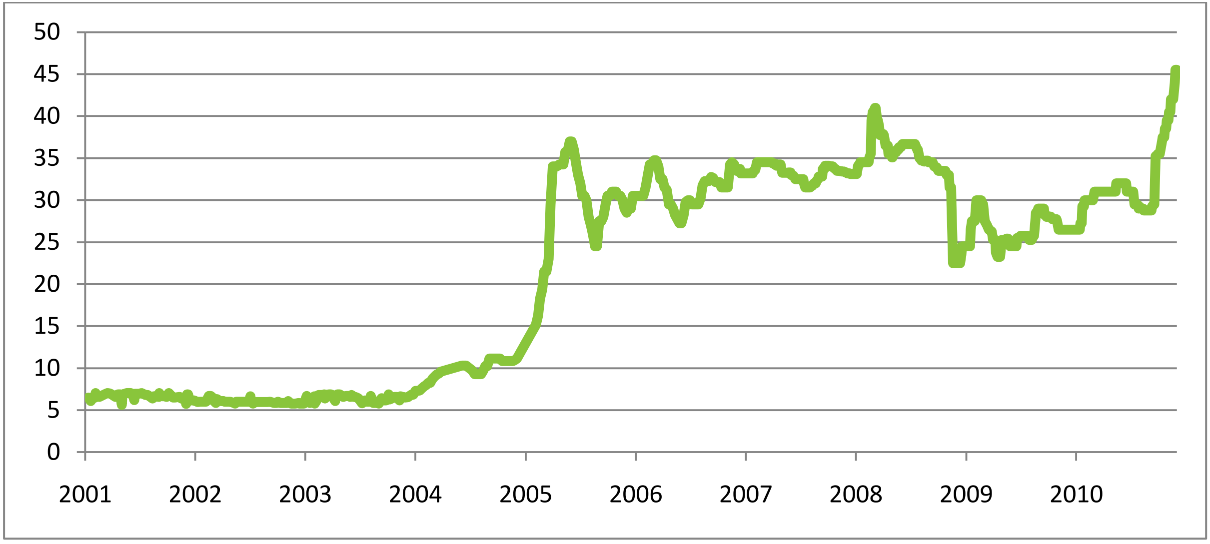
Price developments for Ferro-tungsten are shown in Figure 51. For the early part of the last decade prices were steady at $6-7 per kg. However at the beginning of 2005 prices soared to $35 per kg and since then have move roughly in the $25-35 per kg range; and are currently at a high of $45 per kg. Further prices rises seem probable in the medium term due to the tightness in world supply forecasted.

Figure 50: Tungsten Demand and Supply Forecasts (kt)



Source: CRU (2009) & own calculations based on Roskill (2007), GBRM (2008)

Figure 51: Ferro-tungsten Price Developments min W 75% FOB P.R.C. ($/kg)



Source: Metal Pages

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[a] Roskill (2007), The Economics of Tungsten, 9th Edition

[b] Woulfe Mining Presentation (2010), Outlook for Tungsten

[c] GBRM (2008), A Preliminary Review of Tungsten

2 Annex B – Best Practice Review Methodology

To review best practice of resource efficiency for each material, in particular recycling technologies, a literature review was undertaken. The initial task was to identify and categorise relevant documents for further analysis. This work was performed by the RRF, using their methodology below. The documents were then reviewed internally by Oakdene Hollins staff, with further filtering taking place. The most relevant documents were then summarised as part of the main body of the report.

2.1 Identification of Documents and Categorisation and Screening

2.1.1 Identifying Documents

Using agreed forms of words RRF sought specific information from a number of networks around the world, including the following:

- Members of RRF (around 1,000 contacts in more than 30 countries)
- Subscribers to Warmer Bulletin magazine (some 400 contacts worldwide)
- Contacts (industry and academia) in key countries (including Japan, USA and Australasia) – some supplied by OHL
- Particular waste management associations, sectoral trade associations in Europe, America, Australasia and Japan
- Experts who had made relevant presentations at several international conferences (including for example R'09, held jointly in Davos (CH) and Nagoya (J))
- Supranational agencies, including OECD, European Commission and European Environment Agency.

In all, it is likely that up to 2,000 individuals were reached, and around one hundred useful replies were elicited.

Searches were made of online resources. These went above and beyond conventional search engines and included:

- ScienceDirect (2,500 academic and other peer-reviewed journals – not publicly accessible)
- SpringerLink (2,500+ academic and other peer-reviewed journals – not publicly accessible)
- Subscription-only websites such as www.metal-pages.com

Bibliographies of documents identified in the preceding activities were also reviewed. These searches were supplemented by material from OHL and other partners.

In all, the search yielded more than 250 potentially relevant documents.

2.1.2 Classifying the Screening Documents

In accordance with the project requirements, RRF developed a relational database, using the software FileMaker Pro.

Each of the documents (reports, journal papers, brochures etc) was reviewed, to capture the essential information, including bibliographic descriptors, together with relevant content elements (e.g. drivers for change, critical materials, resource efficiency factor, end-use applications), Figure 52.

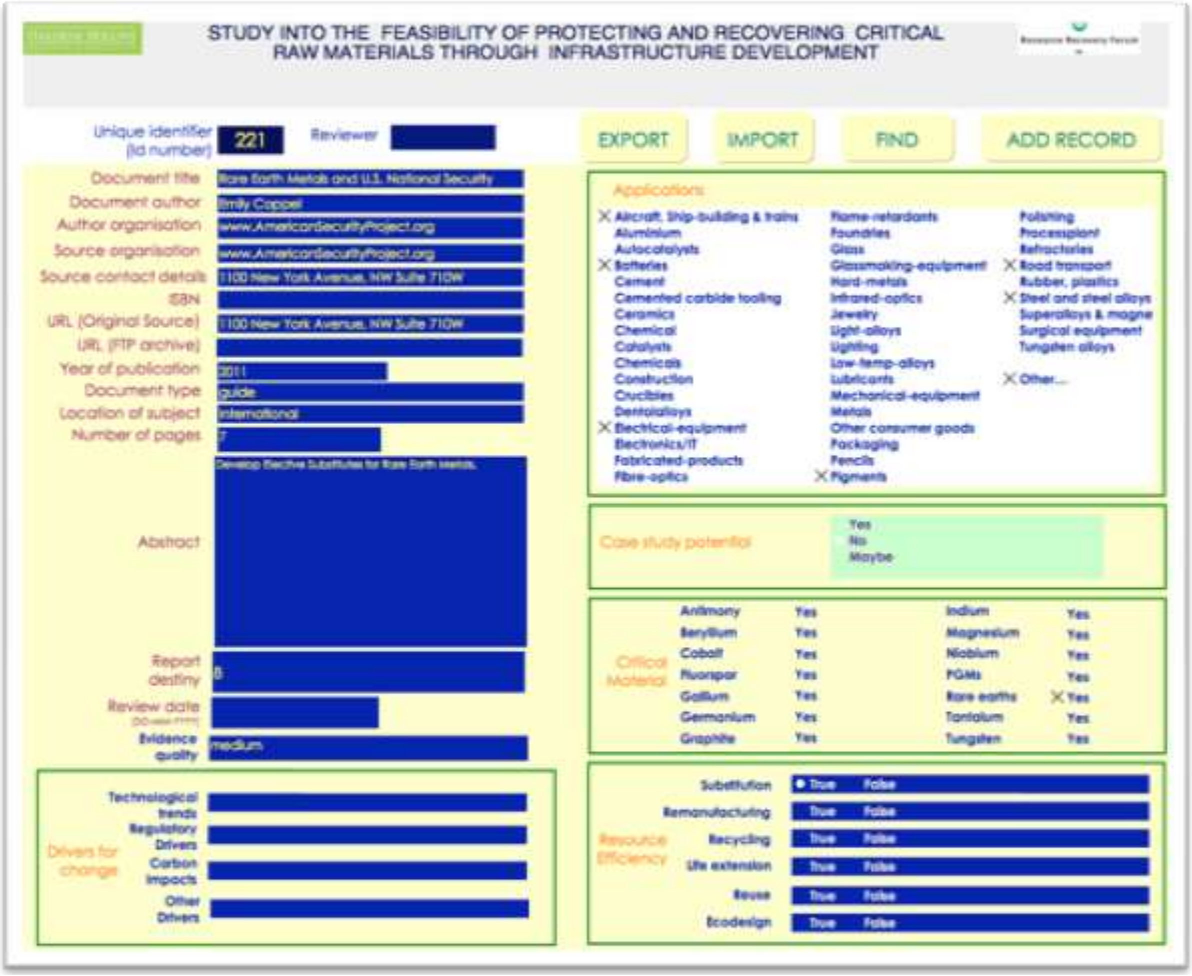
Additional, more subjective attributes were accorded each of the records within the database, which were:

- **'Destiny'** - a simple 1-9 scoring where higher numbers indicate more relevance
- **'Evidence quality'** – where adjectives '*low*', '*medium*' and '*high*' were used to denote higher quality documents
- **'Case study potential'** – perhaps the least subjective of these three descriptors, and arguably the most important.

Exporting all the data from the FileMaker Pro database to an Excel spreadsheet format, Figure 53, it was then possible to sort the records in terms of the potential utility of each.

All the documents were uploaded to a secure FTP server, and the resulting data lists were passed to OHL.

Figure 52: FileMaker Pro database



STUDY INTO THE FEASIBILITY OF PROTECTING AND RECOVERING CRITICAL RAW MATERIALS THROUGH INFRASTRUCTURE DEVELOPMENT

Unique identifier (Id number): 221
Reviewer:
Document title: Rare Earth Metals and U.S. National Security
Document author: Emily Coppel
Author organisation: www.AmericanSecurityProject.org
Source organisation: www.AmericanSecurityProject.org
Source contact details: 1100 New York Avenue, NW Suite 710W
ISBN:
URL (Original Source): 1100 New York Avenue, NW Suite 710W
URL (FTP archive):
Year of publication: 2011
Document type: guide
Location of subject: international
Number of pages: 7
Abstract: Develop Effective Substitutes for Rare Earth Metals.
Report destiny: 8
Review date (DD-MM-YYYY):
Evidence quality: medium

Drivers for change
Technological trends:
Regulatory Drivers:
Carbon impacts:
Other Drivers:

Applications
☒ Aircraft, Ship-building & trains
Aluminium
Autocatalysts
☒ Batteries
Cement
Cemented carbide tooling
Ceramics
Chemical
Catalysts
Chemicals
Construction
Crucibles
Dentalalloys
☒ Electrical-equipment
Electronics/IT
Fabricated-products
Fibre-optics
Flame-retardants
Foundries
Glass
Glassmaking-equipment
Hard-metals
Infrared-optics
Jewelry
Light-alloys
Lighting
Low-temp-alloys
Lubricants
Mechanical-equipment
Metals
Other consumer goods
Packaging
Pencils
☒ Pigments
Polishing
Processplant
Refractories
☒ Road transport
Rubber, plastics
☒ Steel and steel alloys
Superalloys & magne
Surgical equipment
Tungsten alloys
☒ Other...

Case study potential: Yes / No / Maybe

Critical Material			
Antimony	Yes	Indium	Yes
Beryllium	Yes	Magnesium	Yes
Cobalt	Yes	Niobium	Yes
Fluorspar	Yes	PGMs	Yes
Gallium	Yes	Rare earths	☒ Yes
Germanium	Yes	Tantalum	Yes
Graphite	Yes	Tungsten	Yes

Resource Efficiency
Substitution: ● True False
Remanufacturing: True False
Recycling: True False
Life extension: True False
Reuse: True False
Ecodesign: True False

Figure 53: Excel spreadsheet example, exported from database.

3 Annex C – Screening Data

3.1 *Advisory Panel Members*

Stephen Bass, Policy Lead - Low Carbon & Resource Efficient Economy & Eco-Innovation, Defra

Graeme Carus, Director of Business Development, European Metal Recycling Limited

Melvin Caton, European Pathway to Zero Waste / SEEDA (Sponsor)

Simon Collard, Development Director, Johnson Matthey Catalysts, Chemicals and Refining

Ian Hetherington, Director-General, British Metals Recycling Association

Jonathan Light, Director, MDJ Light Brothers (SP) Ltd, East Sussex (Electronic and ELV Recycling)

Julia Sussams, Research Manager - SCP Evidence Base, Sustainable Consumption and Production & Waste, Defra

Willy Tomboy, Environmental Affairs Group, Director / Environment Officer, Toyota Motor Europe

Kerry Vitalis, Assistant Director Waste Policy, Environmental and Technical Regulation, Department for Business Innovation and Skills

3.2 *Full list of markets and applications*

Below is a full list of the markets and applications considered, primarily selected from inclusion in Annex V of the EU Critical Material Study.[a] Whilst care was taken to ensure each market/application was distinct, it is evitable that some overlap occurs, e.g. superalloys also contribute to the aerospace sector. However this coverage ensures that the most important uses are considered.

- **Automotive & Aerospace**
- **Batteries**
- **Catalyst**
- **Cement**
- **Cemented Carbide Tools**
- **Ceramics**
- **Chemicals**
- **Coatings**
- **Construction**
- **Crucibles**
- **Dental alloys**
- **Electrical equipment**
- **Electronics / IT**
- **Fabricated Products**
- **Flame retardant**
- **Foundries**
- **Glass**
- **Jewellery**
- **Low temperature alloys**
- **Lubricants**
- **Magnets**
- **Mechanical equipment**
- **Medical appliances**
- **Optics**
- **Other final consumer goods**
- **Other metal alloys**
- **Others**
- **Packaging**
- **Pencils**
- **Phosphors**
- **Pigments**
- **Polishing**
- **Refractories**
- **Research and development**
- **Rubber/ plastics**
- **Sputtering targets**
- **Steel & steel alloys**
- **Superalloys**
- **Tungsten alloys**
- **Wrought alloys**

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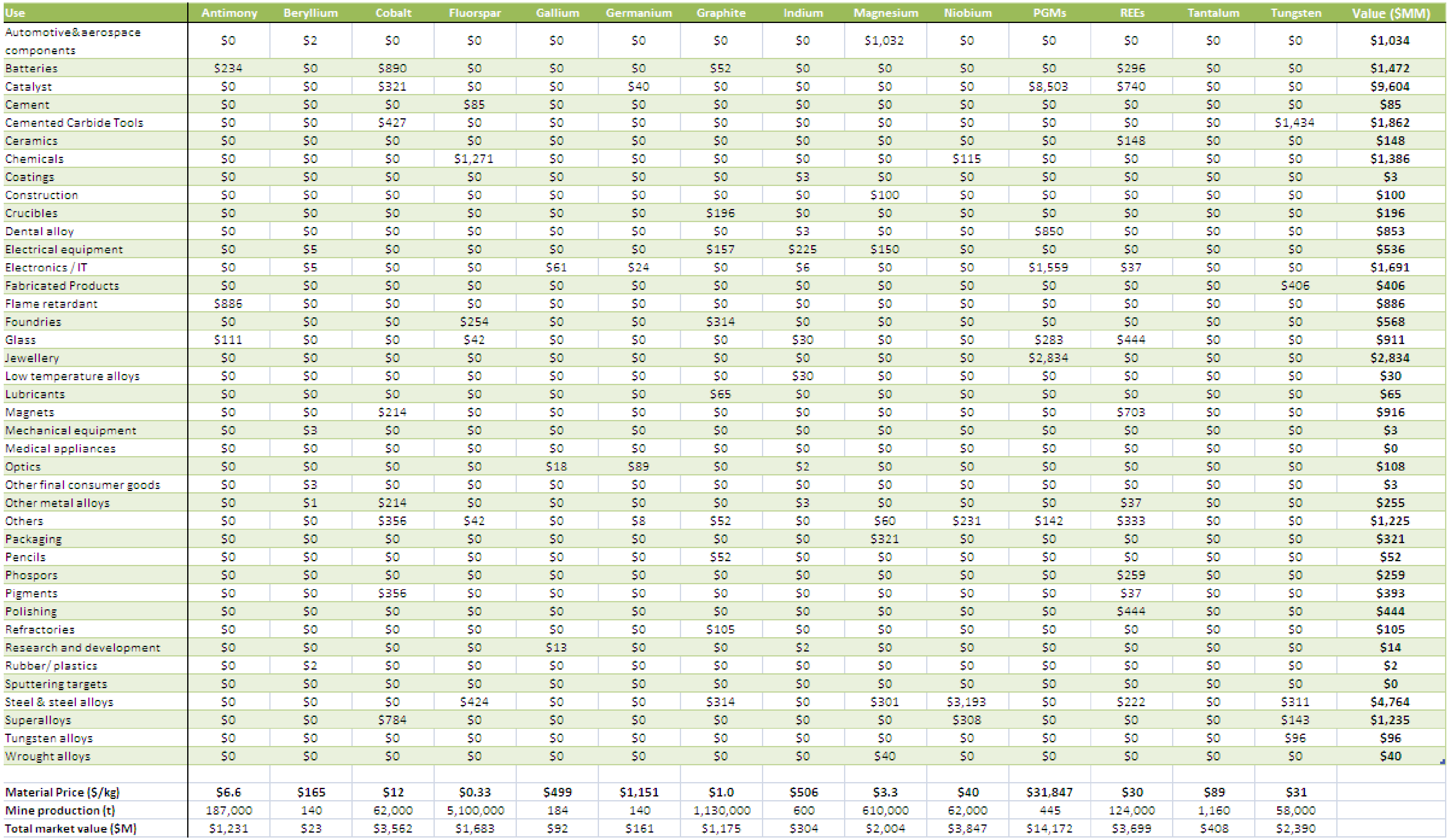
[a] Defining 'critical' raw materials, EU, 2010

3.3 Market share data

Scoring based on: <1%=0; 1% to 4%=1; 5% to 24%=2; 25% to 100%=3.
't' = trace (i.e. less than 1%), highlighted cells are greater than 50%

Use	Antimony	Beryllium	Cobalt	Fluorspar	Gallium	Germanium	Graphite	Indium	Magnesium	Niobium	PGMs	REEs	Tantalum	Tungsten	Score
Automotive&aerospace components		10%							52%						5
Batteries	19%		25%				4%	t				8%			8
Catalyst	t		9%			25%				t	60%	20%			9
Cement				4%											1
Cemented Carbide Tools			12%							t			10%	60%	7
Ceramics												4%			1
Chemicals				60%						3%					4
Coatings				t				1%							1
Construction									5%						2
Crucibles							15%								2
Dental alloy								1%			6%				3
Electrical equipment		20%					12%	74%	8%				10%		11
Electronics / IT	t	20%			66%	15%		2%		t	11%	1%	40%		14
Fabricated Products														17%	2
Flame retardant	72%														3
Foundries				12%			24%								4
Glass	9%	t		2%				10%			2%	12%	t		8
Jewellery						t				t	20%				2
Low temperature alloys								10%							2
Lubricants							5%								2
Magnets			6%							t		19%			4
Mechanical equipment		15%													2
Medical appliances													t		0
Optics					20%	55%		t		t			7%		6
Other final consumer goods		15%													2
Other metal alloys		5%	6%		t			1%				1%			6
Others			10%	2%	t	5%	4%		3%	6%	1%	9%			12
Packaging									16%						2
Pencils							4%								1
Phosphors												7%			2
Pigments	t		10%									1%			3
Polishing												12%			2
Refractories							8%								2
Research and development					14%			t							2
Rubber/ plastics	t	10%													2
Sputtering targets	t												10%		2
Steel & steel alloys				20%			24%		15%	83%		6%		13%	13
Superalloys			22%							8%			15%	6%	8
Tungsten alloys														4%	1
Wrought alloys									2%				8%		3

3.4 Market value for each material



Use	Antimony	Beryllium	Cobalt	Fluorspar	Gallium	Germanium	Graphite	Indium	Magnesium	Niobium	PGMs	REEs	Tantalum	Tungsten	Value ($MM)
Automotive&aerospace components	$0	$2	$0	$0	$0	$0	$0	$0	$1,032	$0	$0	$0	$0	$0	**$1,034**
Batteries	$234	$0	$890	$0	$0	$0	$52	$0	$0	$0	$0	$296	$0	$0	**$1,472**
Catalyst	$0	$0	$321	$0	$0	$40	$0	$0	$0	$0	$8,503	$740	$0	$0	**$9,604**
Cement	$0	$0	$0	$85	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$85**
Cemented Carbide Tools	$0	$0	$427	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$1,434	**$1,862**
Ceramics	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$148	$0	$0	**$148**
Chemicals	$0	$0	$0	$1,271	$0	$0	$0	$0	$0	$115	$0	$0	$0	$0	**$1,386**
Coatings	$0	$0	$0	$0	$0	$0	$0	$3	$0	$0	$0	$0	$0	$0	**$3**
Construction	$0	$0	$0	$0	$0	$0	$0	$0	$100	$0	$0	$0	$0	$0	**$100**
Crucibles	$0	$0	$0	$0	$0	$0	$196	$0	$0	$0	$0	$0	$0	$0	**$196**
Dental alloy	$0	$0	$0	$0	$0	$0	$0	$3	$0	$0	$850	$0	$0	$0	**$853**
Electrical equipment	$0	$5	$0	$0	$0	$0	$157	$225	$150	$0	$0	$0	$0	$0	**$536**
Electronics / IT	$0	$5	$0	$0	$61	$24	$0	$6	$0	$0	$1,559	$37	$0	$0	**$1,691**
Fabricated Products	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$406	**$406**
Flame retardant	$886	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$886**
Foundries	$0	$0	$0	$254	$0	$0	$314	$0	$0	$0	$0	$0	$0	$0	**$568**
Glass	$111	$0	$0	$42	$0	$0	$0	$30	$0	$0	$283	$444	$0	$0	**$911**
Jewellery	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,834	$0	$0	$0	**$2,834**
Low temperature alloys	$0	$0	$0	$0	$0	$0	$0	$30	$0	$0	$0	$0	$0	$0	**$30**
Lubricants	$0	$0	$0	$0	$0	$0	$65	$0	$0	$0	$0	$0	$0	$0	**$65**
Magnets	$0	$0	$214	$0	$0	$0	$0	$0	$0	$0	$0	$703	$0	$0	**$916**
Mechanical equipment	$0	$3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$3**
Medical appliances	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Optics	$0	$0	$0	$0	$18	$89	$0	$2	$0	$0	$0	$0	$0	$0	**$108**
Other final consumer goods	$0	$3	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$3**
Other metal alloys	$0	$1	$214	$0	$0	$0	$0	$3	$0	$0	$0	$37	$0	$0	**$255**
Others	$0	$0	$356	$42	$0	$8	$52	$0	$60	$231	$142	$333	$0	$0	**$1,225**
Packaging	$0	$0	$0	$0	$0	$0	$0	$0	$321	$0	$0	$0	$0	$0	**$321**
Pencils	$0	$0	$0	$0	$0	$0	$52	$0	$0	$0	$0	$0	$0	$0	**$52**
Phospors	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$259	$0	$0	**$259**
Pigments	$0	$0	$356	$0	$0	$0	$0	$0	$0	$0	$0	$37	$0	$0	**$393**
Polishing	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$444	$0	$0	**$444**
Refractories	$0	$0	$0	$0	$0	$0	$105	$0	$0	$0	$0	$0	$0	$0	**$105**
Research and development	$0	$0	$0	$0	$13	$0	$0	$2	$0	$0	$0	$0	$0	$0	**$14**
Rubber/ plastics	$0	$2	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$2**
Sputtering targets	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	**$0**
Steel & steel alloys	$0	$0	$0	$424	$0	$0	$314	$0	$301	$3,193	$0	$222	$0	$311	**$4,764**
Superalloys	$0	$0	$784	$0	$0	$0	$0	$0	$0	$308	$0	$0	$0	$143	**$1,235**
Tungsten alloys	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$96	**$96**
Wrought alloys	$0	$0	$0	$0	$0	$0	$0	$0	$40	$0	$0	$0	$0	$0	**$40**
Material Price ($/kg)	**$6.6**	**$165**	**$12**	**$0.33**	**$499**	**$1,151**	**$1.0**	**$506**	**$3.3**	**$40**	**$31,847**	**$30**	**$89**	**$31**	
Mine production (t)	187,000	140	62,000	5,100,000	184	140	1,130,000	600	610,000	62,000	445	124,000	1,160	58,000	
Total market value ($M)	$1,231	$23	$3,562	$1,683	$92	$161	$1,175	$304	$2,004	$3,847	$14,172	$3,699	$408	$2,390	

3.5 Carbon Impact for Each Material

Carbon impact figures taken from EcoInvent v2.2. Average values taken for PGMs and REE oxides.

Use	Antimony	Beryllium	Cobalt	Fluorspar	Gallium	Germanium	Graphite	Indium	Magnesium	Niobium	PGMs	REEs	Tantalum	Tungsten	t CO$_2$e
Automotive&aerospace components	-	-	-	-	-	-	-	-	23,247,100	-	-	-	-	-	23,247,100
Batteries	458,337	-	128,960	-	-	-	1,356	-	-	-	-	168,640	-	-	757,293
Catalyst	-	-	46,426	-	-	-	-	-	-	-	3,257,400	421,600	-	-	3,725,426
Cement	-	-	-	28,560	-	-	-	-	-	-	-	-	-	-	28,560
Cemented Carbide Tools	-	-	61,901	-	-	-	-	-	-	-	-	-	30,160	334,080	426,141
Ceramics	-	-	-	-	-	-	-	-	-	-	-	84,320	-	-	84,320
Chemicals	-	-	-	428,400	-	-	-	-	-	-	-	-	-	-	428,400
Coatings	-	-	-	-	-	-	-	-	-	-	-	-	-	-	924
Construction	-	-	-	-	-	-	-	-	2,257,000	-	-	-	-	-	2,257,000
Crucibles	-	-	-	-	-	-	5,085	-	-	-	-	-	-	-	5,085
Dental alloy	-	-	-	-	-	-	-	-	-	-	325,740	-	-	-	326,664
Electrical equipment	-	-	-	-	-	-	4,068	-	3,385,500	-	-	-	30,160	-	3,488,104
Electronics / IT	-	-	-	-	24,895	-	-	-	-	-	597,190	21,080	120,640	-	765,653
Fabricated Products	-	-	-	-	-	-	-	-	-	-	-	-	-	94,656	94,656
Flame retardant	1,736,856	-	-	-	-	-	-	-	-	-	-	-	-	-	1,736,856
Foundries	-	-	-	85,680	-	-	8,136	-	-	-	-	-	-	-	93,816
Glass	217,107	-	-	14,280	-	-	-	-	-	-	108,580	252,960	-	-	602,167
Jewellery	-	-	-	-	-	-	-	-	-	-	1,085,800	-	-	-	1,085,800
Low temperature alloys	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9,240
Lubricants	-	-	-	-	-	-	1,695	-	-	-	-	-	-	-	1,695
Magnets	-	-	30,950	-	-	-	-	-	-	-	-	400,520	-	-	431,470
Mechanical equipment	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Medical appliances	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Optics	-	-	-	-	7,544	-	-	-	-	-	-	-	21,112	-	28,656
Other final consumer goods	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Other metal alloys	-	-	30,950	-	-	-	-	-	-	-	-	21,080	-	-	52,954
Others	-	-	51,584	14,280	-	-	1,356	-	1,354,200	-	54,290	189,720	-	-	1,665,430
Packaging	-	-	-	-	-	-	-	-	7,222,400	-	-	-	-	-	7,222,400
Pencils	-	-	-	-	-	-	1,356	-	-	-	-	-	-	-	1,356
Phosphors	-	-	-	-	-	-	-	-	-	-	-	147,560	-	-	147,560
Pigments	-	-	51,584	-	-	-	-	-	-	-	-	21,080	-	-	72,664
Polishing	-	-	-	-	-	-	-	-	-	-	-	252,960	-	-	252,960
Refractories	-	-	-	-	-	-	2,712	-	-	-	-	-	-	-	2,712
Research and development	-	-	-	-	5,281	-	-	-	-	-	-	-	-	-	5,281
Rubber/ plastics	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sputtering targets	-	-	-	-	-	-	-	-	-	-	-	-	30,160	-	30,160
Steel & steel alloys	-	-	-	142,800	-	-	8,136	-	6,771,000	-	-	126,480	-	72,384	7,120,800
Superalloys	-	-	113,485	-	-	-	-	-	-	-	-	-	45,240	33,408	192,133
Tungsten alloys	-	-	-	-	-	-	-	-	-	-	-	-	-	22,272	22,272
Wrought alloys	-	-	-	-	-	-	-	-	902,800	-	-	-	24,128	-	926,928
Carbon Impact (kgCO$_2$e/kg)	**12.9**	**Unknown**	**8.32**	**0.14**	**205**	**Unknown**	**0.03**	**154**	**74**	**Unknown**	**12200**	**17**	**260**	**9.6**	
Mine production (t)	187,000	140	62,000	5,100,000	184	140	1,130,000	600	610,000	62,000	445	124,000	1,160	58,000	
Total impact (tCO$_2$e)	2412300	NA	515840	714000	37720	NA	33900	92400	45140000	NA	5429000	2108000	301600	556800	

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