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

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

Final 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

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Glossary

AFRA	Aircraft Fleet Recycling Association
ATO	antimony trioxide
BFR	brominated flame retardant
BGS	British Geological Survey
BREF	Best Available Technology Reference Document
CBMM	Companhia Brasileira de Metalurgia e Mineração
CCA	Climate Change Agreement
CdTe	cadmium tellurium (PV)
CFC	chlorofluorocarbon
CIGS	copper indium gallium selenium (PV)
CRC	Carbon Reduction Commitment
DECC	Department of Energy and Climate Change
EAF	electric arc furnace
ELV	end of life vehicle
EU ETS	European Union Emissions Trading System
FCC	fluid catalytic cracking
FPD	flat panel display
GaAs	gallium arsenide
GHG	greenhouse gas
GVA	Gross Value Added
HEV, (H)EV	hybrid electric vehicle
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluorolefin
HSLA	high-strength-low-alloy
IPPC	Integrated Pollution Prevention and Control
IR	infra-red
ITIA	International Tungsten Industry Association
ITO	indium tin oxide
JOGMEC	Japan Oil Gas and Metals National Corp
LCD	liquid crystal display
Li-ion	lithium ion (battery)
MLCC	multi-layer ceramic capacitor
NiMH	nickel metal hydride (battery)
NIMS	National Research institute for Metals (Japan)
NIES	National Institute for Environmental Services (Japan)
ONS	Office of National Statistics
PAMELA	Process for Advanced Management of End of Life Aircraft
PCB	printed circuit board
PET	polyethylene terephthalate
PFOS	perfluorosulfonic acid
PGM	platinum group metals
PV	photovoltaic
REACH	Registration, Evaluation, Authorisation and restriction of Chemicals
REE	rare earth element
UBC	used beverage can
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WTO	World Trade Organisation

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Units

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

Contents

1 Executive Summary

There are justifiable concerns about the access of developed countries to raw materials which are critical to high technology or green economy applications. This has led to many territories and organisations undertaking assessments to identify which materials will be critical. The EU Raw Materials Initiative has identified 14 such critical raw materials which are essential to the EU. Within this summary 'critical material' is used to specifically refer to these materials:

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

The critical materials are mainly speciality metals which combine high economic importance to the EU with a high risk of potential disruption to or interference in supply. This report identifies the primary uses of these materials, and describes interventions that could be made to increase recovery and recycling. Opportunities to lower the demand for the primary production of the critical raw materials have been identified, both through specific targeting of applications for improved recovery and through more general resource efficient practices.

Opportunities

Ten opportunities were found which have high potential to recover critical materials. These can be categorised as: growth opportunities for existing activities; implementation opportunities that require further infrastructure development for enablement; and applications which have good potential for critical materials recovery in the future. Estimations of the total value of critical materials associated with these applications based on current consumption figures have been made, along with an indication of the reduction in carbon emissions if recovery was implemented.

Stage	Application	Critical Materials	Value of Critical Materials ($M)	Carbon Benefits
Growth	Catalytic converters	PGMs	7,398	Low
	Beverage cans	Magnesium	321	High
Implementation	Aerospace superalloys	Cobalt Niobium Tantalum	330	N/A
	Aerospace landing gear	Beryllium	3	N/A
	Aerospace aluminium alloys	Magnesium	189	Medium
	Portable Li-Ion batteries	Cobalt Graphite	178	Medium
	Hard disk drive magnets and layers	PGM REE	545	Medium
Future Prospect	LCD screens	Indium	225	Low
	Wind turbine magnets	REEs	183	Medium

A further eleven opportunities were identified as having medium potential. 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. Measures such as substitution, reuse, or elimination may be necessary to reduce the demand for these raw materials in the future.

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

General recommendations:

The following recommendations are made to enable increased recovery of the critical materials in the UK and EU:

- **Improved collection:** Developing more efficient collection schemes and infrastructure for consumer and industrial waste will increase recycling rates for the critical raw materials.
- **Advanced sorting techniques:** Existing business models using practices such as ‘shred and sort’ are poor at isolating small, high value items containing critical materials. Implementation of more sophisticated sorting processes will help encourage the recovery of these materials.
- **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:** Adopting design practices which enable disassembly will improve the efficiency of sorting processes, and therefore recovery of critical materials.
- **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 within 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 smelting and refining occurring elsewhere. Therefore the most likely short term opportunities of improving the recovery of critical materials in the South East of England lie within the improvement of existing collecting and sorting infrastructure, through the measures recommended above. The same opportunities for implementing new recycling technologies for potential future waste streams also exist.

2 Introduction

2.1 *What are Critical Raw Materials?*

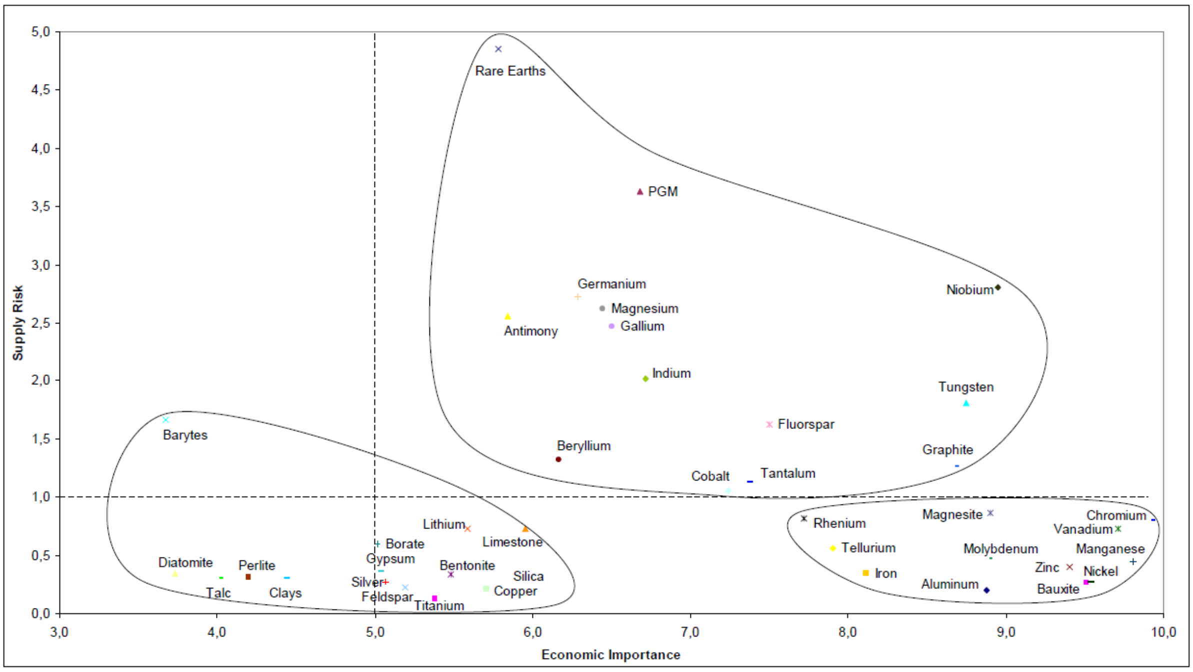
There are justifiable concerns about the access of developed countries to raw materials which are critical to high technology or green economy applications. Existing issues around certain resources (for example rare earth elements), and the prospect of further problems led the EC to launch the Raw Materials Initiative, which identified a group of 14 ‘critical materials’ (Table 1). These consist 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 Raw Materials Initiative study, with the critical raw materials circled in the top right corner of the chart.

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

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



Source: European Commission

Criticality methodology is an emerging field and cannot be considered an exact science. A number of different studies have attempted to evaluate the relative criticality of minerals; however each has obtained somewhat differing results. This is in part due to the metals and minerals included for selection in the study, but also because there is no universal agreement regarding which indicators are relevant or how to weight the different factors. Additional indicators included within other studies include geological and technical availability, and climate change. These sensitivities are important to bear in mind, even though the Raw Materials Initiative study has been taken as the starting point for this report. For further discussion on the definition of critical raw materials, the interested reader is referred to the following (non-exhaustive) list of studies that have assessed criticality:

- *Assessing Metals as Supply Chain Bottlenecks in Priority Energy Technologies*, Oakdene Hollins for EC Institute of Energy (2011)
- *Critical Materials Strategy*, US Department for Energy (2010)
- Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, Defra (2010)
- *Critical raw materials for the EU*, European Commission (July 2010)
- *Minerals, Critical Minerals, and the US Economy*, Committee on Critical Mineral Impacts of the U.S. Economy (2008)
- *Material Security: Ensuring resource availability for the UK economy*, Oakdene Hollins (2008)
- *Les nouveaux métaux stratégiques*, BRGM (2008).

This 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.

2.2 Challenges in Recovering Critical Raw Materials

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 five main sources of market inefficiency for recycling (Table 2). These were 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, and market power in the primary or secondary markets. These interactions between different actors and the associated market power have been shown to be important within critical metal recycling. For example, for electronic waste 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.[a] Research by the Centre for Remanufacturing and Reuse (CRR) established that 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.[b]

Table 2: Potential sources of market inefficiency in recycling markets

Causes of market inefficiency	Explanation
Transaction costs in secondary market materials	Arises from the diffuse and irregular nature of waste generation. May also arise from the heterogeneous nature of secondary materials.
Information failures in relation to waste quality	Arises from the difficulty of buyers to detect waste quality and the relative ease with which sellers can conceal inferior quality waste.
Consumption externalities and risk aversion	Perceived costs associated with the quality of final goods derived from secondary materials relative to those derived from virgin materials.
Technological externalities related to products	Complexity of recycling due to the technical characteristics of the recyclable material and products from which secondary materials are derived.
Market power in primary and secondary markets	Substitution between primary and recyclable materials may be restricted due to imperfect competition and strategic behaviour on the part of firms.

Source: OECD (2006), Improving Recycling Markets, Table 1.3

The recycling rate of 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

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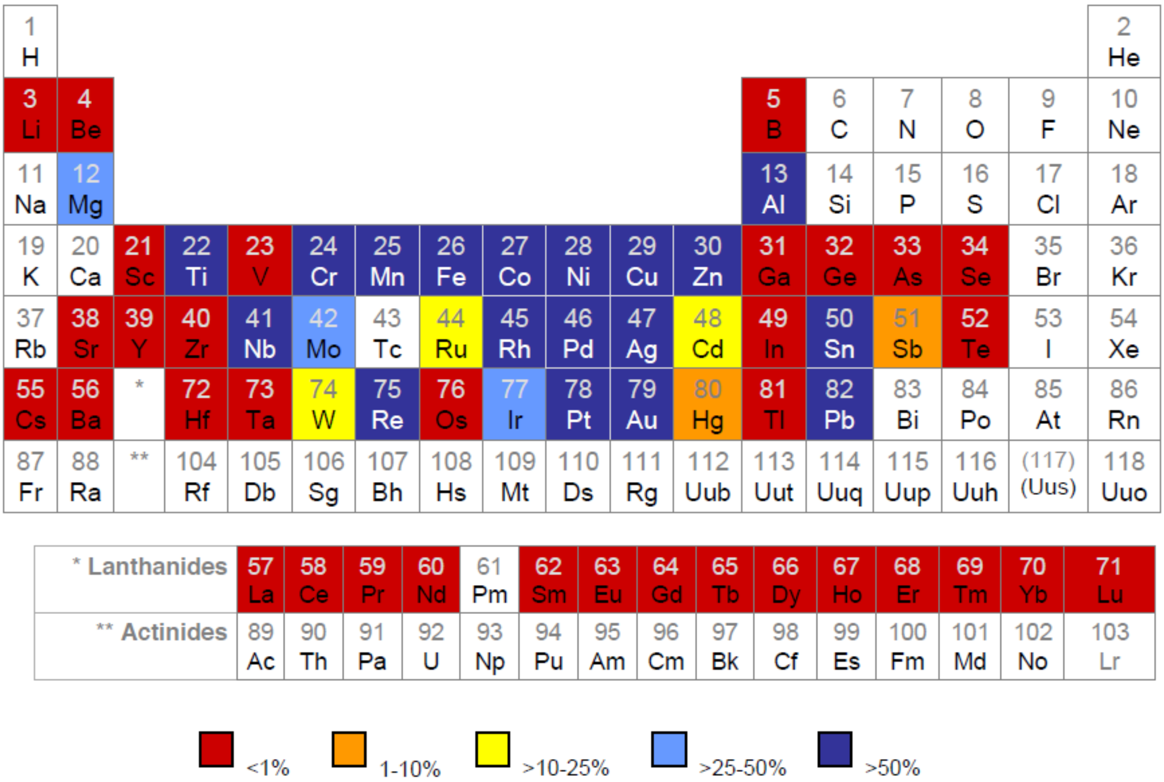
[a] Umicore Presentation (Dec 2010), Opportunities & limits to recycle critical metals for clean energies

[b] CRR (2010), Market Failures in Remanufacturing

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. However a distinction is drawn within this report between recycling rates and a reduction in the use of virgin raw materials. This is important because 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. Additionally there is a significant difference in the recycling rates between production waste (new scrap), which is commonly recycled (with the notable exception of rare earths), and end-of-life or post-consumer scrap where recycling rates are lower.

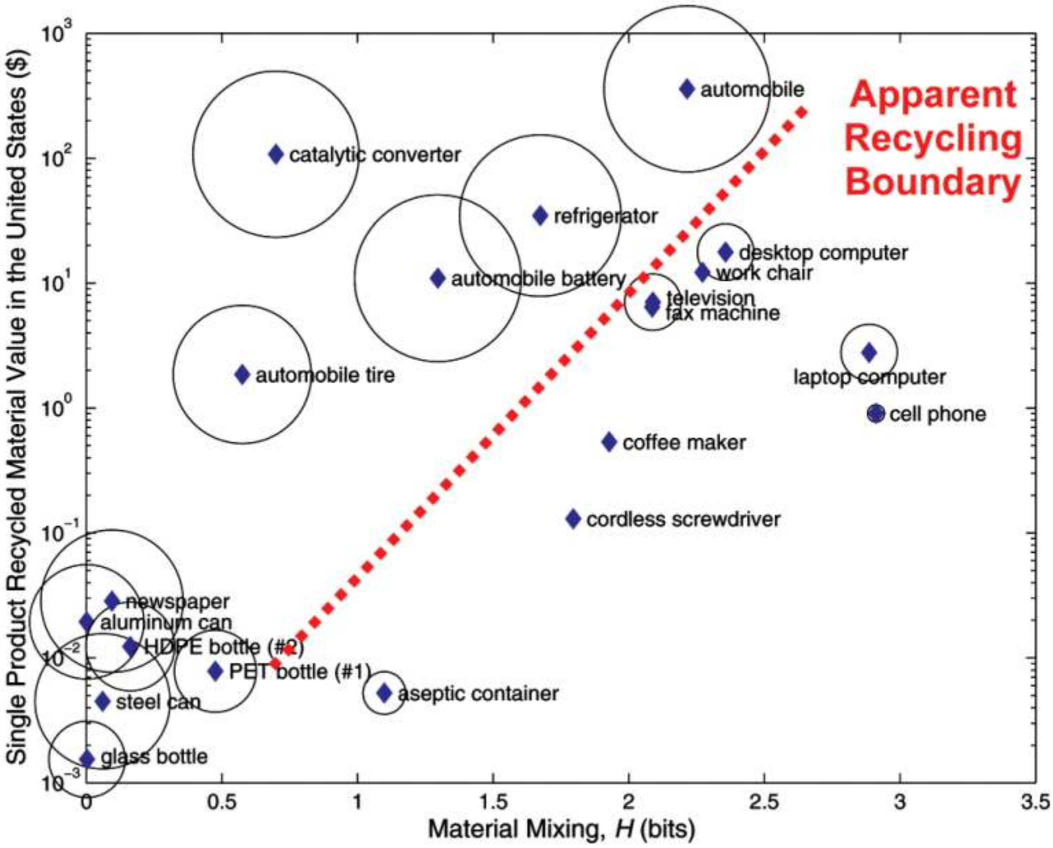
Figure 2: Recycling rates of metals



Source: UNEP/EU Working document

A key issue of importance for the recycling of critical raw materials is in the interaction between the value of the recycled material and the degree of dispersion of the raw material. A greater degree of dispersion of the raw material 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 and in large quantities. These costs are then compared to the value of the material that can be recovered in order to ascertain whether its recycling is economic. This relationship is illustrated by Figure 3, which plots the degree of material mixing within a product against the material value that can be recycled for selected products, many of which contain critical raw materials (see Table 3 in Section 3 for more details on the applications of critical raw materials). In summary this analysis indicates certain products that are economic to recycle, such as catalytic convertors, automobiles and batteries; whereas others such as computers, televisions and small electronic items fall beneath an apparent recycling boundary.

Figure 3: A plot of single product recycled material value against material mixing for the US



Source: Dahmus J. & Gutowski T. (2007), What gets recycled: an information theory based model for product recycling, Environmental Science & Technology 41

This demonstrates the challenge faced to reclaim materials, particularly the recovery of critical materials, which often form a small but essential part of a product or are highly diluted with another material.

2.3 Purpose of this Report

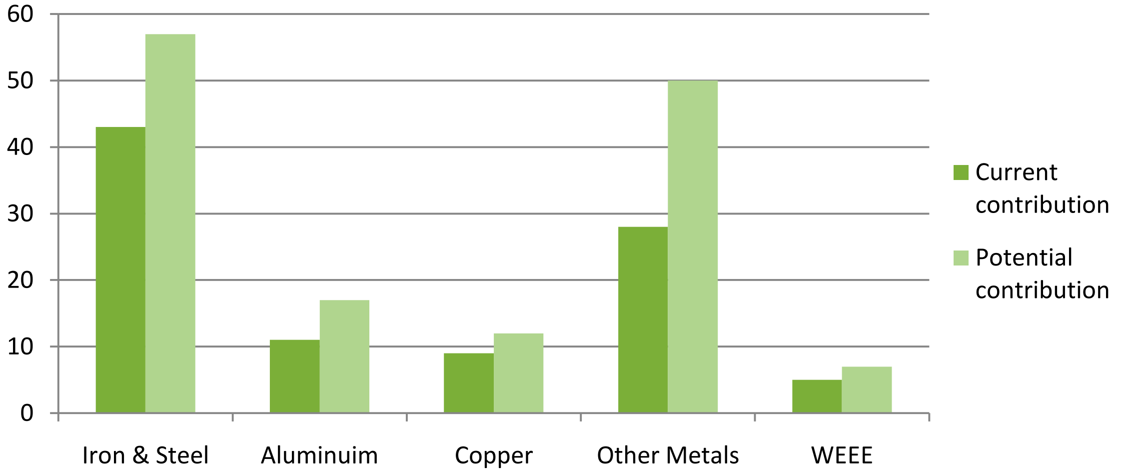
The purpose of this report is to examine the application/markets for the EU's list of 14 critical materials, review existing practices associated with their recovery, and identify the end markets where recovery of these materials has the greatest potential for implementation. The issue of critical materials 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 go beyond 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 to decrease the demand for these critical materials, as well as to look at new hi-tech methods for existing recovery processes. However some interventions may require alterations to existing recycling/recovery processes.

It should be noted, however, that material resource efficiency is in itself not a sufficient response to material security issues. This is because recycling can only contribute towards a proportion of consumption (Figure 4). For certain metals such as iron and steel, recycling is potentially able to contribute up to nearly 60% of consumption, but for WEEE this potential may be less than 10%. Furthermore the high demand growth rates forecast for critical raw materials within emerging technologies (which could more than treble current demand by 2030 in some instances)[a] and the long lifetimes of products (which can be as high as 50 years for buildings, 30 years for transport, 25 years for jewellery and 20 years for industrial durables)[b] limit the potential contribution of recycling to current consumption.

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. For instance it goes beyond the approach undertaken by Öko-Institut for UNEP in their noteworthy report *Critical Metals for Future Sustainable Technologies and their Recycling Potential* and by ADEME in their report *Etude du Potentiel de Recyclage de Certain Métaux Rares*, which 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, although the Öko-Institut report was used as a starting point for this study where overlap existed.

Figure 4: The current and potential contribution of recycling to consumption (%)



Source: European Environment Agency (2010), Green Economy and Recycling in Europe

2.4 *Structure and Methodology of this Report*

The structure of this report is as follows. It is divided into five main sections with accompanying annexes and conclusions:

- applications, future supply and demand issues for the critical raw materials (Section 3)
- resource efficiency best practice for critical materials (Section 4)
- identification of principal end uses (Section 5)
- resource efficient use of critical raw materials (Section 6)
- conclusions and recommendations (Section 7).

In an attempt to ensure brevity of the main report a considerable amount of material has been annexed:

- Annex A provides an overview of each raw material discussing the following issues:
  - key applications and potential future substitution
  - reserves, output, prices; and supply and demand forecasts.
- Annex B details the methodology used to review best practice.
- Annex C gives the data used in the screening of products for resource efficiency.

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[a] IZT & Fraunhofer (2009), Raw Materials for Emerging Technologies

[b] UNEP (2010), Metal Stocks in Society: Scientific Synthesis

3 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. This section provides an overview of the different critical raw materials, summarising the supply, demand and pricing data in Table 3. More information on each critical raw material can be found within the individual material reports located in Annex A, including summaries of applications, substitution and recycling, and further detailed data for supply, demand and pricing.

3.1 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, rare earth elements (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%).

3.2 Demand

There is a diverse number of applications for these critical raw materials ranging from automotive end-uses to electronics to chemicals and construction. For seven of the critical raw materials, a single application accounts for over half of the consumption. From Table 3 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 that was used in the screening process to obtain a short list of product groups for resource efficiency review (see Section 5). 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%[a]) 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.

In terms of prices for each of the critical raw materials, although there is a broad range in prices, these map relatively closely to production levels. 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); and the cheapest being those with the largest levels of production: fluorspar ($0.42/kg), graphite ($1.16/kg) and magnesium ($3.29/kg). Price trends graphs are available in Figure 5, Figure 6 and Figure 7, which highlight the volatility associated with the commodity boom and economic downturn, and government intervention in the case of REEs.

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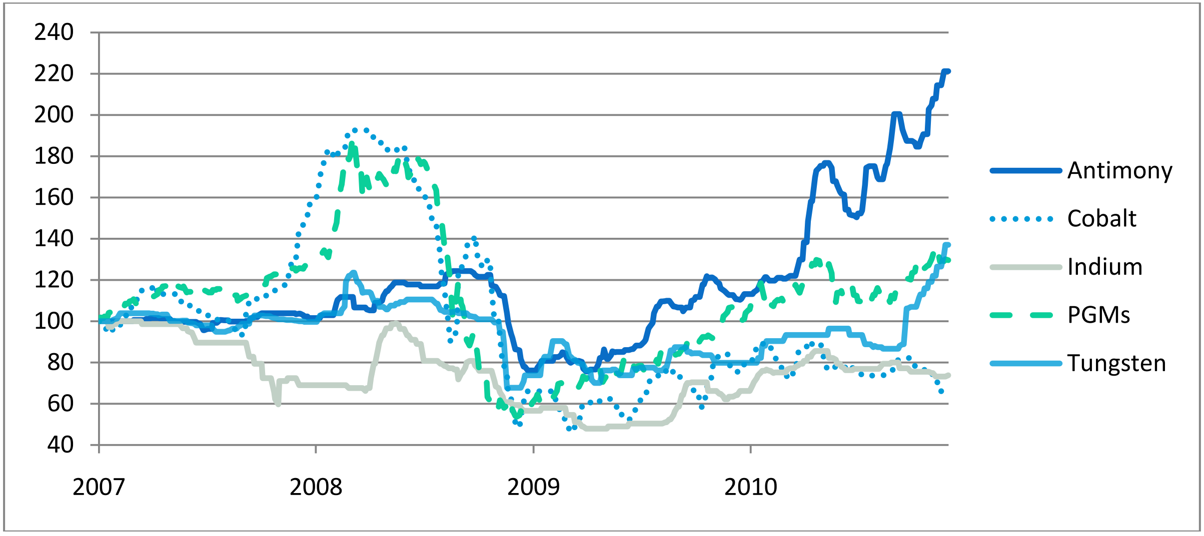
[a] World Bank World GDP Forecast for 2010-2012, available at URL: http://web.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTDECPROSPECTS/EXTGBLPROSPECTS/0,,contentMDK:20675180~menuPK:615470~pagePK:2904583~piPK:2904598~theSitePK:612501,00.html accessed 02/03/11

Table 3: 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%	$11.82
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%	$40.33
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%	$88.53
Tungsten	94,009	China (81%) Russia (4%) Canada (3%)	Cemented carbides (60%) Fabricated products (17%) Alloy steels (13%)	4.9%	$30.91

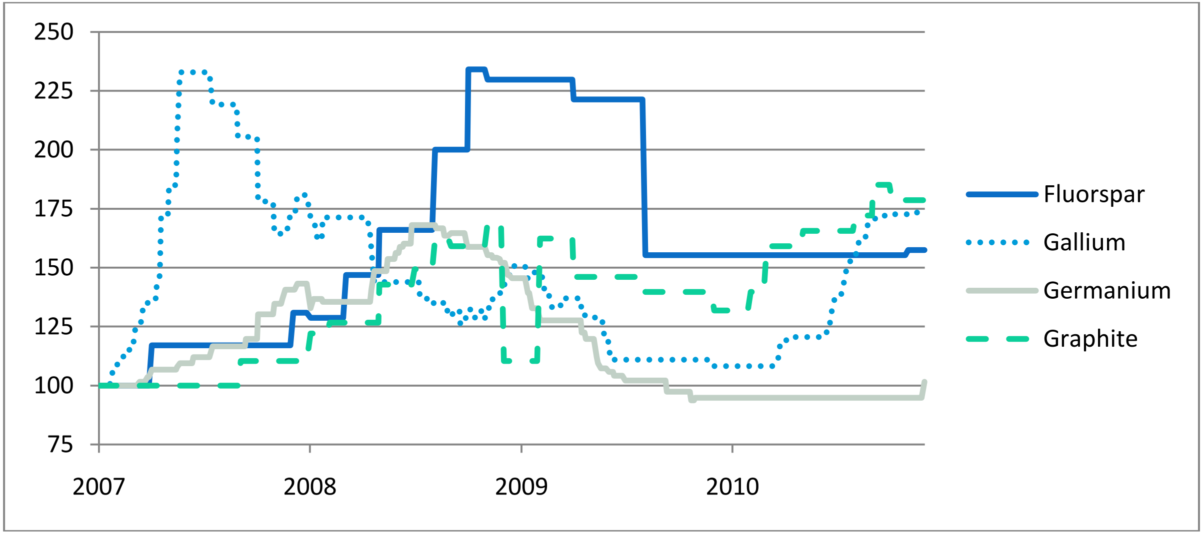
Notes: Supply includes estimates of recycling where available; [#] Beryllium price is 2 year average of US export prices (not publicly traded)*
Source: Annex A

Figure 5: Price trends for antimony, cobalt, indium, PGMs & tungsten (2007 = 100)



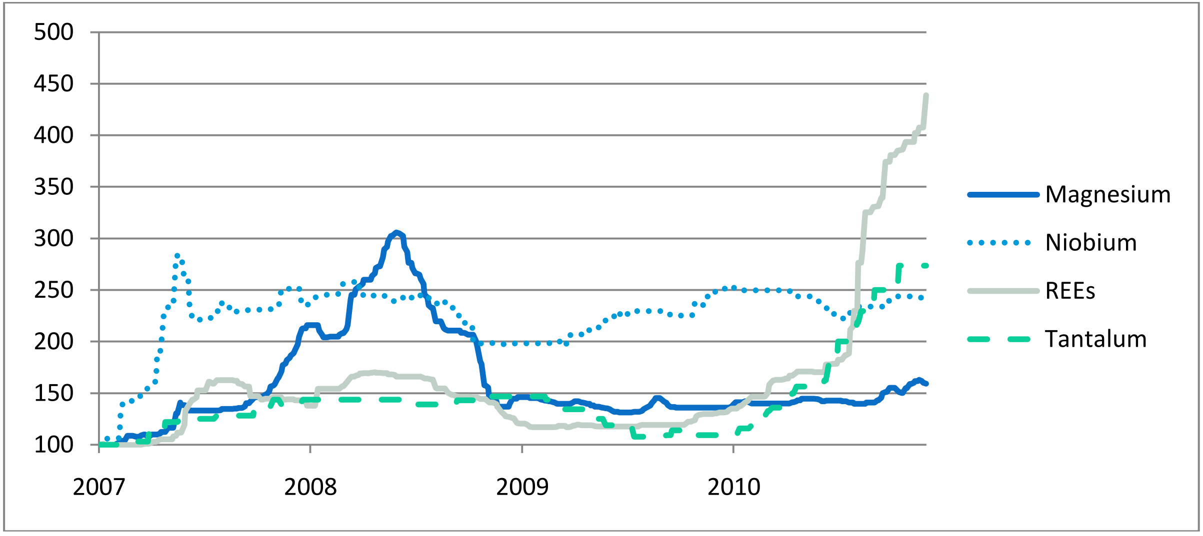
Source: Metal Pages; see Annex A for details

Figure 6: Price trends for fluorspar, gallium, germanium & graphite (2007 = 100)



Source: Metal Pages, Industrial Minerals Magazine; see Annex A for details

Figure 7: Price trends for magnesium, niobium, REEs & tantalum (2007 = 100)



Source: Metal Pages; see Annex A for details

4 Recycling and Recovery Best Practice for Critical Materials

Within this section, existing commercial and near commercial technologies are reviewed to provide an overview of the current recycling and recovery best practice, and an assessment of the current state-of-art recycling technology for the 14 critical materials. This provides an indication of the availability and viability of recycling of these materials on technology grounds. However, before considering each of the materials it is worthwhile considered recycling in its broader context, and factors which may influence the feasibility of recycling these materials from the processes and products in which they are used.

One of the fundamental issues relating to recycling and recycling technology is the dispersion of the material within the feedstock; at the two extremes, the material may exist as a bulk material or in trace or highly diluted form.[a]

Recycling bulk materials is often relatively straightforward compared to recycling minor or trace materials, as bulk materials tend to be the ones that industry is used to recycling, and removal, collection and recycling are well organised on a large scale. If the material is present in trace or diluted form, recycling is more problematic as the material is more widely dispersed, both physically and chemically. Identification and separation of the material is much more difficult, as only small quantities of a given material will be recovered from a large volume of waste. In these cases the strategic materials are often uneconomic to recover and are lost to the production chain. Recovery of trace or minor elements is therefore limited to ones that have very high intrinsic value or are particularly scarce. In either event, recovery is often limited to in-house reprocessing. It is believed that this is the route being taken by many recyclers on a global scale.[b]

It is also important to differentiate between pre- and post- consumer scrap. Pre-consumer scrap - generated through the manufacturing process - generally has higher concentrations of recyclable materials which are in a purer state, whilst post-consumer scrap from end of life products is often less concentrated, less pure and less consistent in composition. Exceptions do exist where a tightly defined, high concentration waste stream exists, for example post-consumer scrap of autocatalysts has a higher concentration of PGMs than do natural ores.

Similarly, WEEE has a relatively high concentration of recyclable materials, but due to the complexity and mixtures of materials present, it is far more complicated to recycle. Despite the adverse nature of many waste streams, one of the major recycling companies in the world, Umicore, recycles 17 metals with very good recovery rates.[c,d] Umicore's processing methods are well described[e], but they differentiate between mass recycling of single bulk materials, which is well established, and technology recycling focusing on recovery of valuable trace elements, which is less well developed.[f] However, given the complex mixtures of substances present in technology recycling it is clear that an integrated process for recovery of a variety of valuable materials is likely to be more attractive than a single discrete process for each.

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[a] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011, Available at http://www.publications.parliament.uk/pa/cm201011/cmselect/cmsctech/writev/metals/metals.pdf

[b] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

[c] Critical materials and mobile devices, OECD Environmental Directorate, 2010

[d] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[e] Securing the supply of precious and special metals, , Umicore,

[f] Opportunities and limits to recycle critical metals for clean energies, *et al.,* 2010

More generally the logistics and economics of recycling have been comprehensively discussed.[a] However, it is widely reported that to be successful at materials recovery in the long term, recycling processes need to be economically and commercially viable. Additionally there is often little incentive to recycle materials, and design improvements to enable recycling opportunities are also necessary. Strategic thinking with respect to critical materials, particularly their importance for clean energy technologies, has been developed by many countries, most notably EU, USA, Japan, China, Korea, Australia and Canada.[b] Perhaps the most advanced country with respect to materials security and recycling is Japan. The Japanese Government is actively pursuing recycling through numerous bodies, such as Japan Oil Gas and Metals National Corp (JOGMEC) which promotes access to raw materials, the National Research institute for Metals (NIMS), the Centre for Strategic Natural Resources, and the National Institute for Environmental Services (NIES) which has, as a subsidiary, the Research Centre for Materials, Cycles and Waste Management.[c]

The EU's current R&D policy is to encourage increased materials efficiency in applications, to identify material substitutes and to improve end of life collection and recycling processes, whilst its business policy is to develop a minerals trade policy for an open market, to gather information and to streamline land permits, as well as to increase recycling regulations.[d]

4.1 Antimony

Historically antimony has been recycled from lead acid batteries. This process is well established, but has become less important due to the decline of antimony use, both through minimisation of use in lead acid batteries, and through growing use of alternative battery technologies.[e]

Antimony is also an essential component of certain electronic products such as mobile phones, but only at estimated levels of 0.1% by weight; therefore there are only very limited recovery paths available.[f] Antimony is currently recovered in the Umicore Group's smelter-refinery recycling facility in Boboken, near Antwerp, Belgium[g,h], where it is recovered alongside PGM and tellurium from the WEEE waste streams. This process has been well summarised and given some detail, but - in brief - separation of trace elements occurs through dissolution in different base metals such as copper or nickel, with further refining steps taking place further down the processing route.[i]

Antimony can also be recovered during copper smelting, with 80% efficiency.[j] However, losses by thermal processes can be high; for instance, antimony is found in the fly ash of processing incinerators.

4.2 Beryllium

Beryllium is, in general, a difficult metal to recycle or reuse due to the high toxicity of many beryllium-containing chemicals, particularly as fumes may be given off during processing. Therefore the additional health and safety considerations mean that reprocessing this metal is challenging, unless by a specialist refiner.

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[a] Backward linkage development in the South African PGM industry: A case study, Marian Lydall, Mineral Economics & Strategy Unit, 2009

[b] Critical Materials Strategy, US Department of Energy, 2010

[c] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

[d] Critical Materials Strategy, US Department of Energy, 2010

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

[f] Steel and specialty metals trend analysis, Defense Contract Management Agency Industrial Analysis Center, 2008

[g] Critical materials and mobile devices, OECD Environmental Directorate, 2010

[h] Technology challenges to recover precious and special metals from complex products, & Christina Meskers, Umicore, 2010

[i] Recycling of Electronic Scrap at Umicore's Integrated Metals Smelter and Refinery. , World of Metallurgy, 2006

[j] Critical materials and mobile devices, OECD Environmental Directorate, 2010

In manufacturing processes around 50% of pre-consumer beryllium scrap is recycled through simple collection and re-use with 90% efficiency (the other 10% is lost during reprocessing). Overall it is estimated that about 19% of the total consumption of beryllium is recycled from old scrap.[a] Beryllium is not recovered from post-consumer scrap, where it can be typically found in small quantities in electronic and automotive waste streams as an alloy of copper. Separation from the slag produced from melting this waste is not practiced at the current time.[b] However, it is possible to recover small quantities of beryllium from this waste depending on the type of waste processing involved. In typical WEEE scrap streams the waste is crushed to help material separation. At this stage if the beryllium-containing WEEE waste stream is thermally processed it is possible to convert the beryllium to its oxide, which can be recovered from the streams by converting it to beryllium chloride and then using it as an industrial or laboratory catalyst . The beryllium oxide may also react with water to form the hydroxide, which can then combine with carbon dioxide in the air to form a carbonate which is thermally decomposed back to an oxide and then reacted with hydrochloric acid to reform the chloride.[c] By contrast, simple incineration of beryllium-containing WEEE streams results in loss of beryllium through the incinerator's fly ash.[d]

Beryllium is also used extensively in the nuclear industry, and can become contaminated. Recycling and recovery is practised but it involves decontamination of the material.[e] The process involves detritiation by high temperature annealing, followed by removal of nucleotides and other impurities by zone refining, chlorine extraction and vacuum distillation, before forming beryllium tiles or pebbles by powder metallurgy.

4.3 Cobalt

Cobalt is extensively recycled, with the tonnage recycled between 1995 and 2005 rising from 4,200 to 10,000 tonnes per annum.[f] In 2010 the end of life recycling of cobalt was estimated to be 68%.[g] Recycling of pre-consumer waste cobalt is common in most uses; post-consumer recycling is focused on batteries, alloys and catalysts.[h] However, it has been reported that the incineration of WEEE can cause an accumulation of cobalt in the fly ash, most likely due to the presence of Li-ion batteries.[i]

4.3.1 Cemented carbide tools

The majority of cobalt is recovered from pre-consumer scrap, such as from hard alloys and the tools industry; this is achieved through well-established hydro-metallurgical or pyro-metallurgical processes.[j] For example, cobalt is extensively recovered from the reprocessing of tungsten carbide tools. During recycling, these carbide materials are placed in a molten zinc bath which dissolves the cobalt to leave the residual tungsten carbide. The cobalt is recovered with a high efficiency from the zinc by distillation.[k] It is expected that the recycling capacities for both cobalt and tungsten carbide will increase as demand increases for both materials.[l]

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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] Recyclability potentials of beryllium oxide from E-Waste Items in Nigeria, Eneh C. Journal of Applied Sciences, 11 (2), *2011,* 397-400

[d] Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations, Gullet, B. *et al*, J Mater Cycles Waste Manag., 9, *2007*, 69-79

[e] Beryllium recycling: feasibility and challenges, Frank Druyts, 8th IEA International Workshop on Beryllium Technology, 2007

[f] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

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

[h] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[i] Characterization of air emissions and residual ash from open burning of electronic wastes during simulated rudimentary recycling operations, Gullet, B. *et al*, J Mater Cycles Waste Manag., 9, *2007*, 69-79

[j] Cobalt—Its Recovery, Recycling, and Application, Shijie Wang, 2010

[k] Tungsten - An Overview, The A to Z of Materials and AZojomo, 2002

[l] Tungsten Cemented Carbides – A Success Story, Wolf-Dieter Schubert, ITIA

4.3.2 Batteries

Recovery of cobalt that is used in batteries (and catalysts, including gas to liquid catalysts[a]) is often undertaken by cobalt refining industry.[b] However, increasingly, cobalt is being recovered by third parties; for example, the Gulf Chemical and Metallurgical Corp processed cobalt catalysts in an electric arc furnace and sold the material to cobalt refineries.[c] This is particularly true of batteries as cobalt is present in both NiMH and Li-ion batteries. The usage of these battery types has grown as new markets, such as electric vehicles, have developed. This is therefore an area of large interest for recyclers and companies such as Mitsui Metal Mining Co., and Umicore plan to recycle cobalt from Li-ion and NiMH batteries.[d]

There are several techniques in development for the recovery of cobalt as part of general recycling processes for the recycling Li-ion type batteries. Generally cobalt is recovered after disassembly of the Li-ion battery to recover the lithium cobalt oxide. Perhaps the most advanced example has been developed by Umicore. This closed-loop process recovers cobalt from both Li-ion and NiMH batteries by a thermo-metallurgical process, whereby the cobalt is melted and reused as lithium cobaltite in new Li-ion batteries. [e] In Li-ion batteries the lithium is in the form of lithium cobalt oxide which can be extracted by dissolution and separation. This process has been comprehensively reviewed; briefly, the plastic material in the batteries is incinerated to leave an alloy of all metals, this alloy is refined and purified to separate the metals through several stages recovering cobalt, lithium and other metals.[fg] Umicore also recycles and recovers cobalt as an alloy comprising 30% cobalt, 30% iron, 20% copper and 5% nickel, for refining and recycling into NiMH batteries. A further example of commercial recycling, operated by Toxco, recovers cobalt by shredding the Li-ion battery and recovering the cobalt from neutral electrolytes.[h]

Other processes are in the research and development stage. One of the most advanced involves crushing, sieving, magnetic separation and acid leaching of the battery material, in order to recover both the lithium and cobalt from the bulk material. Further separation is achieved by both physical and chemical recovery methods, such as mechanical, leaching, solvent extraction and electrochemical methods.[i] Another process at the research phase has demonstrated a recovery rate of 94% of cobalt and REE from both Li-ion and NiMH batteries, using similar processing acid-based techniques to those described above; however this is not yet a commercial process.[j] Other methods of acid leaching as well as electrochemical recovery of cobalt from Li-ion batteries have also been demonstrated, but they are not commercial.[k,l]

4.3.3 Other developments

Recent work has also been carried out with bio-leaching of cobalt from waste streams[m] and the bio-sorption of heavy metals, including cobalt, by fungi.[n] Cobalt can also be recovered by

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[a] Complex Life Cycles of Precious and Special Metals, Christian Hagelüken and Christina E. M. Meskers, Linkages of Sustainability, 2010

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

[c] Cobalt—Its Recovery, Recycling, and Application, Shijie Wang, 2010

[d] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[e] Umicore Technology - recycling of new technology rechargeable batteries, Umicore, 2010

[f] The UMICORE Process: Recycling of Li-ion and NiMH batteries via a unique industrial Closed Loop, Umicore Battery Recycling, 2010

[g] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[h] End of life Vehicle Recycling: The State of the Art of Resource Recovery from Shredder Residue, B.J. Jody and E.J. Daniels, U.S. Department of Energy, 2006

[i] A review of processes and technologies for the recycling of lithium-ion secondary batteries, Xu J. *et al*, Journal of Power Sources 177, *2008*, 512–527

[j] Recovery of metal values from a mixture of spent lithium-ion batteries and nickel-metal hydride batteries, Nan J. *et al*, Hydrometallurgy, 84, *2006* 75–80

[k] A combined recovery process of metals in spent lithium-ion batteries, Jinhui Li et al, Chemosphere, 77, *2009*, 1132–1136

[l] Recovery of cobalt and lithium from spent lithium ion batteries using organic citric acid as leachant, Li L. *et al*, Journal of Hazardous Materials 176, *201,* 288

[m] Biotechnological recovery of heavy metals from secondary sources—An overview, Md E. Hoque , Obbard J. Philip, Materials Science and Engineering, 2010

[n] Biosorption of heavy metals by Saccharomyces cerevisiae: A review, Jianlong Wang, Can Chen, Biotechnology Advances, 24, *2006*. 427–451

electro-winning it (isolating the metal from solution using electrical processing) from cobalt-bearing solutions and sludges.[a]

For other uses such as paints, glasses and pigments, recovery is not possible due to the nature of these products.[b]

4.4 *Fluorspar*

Fluorspar is the mineral name for calcium fluoride. The major industrial uses for it include hydrofluoric acid production, in aluminium fluoride for aluminium manufacture and as a fluxing agent in steel. However, with these uses very little is recoverable.[c]

Direct recycling of the mineral is usually not feasible as it forms an intimate part of the end-use application. However, when economically and environmentally feasible, the end product can be recycled to recover the minerals. Morita Chemical Industries Co Ltd of Japan recycles fluorspar by taking waste water that contains fluorine and reforming high purity (98%) calcium fluoride.[d]

Fluorspar is also used in the enrichment of uranium and this material is recycled. Other uses include petroleum alkylation and the pickling of stainless steels, both of which have a small recycling rate. Nevertheless, the overall recycling rate of fluorspar within the EU is less than 1%, and there is currently considered no potential for improvement.[e]

4.5 *Gallium*

The typical uses of gallium, for example in semiconductors, require that the refined material must have a very low concentration of impurities. Therefore sophisticated processing routes are required to ensure that this purity is achieved.

78 tonnes per annum of gallium are recycled from pre-consumer waste, which is high compared with primary world production of 184 tonnes per annum. Recycling plants operate in the USA, Germany, Japan and UK. No post-consumer scrap is recovered, as there is no large scale feedstock yet available.[f] Hence recycling is limited to pre-consumer scrap and is mainly performed by the manufacturers.[g]

The only fully-integrated gallium producer and recycler is GEO Gallium in Salindres, France, where the primary metal is extracted from the ore bauxite. The company also has a dormant facility in Pinjarra, Australia.[h] In 2009 Neo Material Technologies acquired Recapture Metals to recover gallium, and in 2010 they also acquired a 50% share of Buss und Buss Spezialmetalle in Germany, which also recycles gallium.[i] Nalco in India are also interested in processing spent liquor from bauxite production to recover any gallium[j], but only part of the gallium present in bauxite and zinc ores is recoverable with existing technologies, and the factors controlling the recovery are proprietary.[k] Gallium is obtained as a by-product from bauxite and zinc processing plants[l], but it is recycled by the Dowa Group in Japan.[a]

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[a] Cobalt—Its Recovery, Recycling, and Application, Shijie Wang, 2010

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

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

[d] Fluorine Recycle Business, Morita Chemical Industries, 2010

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

[f] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

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

[h] Gallium, Minor Metals Trade Association, 2008

[i] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[j] Gallium, Minor Metals Trade Association, 2008

[k] Critical Materials Strategy, US Department of Energy, 2010

[l] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

Worldwide processing, uses and consumption of gallium has been very well reviewed[b], and it is estimated that by 2030 the worldwide demand will be six times the present production.[c] The projected uses of gallium - LEDs, semiconductors and photovoltaics[d,e,f] - mean that it will generally found in combination with many other strategic metals; this makes the recovery process very complex and it is not currently undertaken.[g]

Gallium has also been found in incinerator fly ash and urban coal ash, where its concentration is 200 times that of primary refinery production; this may provide an economic source of this metal.[h]

4.6 Germanium

Germanium is used in photovoltaic and thermoelectric devices, as well as optoelectronics and LEDs. It is also found in WEEE streams[i] and is associated with more common metals such as zinc and its ores.[j]

About 30% of total germanium consumed is recycled, with about 60% coming from the manufacture of optical devices. Smaller quantities are also obtained from windows of military vehicles and tanks. However, the decline in fibre optics has reduced the recycling rate in the EU.[k]

The most common pre-consumer recovery of germanium is from photovoltaic panels and fibre optics, whilst post-consumer recovery is still very limited due to its presence in waste streams in low quantities, combined with inherent difficulties in its recovery. A possible end use of post-consumer germanium scrap is fibre optics.[l]

The worldwide processing of germanium has been extensively covered.[m] The preferred route for recovery is hydro-metallurgical processing, with germanium being precipitated as either the hydroxide or sulphide, or with tannic acid. Thermo-metallurgical processing is declining in importance because of issues with the volatility of germanium oxides and sulphides.

In 2010 Neo Material Technologies took 50% share of Buss und Buss Spezialmetalle in Germany, which recycles pre-consumer germanium scrap.[n]

4.7 Graphite

The recovery of high quality graphite flake from the steel manufacturing industry is feasible but not practised because the easy and high global availability of graphite inhibits the economics of recycling and recovery.[o] In the very few examples where graphite is recycled, it is derived from old electrodes and machine turnings, when it is ground, crushed and sized before reforming into new electrodes. However,

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[a] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[b] Review of germanium processing worldwide, R.R. Moskalyk, Minerals Engineering 17, *2004,* 393–402

[c] Materials Scarcity, Huib Wouters *et al*, Materials innovation institute, 2009

[d] Opportunities and limits to recycle critical metals for clean energies, *et al.,* 2010

[e] Review of germanium processing worldwide, R.R. Moskalyk, Minerals Engineering 17, *2004,* 393–402

[f] Critical Materials Strategy, US Department of Energy, 2010

[g] Opportunities and limits to recycle critical metals for clean energies, *et al.,* 2010

[h] Review of germanium processing worldwide, R.R. Moskalyk, Minerals Engineering 17, *2004,* 393–402

[i] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[j] Complex Life Cycles of Precious and Special Metals, Christian Hagelüken and Christina E. M. Meskers, Linkages of Sustainability, 2010

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

[l] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[m] Review of germanium processing worldwide, R.R. Moskalyk, Minerals Engineering 17, *2004,* 393–402

[n] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

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

it is estimated that up to 75% of used graphite electrodes are suitable for recycling as new electrodes. Instead this graphite can be used as a reducing agent and source of energy in thermo-metallurgical recovery processes.[a]

In the future, assuming that carbon nanotubes and graphene meet the predictions regarding use and production, recycling of these materials will be required, bearing mind the health and safety precautions that will be necessary.

4.8 Indium

As with gallium, indium is required at extremely high purity and therefore sophisticated processing is required to produce useable indium, particularly from waste streams.

Indium is difficult to recycle and the process is energy intensive and time consuming.[b] Only very low levels of Indium are recycled from old scrap[c] as there is lack of suitable facilities. Furthermore, it is not currently economically viable for most indium sources such as indium tin oxide (ITO) in flat panel displays and photovoltaic panels.[d] In pre-consumer manufacturing process the deposition of ITO onto liquid crystal display (LCD) units is very inefficient, with only about 15% of the source material being used on the product. The remainder is lost to the sputtering chamber, though it is estimated by the Indium Corporation that up to 85% of this material can be recovered.

The major use of indium is in flat panel displays (FPDs), but this is extremely inefficiently recycled, and only an estimated 1% is recovered: this is due to the dissipative use of indium in this application, as only low concentrations of ITO are present in FPDs. Because of this dissipative use, both tailings and slags are both difficult and expensive to process, but their viability could increase with increased metal value.[e] AEA has reported that indium can be recovered from FPD units, and that there will be an increase in demand for the metal with the growth of photovoltaic panels.[f] Umicore at Boboken, Antwerp, Belgium recovers about 50 tonnes per annum of indium.[g] This facility also recovers the indium in conjunction with antimony and tellurium from WEEE waste streams and has been very well described.[h] The Ashahi Pretec Group in Kobe, Japan also recovers indium from FPDs found in WEEE waste streams by dissolution techniques.[i] The Dowa Group also recycles indium in Japan.[j] In 2009 Neo Material Technologies acquired Recapture Metals to recover indium and in 2010 they also acquired a 50% share of Buss und Buss Spezialmetalle in Germany, who also recycle indium.

4.9 Magnesium

Magnesium is recycled mainly by remelting its alloys – particularly with aluminium - and the recycling rate is estimated to be 33% of consumption, arising from sources such as automotive parts and beverage cans. The technology and industry are well established in Europe and throughout the world. However, it is expected that the increased use of magnesium as a replacement for the heavier steel in cars will further promote recycling, but life cycle analyses that have been carried out on magnesium used in car bodies suggest that better recycling technologies are needed to make this viable.[k]

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[a] The UMICORE Process: Recycling of Li-ion and NiMH batteries via a unique industrial Closed Loop, Umicore Battery Recycling, 2010

[b] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

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

[d] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

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

[f] Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, Department for Environment, Food and Rural Affairs, 2010

[g] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[h] Recycling of Electronic Scrap at Umicore's Integrated Metals Smelter and Refinery, , 2006

[i] Precious Metal Recycling Business, Asahi Holdings Group, 2010

[j] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[k] A Comparative Life Cycle Assessment of Magnesium Front End Autoparts, Alain Dubreuil,

In a typical process, the scrap magnesium alloy is melted in either a batch or semi-continuous facility, using either a controlled protective argon-sparging atmosphere or flux to minimise any oxidation. Once molten, the dense flux sinks to the bottom of the molten magnesium and is removed. Impurities such as iron are removed by adding manganese, which forms a compound with the iron and sinks to the bottom of the molten magnesium. However, this causes a problem because the manganese content of the magnesium becomes variable, but this can be rectified by adding controlled amounts of zirconium, which removes the manganese. Silicon hexafluoride (SF_6) can be used as a covering gas in magnesium remelting to prevent the molten metal oxidising. [NOTE: SF_6 has high GHG potential.[a]]

Magnesium is reused in alloys by Magnesium Elektron[b]; its facility in the Czech Republic has the capacity to reprocess 25,000 tonnes of the metal per annum[c] , and another facility in Manchester UK can process 11,400 tonnes per annum.[d]

The magnesium content of used beverage cans is adjusted by addition of other alloys or pure metals. Alternatively the magnesium concentration is lowered by chlorinating the magnesium (to magnesium chloride) which is then sent for disposal. This waste could be a valuable source of both magnesium and chlorine.

Other technologies are being developed to recycle high quality magnesium-containing alloys, and retain their properties. Melt Conditioned High Pressure Die Casting (MCHPDC) processes represent one such technique, in which the resultant alloy has properties very similar to virgin material because of the uniform structure created by the intensive shearing imposed on the metal during melting.[e] There is a proof of concept by Brunel University for the recovery of magnesium using rheo-diecasting; the process involves imparting intensive turbulence and shearing to solidifying magnesium and magnesium alloys.

4.10 Niobium

Although there are no available data on recycling of niobium as a single metal, it is believed to occur negligibly. Instead, niobium recycling occurs in the steel industry, where niobium-containing steels are recycled in processes with other types of steel. It is estimated that up to 20% of the primary consumption is recycled in this way.[f,g] However, within this processes there is no evidence that grades of steel containing niobium are separated out and recycled separately. All steels appear to be recycled together; therefore, even though niobium is technically recycled, it is also further diluted and dispersed in this processing.

Niobium is used, in the form of Nb_3Sn filaments, as a superconductor to generate high magnetic fields, and the used filaments could be source of scrap niobium.

4.11 PGMs

Both pre-consumer and post-consumer recycling of the platinum group metals - especially platinum - is common, mainly because of their high intrinsic value, and the economics and logistics of PGM recovery have been reviewed in some depth.[h]

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[a] Service contract to assess the feasibility of options to reduce emissions of SF6 from the EU non-ferrous metal industry and analyse their potential impacts, EC DG Environment, 2009

[b] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

[c] Magnesium Recycling For The 21st Century, Magnesium Elektron, 2011

[d] Commodity Profile – magnesium, BGS, 2004

[e] Recycling of high grade die casting AM series magnesium scrap with the melt conditioned high pressure die casting (MC-HPDC) process, S. Tzamtzis *et al*, Materials Science and Engineering A 528, *2011,* 2664–2669

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

[g] Columbium (Niobium) and Tantalum, USGS, 2003

[h] Backward linkage development in the South African PGM industry: A case study, Marian Lydall, Mineral Economics & Strategy Unit, 2009

Pre-consumer scrap is usually recycled by the manufacturers, and these processes are well established and often operated in a closed-loop due to the high value of these metals. For example, industrial applications for platinum such as catalysts and glass production achieve recycling rates of 90-95%. In the case of oil-refining catalysts (fuel cracking catalysts) the PGMs are recovered by acid and alkali solvent extraction combined with ion-exchange techniques.[a]

Post-consumer recycling rates are much less common because of dispersive issues and the consequential problems of recovering low volumes. There is no universal process for post-consumer scrap (such as electronics, jewellery and autocatalysts[b,c,d], but about 50-60% of autocatalyst PGMs are recovered, compared with only about 10% of PGMs in electronic scrap, although this figure should improve as the benefits of the WEEE Directive take hold.[e] In 2007 Umicore reclaimed over 12 tonnes of platinum and it was reported in 2009 that they had achieved a recovery of 15 tonnes with a capacity of 24 tonnes.[f]

4.11.1 Autocatalysts

Technology for the recovery of PGMs from autocatalysts is well developed, and implemented widely. The process is relative simple; after decanning (removal of the outer metal casing), molten iron or copper is used to dissolve the PGM catalyst and fuse the support. The PGMs are then extracted from the molten alloy and further refined into the separate PGMs.

4.11.2 WEEE

Extensive discussion has been published on the PGM content of the WEEE stream.[g] The highest concentrations of PGMs to be found in WEEE streams are in products containing printed circuit boards (PCBs)[h],but generally it is estimated that WEEE streams contain about 6g/tonne of palladium.[i] Treatment of this waste stream is governed by WEEE Directive-type legislation; this is almost global, with the only major omission being Africa.[j]

It has been reported that the majority of PGM recovery derived from WEEE streams is through wet chemical leaching of precious metals. However it is believed that this treatment is inefficient, and alternative methods should be developed and improved.[k,l] Umicore's facility for processing WEEE streams recovers PGM at better than 95% efficiency. Their facility operates both hydro-metallurgical and pyro-metallurgical recovery processes.[m,n] The combined copper and lead smelting facility operated by the Dowa Group also achieves recovery rates of about 95%.[o]

PGMs can also be recovered by thermo-metallurgical processes from the copper waste streams of WEEE.[p] A thermo-metallurgical recovery process for PGMs from PCBs that uses sieving, magnetic separation and

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[a] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

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

[c] Platinum - Definition, mineralogy and deposits, Gus Gunn and Antony Benham, BGS, 2009

[d] End-of-Life Vehicle Recycling: The State of the Art of Resource Recovery from Shredder Residue, US Department of Energy, 2006

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

[f] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[g] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[h] Material flows of end-of-life home appliances in Japan, Shinsuke Murakami *et al.*, J Mater Cycles Waste Manag, 2006, 8:46–55

[i] Setting Priorities for the EOL management of Complex Products, Chancerel P. *el at*, Twelfth International Waste Management and Landfill Symposium

[j] How are WEEE doing? A global review of the management of electrical and electronic wastes, F.O. Ongondo et al., Waste Management, 2010

[k] Recycling from E-Waste Resources, UNEP - StEP Initiative, 2009

[l] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

[m] Critical materials and mobile devices, OECD Environmental Directorate, 2010

[n] Recycling from E-Waste Resources, UNEP - StEP Initiative, 2009

[o] Critical materials and mobile devices, OECD Environmental Directorate, 2010

[p] Waste electrical and electronic equipment (WEEE): innovating novel recovery and recycling technologies in Japan, DTI(UK), 2005

reduced oxygen partial pressure pyrolysis, followed by metal oxide reduction by a hydrogen atmosphere has been comprehensively summarised.[a] Recovery rates of PGMs are often better than 99% from copper smelters using this method.

4.11.3 Others

PGMs are also recovered from military wastes and hazardous sources including nuclear bombs by water-jet cutting and disassembly. PGM recovered by separation and smelting[b] and improved methods of construction, such as Design for Disassembly by using Shape Memory Alloys, will help in the recovery of PGMs.[c]

4.11.4 New technologies

BASF Catalysts has carried out extensive review of PGM recovery routes (including ion exchange) from fuel cell membrane electrode assemblies. Recent approaches to PGM recovery include plasma arc processing[d], liquid surfactant membrane technology[e] and ion exchange can also be used.[f] Recovery of soluble gold by using a highly selective process, based on egg-shell membrane-conjugated chitosans, has been reported.[g]

4.11.5 Operators

PGM recycling is well established, and there are a number of key operators in this area, described below.

Within the UK, PGMs are recovered by companies such as Engelhard, BASF and Johnson Matthey.[h] Johnson Matthey operates refineries at Royston, Hertfordshire and Brimsdown, Enfield, whilst BASF Catalysts (ex-Engelhard) operate in Cinderford, Gloucestershire. Other companies that are active in the technology include AWA Refiners in Harlow, Essex, INCO Europe in Acton, London[i] and Panasonic.[j,k] Tetronics Ltd in Swindon, UK, uses plasma arc technology to recover platinum and palladium from automotive catalysts.[l]

Elsewhere in Europe, the Umicore plant recovers the highest PGM levels in the world, but in 10-15 years it will have only about 15% of required global capacity for PGM recycling.[m] Other companies with a major interest in recycling PGMs include the Dowa Group[n,o] Ashahi Pretec Group[p], Mitsubishi [q]and Ohkuchi Electronics Co Ltd.[r] Ashahi Pretec recovers PGMs from WEEE waste streams as well as from catalysts,

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[a] Techniques to separate metal from waste printed circuit boards from discarded personal computers, Takanori Hino et al., J. Mater Cycles Waste Manag, *2009,* 11:42–54

[b] Recovery of precious metals from military electronic components, H.Gundiler *et al*, 1994

[c] A Feasibility Study on Active Disassembly using Smart Materials - A Comparison with Conventional End-of-Life Strategies, Joseph David Chiodo and Casper Boks, Life Cycle Engineering: LCE'99', 1999

[d] Tetronics: Recovery of Precious Metals, Tetronics, 2011

[e] Selective recovery of palladium from a simulated industrial waste water by liquid surfactant membrane process, Takahiko Kakoi et al., Journal of Membrane Science 118, 1996, 63-71

[f] Equipment Rental precious metal recovery, DOWA, 2011

[g] Recovery of gold by chicken egg shell membrane-conjugated chitosan beads, Ryo Shoji *et al*, J Mater Cycles Waste Manag, 2004,6:142–146

[h] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

[i] Commodity Profile - Platinum Group Elements, BGS, 2004

[j] Panasonic Group ‘eco ideas’ Report 2009, Panasonic, 2009

[k] Eco ideas report 2010, Panasonic, 2010

[l] Tetronics: Recovery of Precious Metals, Tetronics, 2011

[m] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[n] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[o] Equipment Rental precious metal recovery, DOWA, 2011

[p] Precious Metal Recycling Business, Asahi Holdings Group, 2010

[q] Waste electrical and electronic equipment (WEEE): innovating novel recovery and recycling technologies in Japan, DTI(UK), 2005

[r] Recycling Business, Sumitomo Metal Mining, 2011

FPDs and dental scrap.[a] Unspecified PGMs and other materials are being recycled by incineration or dehydration by Panasonic under their zero waste initiative. Recovery processes for PGMs from electronics have been implemented for many years by Ohkuchi Electronics Co Ltd.[b]

4.12 REEs

In general the recycling and recovery of rare earth elements occurs at a low level, with most activity occurring in pre-consumer waste. For example, the Shin Etsu Chemical Co Ltd uses both ion-exchange and dehydration and calcination to recover REEs from product streams.[c] The company also uses electrolytic extraction to extract REEs and any additives made to give the required alloy composition; these are melted, pulverised and sintered. However, wastage still occurs in industries such as magnet production, where cutting scraps are not reclaimed as no mechanism exists for recovery at present.

In post-consumer scrap REEs are available in WEEE waste streams including batteries, lighting and magnets. It is believed as much as 300,000 tonnes of REEs are trapped in this waste stream in Japan alone[d], and methods for recycling and recovery are recycling are actively being sought, and being implemented. By contrast, activity related to REE recycling in the USA and elsewhere has historically been limited, and very small quantities of these materials are recovered in these areas.[e]

Recycling of REEs is problematic. A recent report, focusing on cerium, lanthanum, praseodymium and neodymium (but notably not samarium), discusses the potential for recycling of these materials.[f] The primary uses of the metals were identified and the possibility of recycling assessed; overall it was concluded that it is both difficult and expensive due to the nature of the products and the dispersion of the materials.[g] Other recycling issues have been briefly discussed elsewhere[h] and recovery methods for REEs are known to be dependent on the waste stream and have been extensively reviewed.[i,j,k] These difficulties mean it is not surprising that REE recycling rates are very low in general, and less than 1% of REEs are recycled from old scrap, mainly from old magnets; the technology is being led by Japan.[l] In the UK, REE recycling is led by Great Western Metals Co and Less Common Metals (LCM)[m] but most work is being carried out in Japan.[n]

More generally, both current and historical recovery methods for recovering RE metals from magnets, batteries, lighting and catalysts and other applications has been extensively discussed due to recent supply concerns. It has been concluded that the most cost-effective method is liked to be based on liquid-liquid technologies, but there is currently little commercial activity and what there is remains mostly at laboratory scale and is being carried out mainly in Japan.[o]

One of the few semi-commercial processes is run by Hitachi, recovering REEs from computer disk drives and electrical compressors. This process requires specialist machinery to disassemble the products, then uses a special extraction material that has a high affinity for the rare earths. This process is currently in

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[a] Precious Metal Recycling Business, Asahi Holdings Group, 2010

[b] Recycling Business, Sumitomo Metal Mining, 2011

[c] Sintering process, Shinetsu, 2010

[d] UK Parliamentary Science and Technology Committee, Written Evidence, February 2011

[e] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[f] Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, Department for Environment, Food and Rural Affairs, 2010

[g] Rare Earth Metals, UK Parliamentary Science and Technology Committee, POSTNote, December 2010

[h] Rare Earth Elements - Definitions, mineralogy and deposits, BGS, 2010

[i] Review of the Future Resource Risks Faced by UK Business and an Assessment of Future Viability, Department for Environment, Food and Rural Affairs, 2010

[j] Lanthanide Resources and Alternatives, Oakdene Hollins, 2010

[k] Methods and Opportunities in the Recycling of Rare Earth Based Materials, US Department of Energy, 1994

[l] Critical Materials Strategy, US Department of Energy, 2010

[m] UK Parliamentary Science and Technology Committee, Written Evidence, Feb 2011

[n] Lanthanide Resources and Alternatives, Oakdene Hollins, 2010

[o] Technology challenges to recover precious and special metals from complex products, & Christina Meskers, Umicore, 2010

the pilot scale, but it is anticipated that it will be in full scale by 2013.[a] In other areas Mitsui Metal Mining Co in Japan is to recycle rare earth elements from NiMH batteries[b] and General Electric is looking at recycling RE from lights phosphors and magnets.[c]

A host of potential recycling technologies exist in research stages, which may or may not reach commercialisations stages. Some examples include:

- Rare earth elements that are used in magnets can be recycled by hydrogenation disproportionation desorption recombination (HDDR)[d,e], dissolution in molten magnesium[f] and acid leaching.[g] These materials can be used in new magnets, but with a loss of performance.
- The Fray Farthing Chen (FFC) process for recovery of RE oxides by electrolytic reduction of sintered oxides has been reviewed[h] and a small scale acid-free method has been identified as having potential for industrial application.[i]
- REE enrichment by room temperature molten salts has been shown to be possible on a laboratory scale by using thermal-resistant automotive catalysts that are recovered for their noble metal content. These also contain the rare earth element cerium.[j]
- Yttrium and europium can be recovered from fluorescent lamps by crushing and pressure-leaching in acids. The rare earth elements are recovered by selective solvent extraction and high temperature thermal reduction by hydrogen.[k] It has also been suggested that the presence of mercury in ion fluorescent lights could be used to help recover the REEs from this waste stream.[l]
- Recovery of REEs from mine tailings and effluent using vibratory shear enhanced processing (VSEP) has also been shown to be possible.[m]
- Yyttria-stabilised sintered zirconia (Y_2O_3-ZrO_2) in granulated powder ceramics can be hydrothermally recycled by autoclaving in water and then pulverising and resizing resultant particles and reusing them in sintered zirconia bodies.[n]
- Research groups in Germany and Japan are investigating the use of microbes to remove and separate rare earth elements from magnets.

4.13 Tantalum

It is estimated that post-consumer scrap recovery or recycling is limited to between 1-9% of total consumption.[o] Post-consumer scrap tantalum is found in aero-engines and cemented carbides, where it can be recycled in similar value alloys or downgraded materials. These processes are well established.

However, tantalum is difficult to recover from post-consumer electronic scrap, as it is often dispersed and forms part of a complex mixture of metals and other materials. It is also technically challenging, as thermo-metallurgical processing is difficult.[p] Therefore tantalum is not recovered from electronic scrap

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[a] Japan - Hitachi develops recycling technologies for rare earth metals, Physorg.com, accessed 15/2/2011

[b] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[c] Research Priorities for More Efficient Use of Critical Materials from a U.S. Corporate Perspective, Steven Duclos, GE Global Research, 2010

[d] Recycling of NdFeB - Turning Scrap into New Magnets, Williams A., UK Magnetics Society Presentation,2010

[e] UK Parliamentary Science and Technology Committee, Written Evidence, Feb 2011

[f] Recovery of neodymium from a mixture of magnet scrap and other scrap, Osamu Takeda *et al*, The University of Tokyo, 2005

[g] Recovery of rare earths from sludges containing rare-earth elements, Tetsuji Saito *et al*, Journal of Alloys and Compounds 425, *2006*, 145–147

[h] The Implications For Electric Motors & Drives Of Rare-earth Magnet Cost Reduction Effects on Manufacturers, Raw Materials Suppliers & Users of Rare Earth Magnets, Oakdene Hollins, 2002

[i] Hitachi leads rare earth recycling efforts as China cuts access to supply, Bloomberg, accessed 15/2/2011

[j] Enrichment of rare earth and alkaline-earth elements by countercurrent electromigration in room temperature molten salts, Masahiko Matsumiya *et al*, Electrochemistry Communications 7, *2007*, 370–376

[k] Recyclables recovery of europium and yttrium metals and some salts from spent fluorescent lamps, Mahmoud A. Rabah, Waste Management 28, *2008,* 318

[l] Critical Materials Strategy, US Department of Energy, 2010

[m] Lanthanide Mining and Milling Effluent Treatment - a cost-effective and environmentally-sound solution, Habib Amin *et al*, New Logic International, 2010

[n] Recycling process for yttria-stabilized tetragonal zirconia ceramics using a hydrothermal treatment, Kamiya, M., J Mater Cycles Waste Manag, *2007,* 9:27–33

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

[p] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

to any significant level, and consequently the necessary processing is insufficiently developed. Despite these issues it can be expected that this will increase, because in 2010 Neo Material Technologies took a 50% share of the German company Buss und Buss Spezialmetalle GmBH.[a] This company is currently one of the few specialist organisations undertaking tantalum recovery from both electrical and other scrap from wastes such as foils, off-cuts, anodes and pins, to produce commercially pure tantalum as well as metal products and billets.

Pre-consumer scrap such as that derived from the electronics industry, where tantalum is used in capacitors, is already reclaimed in manufacturing plants.[b] However there is very little reclamation from the biggest market for scrap tantalum which is in capacitors for the electronics industry, due - in part - to the very small quantities of tantalum in each device.

4.14 Tungsten

Tungsten scrap is a very high value resource because its tungsten content is very high when compared with the ores. About 33-34% of the tungsten demand is met from recycling, which also facilitates the recovery of other elements such as niobium, cobalt and tantalum.[c,d]

One of the main uses of tungsten is as tungsten carbide which is used in tool steels, where about 60-70% is recycled. Tungsten used in lighting filaments and as tungsten metal, along with tungsten based chemicals and welding rods, all have low recovery rates.[e,f] Of the 34% demand met by recycled scrap, about 10% comes from processing scrap and 24% from end of life scrap.[g]

When recovering tungsten from clean cemented carbides, the mixed metals are mixed with molten zinc, and the cobalt cement is dissolved out to leave the solid tungsten carbide which is recovered and crushed for reuse.[h] The technology was developed by Sandvik Coromant in the mid 1990s and is normally carried out in a vacuum furnace. About 98% of the tungsten carbide is recovered to be reused in tooling with up to 40% recycled tungsten carbide content. There is no difference between tools made from recovered and virgin carbides.[i]

Contaminated cemented carbide scrap, along with turnings, grindings and powder are processed and oxidised to ammonium paratungstate (APT), a method similar to that used for extraction of tungsten from its ores. Any cobalt, tantalum or niobium that may be present is recovered during this process.[j] The recovery of tungsten as metal, along with other metals, is considered less environmentally friendly, but nevertheless produces good material.[k] It is anticipated that tungsten and cobalt demand will increase in the future, and therefore increase the quantity of tungsten recycled.[l]

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[a] Clean technology scarce and getting scarcer, Lydia Heida, Environmental Finance, November 2010

[b] Critical metals for future sustainable technologies and their recycling potential, Matthias Buckert *et al*, UNEP, 2009

[c] Tungsten - An Overview, The A to Z of Materials and AZojomo, 2002

[d] UK Parliamentary Science and Technology Committee, Written Evidence, Feb 2011

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

[f] Tungsten - An Overview, The A to Z of Materials and AZojomo, 2002

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

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

[i] Recycling on the Rise, Lars Hallberg, Sandvik Coromant, 2010

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

[k] Recycling on the Rise, Lars Hallberg, Sandvik Coromant, 2010

[l] Tungsten Cemented Carbides – A Success Story, Wolf-Dieter Schubert, ITIA

5 Identification of Principal End Use Applications

The overall purpose of this study is to identify the opportunities for recycling or other resource efficiency measures for the group of critical raw materials identified by the EU Raw Materials Initiative, together with the required changes in infrastructure such as collection or processing.

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. Previous research on the materials, outlined in Section 3, identified 40 end uses (Table 4). 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.

Table 4: Full list of end uses identified in the study of critical raw materials

Automotive & aerospace	**Dental alloys**	**Magnets**	**Pigments**
Batteries	**Electrical equipment**	**Mechanical equipment**	**Polishing**
Catalyst	**Electronics / IT**	**Medical appliances**	**Refractories**
Cement	**Fabricated products**	**Optics**	**Research & development**
Cemented carbide tools	**Flame retardants**	**Other final consumer goods**	**Rubber/ plastics**
Ceramics	**Foundries**	**Other metal alloys**	**Sputtering targets**
Chemicals	**Glass**	**Others**	**Steel & steel alloys**
Coatings	**Jewellery**	**Packaging**	**Superalloys**
Construction	**Low temperature alloys**	**Pencils**	**Tungsten alloys**
Crucibles	**Lubricants**	**Phosphors**	**Wrought 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. However, this approach has ensured the greatest possible coverage, and is not believed to have unduly influenced the screening process.

5.1 *Screening Criteria and Methodology*

Screening was carried out using information such as market share and value, generated previously for each of the critical materials. The following screening criteria were used:

1. To allow for individual niche end uses of high importance, where a single end use accounts for over half of the consumption of a particular critical material, that end use was automatically included.

2. Three measures were then used to rank the markets:

Usage	The usage of each critical material in each market was ranked (0-3) based on percentage consumption of the material in that market. The score for each material was summed for the markets, then ranked according to score. This ensures inclusion of markets which have high critical material usage.

Value	The economic value of the material (3 year average price x tonnage) for each market was calculated and used to rank the markets. This prioritised high value material streams of most interest to investors and processors.
Environmental impact	An approximate carbon impact of the market was made (sum of tonnage of each material x carbon impact of each raw material production), and used to rank the markets. This was used to assess environmental impact.

The top ten ranked markets for each measure are shown in Table 5, with full tables with data available in Annex C. The markets for each measure were included based on rank, therefore equal weighting was given to each. The rank level was increased until over 10 different markets were selected.

3. It was also ensured that each critical material was represented once at least, this occurred already using the methodology above.

The following criteria were considered, but were not included so as not to unduly affect the outcome of this study:

- No material was regarded as more critical than any other, provided it is included in the 'EU Critical 14' group. Therefore absolute tonnages of material were not used as a criterion, since this would discriminate between low tonnage materials such as PGMs and higher tonnage materials such as magnesium.

- The use in growing rather than declining industries, the supply risk, and the concentration of supply from particular countries have all been taken into account of the definition of the 'EU Critical 14' group, and will not be further considered.

- The extent of existing resource efficiency measures, such as recycling, was also omitted from consideration.

Using screening criterion 1, the following nine markets were included:

- automotive and aerospace components (magnesium)
- catalysts (PGMs)
- cemented carbide tooling (tungsten)
- chemicals (fluorspar)
- electrical equipment (indium)
- electronics/IT (gallium)
- fire retardants (antimony)
- optics (germanium)
- steel and steel alloys (niobium).

To provide a wider coverage of critical materials and to include other factors, a further group of markets was selected using the ranking system in criterion 2. The markets associated with each rank for each measure were included, starting with those ranked 1st. Further ranks were then included to increase the number of markets selected, with the aim of choosing at least ten. Jewellery and 'others' were omitted during this process on the basis that they did not fit with the overall aims or scope of this project. Therefore a further three markets were included, once the 6th ranked markets were included, bringing the total number to 12.

Table 5: The ten most highly ranked markets for each measurement

Rank	Usage	Value	Environmental Impact
1	Electronics / IT	Catalyst	Automotive & aerospace components
2	Steel & steel alloys	Steel & steel alloys	Packaging
3	Others	Jewellery	Steel & steel alloys
4	Electrical equipment	Electronics / IT	Catalyst
5	Catalyst	Cemented carbide tools	Electrical equipment
6	Batteries	Chemicals	Construction
7	Superalloys	Automotive & aerospace components	Flame retardant
8	Cemented carbide tools	Glass	Others
9	Optics	Flame retardants	Jewellery
10	Other metal alloys	Dental alloys	Wrought alloys

NOTE: full lists and data available in Annex C. Those markets highlighted were included using screening criterion 2

Criterion 3 was not needed, as all materials had been included in these markets at this point. The final selected markets and corresponding materials are shown in Table 6.

Table 6: Final matrix of selected markets and materials

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

**Additional materials included due to importance to market, originally omitted to due inclusion in another market.*

6 Resource Efficient Use of Critical Raw Materials

Each of the markets chosen within the screening exercise is discussed below, preceded by a short review of the impact of overarching legislation and policy within the UK and EU.

Within each market the primary uses of these materials have been identified and current practices for materials recovery at end of life identified. The main focus of this has been on recycling, as this is the most prevalent activity; however other life-extension and resource efficiency activities have been discussed where appropriate.

Within this section carbon impacts have also been estimated using CO_2e as a measure, using the standard IPCC GWP 100a definition. This defines the global warming potential of all emissions, normalised to the impact of carbon dioxide over 100 years. Data have been taken from Ecoinvent v2.2 unless otherwise specified, and Simapro has been used as a modelling tool where appropriate. Measurements should be seen as indicative only, as modelling has been streamlined to fit with the scope of this work and to fit the data available.

6.1 Overarching Policies and Legislation

Before discussing each market in detail it is useful to examine some of the general policy and legislative framework that relates to the scrap metals and waste management industry, which will have an impact across a number of the critical raw materials and end uses. The aim of this is to provide an overview giving references for further information and to supplement the individual product reports, which are more concerned with policies and legislation with specific relevance for that end use e.g. the ELV or WEEE Directives.

6.1.1 Trade restrictions

For primary metals a number of countries have implemented trade restrictions, such as quotas and tariffs, on the export of particular metals. Such measures can have a significant effect on the availability, destinations and prices of critical raw materials. Probably the most high profile example of this is for rare earth elements with China, where quotas have been cut by 35% for the first round of permits for 2011[a], in addition to the cuts in the export quota in 2009 and 2010. As a result of this intervention prices for REEs (composite price) have more than tripled during 2010. For secondary metals, tariffs and trade restrictions are also regularly implemented by various countries; this influences UK export prices and can alter the composition of destination markets. The WTO periodically publishes the tariffs applied on imports for each country.[b] Of the UK's major scrap markets outside the EU, India has been the most active in this area and its tariffs change significantly over time. In addition to tariffs, countries may use regulations as barriers to trade, such as quality certification requirements which can act as an administrative burden. Currently it appears that the number of restrictions is rising, although there is a tendency for restrictions to be placed on exports of secondary material rather than the imports.[c] The OECD lists a number of countries that have increased import tariffs on steel products or introduced non-tariff barriers. The tariff increases are occurring mainly in emerging economies including Egypt, India, Turkey and UAE, which are directly or indirectly important markets for UK exports. Meanwhile it is mainly the Asian economies implementing the non-tariff barriers.

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[a] China Cuts Export Quotas for Rare Earths by 35%, Bloomberg, December 2010

[b] World Trade Organisation, Tariff Download Facility, available at URL: http://tariffdata.wto.org/Default.aspx?culture=en-US, accessed 25/02/11

[c] The Structure and Outlook for UK Markets in Secondary Steel and Aluminium [unpublished], Oakdene Hollins for WRAP, 2009,

6.1.2 Waste regulations

A number of waste regulations are of relevance for scrap metals. The first is the Basel Convention, which governs the movement of waste around the world. The second is EC Regulation 1418/2007 which concerns the movement of wastes, including scrap metal, between European and non-OECD countries.[a] Questionnaires were sent out to all of the relevant countries to ascertain how they would wish to receive such materials, with the possible options being prohibition, prior written notification and consent, no control or other control procedures under applicable national law. Non-respondents were assumed to wish to continue with the current procedure of prior written notification and consent. 43 countries responded, including both India and China, who wished to have control procedures under applicable national law. The third regulation of interest is that relating to End of Waste Criteria. This is an ongoing European initiative that aims to determine procedures that will lead to materials, such as scrap metals, no longer being classified as waste but as products. This would mean that scrap metals would no longer require prior written notification and consent and hence reduce administrative burdens. As such, this initiative is being roundly welcomed by different metal trade associations who see it as having a positive effect for UK scrap exports. However it will be some time before the conclusions on amendments to the End of Waste Criteria are realised.

6.1.3 Environmental policy

A number of UK and European government policies have direct or indirect impacts on waste or the metals industry. In the UK the Landfill Tax is applied on the disposal of waste, aimed at encouraging waste producers to produce less waste, recover more value from waste - for example through recycling or composting - and to use more environmentally benign methods of waste disposal. As of 2010/11, the standard Landfill Tax stands at £48 per tonne for active waste, although it is set to increase at £8 per tonne per year for active waste - announced from 2008/09 to at least 2013/14.[b] A strong relationship between waste to landfill and the standard rate of Landfill Tax has been established.[c] The Integrated Pollution Prevention and Control (IPPC) is a regulatory system set up by a European Directive to control the environmental impact to air, land and water of emissions arising from industrial activities, of which both the metals and waste management sectors are covered. It involves determining the appropriate controls for industry to protect the environment through a single permitting process. In order to gain an IPPC permit, operators of industrial sites must show that they have systematically developed proposals to apply the Best Available Techniques to pollution prevention and control, and that they address other requirements, relevant to local factors.[d]

Carbon emissions are a further area of policy of relevance as they may make energy and carbon intensive processes less financially viable. In the UK, three (overlapping) policies are of importance. The European Union Emissions Trading System (EU ETS) commenced in 2005 with the aim of reducing emissions of greenhouse gases from industrial sources across the EU. The EU ETS is a ‘cap and trade’ scheme – under which a total cap is determined for the amount of CO_2 emissions permitted and is made available to participants in the form of ‘allowances’. At the end of each year participants must submit verified emissions data and enough allowances to cover their emissions, but participants are allowed to trade allowances. Climate Change Agreements (CCAs) were introduced by DECC to recognise a need to give special consideration to energy-intensive industries with regards to climate change, given their energy use and their need to compete internationally. Consequently, energy-intensive industries can obtain an 80% discount from the Climate Change Levy, provided they meet challenging targets for improving their energy efficiency or reducing their carbon emissions.[e] The Carbon Reduction Commitment (CRC) came

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[a] European Commission, Commission Regulation (EC) No 1418/2007, available at URL: http://trade.ec.europa.eu/doclib/docs/2007/december/tradoc_136966.pdf accessed 25/02/11

[b] Defra website available at URL: http://www.defra.gov.uk/environment/waste/strategy/factsheets/landfilltax.htm accessed 14/02/11

[c] Oakdene Hollins for Defra (2011), Further Benefits of Business Resource Efficiency

[d] WRAP website available at URL: http://envirowise.wrap.org.uk/uk/Integrated-Pollution-Prevention-And-Control-IPPC.html accessed 14/07/10

[e] DECC Website, What are Climate Change Agreements, available at URL: http://www.decc.gov.uk/en/content/cms/what_we_do/lc_uk/ccas/what_are_ccas/what_are_ccas.aspx accessed 20/01/11

into force in April 2010 and aims to significantly reduce UK carbon emissions not covered by other pieces of legislation (mainly non-energy intensive sectors). A study by DECC assessed the degree of overlap of the policies and showed that the overlapping EU ETS and CCA covered 41% of carbon emissions between them, the CRC covered a further 35%, and 24% of UK carbon emissions fell outside the coverage of these three policies.[a]

6.2 Aerospace and Automotive

Relevant materials: beryllium, cobalt, graphite, magnesium, niobium, tantalum

The manufacture of transport equipment within the UK contributed Gross Value Added (GVA) of £18.6 billion to the UK economy in 2008, which represented 2.2% of total UK GVA.[b] This sector comprises the manufacture of motor vehicles, including their bodies, parts and electronics (£10.4 billion of GVA), the manufacture of air and spacecraft (£6.9 billion of GVA) and the manufacture of other types of transport equipment e.g. ships and trains.

With the exclusion of REEs and PGMs, (which have been discussed in Sections 6.3 and 6.8, and Section 6.4.1 respectively), six critical materials are used within the sector. Two of these, beryllium and magnesium, were included as a result of the original screening criteria, with another four more materials added due to the inclusion of aerospace superalloys upon broader analysis of the market:

- **Beryllium** usage in the transport sector accounts for 15% of world beryllium consumption, with aircraft brakes being a notable application.
- **Cobalt** use in superalloys represents 22% of world cobalt consumption, with aerospace being the largest market.
- **Graphite**: brake linings are a notable ‘other’ application for graphite.
- **Magnesium** usage represents 51.5% of world magnesium consumption, with casting alloys for automotive representing the largest share, although magnesium is also used widely for aerospace.
- **Niobium**: Automotive steels represent a large market for niobium at 28% of world consumption, with superalloys for aircraft accounting for an additional 8% of consumption.
- **Tantalum** usage in superalloys represents 15% of world tantalum consumption, of which jet engine blades are one application (along with gas and steam turbines and chemical equipment).

6.2.1 Aerospace

Cobalt, niobium and tantalum are all used in varying quantities within nickel-based superalloys for jet engines.

Figure 8 gives a supply-chain map for cobalt, which has the greatest consumption in volume terms, and is typically present between 10% and 15% of the overall composition.[c] The supply chain begins with the mining and processing of cobalt minerals. Cobalt can be produced from a number of different ores, and therefore a wide variety of mining, extraction and refining methods exist, however they typically result in the production of cobalt metal. Congo (Kinshasa) has the largest share, at 40%, of world mine production for cobalt. A different geographic picture however emerges from statistics of cobalt refinery production, where China is the world’s largest cobalt refiner accounting for 32% of global cobalt metal production, while Europe accounts for 29% of the global total. The cobalt is then used in the manufacture of nickel based superalloys, along with niobium and tantalum which aid the carbide formation process.[d] A supply-chain map for niobium can be found in Section 6.7.2, but it is worth noting here that 92% of the world’s

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[a] AEA Technology and Databuild for DECC (October 2010), Assessing the carbon dioxide emissions and cost effective carbon savings potential for organisations not covered by EU ETS, CCAs or CRC (CESA 0903)

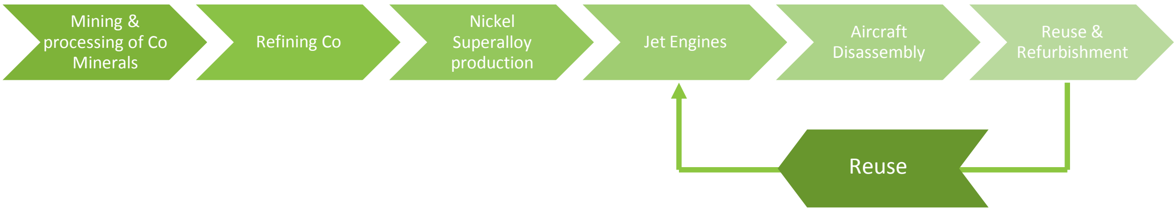
[b] Annual Business Inquiry 2008, ONS, 2010

[c] Cobalt and Cobalt Alloys, http://www.keytometals.com/Article54.htm, accessed 17/02/11

[d] CDI, Superalloys, http://www.thecdi.com/general.php?r=U6ENJVRWAA, accessed 17/02/11

niobium production was in Brazil, most of which came from a single mine owned by Companhia Brasileira de Metalurgia e Mineração (CBMM).[a] The niobium minerals are refined into ferro-niobium with a standard grade of 66% niobium content. As for tantalum around half of the world's production in 2009 originated in Australia. Typical niobium additions are 1-5%; and tantalum additions can be 3-11% (mostly for the turbine coatings).

Figure 8: Supply chain map for cobalt for aerospace superalloys



Beryllium copper is used in aircraft landing gear, particularly in the brakes due to its non-sparking properties. Brakes used in military aircraft 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] The world beryllium markets are dominated by a US company, Brush Wellmann, which is a subsidiary of Brush Engineered Materials. In terms of the landing gear itself, a French company, Messier-Dowty, a subsidiary of Safran, is the world leader, with 20,500 aircraft fitted with their landing gear.[c]

Magnesium is contained within the aluminium alloys of an aircraft, typically as 1-2% of the composition. Although a much smaller market (less than a fifth of the size of automotive, in terms of magnesium consumption), each individual aircraft contains significant quantities of aluminium; for example over 70% of the weight of an Airbus A380's construction is made from aluminium.[d] The supply-chain map for the magnesium contained in aluminium alloys for aerospace is comparable to that described for the construction industry (Section 6.7.1), in that it is mostly wrought alloys, with the best-practice remelting according to alloy family.

Existing practice and infrastructure

The Aircraft Fleet Recycling Association (AFRA) estimates that as many as 12,000 aircraft will reach their end of life over the next 20 years[e], although Airbus estimates a lower number (near 6,000 aircraft). According to Airbus, there are no guidelines or advice relating to end of life aircraft, so "wild destruction of aircraft" or abandonment at airports or in deserts can occur under current practice, meaning that only around 60% of the weight of an aircraft is recovered, half of which is recycled (i.e. 30% of the total).[f] In response, both Boeing and Airbus have programmes in place to increase the recycling rate of end of life aircraft and reduce the amount of waste being sent to landfill. Boeing, as part of AFRA, has set a target of 90% of the materials from an end of life aircraft to be recycled. To this end AFRA is developing best management practices and minimum standards with accreditation, including ensuring that the valuable and complex metal alloys are processed by speciality alloy companies.[g] Currently AFRA members produce 30,000 tonnes of aluminium and 1,800 tonnes of other speciality alloy metals for recycling (from

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[a] Mineral Commodity Summaries: Niobium, USGS, 2011

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

[c] Safran Website, http://www.safran-group.com/site-safran-en/aerospace/aircraft-equipment/landing-systems/ , 23/02/11

[d] Alfed Website, http://www.alfed.org.uk/page.asp?node=76&sec=Aluminium_A_to_Z , 03/02/2011

[e] Aviation industry under pressure to reduce landfill waste from scrapped airliners, Flight Global, January 2011, http://www.flightglobal.com/articles/2011/01/10/351597/aviation-industry-under-pressure-to-reduce-landfill-waste-from-scrapped.html, accessed 23/02/11

[f] PAMELA-Life, Main results of the project, Airbus, 2008, http://www.pamelalife.com/english/results/PAMELA-Life-project_results-Nov08.pdf accessed 23/02/11

[g] William Carberry (Boeing), personal communication

around 150 aircraft).[a] AFRA's international membership includes several companies and organisations based within the UK, such as P3 Aviation in Hertfordshire, as well as a number of others based in Europe.[b]

Airbus' response has been to participate in an aircraft dismantling demonstration project called Process for Advanced Management of End of Life Aircraft (PAMELA), receiving LIFE programme funding from the European Commission. In the trial Airbus examined 16 different dismantling scenarios for an A300 over the course of a year, in order to optimise its processes, before designing a generic methodology. This steps involved in this process are mapping of the aircraft to identify the value, careful disassembly and 'smart' dismantling. This involves higher upfront cost'; taking six weeks rather than six days, but it maximises the value achieved and ensures environmental compliance (e.g. control of pollution and hazardous materials).[c] Because of these upfront costs, Airbus may delay dismantling when metal prices are low in order to receive a higher price for the materials. The achievements of the PAMELA project were a valorisation of 85% of the weight of an aircraft (74.5 tonnes out of 88 tonnes), with reuse and recycling above 70%[d], all of which can be achieved through existing recycling networks. In terms of the critical raw materials, the engines and landing gears (which are the most valuable parts of the aircraft), can often be reused or refurbished and are returned to the manufacturers.[e] Other specialist alloys are sent to specialist recyclers in order to maximise their value. For aluminium alloys these are sorted by type, as mixed alloys are worth only 50% of sorted alloys - if the recycler will even take them[f], which enables the recovery of the magnesium therein.

Relevant policy and legislation

There is no specific policy or legislation of relevance to aerospace other than general environmental compliance e.g. to control pollution and hazardous materials, and to ensure safety standards are met where parts are reused.

Conclusions and recommendations

- Although past and current industry practice for end of life aircraft may not necessarily have allowed the recovery of critical raw materials, both Boeing and Airbus have demonstrated that careful dismantling techniques can be economically viable as well as allow for the recovery of the critical raw materials contained, although companies may choose strategically to delay dismantling when metals prices are low in order to maximise revenue.
- At present the major industry issue is moving to best practice through dissemination, minimum standards and accreditation.
- With the number of aircraft estimated to be set to reach their end of life there will be a need to expand infrastructure and capacity, which offers opportunities for companies in the business of aircraft dismantling, refurbishment of parts for reuse and in complex alloy recycling. In theory this dismantling and recycling could take place anywhere, due to the mobility of aircraft, but in practice the drive towards best practice and accreditation appears to be the best way for UK and European companies to enter the industry.

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[a] Moody E. of Aviation Week, http://www.aviationweek.com/aw/blogs/mro/index.jsp?plckController=Blog&plckBlogPage=BlogViewPost&newspaperUserId=388668c6-b459-4ea7-941e-a0a2206d415f&plckPostId=Blog%3a388668c6-b459-4ea7-941e-a0a2206d415fPost%3a5353c15a-5c93-4b35-9c26-1c8b40756aeb&plckScript=blogScript&plckElementId=blogDest, accessed 23/02/11

[b] AFRA Members, http://www.afraassociation.org/members.cfm, accessed 23/02/11

[c] Olivier Malavallon (Airbus), personal communication

[d] PAMELA-Life, Main results of the project, Airbus, 2008, http://www.pamelalife.com/english/results/PAMELA-Life-project_results-Nov08.pdf, accessed 23/02/11

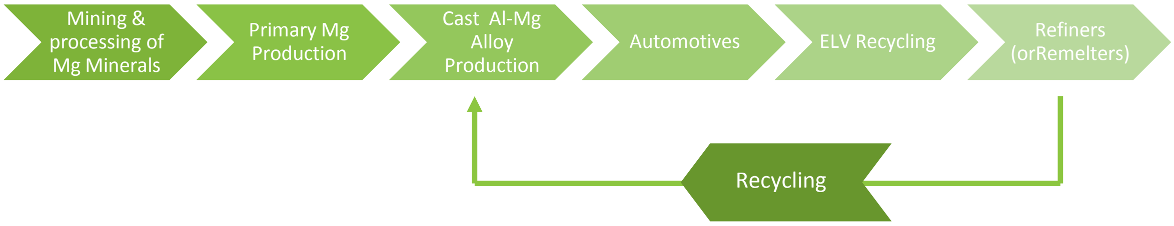
[e] Olivier Malavallon (Airbus), personal communication

[f] Olivier Malavallon (Airbus), personal communication

6.2.2 Automotive

About 150,000 tonnes of aluminium are used in the UK transport market each year: 82,000 tonnes in the form of semi-finished products and 70,000 tonnes as castings[a], and the amount of aluminium used in the manufacture of new cars in Europe has risen from 50 kg per car in 1990 to over 170 kg in 2010.[b] Important applications include engine and transmission parts, chassis and suspension parts and wheel rims; all of which have a market penetration above 50%.[c] These alloys typically have 1-2% magnesium content.[d] Figure 9 outlines a supply-chain map for magnesium used in the automotive industry. The primary processing stages for magnesium are common to those described in the construction sector (Section 6.7.1). The magnesium metal is used as an alloying element within aluminium alloys (mostly cast alloys), of which automotive is a major market. Within Europe in 2004, 3.1 million tonnes of aluminium were made into cast aluminium products by 2,400 separate plants.[e]

Figure 9: Supply chain map for magnesium in aluminium alloys for automotive



Niobium is used as an alloying element to strengthen high-strength-low-alloy (HSLA) steels as a micro-alloying component to improve the surface quality. Typical applications include car bodies, wheels and structural members for automobiles and trucks. Though niobium is a small addition (usually less than 0.1% of the composition of the steel) it is still very important to the performance of the material.[f] In the UK, Tata Steel reports that 0.02% niobium content is typical in their niobium steels, with 0.06% being the highest content.[g] A supply-chain map for niobium is given in Section 6.7.2.

Graphite brake linings for heavy vehicles are a small market for natural graphite in the context of world consumption, but can be dismantled from within the vehicle, returned to graphite processors and then ground and reused.[h]

Existing practice and infrastructure

The average lifetime of a car is around 12 years, but this may be extended to 20 years for luxury cars which are often exported overseas to emerging economies.[i] The steps involved in treatment of vehicles at end of life vehicles (ELVs) are governed by the EU End of life Vehicles Directive (see below) and include the following:

1. collection
2. extraction of fluids
3. dismantling
4. shredding
5. electro-magnet separation
6. sink-float separation (two stages)
7. eddy current separation.

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[a] Aluminium in Transport, Alfed, 2008

[b] Alfed Website, http://www.alfed.org.uk/page.asp?node=76&sec=Aluminium_A_to_Z accessed 03/02/2011

[c] Aluminium in Cars, EEA, 2008

[d] Tom Siddle (Alfed), personal communication

[e] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[f] CBMM Website: Use and End Users of Niobium, http://www.cbmm.com.br/english/capitulos/uses/use&user.htm, accessed 02/02/11

[g] Alun Thomas (Tata Steel), personal communication

[h] Corina Hebestreit (ECGA), personal communication

[i] Gianmatteo Martinelli (Novelis Europe), personal communication

This allows 95% of the aluminium (and magnesium) present in the vehicles undergoing this processing to be collected and then reused or recycled.[a] However the aluminium is separated as a mixture of different alloy grades, owing to the shredding procedure. This does limit the applications for which products can be produced from the recycled metal, as the composition of the alloy is variable and not closely defined. Because the majority of the separated aluminium comes from engine blocks, the recycled aluminium is commonly refined and cast back into these products.[b] Consequently some of the magnesium content contained within wrought alloys may be lost as impurities in the silicon-based cast alloys. At present the low volumes of wrought alloys arising in ELV scrap justify these recycling economics; however there is a trend towards increased wrought alloy content as cars become lighter and use greater quantities of aluminium. New laser and x-ray sorting technology is being developed for future application to sort into alloy families, although the volumes of wrought aluminium contained in ELVs is not expected to make the process economic until at least 2015.[c]

In contrast, the niobium-containing steel scrap is removed by the electro-magnetic separation, along with the other ferrous scrap. This is sold direct to furnaces as grade 3B and recycled[d], typically within an electric arc furnace (EAF). At present the UK is a major exporter of ferrous scrap, exporting 6.6 million tonnes or 59% of the scrap arising. In 2008 over half of this was within Europe (Spain, Turkey, France and Portugal among others), although India and China represent large and growing markets.[e] Due to the low concentration of niobium in scrap, ferrous-metals are not specifically recovered for applications requiring niobium, therefore this additive is diluted among a larger pool of steel scrap.[f]

In order to recycle niobium-containing scrap into niobium-requiring steel grades, one would need to be able to gather and separate large amounts of niobium-containing scrap (for the minimum efficient scale of an EAF), of a high niobium content[g], and be paid a sufficient premium over ferrous scrap to justify this activity (at typical concentration levels the niobium content may only be worth around 7% of the scrap steel price). The following approximate figures highlight the challenges in niobium recovery for automotive: In 2008 steel scrap arisings were estimated at 11.1 million tonnes, of which post-consumer sources (ELV, WEEE and bicycles), which are commonly co-shredded, accounted for around a third of the arisings (i.e. approximately 3.7 million tonnes).[h] This compares to a world niobium production of 16,200 tonnes for 1996 for use in all markets[i] (allowing for the 12 year average lifespan for automotives). Based on UK consuming a 7.1% share[j] of the 73% of world niobium currently consumed in the US and Europe, and 28% being used for automotive (Annex A), only 236 tonnes of niobium will be available from ELV recycling, assuming all ELVs are collected (0.0064% of 3.7 million tonnes). However assuming an average grade of 0.05% niobium content, this implies that around 472,000 tonnes of ELV niobium-containing scrap will arise (13% of 3.7 million tonnes).

Relevant policy and legislation

The recycling of cars is governed by the ELV Directive, the main provisions of which in the UK are[k]:

- restrictions on the use of certain heavy metals in vehicle and component manufacture
- marking of certain rubber and plastic vehicle components, and publication of design and dismantling information
- the introduction of a Certificate of Destruction

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[a] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[b] Gianmatteo Martinelli (Novelis Europe), personal communication

[c] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[d] Graeme Carus (EMR), personal communication

[e] HMRC, UK Trade Info, https://www.uktradeinfo.com/ , accessed 22/02/11

[f] Matteo Rigamonti (Eurofer), personal communication

[g] Alun Thomas (Tata Steel), personal communication

[h] The Structure and Outlook for UK Markets in Secondary Steel and Aluminium [unpublished], Oakdene Hollins for WRAP, 2009

[i] USGS Minerals Yearbook 2000: Niobium (Columbium) and Tantalum

[j] Using World Bank GDP estimates for 2009, http://data.worldbank.org/indicator/NY.GDP.MKTP.CD, accessed 17/02/11

[k] The End of Life Vehicles Regulations 2003, 2005 and 2010: Government Guidance Notes, BIS, 2010

- 'free take-back' of end of life vehicles (ELVs) from 1 January 2007
- licensing of authorised treatment facilities, and the site and operating standards with which they must comply
- producer obligations for providing take-back of ELVs through accessible networks of authorised treatment facilities (ATFs) and collection points
- producer and authorised treatment facility obligations in respect of achieving recovery and recycling targets for ELVs from 2006 onwards.

The targets for the reuse, recycling and recovery of ELVs are[a]:

- 85% of reuse and recovery and 80% of reuse and recycling by 1 January 2006
- 95% of reuse and recovery and 85% of reuse and recycling by 1 January 2015.

The latest UK achievement against the ELV Directive is shown Table 7. In 2008 the rate of reuse and recycling stood at 82.5% and the rate of reuse and recovery stood at 84% by weight. These represent improvements versus 2006 (81% reuse and recycling; 82.3% reuse and recovery); whilst the 2006 reuse and recycling target has been met, the reuse and recovery target was missed. Of the most significant ELV producing countries, this achievement puts the UK ahead of France, but behind Germany, Italy and Spain. Important issues with the ELV Directive include the export of second-hand cars which can mask the illegal export of wrecked or stolen cars, the activities of unlicensed operators and the abandonment of some cars.[b] Official figures for the export of second-hand cars in the EU-27 puts this as representing 26% of new car registrations, although for the UK this is much lower, with only 3% of second hand cars being exported.[c] Overall the recycling of ferrous and non-ferrous metals in the UK stood at 75% of the total weight of ELVs.

Table 7: UK end of life vehicle reuse, recycling and recovery, 2008

Material/Route	**Tonnes**	**%**
Reuse	21,454	2%
Ferrous Recycling	814,726	69%
Non-ferrous Recycling	69,884	6%
Other Recycling	62,451	5%
Energy Recovery	16,605	1%
Disposal	190,811	16%
Total	**1,175,931**	**100%**

Source: Eurostat, Environmental Data Centre on Waste: End of life Vehicles

Conclusions and recommendations

- The recycling of magnesium within aluminium alloys from automotive is currently highly efficient in terms of collection rates and in the recovery of the magnesium content. New technologies are being developed to separate different aluminium alloys, which will facilitate the recovery of magnesium from wrought alloys once the usage justifies the cost of these separation techniques.
- For niobium-containing scrap, the low volumes relative to the overall steel scrap appear to prohibit the separate recycling and recovery of the niobium content within automotive. This is because the cost of separating the niobium-containing steel scrap from other types of ferrous scrap is unlikely to be justified, with the low niobium alloying content unlikely to offer a sufficient premium to give recyclers and incentive.
- For both magnesium and niobium, it is noted that significant exports of scrap aluminium and steel from the UK takes place (see Section 6.7 for more details).
- Higher volumes of ELV processing would increase the recovery rate of critical materials in this sector.

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[a] EC Commission (2007), http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2007:0005:FIN:EN:HTML, accessed 22/02/11

[b] End of Life Vehicles (ELV) Directive: An assessment of the current state of implementation by Member States, European Parliament,2007

[c] Öko-Institute (2011), European second-hand car market analysis

6.2.3 Impact on carbon emissions

Magnesium

The production of magnesium has a significant carbon impact of 73.7 $kgCO_2e$ per kg, which is mostly attributable to energy consumption during ore refining. By comparison, the impact of primary aluminium, which excludes recycling, is 12.2 $kgCO_2e$ per kg; again this is mostly attributable to energy consumption. From these figures it is estimated that the impact of aluminium alloy production, assuming primary aluminium and 1.5% magnesium content, is 13.7 $kgCO_2e$ per kg. Within this value the magnesium accounts for 8% of the impact. Based on figures available for other types of aluminium alloy, recycling requires around 5% of energy compared with primary production.[a] As energy is the main contributor to the carbon impact it can be estimated that recycling of 1 kg of magnesium-containing aluminium alloy can save 13 $kgCO_2e$. (It should be noted that this figure only takes into account production of the alloy, and no further metal working.)

Based on figures from Boeing and Airbus, around 30% of an aircraft is recycled. If it is assumed that this is all aluminium, and a typical aircraft weights 285 tonnes[b], current practices save an estimated 1,112 tonnes CO_2e per plane. Aircraft consist of 70% aluminium alloy by weight; therefore recycling all aluminium alloy parts in a plane of this size could save up to 2,590 tonnes CO_2e per plane.

In the automotive sector it is estimated that 95% of aluminium is recovered for vehicles undergoing ELV processing which, for modern vehicles containing 170 kg aluminium, is a saving of 2,100 $kgCO_2e$ per car if recycled. Other options also exist in this market, for instance remanufacturing of aluminium alloy-containing parts, which can reduce the carbon impact of a part by a third or more.[c]

Superalloys

The carbon impacts from the primary production of 1 kg of cobalt and tantalum are 8.32 $kgCO_2e$ and 260 $kgCO_2$ respectively. The primary factor contributing to this is the energy for processing from ore to metal, which indicates that recycling and reuse could provide significant benefits if the alloys can be reused without need for separation. However no data could be identified for the carbon impacts of superalloys or production, therefore it is impossible to quantify the extent of this benefit.

Niobium steel and beryllium

No data for the production of niobium or any niobium-containing steel could be identified. The low concentration of this metal (0.05%) for uses in the automotive industry means that it is unlikely to have a large contribution to the overall impact of the steel.

No data for the production of beryllium was found. As beryllium is more likely to be found in high concentrations in products, it is likely that it has an impact on the potential benefits of reuse and recycling.

6.2.4 Overall recommendations for automotive and aerospace

The overall conclusions for aerospace and automotive can be found in Table 8. For the aerospace submarket the industry is in the process of moving away from the current practice where end of life aircraft are abandoned in deserts and non-specific recycling and reuse; the extent to which the critical raw materials (cobalt, niobium, tantalum, beryllium and magnesium) are recovered is not clear. In response, both Boeing and Airbus have best practice initiatives including selective dismantling, reuse, refurbishment and specialist recycling, which will ensure that the critical raw materials are available. Due to the large estimates of aircraft expected to reach their end of life over the next 20 years, and the

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[a] Making the Most of Packaging, Defra, 2009

[b] AFRA data – 200 tonnes of aluminium per aircraft, which is 70% of the weight

[c] Carbon Impact of Remanufactured Products – 6 speed gearbox, Centre for Remanufacturing and Reuse, 2009

demonstrated efficiency and viability of the best practice techniques, there is a strong prospect of increasing the recovery of all of the critical raw materials associated with aerospace.

For the automotive submarket current practice is governed by the EU ELV Directive, which sets targets for the weight of a vehicle recycled and recovered. For magnesium contained within aluminium alloys, 95% of the aluminium contained is collected and reused or recycled (mostly back into cast products). Future opportunities exist to sort the mixed aluminium into cast and wrought families, which would improve the utilisation of the magnesium content within the wrought alloys, but the low volumes of wrought alloys currently contained within ELVs is not expected to make sorting economic until 2015, which gives this a medium prospect for increased recovery. In contrast the niobium contained within the steel alloys is not specifically recovered, but rather diluted within a larger pool of scrap steel. It may be possible to sort by alloys, but the low niobium content within the alloys is unlikely to make this economic. As for graphite, the dismantling of brake linings from ELVs is possible, but could be increased.

Table 8: Conclusions for aerospace and automotive

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Potential for Increased Recovery	Carbon Benefit
Aerospace	Superalloys	Cobalt Niobium Tantalum	Abandoned, non-specific recycling & reuse	Selective dismantling, reuse/ refurbishment, specialist recycling	High	N/A
	Landing gear	Beryllium			High	Medium
	Aluminium alloys	Magnesium			High	High
Automotive	Aluminium alloys	Magnesium	Shredded & mixed aluminium alloys recycled	Laser & X-ray sorting of aluminium alloys	Medium	N/A
	Steel alloys	Niobium	Shredded & general steel recycling	Sort steel by alloys	Low	N/A
	Brake linings	Graphite	Some dismantling & return for reuse	Increased dismantling levels	Low	N/A

6.3 Batteries

Relevant materials: antimony, cobalt, graphite, REEs

Batteries can be classified according to either their chemistry or under which recycling legislation they fall.[a] Their chemical composition is important for resource efficiency and material recovery in the recycling process, while their legislative category is important with respect to collection and availability of recyclable batteries. Further distinction between primary (single-use) and secondary (rechargeable) batteries can be within these other categories.

The screening exercise identified four critical raw materials are used in batteries:

- **Zinc carbon** batteries contain graphite
- **Li-ion** batteries contain cobalt and graphite
- **Nickel Metal Hydride** (NiMH) batteries contain REEs and can contain cobalt
- **Lead acid** batteries contain antimony.

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[a] Battery Directive, EU, 2006

Table 9 provides an overview of battery types, their chemistries, and in what applications they are used.

Table 9: Overview of battery types, chemistries and common applications

Type	Primary Chemistries	Secondary Chemistries	Containing Critical Materials	Applications
Portable	Alkaline - manganese Zinc carbon	Lead acid Li-Ion Nickel cadmium NiMH Nickel zinc	Zinc carbon Li-ion, NiMH	*Zinc carbon:* General purpose *Li-ion, NiMH:* Audio visual , mobile phones, laptops, shavers, power tools
Industrial (including automotive)		Lead acid Li-Ion Nickel Cadmium Nickel zinc NiMH	Lead acid Li-ion NiMH	*Li-ion, NiMH:* Hybrid electric vehicles, electric vehicles
Automotive		Lead acid Li-Ion NiMH	Lead acid Li-Ion NiMH	*Lead acid:* Automotive (current) *Li-ion, NiMH:* Hybrid electric vehicles, electric vehicles

At present only lead acid batteries are fully treated in the UK, where antimony is recovered (described in full in Annex A). The current high recycling rate of lead-acid batteries, combined with a predicted decline in the use of antimony in these batteries, means that they have been omitted from further discussions here.

Based on recent developments in battery recycling legislation (Table 10) and expected developments in the electric or hybrid vehicle industry, the types of batteries investigated further are portable and Industrial batteries of the Li-ion and NiMH chemistries. Further discussion of the impact of the legislation is discussed more fully below.

Table 10: Relevant UK and EU legislation for battery recycling

Policy	Level of implementation	Relevant issues
Battery Directive 2006	EU	Target on recycling efficiency: for Li-ion and NiMH, 50% of material needs to be recycled
Batteries Regulations & Accumulators Regulations 2009	UK	The Waste Batteries Regulations place targets for collecting 25% of portable batteries by 2012 and 45% by 2016.
Electric Vehicle Directive	EU	Targets on reuse, recycling and recovery

Source: RENEW[a]

6.3.1 Portable batteries

Portable batteries are used in portable electronic devices such as cameras, mobile phones, PDAs, iPods and power tools. Single-use batteries, with the exception of zinc carbon batteries, do not contain any critical materials. However, zinc carbon batteries are excluded from this study on the basis of share of collected batteries, as they are estimated to represent less than 0.6% of battery waste arising in the UK.[b] Portable rechargeable batteries have a wide variety of chemistries, and those relevant to this study are the Li-ion and NiMH type, due to their cobalt, graphite and REE content.

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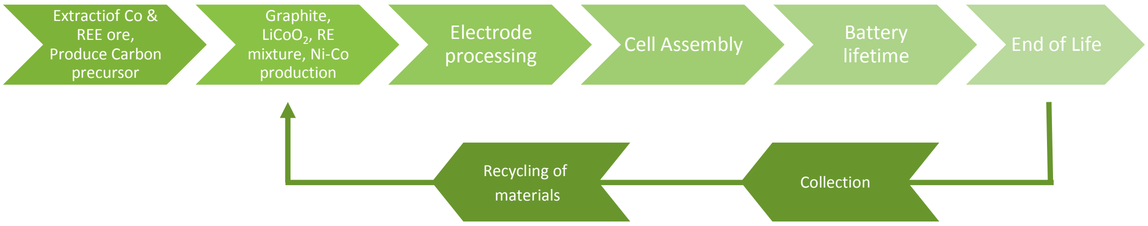
[a] Battery Recycling Market Research Study, RENEW, 2010

[b] Battery Recycling Market Research Study, RENEW, 2010

Estimates of yearly portable battery arisings in the UK range between 45, 000 tonnes[a] and 47,000 tonnes[b] Of these portable batteries, around 700 tonnes are of the Li-Ion and 950 tonnes are of the NiMH chemistries.[c]

Li-ion batteries have a variety of chemistries that use various combinations of electrode materials, including the common Li-polymer batteries. Standard Li-ion batteries contain up to 16% cobalt in lithium cobalt oxide[d], however Li-polymer types can contain up to 25% cobalt.[e] NiMH batteries typically contain around 15% cobalt.[f] Other critical materials are also used; Li-Ion batteries use graphite as the anode (between 15-16%), and in NiMH batteries small amounts of a rare earth mixture of lanthanum, cerium, neodymium, and praseodymium are found (about 5%). Figure 10 outlines the supply-chain map for portable Li-ion and NiMH batteries. Once the raw materials have been extracted, they are processed to make the individual electrodes of the battery. These electrodes are then assembled into cells for use in portable devices. At end of life, batteries can be collected and recycled, although the rates of recycling differ vastly between countries. In 2009 for example, less than 3% of household batteries were recycled in Britain, while Belgium then had a record of 59% recycling rates.[g] Alternatively the batteries are retained indefinitely by the user, typically in a product, or find their way into other waste streams, such as WEEE.

Figure 10: Supply chain map for Li-ion and NiMH batteries



Existing practice and infrastructure

In 2010 around 10 % of all portable batteries arising in the UK is collected for recycling, therefore around 70 tonnes of Li-Ion and 95 tonnes of NiMH batteries entered the waste stream in the UK in 2010.

There are three different routes through which batteries reach recyclers: national collection schemes, battery manufacturers, and traders of end of life batteries. In the UK, portable Li-ion and NiMH batteries are gathered by Grundon Waste Management Ltd, G&P Batteries, Willow Environmental and Mercury Recycling Ltd. These batteries receive part-treatment in the UK and are sent mainly to Western Europe for further treatment.[h] However, batteries in WEEE are often not separated from the electrical items, often due to the design of the equipment, and follow alternative waste processing routes with no recovery.

The recycling process for portable batteries is currently very much focused on retrieving the relatively easily recoverable metals.[i] For example, it was stated by many interviewees that it is possible to retrieve the carbon from a Li-ion battery, but they were not aware of any commercial graphite recycling as the recovery of lithium is the focus of these activities. Existing treatment of NiMH uses the same recycling process as nickel cadmium batteries. In this process a metal residue containing Iron, nickel and REE is

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[a] Binning Battery Recycling, http://www.rsc.org/chemistryworld/News/2011/February/01021102.asp, accessed 15/02/11

[b] Personal Communication, Michael Green, March 2011

[c] Personal Communication, Michael Green, March 2011

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

[e] The UMICORE Process, UMICORE Battery Recycling, April 2010

[f] Cobalt, BGS, August 2009

[g] Recycling Batteries - Why We Need To Do More, The Ecologist, June 2009

[h] Battery Recycling Market Research Study, RENEW, 2010

[i] Personal communication Michael Green, G&P Batteries

produced, which is usually offered to the stainless steel industry, where the REEs are lost in the steel mill in the huge volume of slag. Table 11 gives an overview of compositions of critical materials in different types of portable batteries and the fate of those materials during recycling.

Table 11: Critical material content of Li-ion and NiMH batteries by battery type (weight %)

Battery	Cobalt	Graphite	REEs	Fate
NiMH	Up to 15%	-	5.3%	Cobalt in alloy. Steel slag
Li-ion (general)	15-16%	10%	-	Cobalt in alloy. Graphite is used as a reducing agent or is burnt in the incinerator
Li-polymer	25%	15%	-	Cobalt in alloy. Graphite is used as a reducing agent or is burnt in the incinerator

Source UMICORE[a]

At present no attention is paid to graphite because of its low value, and it is lost through incineration or used as a reducing agent in other processes. However, according to industry representatives in the United States, the carbon content of these batteries could be important at a later date when volumes increase (particularly vehicle batteries), indicating that the graphite could be reintroduce as battery grade.

Belgium-based material technologies group Umicore operates a small-scale facility that treats portable Li-ion, Li-polymer and NiMH batteries. A new facility with a capacity of 7,000 tonnes, the equivalent of 150,000 HEV batteries or 250 million mobile phone batteries, is expected to start operating in early 2011.[b] The treatment facilities for Li-ion and NiMH batteries in Europe are given in Table 12.

Table 12: Treatment facilities of batteries relevant to this study in Europe

Treatment Facility	Location	Chemistries
Redux	Germany	NiMH
Saft	Sweden	NiMH
SNAM	France	NiMH
Umicore	Belgium	Li-ion, NiMH

Relevant policy and legislation

Regulation on battery collection and recycling is becoming increasingly stringent. In the EU, 25% of all portable batteries placed on the market will have to be recycled and collected by 2012. This figure rises to 45% by 2016.[c] Although only 3% of portable batteries were recycled in the UK in 2009, battery recycling grew steadily in 2010. In the second quarter of 2010, it was estimated that 16% of portable batteries were recycled, compared to 9% in the first quarter.[d]

The 2006 European Battery Directive set a target of 50% recycling of the material of Li-ion and NiMH batteries. However, the Directive does not distinguish between which materials are recycled and to what degree they should be refined, leaving these decisions to the laws of economics. An industry representative commented that, as part of the European Battery Directive, a technical adaptation committee is now working on a recycling efficiency definition, which will possibly provide a more specific definition of recycling requirements in the future.[e]

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[a] The UMICORE Process, UMICORE Battery Recycling, April 2010

[b] UMICORE invests in recycling of rechargeable batteries, http://www.umicore.de, November 2009

[c] UMICORE invests in recycling of rechargeable batteries, http://www.umicore.de, November 2009

[d] Battery Recycling On The Up, http://www.wastecare.co.uk/battery-recycling-on-the-up/, accessed 24/02/11

[e] Personal communication - Michael Green, G&P Batteries

Conclusions and recommendations

- Because of the low volumes of Li-ion batteries in the waste stream, any new facility to treat portable batteries would have difficulty sourcing enough batteries to feed a 150 tonne pilot plant to make such an operation economic, according to a study in the North East of England.[a] This is likely to be representative of the scale required if implemented elsewhere in the UK.
- Batteries are expected increasingly to end up in the waste stream in the near future. In Belgium and the Netherlands growth in batteries in the waste stream will be limited, but the UK is a long way from the 2016 target of a 45% collection rate. However, it is not certain that this will influence the collection of portable batteries relevant to this study, as the legislation does not yet specify which types of portable batteries need to be collected and recycled.
- In terms of design, two approaches would help to improve the ease of recycling of these batteries:
  - **Labelling -** An industry representative stated that, currently, the labelling of a battery to signal its chemistry is poor to non-existent, particularly in batteries from end of life electronic equipment. Labelling schemes might help in making collection more economic, and allow for better sorting to allow for more efficient recycling and potentially more specific refining processes.
  - **Easier removal –** Enabling simpler removal of batteries from devices would help processors isolate batteries in mixed waste streams, leading to better segregation.

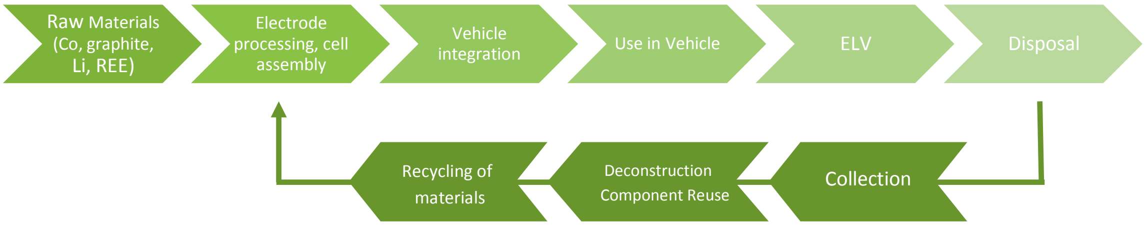
6.3.2 Industrial batteries

Industrial batteries are found in variety of applications, such as HEVs, alarm systems, emergency back-up systems, rail and telecommunications and satellite applications. In most applications industrial batteries are of lead-acid and nickel-cadmium chemistries. This section will therefore focus on the industrial batteries found in HEVs, which are predicted to be the major uses of Li-ion and NiMH batteries in the future.

In 2009, 14,645 hybrid electric vehicles and 55 electric vehicles were registered in the UK[b] each of which uses either a Li-ion of NiMH battery to store electricity. To date, NiMH batteries are far more numerous than Li-ion batteries for (H)EVs, and vehicles containing Li-ion batteries are only just beginning to enter the market. Although on the decline from 2007 and 2008, growth estimates are in the order of around 16% per year until 2015[c], indicating that the market for end of life batteries might begin to take shape in the medium term.

Figure 11 outlines the supply-chain map for Li-ion and NiMH batteries in electric vehicle applications. Once produced by specialist manufacturers, battery cells are integrated in the electric vehicle by the vehicle manufacturers. Battery lifetimes are lengthening with every model, and industry stakeholders stress that it takes a relatively long time for batteries to reach end of life. When the batteries do reach their end of life or break down, different car manufacturers will employ different strategies to recover the batteries for recycling.

Figure 11: Supply chain map for Industrial Li-ion and NiMH batteries



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[a] Battery Recycling Market Research Study, RENEW, 2010

[b] http://www.smmt.co.uk/downloads/MotorIndustryFacts.pdf, accessed 25/02/11

[c] Battery Recycling Market Research Study, RENEW, 2010

Existing practice and infrastructure

Industrial battery collection is in its infancy: estimates are that from the 100,000 tonnes of automotive (mostly lead-acid) and industrial batteries combined[a], the share of collected industrial Li-ion batteries is less than 1%, as is the collection of industrial NiMH batteries.[b] There are three main routes an end of life battery could take after collection:

- recycling using existing recycling processes or by retrieving the (relatively easily recoverable) metals[c] in a similar process to that for portable batteries, or refurbishing the batteries
- remanufacturing and re-use by separating the anode and cathode materials and replacing them.
- reuse, either for similar uses or through cascaded reuse to less demanding applications once battery performance has dropped below the desired level for (H)EVs

Recycling is the most advanced strategy of these three. Tesla motors and Umicore have recently come to an agreement for treating Tesla's end of life industrial Li-ion batteries, where Umicore will recycle the battery packs to produce an alloy that will be further refined into cobalt, nickel and other metals. The cobalt is then processed into high grade lithium cobalt oxide, which can be resold to battery manufacturers.[d] Umicore is also currently developing a method of recycling the lithium in Li-ion[e], indicating that they believe that the market for these end of life batteries, particularly of the industrial type, will become more important in the future. According to industry representatives in the United States, there have recently been efforts to look into more effective recycling of REE in NiMH batteries.

A complication that was mentioned, in terms of devising new recycling processes, is the uncertainty about the exact nature of Li-ion batteries chosen for (H)EVs of the future. However, recyclers mentioned that they would probably contain less cobalt, and be more complex. In a 2010 study, it was found that no single existing Li-ion chemistry performs well in all factors that are important for (H)EVs, and that the conditions for a large electric vehicle market to emerge still need to be put in place.[f] Industry stakeholders expect that the nature of the batteries of the future will emerge during the latter half of this decade. They also stated that there is little evidence that recyclers have taken account of the uncertainties of which batteries will enter the waste stream.

According to many interviewees, one of the current key issues in industrial battery recycling is collection. However, there are clear indications from car manufacturers that they want batteries in the vehicles to be collected and recycled effectively. At present the low volume of end of life car batteries precludes this, and although some expect the market for electric vehicles to grow, it remains to be seen what the battery technology will be, whether the regional markets for (H)EVs will also develop, and what collection method for batteries the car manufacturers will choose.

Relevant policy and legislation

Industrial and automotive batteries are banned from disposal to landfill and incineration, which effectively encourages a 100% collection rate. This leads industry representatives to believe that these batteries will become available in significant quantities in the second half of this decade.

Conclusions and recommendations

- The availability of industrial batteries from (H)EVs will depend on the future choices of the manufacturer with regard to the collection of batteries. Renault, for example, leases its Li-ion batteries, but the exact - and most economic - channels through which batteries will be collected still needs to take shape.

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[a] Due to the recent legislation estimates these are taken together to avoid double counting in the estimates of industry representatives in the RENEW battery recycling market study

[b] Battery Recycling Market Research Study, RENEW, 2010

[c] Personal communication Michael Green, G&P Batteries

[d] http://www.teslamotors.com/about/press/releases/tesla-launches-battery-recycling-program-throughout-europe, accessed 24/02/11

[e] UMICORE invests in recycling of rechargeable batteries, http://www.umicore.de, November 2009

[f] Batteries for electric cars, challenges, opportunities and the outlook to 2020, BCG, January 2010

- The low REE content in NiMH batteries, combined with the low volumes of end of life batteries, currently does not allow for refining output of these batteries to retrieve the REEs. It is not expected that economic volumes will be reached soon. If volumes increase as expected, recycling needs to be concentrated in a few facilities if REE recycling is to be economically efficient. Future recycling targets for specific battery chemistries could be put in place, which could make increased refining of recycling output important in the future. Also, since a range of car manufacturers use industrial Li-ion and NiMH batteries[a], it is vital that market figures for different types of cars are monitored when considering collection processes.
- Other strategies for end of life batteries, such as remanufacturing, reuse and cascaded reuse, should be examined for potential viability. These options may present simple but effective alternatives to recycling.
- In thinking about batteries' design for the environment, functionality is key for batteries in (H)EVs: no single battery performs well on all indicators of functionality in (H)EVs, and functionality will dominate the design of batteries in the near future.

6.3.3 Impact on carbon emissions

Batteries are typically used in energy-using products, which often have a large carbon footprint associated with their use-phase due to electricity use. While the carbon footprint of manufacture and recycling of the battery is considered here, the manufacture of the product and its use-phase is not.

The carbon impact from the production of 1 kg NiMH battery was calculated to be 18.3 $kgCO_2e$. The production of the raw materials was found to have a large contribution, with nickel accounting for 23% of the carbon impact, and REE production 27%. A recent study investigating the use and recycling of NiMH batteries in HEVs estimated recycling reduced the impact of a battery by about 5% (excluding use).[b] Whilst this is a modest benefit it was stated that greater benefits could be realised through scale up of the processing and further optimisation.

A recent Umicore study identified that large carbon benefits were possible through the recovery of cobalt from Li-Ion batteries.[c] In a like for like comparison of manufacturing for a typical Li-ion cell, weighing 132g the impact was found to be reduced from approximated 0.68 $kgCO_2$ per cell to 0.15 $kgCO_2$ per cell, due to both material and energy savings through the reclamation of cobalt. Therefore, through cobalt recycling there is large potential for reducing the impact of Li-Ion batteries through recycling. Based on these figures, a pilot plant, such as that proposed above, could save around 602 tonnes CO_2e per annum through processing 150 kg of Li-ion batteries.

6.3.4 Overall recommendations for batteries

- In general, three factors influence whether there is opportunity for increased resource efficiency in the battery recycling industry: critical volume of recyclable batteries, price of the materials in the batteries, and geostrategic considerations. There is a large supply of waste portable batteries, however collection of these is poor. Conversely, batteries present in (H)EVs are expected to provide a large waste stream in the future, but uncertainties have prevented an optimised recycling system to form.
- In the UK, the Technology Strategy Board is currently launching a 500K competition to support projects related to the recycling and re-use of batteries used in (H)EVs. Such initiatives might indicate that existing practice is in motion, and dynamics might change in the near future. This is underscored by industry stakeholders and academics on all continents, indicating that the timing off this study was particularly interesting.

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[a] For an overview of players in the global market, see http://www.calcars.org/carmakers.html

[b] Life Cycle Assessment of Nickel Metal hydride Batteries for HEV Application, Matthias Buchert,, IARC, Basel, 4thMarch 2010

[c] Li-ion and NiMH battery recycling at Umicore, Jan Tytgat,

Table 13: Conclusions for the batteries sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Potential for Increased Recovery	Carbon Impact
Portable Batteries	Li-Ion	Cobalt Graphite	Not collected, not separated or recycled	Increased recovery and separation	High	Medium
	NiMH	REEs Cobalt	Not collected, not separated or recycled	Increased recovery and separation	Medium	Low
(H)EV Batteries	Li-Ion	Cobalt Graphite	Not implemented	Infrastructure development	Medium	Medium
	NiMH	REEs Cobalt	Not implemented	Infrastructure development	Medium	Low

6.4 *Catalysts*

Relevant materials: cobalt, germanium, REEs, PGMs

Catalysts are substances which increase the rate of a specific chemical reaction, without being consumed by the reaction. The use of catalysts is well established in the chemical using industries and the automotive industry. The differences in these markets mean that two separate sub-markets have been investigated in this section:

- **Catalytic converters** – Primarily containing platinum and palladium, with the REE cerium also in catalytic converters as an oxygen storage material.
- **Process catalysts** including:
  - germanium used in plastics production
  - PGMs used in chemicals manufacture
  - cobalt, PGMS and REE used in the petrochemicals industries.

6.4.1 Catalytic converters

Catalytic converters were developed to reduce the harmful emissions from by engines, particularly automotive petrol and diesel engines. PGMs and the rare earth element cerium is used to convert polluting post combustion gases such as carbon monoxide, nitrous oxides and non-combusted hydrocarbons into more environmentally benign chemicals such as carbon dioxide, nitrogen and water. This technology was introduced in the 1970s, and is a requirement for all new vehicles due to engine emissions regulations. Though the primary use is in automotive applications, which is the focus of this study, smaller markets for catalytic converters include other engine using equipment such as aircraft, generators and other stationary motors.

Catalytic converters are the primary consumer of the PGMs platinum and palladium. In 2010 this use accounted for approximately 50% of the overall demand for these metals, corresponding to 93 tonnes and 160 tonnes, or 44% of platinum demand and 63% of palladium demand respectively.[a] In addition to this, autocatalysts were responsible for 86% or 22 tonnes of rhodium consumption. Based on a composite priced for PGMs, these metals have a market value of $8,760 million. However, it should be noted that a significant proportion of this demand is fulfilled by recycling of autocatalysts.

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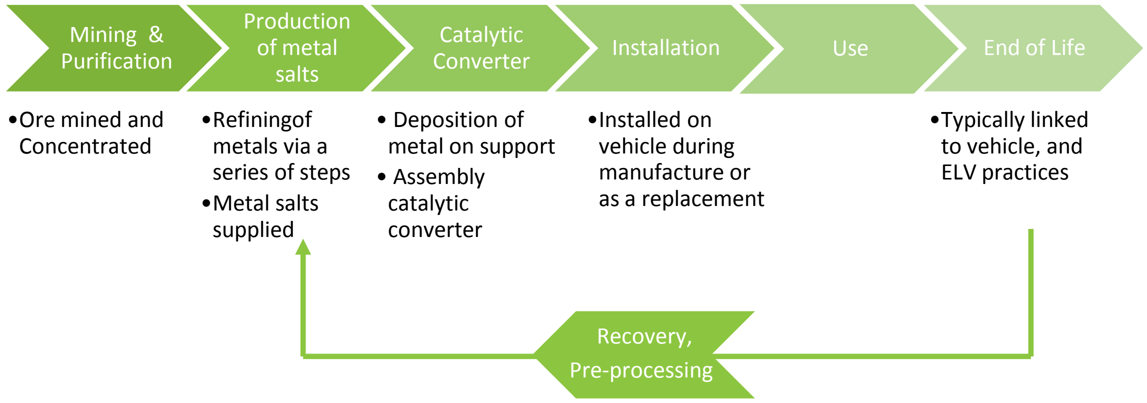
[a] Platinum 2010 Interim Review, Johnson Matthey, 2010

Due to the differing emissions and conditions associated with different engine types, the ratio of different PGMs used in catalytic converters varies. Catalytic converters associated with petrol engines typically have a higher proportion of palladium, which is preferentially chosen over platinum as it is lower in cost. Catalytic converters used for diesel engines typically use a higher ratio of platinum as it cannot be substituted for palladium or other metals in this case. Rhodium is present in both types, as it is specifically required for the conversion of nitrogen oxides gases in three-way catalytic converters. In addition to this larger engines which produce more emissions require larger quantities of catalyst, therefore quantities of PGMs present vary significantly depending on use.

Cerium is also commonly present in catalytic converters as cerium oxide. It helps to ensure there is enough oxygen present for the catalytic reactions by storing oxygen when excess if present, then releasing when the engine is burning lean. Based on information from the Lynas Corporation, around 9,400 tonnes of rare earth oxides are used in catalytic converters per year, 90% of which is cerium oxide; this represents around 14% of all REE consumption based on weight. Using the recent price of cerium oxide (52.5 $/kg[a]) the value of this material can be estimated to be worth $480 million in total, however it is important to note that the price of cerium oxide has increased considerably, rising more than 13-fold since 2009. Despite the different types of catalytic converter available, the general process of autocatalyst manufacture is similar for all applications (Figure 12).

Figure 12: Schematic of the autocatalyst supply chain



The manufacturing process starts with the production of the PGMs from ore. PGM ores are typically very low grade; therefore concentration is required before extraction of the metals. At one of the largest mines in South Africa, one tonne of ore produces between 3 and 6 grams of PGMs.[b] PGMs can then be extracted through a high temperature smelting process, yielding the unrefined PGMs with other metals. Due to the similar properties of the PGMs, refining is a complex procedure, and involves separate processes to produce the individual metals. For the purposes of autocatalysts PGMs are supplied as metal salts to the catalytic converter manufacturers.

In autocatalysts, PGMs are dispersed on a fine honeycomb, typically made of aluminium oxide to maximise surface area.[c] This minimises the quantity of PGMs required to meet desired performance. The quantity of metal depends on application, converters for larger engines require more PGMs. However figures indicate that a typical catalytic converter may contain around 6 grams of PGMs, corresponding to less than 1% of the weight of the support structure, before the casing is considered.[d] The honeycomb structure may also support some of the rare earth element cerium, as cerium oxide, again in low concentrations. Once assembled the catalytic converter is installed in either a new vehicle or as replacement for a damaged or deactivated unit.

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[a] Figure for Q4 2010, http://www.lynascorp.com/page.asp?category_id=1&page_id=25, accessed 25/02/11

[b] The Bushveld Complex, http://www.platinum.matthey.com/production/south-africa/, accessed 18/02/11

[c] Catalytic Converter, http://www.preciousmetals.umicore.com/recyclables/SAC/CatalyticConverter/ accessed 18/02/11

[d] Closing the Loop – Recycling of Automotive Catalyst, Hagelüken, C.2007

The fate of a catalytic converter is typically tied to the end of life of the associated vehicle. If the vehicle is scrapped in the UK/EU the catalytic converter is removed prior to further processing. Alternatively the vehicle may be sent abroad for continued use or scrapping, this may result in the los of the catalytic converter from the recycling process and therefore the critical materials. Where a catalytic converter becomes unusable due to damage or deactivation it is typically replaced, with the old unit returned for scrap value. Though the catalyst may still be functioning well when it is not longer needed, reuse or remanufacture of catalytic converters is not extensively practiced, though does occur on a small scale with older vehicles which require an out of production part.

Existing practice and infrastructure

Recycling of PGMs contained in catalytic converters is well established. Figures from Johnson Matthey indicated that recovery and recycling of PGMs in automotive catalysts provides 12% of both platinum and palladium supply and 24% of rhodium supply, with an estimated value of $2,000 million. The value of the metals contained in converters means that this worthwhile for both scrap collectors, processors and metals refiners; a value of the PGMs contained in a typical catalytic converter can be estimated to be $191[a], though this value has fluctuated recently due to the lower prices of these metals as a result of poor vehicle sales.

The logistics chain is similar to other recycling industries, and is well established and extensive in the UK and Europe. Primary collection occurs through a large number of actors such as scrap dealers, garages and shredders. These may be sold on to collection companies which supply a small numbers of refiners performing the PGM extraction. Alternatively, if volumes are large enough the collector will deal directly with the refiner. Once refined, the metals supply the general PGM market, therefore may end up in any product containing PGMs.

A typical recycling process of a catalytic converter involves decanning (removal of the outer container), addition to molten iron or copper to fuse the honeycomb support and dissolve the PGMs. The PGM are extracted as a mixture from the molten alloy, and further refined into individual metals at a specialist refinery.[b] The exact processes vary dependant on the processor, but recovery rates are high; Umicore state that they can reach 90% efficiency for the recovery of PGMs.

Within the UK and EU, Johnson Matthey (with sites at Royston, Hertfordshire and Brimsdown, London) are the largest refiners of PGMs. In the UK, Tetronics (with a site at Swindon, Wiltshire) have technology in this area, as do several other smaller companies. Within the EU Umicore refines significant quantities of spent autocatalyst.

The recycling of automotive catalysts focuses on the recovery of the PGMs, due to their value, and to date the recovery of other materials such as the cerium has not been explored. Where recovery of catalytic converters takes place the cerium oxide is lost in the slag during processing. No technology has been identified which could recover this material.[c] If a recovery rate of 22% is assumed (based on the value of PGM recycling), this corresponds to a value of almost $150 million of cerium oxide. Though these figures are not truly accurate of today's waste streams, they indicated that significant value is lost, which will increase if the price of rare earth elements continues to rise.

The data for PGM recycling above indicates that a significant proportion of catalytic converters are not recycled, even when growth in the market and product lifetime is taken into consideration. This is true of vehicles in general, and anecdotally it is known that a significant number of vehicles are exported abroad either for further use or for scrap once they are non longer suitable for use in the UK or EU. Therefore ensuring that a greater number of end of life vehicles are subject to ELV processing would improve the recovery rate of critical materials from these applications.

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[a] Based on a weight of between 6g of PGMs and a composite price for PGMs of $31,850 per kg

[b] Platinum – Definition, Mineralogy and Deposits, BGS, 2009

[c] -Institut e.V., 2011

Within this technology sphere, other work has looked at the minimisation of the use of PGMs in catalytic converters. For example Panasonic have developed a new type of catalytic converter which uses 80% less platinum than existing types, which is now being introduced to the market.[a] Whilst this clearly lowers the resource demand of these components, it may also reduce the incentive to recycle. However, it is likely to be several years before these units enter waste streams as the average life of a car is around 12 years.

Relevant policy and legislation

The requirement for catalytic converters is a consequence of European Emission Standards, which defines the acceptable tailpipe emissions of new vehicles sold in the EU. These are likely to become more stringent in the future with a new targets set for 2014/15.[b] Therefore catalytic converters will remain essential for petrol and diesel engines in the future.

The fate of catalytic converters is primarily influenced by the ELV directive. This legislation states that catalytic converters must be removed prior to processing; this allows separate treatment of these parts. However, it is clear that many vehicles are not subject to this processing when they are finally scrapped.

Conclusions and recommendations

- The value of PGMs contained in catalytic converters is typically high enough to warrant recycling where they can be easily accessed and the processes and supply chain are well established. Though not a closed-loop process, this allows PGMs to be recycled with little loss of material.
- Improving the recovery rates of catalytic converters would appear the most suitable way to increase PGM recycling. Improved collection and separation from ELVs would help achieve this.
- No recycling of REEs takes place, nor does it appear that this is being investigated. The value of REE used in catalytic converters is now becoming significant, though the value of material per unit is not clear.
- The increasing prices of REEs mean that possible recovery may become attractive in the future; however, technology may need to be developed to achieve this. If implemented it is likely to be closely tied to the recycling of PGMs in catalytic converters.

6.4.2 Process catalysts

The characteristics of catalysts are very useful for the production of chemicals as the use of a catalyst can lower the energy required to perform a reaction, decrease the time a reaction takes and help reduce waste by increasing the selectivity of a process. These benefits mean that catalysts are used ubiquitously within industry for the efficient production of plastics, synthetic chemicals and in the petrochemical industry.

Although by definition catalysts are not consumed through the action of catalysis, almost all have a finite lifespan. Over their lifespan the efficiency of catalysts can lower, or they may become deactivated or destroyed through the presence of impurities, through coking or through side reactions. Therefore replacement is necessary, or regeneration of existing catalytic stock is required to maintain production levels. As catalysts are central to the production in the chemical and petrochemicals industry, growth in these sectors causes greater demand for the catalytic material.

Three general catalysts types have been identified as being reliant on critical materials: polymerisation, process chemicals and petrochemicals. These are discussed separately below.

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[a] Panasonic begins shipping samples of new catalyst for diesel exhaust gas purification, www.panasonic.co.uk, accessed 17/02/11

[b] http://www.environmental-protection.org.uk/transport/emissions/, accessed 18/02/11

Polymerisation catalysts[a]

Germanium oxide is commonly used in the production of polyethylene terephthalate (PET), representing about 25% or about 38 tonnes of germanium metal consumption. The PET manufactured using germanium is primarily used in drinks bottles, corresponding to around 7% of the PET market. Whilst germanium oxide is an effective catalyst for PET production it is more expensive than alternatives, and like other catalysts it is retained in the plastic and cannot be recovered. Therefore in most markets (Japan being the exception) cheaper antimony and titanium based alternatives are used in preference.[b] However, germanium oxide is still added, but only in quantities enough to impart specific characteristics such as brightness and shine rather than, as with the other materials describe above, to reach the desired catalytic level.

The concentration of germanium oxide in PET is estimated to range between 10 and 70 mg/kg. Therefore in a 1L PET bottle weighing around 70g there will be approximately 2.5mg of germanium oxide. Based on current germanium prices, approximately 240kg of PET would be needed to recover $1 worth of germanium. Current merchant prices for this weight of used PET bottles range from $38 to $114 (£25 to £75) depending on the grade.[c]

The dispersion into this material means that recovery is not feasible; instead the germanium oxide is either retained in the plastic or leached out during use. When PET is recycled germanium oxide remains in the plastic matrix, as current mechanical techniques do not separate it out; therefore it will end up in the final recycled plastic. However there is little value to its presence and the PET will typically be put to a secondary use such as carpet or fleece material. At present the only likely resource efficiency measure is to remove it altogether.

Chemical industry catalysts

A vast array of process catalysts are used in industry for the production of a large variety of chemicals, therefore it is not possible to discuss all these within this report as many represent comparatively minor uses. However, of most interest to this study is the use of PGMs, and specifically platinum used to produce nitric acid from ammonia, an important step in fertiliser production. This represents about one quarter (3.5 tonnes) of all platinum demand for the chemical industry, and can be seen as representative of other processes involving platinum and other PGMs.[d]

The value of these catalysts, and their use for bulk chemicals manufacture means that there is little margin for inefficiency. Therefore these catalysts are kept active for as long as possible by careful control of use and conditions. In general PGM catalysts are not dispersed into products, the exception being silicone where platinum is used a cross-linking agent which is incorporated into the product in very low concentrations; as a result recovery is not worthwhile. In other uses the catalyst is retained and once activity has dropped they can be recovered and sent back to the catalyst manufacturer for reprocessing. Companies which recycle PGMs and other types of catalyst include Johnson Matthey and BASF. An infrastructure exists with smaller companies which specialise in the retrieval of spent chemical catalysts from smaller uses also exists; these are then sold on to the refiners and catalyst producers. The scale of this industry is not clear.

Petroleum refining and petrochemical catalysts

A selection of catalysts is used within the petrochemicals industry; these include cobalt based catalysts in gas to liquid processes and desulphurisation, platinum and palladium for petroleum refining and REEs - specifically lanthanum - for hydrocarbon cracking.

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[a] Information was primarily provided by PETCore, http://www.petcore.com/.

[b] Antimony is a commonly used catalyst for this purpose, but this does not represent a significant use of this material, therefore it is not considered further. However, it is likely that antinomy follows a similar path to germanium.

[c] Merchant prices for recovered plastic bottles, www.wrap.org.uk, accessed 25/02/11. Exchange rate of 1.6 USD/£ assumed

[d] Platinum Interim Review, Johnson Matthey, 2010

The use of cobalt within this industry is relatively efficient, partly due to the bulk nature of the process. Cobalt is used in combination with other metals in catalysts, and is supported in a honeycomb-like structure to increase surface area. Supporting the catalyst in this way helps minimise the quantity of catalyst needed, and prevents it from leaching into the product stream. In the desulphurisation process, which is common to all petrochemical refining sites, the cobalt catalyst is used to convert chemicals containing sulphur to hydrogen sulphide, removing sulphur for health and safety and other reasons. These catalysts are designed to be resistant to deactivitation and degradation. These catalysts are also regenerated *in situ*, keeping them in use for several years[a]; therefore the use of cobalt in these processes is highly efficient, and it is unlikely to present much opportunity for improved resource efficiency.

The oxides of REEs, primarily lanthanum, are used in the petroleum industry in a process called fluid catalytic cracking (FCC). FCC is used to convert unwanted long chain hydrocarbons into more desirable short chain species, a process which is key for the production of petrol and diesel. It estimated that around 600,000 tonnes of this catalyst are consumed every year; these have a REE oxide content of around 2%.[b] This corresponds to weight of 12,000 tonnes of lanthanum oxide, with an estimated value of $631 million.[c] Recent evidence suggests that no recovery of these catalysts takes place, indeed one study found that spent FCC catalysts were simply used as cement additives.[d] This is most likely as historically the value of lanthanum oxide has been low, however it has risen 10-fold since 2009, presenting a possible opportunity of catalyst recyclers.

By contrast, the PGMs used for similar processes in petroleum refining are well recovered at end of use, and it has been demonstrated that close to a 100% collection rate of these catalysts was possible. This was found to be down to two key factors: the inherent value of the PGMs, meaning recovery made good economic sense, and the business to business relationship between the refiners and the catalyst producers. This demonstrates that recovery of catalysts is viable where there are strong economic drivers, and also where businesses' needs are understood. Based on Johnson Matthey figures, the overall value of PGMs used in this industry is estimated to be $208 million in 2009.

Conclusions and recommendations

- Catalysts used for bulk processes typically have long lifetimes and are retained wherever possible rather than being included in a product.
- When the catalyst is included in a product it will be dispersed in low concentrations, making recovery more difficult and less attractive. This is especially true if the product is a small consumer item such as a PET bottle.
- Recovery of catalysts which remain in situ is highly dependant on the value of the material. In the case of PGMs where prices have historically been high there are well established collection and processing routes. Where prices have been low, such as for REEs, there has been little consideration for recycling. Other catalysts fall between these categories, with varying levels of recovery and recycling taking place.
- The rising prices of certain materials, especially REEs, will mean that recovery is more attractive, however there may be a lag before commercially viable recycling technology is available.

6.4.3 Impact on carbon emissions

The use of catalysts themselves can be seen as resource efficiency, and reducing the carbon impact of conducting chemical reactions. However, no attempt has been made to quantify the benefits of these activities, though it is expected for catalytic converters and process catalysts that their presence significantly outweighs the impacts of their production.

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[a] Information from the Cobalt Development Institute, http://www.thecdi.com/

[b] -Institut e.V., 2011

[c] Figure for Q4 2010, http://www.lynascorp.com/page.asp?category_id=1&page_id=25, accessed 25/02/11

[d] -Institut e.V., 2011

Catalytic converters
The impact of PGMs production is very high, so despite only small quantities of these metals being present in catalytic converters they have a relatively large contribution. For the manufacture of 6g of PGM the impact is approximately 6.1 $kgCO_2e$, equivalent to 0.5kg of primary aluminium production. Using figures above, it can also be estimated that each catalytic converter contains 200g of cerium oxide, which has a carbon impact of around 3.4 $kgCO_2e$ for manufacture. These relatively low figures for materials production mean that on a per unit basis the potential for carbon impact savings through recycling of the critical materials is low. No data were available for the complete manufacture of a catalytic converter, so overall comparison is difficult.

It is also likely that there will always be environmental and economic incentive to undertake recycling, as to produce the PGMs for a single catalytic converter requires around 1 tonne of ore. Therefore, catalytic converters will always provide a more concentrated source of PGMs.

Process catalysts
Due to the variety of catalysts used it is difficult to provide useful figures without generalising. In the types examined above, the germanium content in plastics is at such a low level that the carbon savings occurring through recovering these materials would be minimal; recovery of PGMs in the chemical and petrochemical industry is already efficient and it is difficult to estimate the benefits of this activity.

The reuse/recycling of lanthanum oxide presents a possible target in order to lower carbon impacts through recycling. Around, 12,000 tonnes of this material are used each year, which has an impact of 204,000 tonnes CO_2e for production. As it is present in this form both after production and in use there are potentially benefits to recovery, as little post recycling processing will be required.

6.4.4 Overall recommendations for catalysts

Table 14 Conclusions for the catalysts sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Potential for Increased Recovery	Carbon Impact
Catalytic Converters	Vehicles	PGMs	Recycled or lost	Increased recovery and separation	High	High
		REEs	No recovery	Initiation of Recovery	Medium	Low
Process Catalysts	Plastics	Germanium	No recovery	None	Low	Low
	General	Cobalt	Some recycling, dependent on process	Increased recovery and recycling	Low	Low
		PGMs	Extensive recycling	None	Low	Low
		REEs	No recovery	Initiation of Recovery	Medium	Medium

6.5 *Cemented Carbide Tools*

Relevant materials: cobalt, tungsten

Cemented carbides, or ‘hardmetals’ as they are also known, refer to a range of composite materials which consist of hard carbide particles bonded together by a metallic binder. These materials have extremely high toughness and wear resistance, and can withstand high temperatures with no loss of performance. The basic structure of cemented carbides is formed by tungsten carbide, the hard phase, held together with cobalt, the binder phase. The exact composition can be varied to tune the properties of the material, and the tungsten and cobalt content of cemented carbide vary between 72-96% and 4-25% respectively.[a] Further variation of properties is also possible by the addition of other carbides such as titanium carbide, tantalum carbide or niobium carbide to the tungsten carbide cobalt mixture. Variation of the binding phase is also possible with cobalt partially or completely replaced by other metals such as iron, chromium, nickel, molybdenum, or alloys of these elements.

The largest use of cemented carbide is for high specification industrial tooling, due to its high wear resistance compared to other materials such as high speed steels. A huge variety of tooling is reliant on these materials, and examples of uses include:

- general turning, milling and drilling tools and hobs
- cutting tools for metal, stone, wood, plastic and paper
- large bore drills in the mining, gas and in the oil industries for rock drilling
- micro drills for putting tiny holes in printed circuit boards.

The cost of these materials means that it is often not economic to make the full tool entirely from these materials. Therefore often only the parts which come into direct contact with the material being worked are made from cemented carbide; these small sections are known as wear parts. An example of this is placing inserts of the cemented carbide on a larger tool piece made of a less expensive material, such as steel.

Both of the main components of carbide tool, tungsten and cobalt, have been identified as critical materials by the European critical raw materials report. Excluding recycled material, it is estimated that some 60% or 36,600 tonnes of tungsten and 13% or 11,400 tonnes of global cobalt consumption are used in cemented carbides.[b]

Figure 13 shows the stages in cemented carbide tool production, starting with tungsten production (the separate production of cobalt is not shown here). Globally the most commonly traded tungsten material is ammonium paratungstate, which is used as the precursor for other tungsten intermediates as well as pure tungsten metal. The processing technique used, reduction by hydrogen, to produce tungsten powder from APT allows the grain size of the tungsten powder to be accurately controlled. This is important for cemented carbide tooling production as it allows control over the properties of the material. The production of APT is also an important step in cemented carbide recycling.

The final cemented carbide materials are then produced by powder metallurgy techniques. The manufacturing process of cemented carbides begins with the composition of a specific tungsten carbide powder mixture tailored for the application. The tungsten carbide powder is then formed by different shaping technologies such as direct forming, extrusion, and powder injection moulding. After shaping, the materials they undergo sintering treatment to form a dense, near-pore free body. The sintered cemented carbide component gains its final finish by additional grinding, lapping and/or polishing processes.

The unique combination of hardness from the tungsten carbide and toughness from the cobalt binder makes these cemented carbides outstanding as tool materials in the manufacturing industry. Today’s market for cemented carbides is universal and growing. The International Tungsten Industry Association (ITIA) estimates that, including new and recycled material, some 50,000 tonnes of tungsten were consumed in cemented carbides world wide in 2008. These materials also represent the third largest use of cobalt after batteries and superalloys, and consume around 7,900 tonnes per annum based on figures above.

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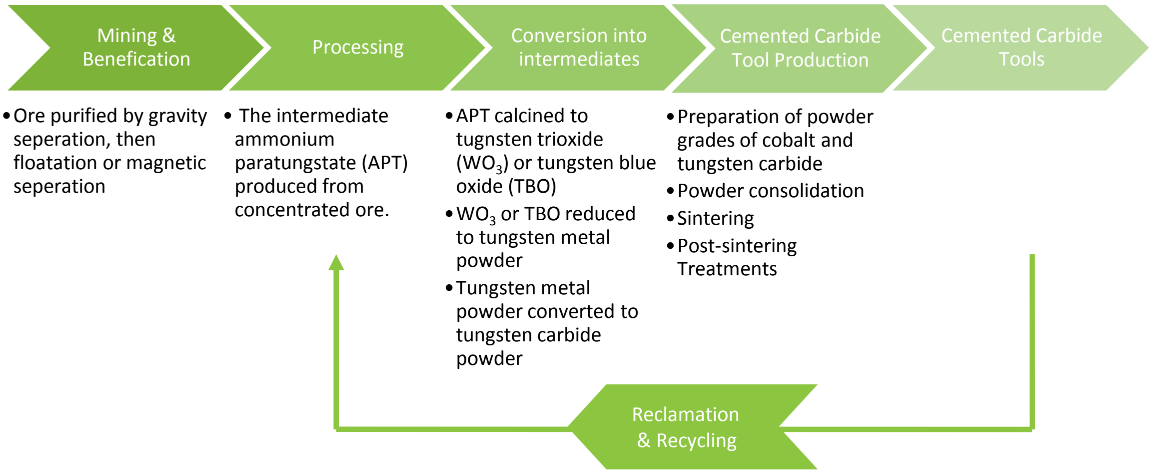
[a] All about cemented carbide, Sandvik Hard Materials, http://www.allaboutcementedcarbide.com/, accessed 09/02/11

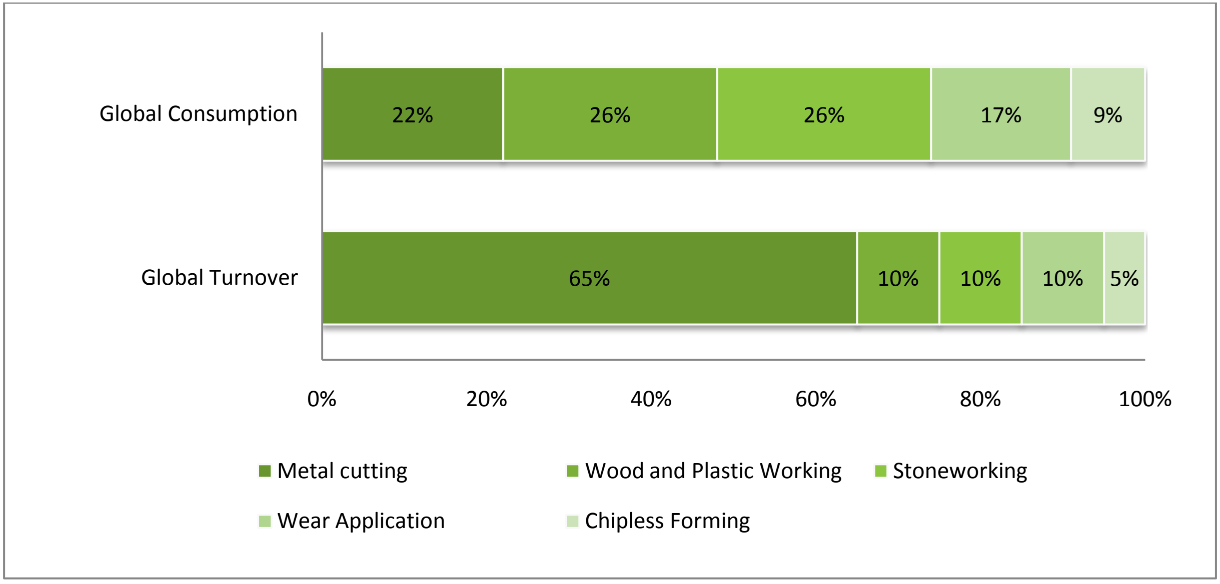
[b] Critical raw materials for the EU, EC, 2010

Figure 13: Cemented carbide tool production



The market for cemented carbide tools can be sub-divided into five general sections, Figure 14. The largest in term of material consumptions are wood and plastic working and stoneworking, requiring 26% of the market each. However, the largest value is attributable to metal cutting tools, which represent 65% of the market for tools, but only 22% of the volume.

Figure 14: General application areas of cemented carbides



Source: ITIA CCs a success story, 2008

Life extension options

The intrinsic value and usefulness of cemented carbide tools means that various different life extension possibilities are available to users, and processing to extend the lifetime of these tools is common, as is recycling.

Coating and regrinding

Coating and regrinding provide methods of extending the lifetime of tools. According to the ITIA, more than 80% of all turning inserts and about 70% of milling inserts are coated with materials such as titanium carbide, titanium nitride or more recently ‘diamond like carbon’. These coatings can be applied via chemical vapour deposition or physical vapour deposition, and extend the lifetime of the tools and wear parts by increasing the surface hardness. It is estimated that using the super hard and multi-layer coatings improve the lifetime by 5 to 10 times.[a] Recoating and regrinding are also possible to prolong the life of tools further, however it is unclear what impact this has on the use of these tools and consumption of materials.

Recycling

Data from Seco, a leading global manufacturer and supplier of carbide cutting tools, indicates less than 5% of the tools are actually worn away when replaced by the operator, leaving around 95% of the carbide intact and capable of being recycled.[b] The quantity and value of this material means that recycling of cemented carbides is well established, and according to industry representatives, there is no difference between cemented carbide tools made from virgin or recycled materials.

There are two common processes in operation for recycling these tools. In the first the sorted and cleaned cemented carbide parts are converted to powder by the zinc process which can reclaim up to 98%[c] of the materials. This process treats the material in molten zinc, with purification occurring after distillation of the zinc. Pure tungsten carbide and cobalt are recovered, as well as other minor additives if present. This process is distinct from primary tungsten production, and is carried out where primary tungsten production is not available.

The alternative recycling process is more suitable for mixed carbide scrap, and allows 100% of the recycled material to be recycled into new tools. However, it is more energy intensive and expensive than the previous method, and rather than recovering the tungsten in carbide form, the intermediate APT is produced. [d] In this process, the waste cemented carbide, including contaminated cemented carbide scrap, turnings, grindings and powder scrap undergoes similar processing to that performed on the purified tungsten ore to produce APT. Where present, cobalt, tantalum and niobium are recovered in separate processing lines. This process requires additional chemical processing facilities, which are typically associated with primary tungsten production, therefore this process primarily occurs in the same refineries as primary tungsten production.

The price of tungsten raw material has more than quadrupled in recent years to reach an all time high[e], and the price of cobalt has also risen to new highs before dropping more recently. These increases in price, combined with the uncertainty of future tungsten supply has encouraged companies to become active in reclamation with the aim of involving their customers in the recycling process by buying back scrap cemented carbide. Large cutting tool manufacturers, such as Ceratizit, Kennametal, Stellram and Sandvik have established schemes where their customers collect all used hardmetal materials in boxes placed by the machine tool. The full boxes are then sent back to their own manufacturing plants for recycling. In return the customer benefits from cash back, invoice reduction or new tooling, depending on the customer needs. Ceratizit and Kennametal indicate that as much as 25% of the market demand for tungsten carbide could be satisfied by reclamation if this process was more commonly implemented.[f]

The difficulties associated with implementing recycling practices are highlighted by Sandvik Coromant's Recycling Concept scheme, launched in 1996. During its early years, the program met with limited success, as it faced major challenges in establishing the logistics required to access and gather used tools. Issues around the return supply chain remain, as it is subject to different regulations dependant on location, which is discussed below. Other challenges faced by the scheme include the fluctuating collection rates of each participating company. This can be caused by the types of parts being produced to the overall health of the economy. The collected materials also need to be sorted and inspected, as it is common for manufacturers to accidentally mix steel or ceramic goods with cemented carbide. To

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[a] Cemented Carbides – A Success Story, ITIA, June 2010

[b] Seco Tools establishes new carbide recycling program, Cutting Tool Engineering, October 2010

[c] Hallberg L. (Sandvik Coromant), Recycling on the Rise, October 2010, Volume 62, Issue 10

[d] Hallberg L. (Sandvik Coromant), Recycling on the Rise, October 2010, Volume 62, Issue 10

[e] Cutting Edge Recycling, Machinery, June 2006

[f] Cutting Edge Recycling, Machinery, June 2006

overcome this, each national collection point maintains manual visual inspection of incoming materials, as well as automated sorting facilities that incorporate various technologies to separate usable materials from unusable ones.[a]

The Sandvik scheme is now well established, and from 2005 to 2010 the recovery of cemented carbide tools rose from 2 to almost 50 tonnes in the US.[b] However, despite these collection systems now being well established in the U.S and parts of Europe, the UK too lags behind according to one industry representative, though no figures for collection rates in the UK are available. The reason identified for this was because many of the smaller companies which use these tools are not aware of the value of recycled carbide scrap, and tend to recycle it with the general metals scrap. However, the financial benefit for the engineering industry can be fairly substantial. Sandvik are currently offering £13.10/kg of mixed carbide scrap, and in the US Kennametal estimate that 1 tonne of carbide scrap per year would result in a financial return of around $20,000[c]. This has provided incentive for some third party operators to introduce collection small scale collection schemes on a limited basis.

Relevant policy and legislation

Differences in waste legislation affect how the operators treat used carbide tooling, which impacts on their ability to obtain and reprocess it. Within Canada and the US, used tools are legally considered products, making recovery simple. However in Europe and some Asian nations, used tools are classified as waste, causing their handling to be subject to a varying array of separate, stringent regulations; this reduces the incentive to collect this material.

Whilst there appear to be no specific regulations affecting this scrap other than that described above, policy in the UK has generally pushed towards recycling of waste metal. However, this has not necessarily encouraged distinction between the different metals present in this waste. Indeed, anecdotal evidence indicates that users of this tooling are often not aware of the ‘exotic’ nature of these materials compared to typical steel grades.

The implementation of REACH has had an impact on the tungsten production and therefore recycling based on the production of APT, as this is often reliant on primary production sites. This processing requires chemical treatment of ore which covered by REACH, though only a small amount of this occurs in Europe. Chemicals used for recoating parts/the recycling process are also subject to REACH regulations.

6.5.1 Impact on carbon emissions

Within the cemented carbide tools market 36,600 tonnes of tungsten and 11,400 tonnes of cobalt are consumed annually, the carbon impact of producing these metals is 350,000 tonnes CO_2e and 94,800 tonnes CO_2e respectively. Energy intensive processing of these materials is also required to produce the final cemented carbide tools from the raw materials. No data were available for this processing, therefore it is impossible to fully quantify the carbon impact of tool production and therefore recycling.

However, examination of the recycling process indicates that it is likely to provide benefits as this avoids the intensive raw metal production, and can also avoid some steps in the manufacturing process. Of the two recycling methods available the zinc method is likely to be most beneficial, as it is less energy intensive and also retains the tungsten in carbide form rather than converting it to tungsten metal. This bypasses several production stages.

Remanufacturing and reusing tools is likely to provide large benefits if the life of a tool is prolonged by a significant period of time. Lifecycle analysis for similar tools has shown that a remanufactured tool has a

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[a] Recycling on the Rise, Hallberg L. (Sandvik Coromant), October 2010, Volume 62, Issue 10

[b] Cutting Tool Engineering, October 2010

[c] Kennametal Complete (2007), http://www.kennametal.com/images/pdf/US/A05-23_CarbideFlyer2.pdf, accessed 16/02/11

carbon footprint which is one fifth of an equivalent new tool.[a] Similar benefits are likely for cemented carbide tooling.

6.5.2 Conclusions and recommendations for cemented carbide tooling

- The prices for the raw materials (tungsten and cobalt) have both risen over the last decade, particularly tungsten; this is expected to continue and therefore influence the price of cemented carbide tools.
- Recycling technology is well established for these materials, and reduces resource consumption, reduces production costs and lowers pollution and energy consumption.
- Two recycling processes are common - the zinc process, typically used for higher grade scrap, and processing to the intermediate APT for lower grade scrap. The later of these is able to reclaim elements individually with a higher efficiency, but requires more energy and at a higher cost. The zinc process is able to produce tungsten carbide and cobalt which can both be reused in the cemented carbide tools. The actual recycling process of used carbide tools does not take place in the UK but in countries such as Sweden, Austria, China and India.
- The recovery infrastructure is well developed in many countries such as the US and parts of Europe, however the UK appears to be lagging behind in recovery despite the economic and environmental benefits.
- Improving collection of spent tools would improve this situation, partly through increasing awareness in cemented carbide tool using industries, and partly through improving infrastructure. However, even if recovery rates are improved it is likely that the recycling will remain outside of the UK at established recycling sites.

Table 15: Conclusions for the cemented carbide tools sector

Submarket	**Application**	**Raw Material(s)**	**Current Practice**	**Opportunities**	**Increased Recovery Prospect**	**Carbon Impact**
Cemented Carbide Tools	Tooling	Cobalt	Tools recovered and recycled or lost in general scrap	Improved recovery and separation of tools	Medium	Medium
		Tungsten				

6.6 *Chemicals*

Relevant materials: fluorspar, (niobium)

The critical raw material of most relevance to the chemical sector is fluorspar. It is the raw material on which most of today's fluorochemical industry is based. The main applications of fluorspar in the chemical industry are the:

- production of fluorocarbons for refrigerants and foam blowing
- production of flux for primary aluminium manufacturing.

The other important use of fluorspar is as flux in steel manufacturing. Smaller amounts of hydrofluoric acid from fluorspar are used as reagent in the pharmaceutical, agrochemicals and fine chemical industry, or as etching agent in the electronics industry. An overview of the main products derived from fluorspar is given in Figure 15.

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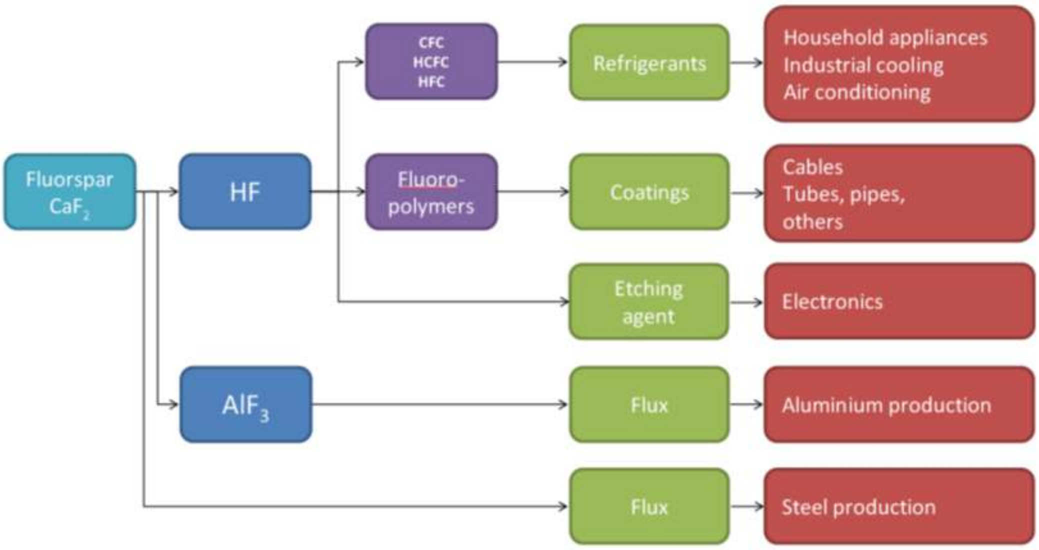
[a] The Carbon Impact of Remanufactured Products – End Mill Cutting Tools, Centre for Remanufacturing and Reuse, 2009

Figure 15: Overview of product tree for fluorspar (only main applications shown)



Source: Oakdene Hollins

This report will focus on fluorspar, hydrofluoric acid and the large sectors of fluorocarbons and aluminium fluoride.

The other material identified, niobium, was found to be not relevant to this discussion as its major use within this sector was in steel for chemical plants rather than chemicals. This use is discussed in Section 6.7.

6.6.1 Fluorspar

Industrially fluorspar has two main uses: as a source of fluorine and as the mineral itself which has useful properties for metal production. For both applications different grades of fluorspar are typically used: high purity acid-grade and lower-purity metallurgical and ceramic grade (Table 16).[a]

Table 16: Grades of fluorspar

Grade	Specification	Use	Final products	Application
Acid grade	>97% CaF_2	50-60%	Hydrochlorocarbons Hydrofluorocarbons Fluoropolymers Hydrofluoric acid	Appliances: refrigerants Electronics: etching agent
		12-18%	AlF_3, Cryolite	Aluminium production: flux
Metallurgical and ceramic grade	<97% CaF_2	20-25%	Fluorspar	Steel industry: flux
		-	Fluorspar	Additive to ceramics

Sources: Oakdene Hollins based on the report "Critical raw materials for the EU" [b]

In the Southeast of England no fluorspar is mined. The only recently operating mine in the UK was Glebe Mines Ltd. (belonging to INEOS Fluor) in the Peak District with an annual production of acid grade fluorspar of about 40-50,000 tonnes.[c] Production levels have dropped over the last decades from 230,000 tonnes in the 1970s, mainly due to a drop in fluorspar prices due to increased competition from overseas (especially China), but most of all due to a drop in demand due to the restrictions imposed on the production and use of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), after the

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[a] In many publications ceramic (85-97% CaF_2) and metallurgical grade (80-85% CaF_2) are combined reflecting the use of both qualities for the main application of steel manufacturers with a recent trend towards preferring higher quality fluorspar (USGS, 2008 Minerals Handbook: Fluorspar, 2010).

[b] European Commission, Critical Raw Materials for the EU, 2010

[c] British Geological Survey, Mineral Profile: Fluorspar, 2005

discovery of their ozone depleting properties. According to recent news, Glebe Mines is expected to be closed[a] because of forbiddingly high investments needed to extend the currently exhausted pits.

Imports of fluorspar are varying from year by year, however, they were generally below domestic production volumes. In 2009 approximately 5,000 tonnes of fluorspar were imported (typically metallurgical grade), nearly all of it from South Africa.[b] After the closure of Glebe Mines it is expected that imports will rise significantly to cover the demands of the remaining fluorochemical company Mexichem.

Across Europe the most important producers besides the UK are Spain (approx. 150,000 tonnes per annum) and Germany (approx. 50,000 tonnes per annum), while France and Italy stopped their operations recently.[c]

Existing practice and infrastructure

The main loss of fluorspar during mining and processing and which is available for recovery and reprocessing are the tailings. These were recycled by mixing them with fresh mining to increase the yield. However due to their high content of impurities, sufficient fresh material is needed to obtain good quality acid-grade fluorspar. No information on the extent of the recycling of tailings is available.

Relevant policy and legislation

The main piece of legislation relevant to recovery of fluorspar in mining is the European Integrated Pollution Prevention and Control (IPPC) Directive.[d] This Directive refers for managing of waste from mining and tailings to the corresponding Best Available Technology Reference Document (BREF) on “Management of Tailings and Waste Rocks in Mining Activities”.[e] However, this document makes no mention of any measures to improve efficiency and recovery rates of fluoride-containing materials.

Conclusions and recommendations

- Due to the expected discontinuation of mining in the UK it is not recommended to implement any measures to improve the efficiency of mining and recovery of fluorspar from tailings or otherwise.

6.6.2 Hydrofluoric acid

Hydrofluoric acid is the basic raw material for the fluorochemical industry. Approximately 50-60% of all fluorspar being mined is used to produce hydrofluoric acid. Nearly all of the fluorspar mined in the UK went into hydrofluoric acid.

European hydrofluoric acid production reached around 200,000 tonnes in 2008 (approx. €200 million) with production sites in Spain, Germany, Italy and the UK.[f] All of these countries either have or had fluorspar mines, highlighting the close link between availability of fluorspar and existence of subsequent chemical industry.[g] After the closure of Rhodia’s operations in Avonmout, only Mexichem UK Ltd (Runcorn, Cheshire) remains as producing site in the UK.

Based on the consumption of acid-grade fluorspar in the UK and the overall yield of the process it can be assumed that approximately 20,000 tonnes per annum of hydrofluoric acid are being produced and consumed domestically.

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[a] BBC, Quarry company in Peak District to cease operation, http://www.bbc.co.uk/news/uk-england-derbyshire-11653269, accessed 22/01/11
The Star, 65 jobs to go at Peak mine, http://www.thestar.co.uk/news/65_jobs_to_go_at_peak_mine_1_2968048, accessed 22/01/11

[b] UK Trade Info, 2009

[c] USGS, 2008 Minerals Handbook: Fluorspar, 2010

[d] Directive 2008/1/EC (referred to in the Environmental Permitting (England and Wales) Regulations 2010)

[e] JRC (European Commission), Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities, 2009

[f] CTEF, Eurofluor HF, http://www.eurofluor.org/html/publications.php?cmd=download&p=1&file=eurofluor_e.pdf, accessed 20/02/11

[g] A case has been made linking the breakdown of the French flurochemical industry to the closure of the French fluorspar mines. (PAJ Lusty, TJ Brown, J. Ward, S. Bloomsfield, The need for indigenous fluorspar production in England, British Geological Survey, 2008)

The main applications of hydrofluoric acid are:

- production of fluorocarbons for refrigerants
- etching agent in the electronics industry
- raw material for production of pharmaceuticals, agrochemicals and special chemicals.

Existing practice and infrastructure

Main resource efficiency measures around the process of hydrofluoric acid are concerned with the way the loss of fluorine in the process can be either minimised or waste can be transformed into products. Both approaches lower the demand for fluorspar. Some examples presented in the literature are[a]:

- The fluorine-containing by-product, siliciumtetrafluoride (SiF_4), can react with hydrofluoric acid solution to yield fluosilic acid. This acid can be used for the fluorination of water or the production of sodium fluoride, hexafluorosilicates or aluminium fluoride and cryolite. However, demand is limited, as it competes with other waste products from applications of hydrogen fluoride as well as from the production process of phosphoric acid.
- Scrubbing of off gases to obtain 20% aqueous hydrofluoric acid. Again demand for this acid is limited.
- Alternatively to the fluorspar process fluosilic acid can be won as by-product from the production process of phosphoric acid. However, the transformation of fluosilic acid into hydrogen fluoride is currently not economically feasible in the UK and 5-6 times more energy intensive than the fluorspar process.[b] However, new developments might change this assessment and may lead ultimately to a reduced pressure on fluorspar.

Relevant policy and legislation

The production and storage of hydrofluoric acid is covered by the BREF for Large Volume Inorganic Chemicals (LVOCs) under the IPPC Directive[c]. Additionally, hydrofluoric acid itself is covered by the REACH regulation.

Conclusions and recommendations

- As both the production and consumption is already covered by existing legislation, especially the IPPC Directive and the BREF document, and additionally only one site for the production of hydrogen fluoride exists in the UK, there does not seem to be a need for additional infrastructure.

6.6.3 Fluorocarbons

Fluorocarbons are the main field of application for hydrofluoric acid. Around 55-65% of all hydrofluoric acid produced worldwide goes into fluorocarbons.[d] Over the last two decades the market for fluorocarbons has seen dramatic changes due to the Montreal Protocol imposing a phasing out of chlorofluorocarbons (CFCs) in developed countries until 2004 and of hydrochlorofluorocarbons (HCFCs) until 2020. The industry has reacted by first substituting CFCs by HCFCs and then developing refrigerants without any chlorine leading to hydrofluorocarbons (HFCs), which have no ozone depletion potential. However, most HFCs have a very high global warming potential (typical 100-10,000 times that of CO_2[e]) and the industry is now required to phase out some of the HFCs and to develop improved refrigerants (hydrofluorolefins HFOs).

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[a] JRC (European Commission), Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals –Ammonia, Acids and Fertilisers, 2007

[b] JRC (European Commission), Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals –Ammonia, Acids and Fertilisers, 2007
British Geological Survey, Mineral Profile: Fluorspar, 2005

[c] JRC (European Commission), Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals –Ammonia, Acids and Fertilisers, 2007

[d] Based on data in the US R. Will, Global Fluorspar Supply and Demand Trends, SRI Consulting, 2007

[e] Fluorocarbons, Fluorocarbons and Sulphur hexafluoride, http://www.fluorocarbons.org/documents/Applications/New_tables_Fluorocarbons_November2010%20FGD.pdf, accessed 20/02/11

Even though the demand for fluorocarbons has been declining in the last decade, it is now picking up again. This is mainly due to a strong increase in emerging economies countering the phasing out or decline of fluorocarbon consumption in OECD countries. Emerging economies have time until 2030 to phase out HCFCs, which has led to a significant shift of production of HCFCs from developed to emerging economies.[a] It remains to be seen whether these production capacities will later switch over to HFCs and thus lead to a further decline of the fluorochemical industry in Europe.

The main applications of fluorocarbons are:

- refrigeration
- foam blowing.

A main product for refrigeration applications currently used in Europe is HFC 134a (1,1,1,2-Tetrafluoro-ethane), which was also being produced by Mexichem at their Runcorn site in Cheshire. The main uses of refrigerants are[b]:

- process cooling, food processing, industrial refrigeration
- transport, commercial and domestic refrigeration
- air conditioning.

Foam blowing is used to produce plastics (polyurethane and polystyrene) with high insulation properties. The advantage of using fluorocarbons in foam blowing is the high performance of the foams and especially the reduced safety risk, especially compared to flammable hydrocarbons. The main foam application areas are[c]:

- domestic appliances
- construction insulation
- insulation in transport.

Existing practice and infrastructure

- **Substitution:** A major practice in reducing the overall consumption of fluorine is the substitution of fluorocarbons by non-fluorine-containing substances. Main appliance producers, but also users (retailers, fast food restaurants), have committed themselves to using only hydrocarbons as refrigerants in their refrigerators. A switch away from fluorocarbons is possible for many larger scale refrigeration systems in supermarkets, as well as for many applications in the food and chemical industry. In air conditioning devices the switch to hydrocarbons may be difficult due to safety reasons. However, recent developments have e.g. provided fluorocarbon-free air conditioning devices for cars.[d] The field of foam blowing already had to phase out both CFCs and their immediate substitutes HCFCs. Currently, much of the market has moved to hydrocarbons as blowing agent, with HFCs still being used where there are special requirements regarding high insulation performance or safety.[e]
- **Prevention of leakages** is the next step to reduce the pressure on fluorspar as a critical raw material. Due to current regulation operators of refrigeration and air conditioning equipment are required to take measures to detect and prevent leakages. According to both a UK[f] and a German[g] study supermarkets are the single most important sector, estimated to be responsible for about a third of all fluorocarbon emissions.

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[a] UNEP, Report Of The Task Force Response To Decision XVIII/12, 2007

[b] CTEF, Eurofluor HF, http://www.eurofluor.org/html/publications.php?cmd=download&p=1&file=eurofluor_e.pdf, accessed 20/02/11

[c] CTEF, Eurofluor HF, http://www.eurofluor.org/html/publications.php?cmd=download&p=1&file=eurofluor_e.pdf, accessed 20/02/11

[d] Umweltbundesamt, Halogenierte Kältemittel, 2009

[e] LACORS, UK implementation of fluorinated greenhouse gases and ozone-depleting substances regulations, 2007

[f] LACORS, UK implementation of fluorinated greenhouse gases and ozone-depleting substances regulations, 2007

[g] Umweltbundesamt, Halogenierte Kältemittel, 2009

- **Reclaiming of refrigerants:** Using mobile equipment it is possible to clean used refrigerants on site. Even though these refrigerants will in general not fulfil the specifications of new fluorocarbons, they can still be reused in the equipment they came from.
- **Reprocessing of refrigerants:** Some companies (e.g. Solvay Fluor[a]) offer to 'primary recycle' used refrigerants. In this case the refrigerant is processed back to the original specifications. This processing may not be possible for blends of refrigerants for technical, or for certain refrigerants (e.g. CFCs) for legal reasons. Additionally, the recycled refrigerant may be more expensive than the new one.
- **Recycling as hydrofluoric acid:** An alternative to 'primary recycling' (i.e. remanufacturing) is 'secondary recycling' which involves a controlled combustion of the fluorocarbons in combination with a recuperation of fluorine as hydrofluoric acid.[b]
- **Destruction of fluorocarbons:** More than three million household fridges reach the end of their life each year.[c] However, recycling of these fridges does not involve the recycling of any contained fluorocarbons. During the recycling process the fridge is shredded leading allowing the process to collect any refrigerants and insulation gases, which will then be destroyed by incineration.[d] This is also the route taken for fluorocarbons contained in insulation foam. The foam is either incinerated directly (e.g. from building sites) or is shredded together with the appliance it has insulated (fridges). In both techniques the fluorine is lost.[e]

Relevant policy and legislation

The main pieces of legislation applicable to fluorocarbons are given in Table 17.

Table 17: Main legislation covering fluorocarbons

Legislation	Applicable to	Relevance for critical material
IPPC/BREF	production of fluorocarbons	best practices to reduce leakages
Ozone Depleting Substances	chlorofluorocarbons (CFC)	ban of CFCs leading to substation, regulations regarding leak prevention
F-Gases Regulation	hydrofluorocarbons (HFC)	ban of certain HFCs leading to substation, regulations regarding leak prevention
POPs regulation	perfluorsulfonic acid (PFOS)	not relevant, as PFOS is substituted by other fluorinated compounds (fluorotelomers)

Source: Oakdene Hollins

The most important regulation is the F-gases regulation which covers three areas related to reducing the consumption or increasing the recycling of fluorocarbons[f]:

- **Prevention of leakages:** Depending on the size of the refrigeration equipment operators of refrigeration equipment are required to take measures to prevent leakages (inspections, automatic detections, reporting).
- **Recovery of fluorocarbons:** No emissions are permissible during either servicing or at the end of life. However, the regulation allows not only recycling but also destruction.
- **Banning of certain applications:** relevant to the UK were especially the ban of non-refillable containers and the use of fluorocarbons in one component foams.

Conclusions and recommendations

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[a] Solvay Fluor und Derivate, Thermal Separation and Recycling of Refrigerants, 2002

[b] Solvay Fluor und Derivate, Thermal Separation and Recycling of Refrigerants, 2002

[c] Let's recycle.com, UK's first licensed fridge reprocessing site opens, 2002; http://www.letsrecycle.com/news/latest-news/general/uk-39s-first-licensed-fridge-reprocessing-site-opens, accessed 21/02/11

[d] SIMS Recycling Solutions, Fridge recycling - preventing harmful ozone depleting substances entering the atmosphere, http://uk.simsrecycling.com/weee-recycling-services/fridge-recycling; accessed 22/02/11

[e] Fridge recycling, EMR http://www.emrltd.com/services.asp?id=5, accessed 22/02/11

[f] LACORS, UK implementation of fluorinated greenhouse gases and ozone-depleting substances regulations, 2007

- The preferred route to reduce the dependence on fluorspar as a critical raw material is to substitute the use of fluorocarbons as refrigerants and foam blowing agents. For many applications technical feasible alternative substances are available. Care must be taken, however, that alternatives do not lead to unintended consequences; the substitutes may cause higher greenhouse gas emissions due to a lower capacity of the insulation or a higher energy consumption of the refrigeration unit.
- Reduction and prevention of leakages has a high priority. For commercial applications this is already implemented via the F-gases regulation.
- Investigate potential for recycling of refrigerants from commercial applications.
- No examples of recycling of refrigerants from household fridges were found in the literature, in spite of this option being available to commercial refrigeration units; however large applications of the recycling of refrigerants is not in general an economically feasible option, so it is difficult to see the viability of extending such a scheme to the more complex field of household appliances.

6.6.4 Fluoropolymers

Most fluoropolymers are based on a combination of different fluorocarbons. Best known is polytetrafluoroethylene (PTFE) which is used not only for cookware, but also for wire and cable insulation or for coatings to render pipes, valves and vessels corrosion resistant.

Unlike the fluorocarbons which may quickly dissipate into the air when leaked, fluoropolymers pose no risk as ozone depleting agents or greenhouse gases. However, the contained impurities or decomposition products are sometimes problematic due to their persistent nature (e.g. perfluorosulfonic acid, PFOS). The market for fluoropolymers has been rising at 5% per year globally in recent years.[a]

Unlike CFCs, HCFCs and HFCs that are covered by regulation due to their potentials to deplete the ozone layer or to increase global warming, fluoropolymers are not covered by comparable regulations as they are much more environmentally benign.

Existing practice and infrastructure

Due to the initially high prices for fluoropolymers the economic incentive for recycling fluoropolymers was sufficient to build up both capacities and a market.

- **Recycling during production:** Producers of fluoropolymers and of products with fluoropolymer coating may collect scraps, off-cuts or parts not complying with specifications and send them to recycling.
- **Recycling of end-use products:** A main market for recovering fluoropolymers is the construction sector. Fluoropolymers are – besides PVC – an important component of many cable insulations. Even though recycling of cables is typically focussed on the metal content (especially copper) the plastics can be recycled as well. The first step is to remove the insulation from the cable's core which is usually down mechanically. Specialist recycling companies or producers of fluoropolymers, including recyclers (e.g. DuPont[b]), offer to take or collect old cables and to recycle the polymers.[c] According to DuPont recycling is typically employed for construction/demolition projects with more than 30,000m of cable (6,000m^2 area).

In the UK the main recycler of fluoropolymers is PTI Plastics Ltd.[d] They recycle approximately 20 tonnes per month.[a] Most of it is going as fluoradditive into lubricants, while a part is melt-filtered and re-used

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[a] Fluoride Action Network, Fluorspar Prices are Likely to Stabilise as Environmental Pressures Moderate Demand, http://www2.fluoridealert.org/Pollution/Miscellaneous/Fluorspar-Prices-are-Likely-to-Stabilise-as-Environmental-Pressures-Moderate-Demand, accessed 22/02/11

[b] DuPont, Recycling Copper Communications Cable , http://www2.dupont.com/Cabling_Solutions/en_US/uses_apps/abc_recycle_copper.html, accessed 22/0/11

[c] Cabling, Recycling used cable: Challenges and opportunities, http://www.cablinginstall.com/index/display/article-display/266653/articles/cabling-installation-maintenance/volume-14/issue-8/features/installation/recycling-used-cable-challenges-and-opportunities.html, accessed 22/02/11

[d] http://www.ptiplastics.co.uk/fluoropolymers.html

for moulded parts. The raw material is coming primarily from producers of parts with fluoropolymer coating (e.g. lined tubes), but also from other recyclers handling lined equipment from the chemical industry or cables from the construction sector.

Relevant policy and legislation

The IPPC regulation which covers the production of fluoropolymers is mainly concerned with emissions and pollutions but does not contain relevant recommendations/regulations regarding measures to improve the resource efficiency.

Cables, whose insulation is a major application of fluoropolymers, are usually not covered by the WEEE regulation as the largest share of cables is used in construction and not in household gadgets.

Conclusions and recommendations

- Even though the importance of fluoropolymers is increasing, it is still a small segment of the market (approximately 10-15% of fluorocarbons).[b] They are typically used in small components and complex applications and, while specialised recycling - especially at the source (i.e. from manufacturers of coated/lined products) - is a viable business model, a broad recycling does currently not seem economically feasible.

6.6.5 Aluminium fluoride

The production of aluminium fluoride is the second largest user of acid-grade fluorspar after fluorocarbons, using approximately 20-25% of all acid-grade fluorspar and 12-18% of total fluorspar production.

In the production of aluminium the key step is the electrolysis of bauxite. This is a very energy intensive process whose efficiency can be significantly improved by adding aluminium fluoride to reduce the melting point of the raw material significantly.

The process of producing aluminium fluoride involves the production of hydrofluoric acid from fluorspar in a first step. The hydrofluoric acid is then directly reacted with aluminium hydroxide to obtain aluminium fluoride.[c] Currently, no aluminium fluoride is produced in the UK; however, production facilities in Spain, Italy and Norway exist.[d] Due to strong competition from China, who dominates the market for aluminium fluoride, a number of Western producers have recently stopped their operations.[e]

Existing practice and infrastructure

An example of a recovery of fluoride from the waste water of the aluminium fluoride process can be found in the literature.[f]

Regarding the application of aluminium fluoride it has been observed that improvements in aluminium smelting technology in the US have led to a decrease of fluorocarbon emission by 35% from the 1980s to the 1990s.[g] Even though no data on current fluorocarbon emissions are available it may be assumed that producers following current best available techniques will achieve even better results.

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[a] Personal communication

[b] R. Will, Global Fluorspar Supply and Demand Trends, SRI Consulting, 2007

[c] R. Aldaco, A. Garea, I. Fernandez, A. Irabien, Fluoride Reuse in Aluminium Trifluoride Manufacture: Sustainability Criteria, 2005, http://aiche.confex.com/aiche/2005/techprogram/P25675.HTM, accessed 22/02/11

[d] JRC (European Commission), Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals – Solid and Others industry, 2007

[e] Aluminium International Today, Aluminium Fluoride (AlF_3) – A market striving towards equilibrium, 2010

[f] R. Aldaco, A. Garea, I. Fernandez, A. Irabien, Fluoride Reuse in Aluminium Trifluoride Manufacture: Sustainability Criteria, 2005, http://aiche.confex.com/aiche/2005/techprogram/P25675.HTM, accessed 22/02/11

[g] J. Harnisch, I.S. Wing, H.D. Jacoby ,R.G. Prinn, Primary Aluminium Production: Climate Policy, Emissions and Costs, http://dspace.mit.edu/bitstream/handle/1721.1/3603/MITJPSPGC_Rpt44.pdf?sequence=1, accessed 20/02/11

One best available technology recommended in the BATREF document for non-ferrous metals[a] is to use dry-scrubbing with alumina to remove hydrogen fluoride from the off-gas of aluminium smelters. The resulting aluminium fluoride can be returned to the process.

Furthermore, it is possible to produce aluminium fluoride from fluosilic acid, a by-product of the production of phosphoric acid, thus avoiding the use of fluorspar. Currently, only 35% of the global production is based on the fluosilic acid process, but the process is becoming more and more important.

Relevant policy and legislation
The main legislation applicable to both the production of aluminium fluoride and of aluminium is the IPPC Directive and the corresponding BATREF documents on large-volume inorganic solids[b] and on non-ferrous metals[c]. Even though it primarily aims at the prevention of emissions, some of the best techniques recommended are able to improve resource efficiency. On example would be the use of alumina for dry scrubbing, mentioned above.

Conclusions and recommendations

- As no aluminium fluoride production is currently taking place in the UK there does not seem to be the need for any measures in this field.
- For the production of aluminium the responsible use of aluminium fluoride is covered by the IPPC Directive and should be addressed directly with the affected producers.

6.6.6 Impact on carbon emissions

The small carbon impact of fluorspar itself, 0.14 kgCO_2e/kg, means that there is unlikely to be much benefit seen from recovery and or recycling from recovery fluorspar, and benefits are more likely to be associated with upstream products.

HF
The production of hydrogen fluoride (HF) gas from fluorspar has an impact of 2.6 kgCO_2e/kg, with around half of this associated with processing of raw materials (fluorspar and sulphuric acid). Based on an average of 55% of fluorspar being used in HF production, the overall carbon impact is estimated to be 3.6 million tonnes CO_2e from 1.4 million tonnes of HF. However, as described below, much larger impacts are associated with the derivative chemicals.

Fluorocarbons
Fluorocarbon 134a is used as representative of other fluorocarbons used for refrigeration. The manufacture of this refrigerant has a carbon impact of 8.4 kgCO_2, however very small releases of HFCs during production raises this to 94.6 kgCO_2 overall. This large impact due to small releases indicates that to be beneficial in CO_2e terms, reuse and recycling processes need to release less gas than alternatives. In terms of materials, approximately one quarter of the smaller figure for manufacture is attributable to the precursor HF. Therefore reuse through either reclamation or reprocessing is likely to provide greater benefits than recycling. However, it should be noted that the carbon impact of 134a gas itself is much higher, and has intrinsic impact of 1,430 kgCO_2e/kg.[d] Therefore it is likely that any action which prevents release of these gases will be favourable in carbon impact terms.

Fluoropolymers
PTFE is the most commonly used fluoropolymer, and is used here to be representative of other fluoropolymers. The carbon impact for manufacture of 1 kg of PTFE is 324 kgCO_2e, with losses during

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[a] JRC (European Commission), Reference Document on Best Available Techniques in the Non Ferrous Metals Industry, 2001

[b] JRC (European Commission), Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals – Solid and Others industry, 2007

[c] JRC (European Commission), Reference Document on Best Available Techniques in the Non Ferrous Metals Industry, 2001

[d] IPCC data, GWP 100years

manufacture accounting for around 15.2 $kgCO_2e$ and the remainder arising from losses of chlorine and fluorine-containing gases during production. Again this demonstrates the importance of recovery and recycling processes which do not release gases as by-products. The contribution of HF production to the overall manufacture is 2.6 $kgCO_2$ per kg of PTFE therefore is a minor contribution.

Aluminium trifluoride
No data for the production of aluminium trifluoride using HF could be found.

6.6.7 Overall recommendations for chemicals

Table 18: Conclusions for the chemicals sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Potential for Increased Recovery	Carbon
Fluorocarbons	Refrigerants	Fluorspar	Mostly incinerated	Switch to non-fluorine refrigerants; refrigerant recycling for commercial applications exists	Low	High (substitution)
	Blowing agents	Fluorspar	Foams shredded and incinerated	Non-fluorine blowing agents	None	High (substitution)
Fluoropolymers	Lining of pipes	Fluorspar	Some recycling where easily available raw material exists	Existing practice depends on availability of fluoropolymers	None	Medium (substitution)
Aluminium fluoride	Flux agent	Fluorspar	Dry absorption of offgases on alumina to recover fluorine	Process optimisation by manufacturers	Low	Low

6.7 *Construction*

Relevant materials: magnesium, niobium

Construction is an important sector with a gross value added of £68.0 billion in 2009, which represents nearly 8% of the UK economy.[a] The sector encompasses development of building projects, site preparation, construction of residential and non-residential buildings, civil engineering, finishing and installation and demolition.

Two critical raw materials have significant usage within the sector:

- **Magnesium:** Construction accounts for 5% of world consumption in aluminium alloys
- **Niobium:** Structural purposes in construction and pipelines account for 31% and 24% of world consumption respectively.

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[a] Annual Business Survey 2009 Provisional Results, ONS, 2010

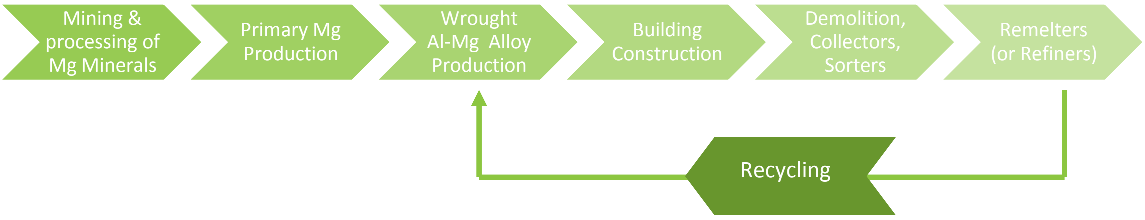
No policies or legislation relating to metal recycling in construction were documented, other than for the decommissioning of oil and gas pipelines.

6.7.1 Magnesium-aluminium alloys

Over 150,000 tonnes of aluminium are used within the construction industry in the UK each year, typically in extruded and rolled products i.e. wrought alloys.[a] Aluminium is used for a wide number of uses with the major applications being the construction of windows, doors and facades, roofs and walls, but other applications include shop fronts, super-structures, door-handles, window catches, staircases, roller shutters, sun-shading and heating / air conditioning systems.[b] The magnesium content of the alloy depends on the specific application of use. This can be as high as 3% for aggressive environments where enhanced corrosive resistance is required such as seafronts[c], although more typical compositions are 1-2% magnesium content.[d]

Figure 16 outlines a supply-chain map for magnesium used in construction. Once produced from ores, the magnesium is then used as an alloying element within wrought aluminium alloys, of which construction is a major market.

Figure 16: Supply chain map for magnesium in aluminium alloys for construction



Within Europe in 2004, 9.9 million tonnes of aluminium was produced; 5.2 million tonnes as primary metal (by 38 separate plants) and 4.7 million tonnes as recycled metal (by 286 separate plants); a further 2.8 million tonnes were imported.[e] For wrought products 4.4 million tonnes of rolled semis were produced by 57 separate plants, 3.1 million tonnes of extrusions by 300 separate plants. For UK, 2009 production of wrought despatches totalled 276,000 tonnes.[f]

Existing practice and infrastructure

Because of the long lifetimes of buildings at typically 30-50 years, specialised companies, often small dealers, take on the role of collection and return of aluminium scrap for recycling. Nonetheless collection rates for aluminium are very high. A 2004 study by Delft University on the collection of aluminium from the demolition of commercial and residential buildings in six European countries, found that the collection rate averaged 96% of the overall aluminium content, with a range of 92-98%.[g] In the study it was noted that, although the aluminium accounted for less than 1% of the demolition mass, it represented a significant profit opportunity. A high degree of sorting by different alloys is performed, e.g. by different extrusion grades for windows, roofs etc., which enables the composition of the alloys to be well-defined and maximises the value achieved to the demolisher.[h]

The collected aluminium products are then reused or recycled. It is possible to chemically separate the magnesium from the host aluminium using chloride techniques, but this is not performed. This is

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[a] Aluminium in Building and Construction, Alfed, 2008

[b] Global Aluminium Recycling: A Cornerstone of Sustainable Development, IAI, 2009

[c] Gianmatteo Martinelli (Novelis Europe), personal communication

[d] Tom Siddle (Alfed), personal communication

[e] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[f] Alfed, Production Stats, http://www.alfed.org.uk/page.asp?node=37&sec=Production_Stats, accessed 22/02/11

[g] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[h] Tom Siddle (Alfed), personal communication

because magnesium is a beneficial and valuable alloying element for most aluminium alloys and would involve unnecessary costs to the recycling process, as the magnesium would be later be re-added and there would be losses associated due to the magnesium oxidising.[a] The magnesium contained is therefore recycled as part of the aluminium, usually through remelting as the chemical composition is well-defined (rather than refining). When the aluminium alloys are remelted, they are combined to formulate a precise alloy composition using computer-assisted optimisation of selection and mixing of scrap and limited corrections are necessary after melting.[b] The effect of this process is that magnesium-containing aluminium grades are recycled back into similar grades, (although not necessarily the same products), but the resulting losses of magnesium in the recycling process are very limited. For the recycling of coated aluminium windows and sheets and composite aluminium panels, a growing number of remelters are using two-chamber furnaces.[c]

The structure of the aluminium scrap metal sector is as follows. An estimate of UK aluminium scrap arising can be obtained indirectly from trade and production data. In 2009 UK net exports of scrap aluminium were 302,000 tonnes, with Asian markets notably China and India as the major importing countries (other export markets exist within Europe, but exports and imports are roughly in balance).[d] As for secondary scrap ingots, the UK produced 130,000 tonnes in 2009 (of which net exports are 96,000 tonnes).[e] This secondary metal production was undertaken in the UK by 25 aluminium refiners and 10 remelters (2004 data).[f] This gives a total of 432,000 tonnes of types of aluminium scrap arising in the UK for 2009[g]. For aluminium products, the UK is a net importer of both extruded and rolled products (totalling 281,000 tonnes in 2009). This therefore gives the striking feature that the UK is a large exporter of scrap or secondary ingot aluminium (92% of scrap arisings), but a net importer of aluminium products.

Conclusions and recommendations

- The recycling of magnesium within aluminium alloys for construction is highly efficient in terms of collection rates and recycling rates. The quality of the scrap is high due to the alloys being highly sorted and this allows for the recovery of the magnesium content.
- The importance of export markets for aluminium scrap within Asia for their growing economies is noted. This carries the implication that much of critical raw material is sent aboard and outside of Europe.

6.7.2 Niobium high strength low alloy steel

The most important application for niobium is as an alloying element to strengthen high-strength-low-alloy (HSLA) steels (accounting for a total of 55% of world niobium consumption), with higher strength steels preferred by some structural engineers because they allow for the construction of lighter and less costly structures. The precursor ferro-niobium is however a small addition at usually less than 0.10% of the composition of the steel.[h] In the UK, Tata Steel reports that that 0.02% niobium content is typical in their niobium steels, with 0.06% as the highest content.[i] The main applications for which niobium steels are used include[j]:

- Long Products: structural shapes, railroad sections, reinforcing bars, engineering bars, wire rods
- Flat Products: gas and oil pipelines, offshore platforms, bridges, viaducts, high-rise buildings.

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[a] Gianmatteo Martinelli (Novelis Europe), personal communication

[b] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[c] Sustainability of Aluminium in Buildings, EAA, 2009

[d] HMRC, UK Trade Info,: https://www.uktradeinfo.com/ , accessed 22/02/11

[e] Alfed, Production Stats, http://www.alfed.org.uk/page.asp?node=37&sec=Production_Stats, accessed 22/02/11

[f] Aluminium Recycling in Europe: The Road to High Quality Products, EAA, 2007

[g] This compares to a 2005 estimate by the BMRA that over 1 million tonnes of non-ferrous scrap metals were processed; of which 45% of this was aluminium, i.e. 450,000 tonnes). Available at URL: http://www.recyclemetals.org/about_metal_recycling accessed 22/02/11

[h] CBMM Website: Use and End Users of Niobium, http://www.cbmm.com.br/english/capitulos/uses/use&user.htm , accessed 02/02/11

[i] Alun Thomas (Tata Steel), personal communication

[j] CBMM Website: Use and End Users of Niobium, http://www.cbmm.com.br/english/capitulos/uses/use&user.htm , accessed 02/02/11

Figure 17 outlines a supply-chain map for niobium used in Construction. Brazil is by far the leading producer of niobium, 92% of the world's production in2010, most of which came from a single mine owned by CBMM.[a] CBMM's currently has niobium capacity of 56,000 tonnes per year or 85,000 tonnes of standard grade ferro-niobium at 66% Niobium content.[b] It is from this ferro-niobium that HSLA steel is produced and then used for construction purposes, such as by Tata Steel within the UK. Recycling of the steel is typically conducted at an electric arc furnace (EAF) where the secondary steel is remelted.

Figure 17: Supply chain map for niobium HSLA steel for construction

Existing practice and infrastructure

For oil and gas, it has been estimated that up to 600 North Sea installations are due to be taken out of service in the next 20 years, which represents around 10,000 km of pipelines.[c] Based upon a median pipe weight and thickness of 392 tonnes per km[d], this represents 3,920,000 tonnes of pipeline scheduled for decommissioning. The practice of leaving pipelines in-situ is common practice within the industry with limited instances of reuse of recycling reported.[e] Comprehensive studies have been conducted by BP and Shell of the decommissioning options available for pipelines for particular North Sea platforms. BP concluded in the decommissioning of North West Hutton that its gas pipeline should be left in-situ and the oil pipeline should be trenched and buried beneath the sea bed. The recovery option was rejected as it would lead to a ten-fold increase in the safety risk, as measured by the probability of loss of life and the cost would increase more than three-fold.[f] These barriers were even more insurmountable in Shell's assessment of the decommissioning options for its Indefatigable Field Pipelines, increasing the safety risk by 42 times and with 12 times the relative cost.[g] Greater potential exists for the recovery of onshore oil pipelines, which have been dug up by US company, Pipeline Equities, at a cost of less than one third of the cost of new pipelines and reused for purposes such as water lines, cable, sewage, irrigation[h]; although it is unclear to the extent that these old pipelines either contain niobium or replace applications that would have required niobium.

Structural steel in contrast is much more widely recycled. In 2008 steel scrap arisings were estimated at 11.1 million tonnes, of which construction accounted for around a third of the arisings, i.e. approximately 3.7 million tonnes (a similar value to automotive scrap).[i] At present the UK is a major exporter of ferrous scrap, exporting 6.6 million tonnes or 59% of the scrap arising. In 2008 over half of this was within Europe (Spain, Turkey, France and Portugal among others), although India and China represent large and growing markets.[j] Due to the low alloying component, niobium-containing scrap niobium is not specifically recovered for applications requiring niobium and is diluted among a larger pool of steel scrap[k]. It is noted however that construction is a major end-market of the electric arc furnaces (EAFs) where much of the scrap will be processed.

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[a] Mineral Commodity Summaries: Niobium, USGS, 2011

[b] The Future of Tantalum and Niobium, Mining Technology, 14 January 2010

[c] Pipeline disposal: What's around the bend?, Decom World , July 2010,:http://social.decomworld.com/industry-insight/pipeline-disposal-what%E2%80%99s-around-bend, accessed 04/02/11

[d] Assessing Metals as Supply Chain Bottlenecks in Priority Energy Technologies Oakdene Hollins for JRC ,(forthcoming).

[e] DECC Oil and Gas, https://www.og.decc.gov.uk/upstream/decommissioning/programmes/approved.htm, 09/02/11

[f] North West Hutton Decommissioning Programme, BP, 2006

[g] Indefatigable Field Platforms and Pipelines Decommissioning Programmes, Shell, 2007

[h] Pipeline Equities: The Case for Pipeline Recycling, http://www.pipelineequities.com/case-for-pipeline-recycling.php, 04/02/11

[i] The Structure and Outlook for UK Markets in Secondary Steel and Aluminium [unpublished], Oakdene Hollins for WRAP, 2009

[j] HMRC, UK Trade Info, https://www.uktradeinfo.com/ , accessed 22/02/11

[k] Matteo Rigamonti (Eurofer), personal communciation

In order to recycle niobium-containing scrap into niobium requiring steel grades, one would need to be able to gather and separate large amounts of niobium-containing scrap (for the minimum efficient scale of an EAF) of a high content[a], and then of course be paid a sufficient premium to ferrous scrap to justify this activity. The following approximate figures highlight the challenges in niobium recovery for construction. The 3.7 million tonnes of scrap steel from construction sources compares to a world niobium production of 21,269 tonnes for 1978 for use in all markets[b] (allowing for a 30 year lifespan for construction). Based on UK consuming a 7.1% share[c] of the 73% of world niobium currently consumed in the US and Europe and 31% being used for structural purposes (see Annex A), only 344 tonnes of niobium will be available from structural steel recycling (0.0093% of 3.7 million tonnes). However assuming an average grade of 0.05% niobium content, this implies that around 689,000 tonnes of structural steel niobium-containing scrap will arise (19% of 3.7 million tonnes). In terms of the value of the niobium contained, OA Plate and Girder (a benchmark scrap steel grade) has averaged £117 per tonne over the last three years[d] compared to $40,330 per tonne for ferro-niobium. Assuming 0.05% niobium content and allowing for currency conversion[e] and the 65% niobium content of the ferro-niobium, this puts the value of the niobium contained at around 7% of the value of the steel scrap.

Relevant policy and legislation

The decommissioning of oil and gas pipelines in the UK is regulated by DECC under the Petroleum Act 1998. A decommissioning programme sets out the measures proposed to be taken in connection with the decommissioning of disused installations and/or pipelines and describe, in detail, the methods that will be employed to undertake the work. In some cases this process can cover a wide range of activities, such as radioactive material handling, removal of debris from the seabed and environmental monitoring of the area after removal of the installation.[f] No specific requirements are made on the recovery of pipelines, although this is typically an option that will be explored.

Conclusions and recommendations

- The recovery of niobium steels from offshore oil and gas pipelines is generally not feasible due to the safety and cost implications involved. Opportunities may exist however for the recovery of onshore pipelines where these are being commissioned and for structural steel, although the cost of separating the niobium-containing steel scrap from other types of ferrous scrap is unlikely to be justified, with the low niobium alloying content unlikely to offer a sufficient premium to incentivise recyclers.
- Additionally it is noted that significant quantities of scrap steel are exported for recycling, although much of this remains within Europe.

6.7.3 Impact on carbon emissions

The construction industry consumes similar grades of aluminium to the automotive industry; therefore it is assumed that the impact of primary aluminium production is 13.7 kgCO_2e per kg. However, further production is needed to make the end products, which is not accounted for here. If the same impact saving of 95% is used as previously, the saving in terms of carbon impact can be estimated as 13 tonnes CO_2e for 1 tonne of scrap.

No data were available for niobium, therefore no estimate of the impact of recovery or recycling of HSLA steels has been made.

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[a] Alun Thomas (Tata Steel), personal communication

[b] Minerals yearbook metals and minerals 1980 (Volume 1): Columbium and tantalum, Bureau of Mines,1980

[c] Using World Bank GDP estimates for 2009, http://data.worldbank.org/indicator/NY.GDP.MKTP.CD, accessed 17/02/11

[d] LetRecycle website, http://www.letsrecycle.com/prices/metals/metals-prices-archive/prices, accessed 23/02/11

[e] Using a currency conversion of $1.6 to £1

[f] DECC Oil and Gas, https://www.og.decc.gov.uk/upstream/decommissioning/intro.htm, accessed 09/02/11

6.7.4 Overall recommendations for construction

The overall conclusions for construction can be found in Table 19. For the magnesium contained within the aluminium alloys collection rates are high at 96% and a high degree of sorting by alloy type, both maximises the value achieved by the demolisher and the magnesium content that is recovered during recycling. However it is noted that the majority of scrap aluminium is exported to Asia and the UK is a net importer of aluminium products. In contrast, very little of the niobium contained within HSLA steels is recovered. For oil and gas pipelines these are typically left in-situ at their end of life due to safety and cost implications, which gives no opportunity for recovery. For structural steel the niobium contained is not specifically recovered, but rather diluted within a larger pool of scrap steel. It may be possible to sort by alloys, but the low niobium content within the alloys is unlikely to make this economic.

Table 19: Conclusions for construction

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Potential for Increased Recovery	Carbon Benefit
Magnesium-Aluminium Alloys	Wrought Products	Magnesium	High collection & recycling rates, but importance of export markets	Greater recycling within the UK & Europe	Low	High
High Strength Low Alloy Steel	Oil & Gas Pipelines	Niobium	Left in-situ	None, due to safety & cost implications	None	N/A
	Structural		General steel recycling	Sort steel by alloys	Low	N/A

6.8 *Electrical Equipment*

Relevant materials: gallium, indium, REEs

In 2006, the value of electrical equipment sector to the EU economy was €83.7 billion, and constituted 5% of the EU's manufacturing output.[a] This category of electrical equipment, based on the NACE categorisation, includes electric motors, generators and transformers, household electrical equipment as well as other similar items.[b] Within this categorisation the main uses of the critical materials were found to be in rotating electronics and other motors, and solar panels (Table 20).

Table 20: Summary of applications considered within this section

Application	Component	Materials
Rotating Electronics	Permanent Magnet	REEs
Solar panels(thin film)	Photovoltaic Thin Film	Indium, Gallium

Future uses of this equipment were also considered, leading to the following being included:

- permanent magnets in (H)EVs (electric motors) and wind turbines (generators) for their REE content
- permanent magnets in household electrical equipment for their REE content
- solar photovoltaic (PV) thin film technologies for their indium and gallium content.

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[a] Critical Raw Materials for the EU, European Commission, June 2010

[b] To avoid confusion around this categorisation, this section excludes any electrical equipment that contains circuit boards; these are included in Section 6.9

6.8.1 Permanent magnets

REE magnets are the strongest known permanent magnets, with neodymium iron boron (NdFeB) being the most powerful, and therefore finding the most uses. Magnets of the NdFeB type consist of 66% iron, 32% neodymium and 1% boron[a], but other REEs can be substituted in place of neodymium to provide the magnet with different properties for specific applications. One of these, dysprosium, is believed to represent the main supply bottleneck in the future.[b]

An alternative REE magnet is based on samarium cobalt; however, since the discovery of NdFeB magnets its use has declined. It is now only used for niche applications, for example in uses which require high temperatures. As samarium-based magnets are only a minor part of the permanent magnet market they have been excluded from further discussion, but may provide substitution options.

The applications of rare earth permanent magnets relevant to this study are: electric drive and propulsion applications in (H)EVs; power generation in wind turbines; and magnets used in electrical equipment such as the drive motors in headphones and speakers or more recently in vacuum cleaners. Figure 18 shows a generic supply-chain map for the magnets used in these different applications.

Figure 18: Supply chain map for permanent magnets

Permanent magnets deliver a stable magnetic field without needing an external power source, and are therefore a key component of the high-power and lightweight motors used in (H)EVs. As briefly discussed in the Section 6.3, figures on the uptake of (H)EVs vary greatly. In 2009 14,645 hybrid electric vehicles and 55 electric vehicles were registered in the UK, which was a decrease from 2008.[c] Estimates of the future uptake of EVs (excluding HEVs) vary, and range from 10% of the global car market by 2020, to 1.5-2%.[d] Although the actual uptake of these vehicles in the coming decade is uncertain, using the lower estimate nevertheless gives a significant number: assuming the same figure for new vehicle registrations as 2010, 2% equates to approximately 40,000 new vehicles on 2020.[e]

Permanent magnets are also increasingly used in wind turbines. Modern direct-drive units based on permanent magnet generators help reduce the reliance on gear-boxes which require maintenance. This reliability makes the turbines particularly suitable for use under conditions where maintenance is difficult and expensive, for example offshore wind turbines. Installation of direct-drive turbines began in 2009 with 5 GW of installed capacity, the equivalent of 3,500 magnets.[f] However, this number is expected to increase rapidly, and existing projections suggest that 23 GW will be installed in the period 2010-2014 (16,064 magnets) to 154 GW (108,074 magnets) in 2020.[g]

Smaller quantities of magnets are used in electrical equipment such as speakers, earphones and other electronic items. These uses are expected to represent a small amount of the total demand for NdFeB based magnets.[h]

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

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

[c] Motor Industry Facts 2010, SMMT Automotive Information, Available at http://www.smmt.co.uk/downloads/MotorIndustryFacts.pdf accessed Feb, 2011

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

[e] Assuming 2 million new car registrations per year

[f] World Wind Energy Report 2009, WWEA, available at http://www.wwindea.org

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

[h] Hard disk drives are discussed in section 6.9 as a separate item.

Existing practice and infrastructure

Pre-consumer waste is an issue for NdFeB magnets as they are brittle and fracture easily. An estimated 20-30% of the magnet material is scrapped during manufacturing due to breakages or waste cuttings.[a] At present it is cheaper to buy newly manufactured magnets than to reprocess the scrap material, and typically the scrap materials can end up in generic scrap metal waste streams.

NdFeB magnets are not expected to enter waste streams in large quantities for some time. When kept under correct conditions, no significant demagnetisation is experienced even over long periods of time. Their use in durable goods also means that the appearance of magnet material in the waste stream will take a significant amount of time.

Representatives from the recycling and car manufacturing industry stated that no systems had been put in place for the recovery and recycling of rare earth magnets in electric vehicles. This is because the number of (H)EVs that are approaching end of life is still low, and it is not yet viable or cost-effective to implement these activities. However, recovery and recycling of (H)EV magnets is expected to become attractive in the second half of this decade.

Similar dynamics apply to the magnets used in wind turbines, though on a longer time scale. Wind turbines, particularly those offshore, are designed for longevity and it will take time for these turbines to reach end of life. If it is assumed that wind turbines have a 20 year lifespan, these magnets are unlikely to reach waste in any volume for over 20 years, as installations have only just begun. In addition to this, difficulties in recycling practices are likely to be exacerbated in the future as, unlike vehicles, there is no real precedent for the recycling of wind turbines. Hence processes for the dismantling and separation of wind turbine parts will need to be developed.

The permanent magnets used in small electrical items are already reaching waste streams. These applications have a high turnover rate, but are dispersed into the waste stream at end of life. Recovery of these magnets is not practically or economically feasible due to their small size and because they are often glued to other components making separation impossible. When processed as WEEE, the metal in magnets enters light iron processing routes where it is diluted beyond recovery.

Even when recovery is possible options are limited; in the UK there is currently no infrastructure for the recovery of magnets or recycling of material.[b] Reuse is one potential option, as these magnets do not lose much strength over their lifetime. However, as the specification of the magnets in the original design is often exact, and the processes to change the properties of the magnets are complex and expensive, reuse does not occur.

Several technologies for the recycling REE magnets have been described in the literature (Section 4). These may recycle the material itself as an alloy to form new magnets, or return the materials back to the individual metals for processing into new magnets.[c] At present these methods are not applied commercially, partly due to technical limitations, but also because volumes from waste are not large enough for reasons explained above. However, in the future increased waste from (H)EVs and end of life wind turbines may provide an opportunity for implementing these technologies.

Developments in design and substitution are also being investigated, due to the recent price spike and uncertainty of supply of these materials. At present it is unlikely that alternative materials which can replace REE magnets will be found, therefore complete substitution of the motor is more likely.[d] Toyota has announced that it is developing a new type of electric motor which does not require REE-based

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[a] Recycling Rare Earth elements; Akai, T, AIST Today, 2008, No29 pp8-9

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

[c] Personal communication, Christian Hageluken, Feb 2011

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

magnets.[a] If successful, this could significantly decrease future demand for certain REEs, particularly neodymium and dysprosium.

Relevant policy and legislation

The ELV Directive sets out regulations for vehicle manufacturers and importers to cover all or most of the costs of taking back (H)EVs, and sets reuse, recycling and recovery targets.[b] However, at present it does not specifically target the recycling of permanent magnet containing motors in (H)EVs.

No European-wide legislation is in place for wind turbines at end of life, therefore there are uncertainties about end of life demands for this application.

For household appliances and earphones, current WEEE legislation means that to achieve the recycling quota it is often more important to recover the high content of plastics, iron, aluminium and copper. This leaves little space for the recycling of low quantity critical metals (e.g. REEs) in these applications to contribute to recycling targets.[c]

Recommendations

- When concentrated in electric motors or generators, it is technically feasible to recover the REEs from permanent magnets. The market price for the metals determines whether recovery is economically viable or not; however, volumes arising in waste mean that this is not viable at present.[d]
- The volume of (H)EVs in the waste stream will increase in the second half of this decade, therefore it is timely to consider what recovery infrastructure is required.
- The use of permanent magnets in offshore wind power plants has only recently started. The difficulty of reaching these turbines offshore, and of retrieving the magnets, will have a major impact on the cost of recovering the materials in these turbines when they do reach end of life. However, in the future this may be offset by the value and large volumes of the materials.
- The difficulties in recovering REE magnets from WEEE arise in the dispersion of the permanent magnet materials and the methods of fixing. Current legislation favours the recovery of other materials in these applications. Therefore it is unlikely that recycling of critical materials from these uses will become viable.

6.8.2 Thin film solar PV

A variety of different PV materials have been developed for gathering solar energy. Of importance to this study are thin film based PVs, specifically the cadmium tellurium (CdTe) type for their indium content, and the copper indium gallium selenium (CIGS) type for their indium and gallium content.

At present, conventional crystalline silicon (c-Si) based cells have the largest share of the global PV market. Thin film technologies, such as those containing critical materials, are estimated to have 18-20% of the market share.[e] However, thin film PVs are experiencing higher growth rates since, although they are less efficient, they are typically cheaper to produce than conventional c-Si PV cells.[f]

CdTe and CIGS are relatively new types of thin film PV, and form only a small proportion of the existing market. However CIGS are more efficient and have a faster and cheaper production process than other

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[a] Toyota Motors to develop electric motor sans rare earth, IBTimes staff reporter, January 2011. Available at Read more: http://www.ibtimes.com/articles/101996/20110118/rare-earth-minerals-toyota-electric-motor-auto-strategy-new-technology-china-japan-metals.htm#ixzz1FY8PcUWG

[b] WEEE regulations, UK Environment Agency, available at http://www.environment-agency.gov.uk/business/topics/waste/32106.aspx accessed February 2011

[c] Recycling of electronic scrap at Umicore's integrated Metals Smelter and Refinery, Christian Hageluken, 2006

[d] Personal Communication, Christian Hageluken, Feb 2011

[e] Thin - Film Photovoltaic (PV) Cells Market Analysis to 2020 - CIGS (Copper Indium Gallium Diselenide) to Emerge as the Major Technology by 2020, GBI research, July 2010

[f] Critical Materials Strategy, US Department of Energy, December 2011

PV thin film technologies.[a] These are therefore expected to be the market leader in the thin film PV industry as it grows. Figure 19 illustrates a generic supply-chain map for thin film PV technologies. After mining, processing and purification, thin film PV layers are deposited on to either coated glass or stainless steel sheets. These are used to produce PV modules which are integrated into a complete PV system.

Figure 19: Supply chain map for PV thin film technologies

Existing practice and infrastructure

The number of PV modules currently entering the waste stream is low. A voluntary take-back scheme, established by the PV industry in 2007 (PV CYCLE), collected 80 tonnes of end of life PVs in Europe in 2010 (despite estimating 6,000 tonnes). As CIGS and CdTe are relatively recent technologies, their market share is still low and the availability of end of life modules was stated to be non-existent.[b] However, the PV industry is beginning to establish recycling of thin film PVs within Europe. In addition to the PV CYCLE scheme, initiatives by the German companies Saperatec and Loserchemie to recover end of life PVs are expected to start in 2011.

Recycling of pre-consumer production waste of CIGS already occurs at Umicore in Belgium, which recovers metals from high grade PV residues. These are typically production scrap residues from CIGS thin film solar cells, which are processed to recover the copper, indium, selenium and gallium. This process is viable due to the concentrated nature of the waste feed.

However, to make this recycling process standard for CIGS modules in the future, effective collection and sorting of PV thin film modules is necessary. For example, gallium would be lost if the process followed Umicore’s standard route for electronics, but would be recovered if fed into the specialist processing route.[c] Although Umicore operates this process to retrieve the indium and gallium from PV manufacturing residues, it has been stated that the metals concentration in general PV waste is too low to make the process sufficiently economic on a large scale at present, even with complete separation.[d]

For CdTe thin film recycling, First Solar operates a process in the US and Germany which is able to separate out the metals. It is a lengthy process, involving several steps to isolate the critical materials.[e] However, the process is highly efficient and can recover 95% of the semiconductor materials for use in new solar modules, as well as 90% of the glass.

The similarities between the materials composition and films used for LCD flat screens and thin film PV mean that LCD and PV recyclers are looking at the possibility of tying the recycling of these products together, particularly for the recycling of indium. This would help generate a larger waste stream to process, making it more viable in the short term while the quantities of end of life LCDs and PVs grow.[f]

Substitution of materials in solar cells is possible, but is typically cost driven: a new material needs to offer either similar performance at a lower cost, or higher performance at the same cost when compared with the incumbent technologies. One recent report identified research-stage technologies as possible

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[a] Thin - Film Photovoltaic (PV) Cells Market Analysis to 2020 - CIGS (Copper Indium Gallium Diselenide) to Emerge as the Major Technology by 2020, GBI research, July 2010

[b] Personal Communication, Dr. Virginia Gomez, Feb 2011

[c] Personal Communication, Christian Hageluken, Feb 2011

[d] Technology Challenges to Recover Precious and Special Metals from Complex Products, Christian Hagelüken and Christina Meskers, 2009

[e] End-of-life PV: then what? - Recycling solar PV panels, Kari Larsen, August 2009 Avilable at: http://www.renewableenergyfocus.com/view/3005/endoflife-pv-then-what-recycling-solar-pv-panels/

[f] Personal Communication, Christian Hageluken, Feb 2011

replacements, including iron sulphide (FeS_2), copper sulphide (Cu_2S) and zinc phosphate (Zn_3P_2), but it is stressed that these are in early stages of development.[a]

Relevant policy and legislation
Solar panels are currently not subject to WEEE legislation, nor to the EU Directive on the Restriction of the Use of Hazardous Substances. The collection schemes for end of life PV are voluntarily set up in an attempt to take responsibility for the modules throughout the whole value chain.

Energy feed in tariffs in countries have had unintended consequences on the collection of waste PV panels. These tariffs are often set for long periods, for example Germany has a 20 year tariff, and Spain's lasts until end of life. Therefore if a panel continues to work, there is little incentive to discard it and replace with more efficient technology. The effect of this was seen when in 2010 an estimated 6,000 tonnes of waste PV panels were expected to be collected, but only 80 tonnes were actually collected. Therefore such incentives can have significant consequences for the number of CdTe and CIGS modules in use and in future waste streams.

Conclusions and recommendations

- The low volumes of PV waste mean that PV thin film recycling is not financially viable at present. For all solar PV technologies, the waste streams are still very small and the recycling of any type of solar PV module is currently marginally viable. CdTe and CIGS modules are virtually non-existent in the waste stream; only residues from the industry are currently recycled. Moreover, the metal content of the modules currently does not create an incentive for commercial recycling of PV thin films.
- The exclusion of PV modules from WEEE might be a positive development. The voluntary industry commitments seem to be more stringent to recycling rates: the PV CYCLE collection scheme is actively looking for recyclers willing to recycle 85% or more of the module content, which is higher than any other WEEE category.
- Future growth in PV use and therefore waste streams may enable the recycling of PVs, specifically CdTe and CIGS, in the future. However, at present the timescales are uncertain.
- Due to similarities in composition there may be synergies between LCD and CdTe recycling, which could be exploited to accelerate the adoption of recycling in these areas.

6.8.3 Impact on carbon emissions

Motors magnets
The impact of the production of 1 kg of neodymium oxide, the precursor to NdFeB magnets is 34 $kgCO_2e$.[b] By comparison the impact of iron production is estimated to be 1.5 $kgCO_2e$, and no data were available for boron (though this only forms 1% of the overall weight of the magnet). Based on a composition of 66% iron and 32% neodymium, the impact for materials production can be estimated to be 12 $kgCO_2e$ per kg of magnet: this figure excludes processing such as sintering, bonding and magnetisation and also the impact of boron. Whilst this does not indicate the impact for full magnet production, it does indicate that the majority of the impact from materials arises from neodymium. Therefore recovery of these magnets for recycling or reuse may present significant carbon benefits in terms of the critical material recovered.

PV panels
The impact of the critical materials used in PV panels can be viewed as similar to that found for FPDs (Section 0). For this use, the critical materials have a small contribution to the overall carbon footprint of the product. However, alternative options such as reuse and remanufacture for these products may be possible: this retains the function of the semiconducting materials, without the need for extensive processing and manufacturing. A recent study indicated that the remanufacture of similar PV cells

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[a] Critical Materials Strategy, US Department of Energy, December 2010

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

(though not ones contain critical materials) could save up to 60% of the carbon impact, compared with the manufacture of new.[a]

6.8.4 Overall conclusions for electrical equipment

- None of the technologies above has high enough volumes in current waste streams to justify large scale recycling activities. However, this may change in the future.
- In case of (H)EVs, larger volumes of REEs in the waste stream requires the development of the electric vehicle market, and also the development of suitable mechanisms to enable recycling. This is in contrast to batteries where much of the infrastructure already exists from other uses.
- Permanent magnets from wind turbines are currently non-existent in the waste stream due to their recent implementation and long life time. The time-lag between these turbines being installed, reaching end of life and entering the waste stream is even larger than in the case of (H)EVs.
- Without significant changes to WEEE processing or to the design of consumer goods, recovery of REE magnets is not likely to be viable.
- Opportunities in PV thin film recycling also suffer from the low numbers of modules in the waste stream. Market penetration of CIGS and CdTe PVs is very low, but is expected to increase in the future. Although processes exist to recycle the modules and retrieve their indium and gallium content, there is no ‘paying metal’ in PV thin films to make this economically attractive in the near future. No significant increase in the volume of the waste stream of these modules is expected in the next 10-20 years.

Table 21 Conclusions for electrical equipment sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Increased Recovery Prospect	Carbon Benefit
Permanent Magnets	(H)EVs	REE	No sufficient volumes in waste stream	Larger volumes of end of life (H)EVs in the future	High	Medium
			No sufficient volumes in waste stream	Long term opportunities for recovering magnets from end of life turbines	High	Medium
	Wind turbines		Part of light iron recycling process	Improve WEEE separation	Low	Low
	Small domestic appliances					
Solar PV	CIGS	Indium, Gallium	No sufficient volumes in waste stream	Volumes will be greater in the future, possible synergies with LCD recycling	Medium	Low
	CdTe	Indium	No sufficient volumes in waste stream	Increased volumes in the future may enable recycling	Medium	Low

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[a] Carbon Impact of Remanufactured Product, Centre for Remanufacturing and Reuse, 2008

6.9 Electronics and IT

Relevant materials: antimony, beryllium, gallium, germanium, indium, PGMs, tantalum, REE

The UK is a leading market for consumer electronics with a 22% share of the European market in 2009 and retail sales reaching £10 billion. The UK spends more per head than any other EU country on product categories such as mobile handsets, HD-ready TVs and Blu-ray players.

Electronic equipment encompasses a broad range of applications and products making it impractical to assess resource efficiency implications within the constraints of the project. By examining the component make-up, use and disposal routes, the number of products requiring investigation can be reduced to a more manageable number. At a materials level, most electronics are made from a number of common components:

- **Printed circuit boards:** These are the plastic boards within electronic devices that contain many different components.
- **Screens:** This report will focus on flat panel displays (FPDs) rather than the older, bulkier cathode ray tube. FPDs have many uses including as televisions, laptop screens and computer monitors.
- **Hard disk drives**: The encased spinning magnetic platters for storing data, usually found within computers or data centres.
- **Cases:** Encasing the electronics, these are made of a variety of materials including metals and plastics.
- **Batteries:** Portable electronic devices primarily use batteries based on NiMH or Li-ion.

By examining the critical material flows into these components, all common electronic equipment can be described. This process will only highlight resource efficiency savings for the critical materials up to the point of sale. The important end of life phase needs to be treated separately. The section below describes the flow of critical materials into the manufacture of the first three of these components - the analysis for cases (particularly the antimony flame-retardant synergists) is discussed separately in Section 0 and batteries have been discussed in Section 6.3.

6.9.1 Electronics and IT components

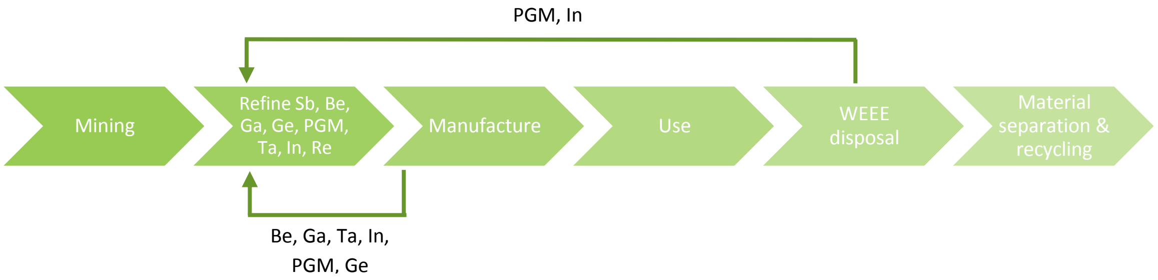
Table 22: Summary of the use of critical elements in electronics

Component	Element	Use
Printed Circuit Boards	Antimony	A dopant in n-type semi conductors
	Beryllium	Beryllium copper alloys for connectors High strength, low density materials used as a support on circuit boards.
	Gallium	Used as gallium arsenide in wireless communication
	Germanium	An alternative to gallium arsenide
	PGM	Capacitors and integrated circuits
	Tantalum	Used extensively in capacitors
Flat Panel Displays	Indium	Used as ITO in LCD screens
Hard Disk Drives	PGM (Ru)	80% of ruthenium produced is used in hard disks
	REE	Neodymium is used in magnets for HDD

The analysis below identified eight out of the 14 critical materials as being important for electronics. Table 22 summarises the use of these materials within the three components identified above.

The material flows for electronics are presented in Figure 20.

Figure 20: The material flows for the critical 14 materials for electronic devices



Printed circuit boards

PCBs contain microchips and other electronic components necessary to run electronic devices, connected with embedded copper wire. All electronic devices have at least one PCB installed, and many non-WEEE Directive products (for example, in the automotive and aviation industry) contain PCBs, which has a bearing when it comes to disposal.

The board itself is usually a glass-reinforced epoxy laminate containing a polybrominated flame retardant. However, the use of antimony as flame retardant synergist does not appear to be common.[a] The majority of the electronic components attached to PCBs contain one or more of the critical 14 materials. The uses of antimony, beryllium, gallium, PGMs and tantalum are described below:

- Antimony is used in very small quantities for the production of n-type silicon semiconductors. These are used in semiconductor technology for making infrared detectors, diodes, and Hall-effect devices. Although of great importance to these devices, the actual quantities of material used are very small and there is little production nor information on resource efficiency data available. However, these elements each produce unique electrical conductivity properties when used as dopants. As a result, they are not interchangeable.[b]

- Beryllium copper alloys are used as contacts in high performance electrical connectors. These alloys usually contain 2% beryllium and it is estimated that an average PC contains 2.1 grams of beryllium. Approximately 75% of all beryllium consumption in the US is in the form of beryllium copper alloys.[c]

  Beryllium oxide is most often used as an electronic substrate, exploiting its high thermal conductivity and good electrical resistivity to give an effective heat sink. The material is particularly used in high power devices or high-density electronic circuits for high speed computers. Beryllium oxide is highly toxic in its powder form and must be carefully controlled. Although more benign when formed into products, processing is expensive due to additional control procedures needed. There have been efforts by some consumer electronics manufacturers to eliminate the use of beryllium oxide,[d] suggesting that there will, where possible, be a move away from its use within mainstream electronics.

- The major industrial use of gallium is in the semiconductor, gallium arsenide, which is used mainly in the circuitry of many wireless and wi-fi consumer electronic products (including mobile phones). Along with the use of gallium semiconductors within light emitting diodes and lasers, total worldwide use within these three areas exceeds 95% of global demand for gallium.

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[a] Fire Retardant Technologies: safe products with optimised environmental hazard and risk performance , Final Technical Report, Defra, 2010

[b] Arsenic and Gallium Arsenide are fundamental to Semiconductor (Microchip) Manufacturing, European Semiconductor Industry Association, 2007

[c] Beryllium Recycling in the United States in 2000 , Larry D. Cunningham, USGS Circular, 2004.

[d] Guide to Greener Electronics, Greenpeace, October 2010

Gallium is almost exclusively sourced as a by-product of alumina production. The concentration of gallium in bauxite ranges between 0.003% and 0.008%.[a] During the production of aluminium, gallium is extracted in an impure form from the crude aluminium hydroxide solution resulting from the Bayer process.[b] This impure gallium is further refined to high purity gallium. Production capacity of gallium is highest in Australia, followed by China and Germany.

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

- A minor use of germanium is in the production of specialist semiconductors for high-speed applications. These include the use, as alternatives to gallium arsenide, in microwave transmitters in wireless applications. Worldwide demand for germanium in the electronics and solar industry is approximately 15%.[d,e] These materials have similar performance characteristics to GaAs-type semiconductors but can be manufactured at a fraction of the cost. The market appears to be developing for these materials and there is likely to be an increase in their use over the next few years[f], however there is little evidence on the effect of these compounds on the mature GaAs market.

- 12.2 tonnes of ruthenium are used in thick film chip resistors; this represents 61% of the total supply of ruthenium. The number of these components manufactured rose during 2008 but an ongoing trend towards miniaturisation drove the average ruthenium content of each resistor downwards.[g]

- Palladium remains a key material in the production of multi-layer ceramic capacitors (MLCC), a passive component used in computers and other consumer electronics devices. Annual demand for palladium for such capacitors is more than 15.5 tonnes. Production volumes of all types of MLCC continue to grow at a great pace and exceeded one trillion in 2006. In total, electronics consumes 33 tonnes of palladium per year (net of recycling). Nickel has recently been substituted for palladium in many types of MLCC.[h]

- Tantalum capacitors offer a high capacity density, and provided they are operated within their ratings, they offer a high degree of reliability; also they lend themselves to surface mount technology. In total, over 60% of all tantalum is used in capacitors.[i] However, only 3-5% of all capacitors use tantalum; hence - without identification and segregation of these capacitors - the tantalum is highly dispersed. Approximately 20% of produced tantalum is sourced from recycled post-industrial scrap, with very little post-consumer waste being reprocessed.[j] On-going miniaturization of electrical capacitors in electronic devices leads to dissipative problems. Although each capacitor contains less tantalum, the number of produced capacitors increases constantly.

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

[b] Gallium, Minor Metals Trade Association

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

[d] Critical raw materials for the EU, 2010

[e] Germanium, USGS, 2009 Minerals Yearbook

[f] Compound Semiconductor, http://compoundsemiconductor.net/csc/features-details.php?id=40433, accessed 26/02/2011

[g] Platinum Year Book 2009(other metals), Johnson Matthey, 2009

[h] Platinum Year book 2007 (palladium), Johnson Matthey, 2007

[i] Critical Materials for Future Sustainable Technologies and Their Recycling Potential, UNEP 2009

[j] Electronic Industry Citizenship Coalition, www.eicc.info, accessed, 25/02/11

An additional use of tantalum is in semiconductors that can be protected from short circuits between conducting materials by a barrier film of insulating tantalum oxide.

Flat panel displays
Indium is widely used in FPDs as part of the transparent conductive matrix of indium tin oxide (ITO). 85% of indium is used in making ITO for displays and other minor uses of conducting transparent surfaces. The process of manufacturing displays involves removing a layer of ITO from a glass substrate. This process generates a significant amount of post-industrial waste material. Recycling of this material is common practice, resulting in more recycled ITO than virgin material re-entering the manufacturing supply chain.[a]

Certain PGMs and REEs are also required during manufacture of the glass for these displays; however these are excluded as they are not incorporated into the finished product.

Hard disk drives
Global consumption of ruthenium is fuelled by the electronics industry, where it is used in hard disk drives as three-atom-thick layer sandwiched between two magnetic layers.[b] The market using this technology has risen rapidly and by the end of 2008 almost all disks manufactured used ruthenium. In 2009 over 80% of ruthenium was used in hard disks.[c] Despite this increase in use, the average ruthenium content was reduced resulting in a relatively slow growth in the amount of metal consumed.[d]

Neodymium magnets are the most widely-used type of rare earth magnet; they are permanent magnets made from an alloy of neodymium, iron and boron. 50% of the supply of these magnets is used in hard disk drives to power the movement of the read-heads of the disks. Global output of neodymium magnets totalled 68,980 tonnes in 2008, with a total value of $3.86 billion. Manufacturing output is dominated by China (62%); followed by Japan (20.9%), the United States (0.3%), Europe (1.4%) and other countries (1.2%).

Existing practice and infrastructure

Printed circuit boards
The UK does not have the capacity to recover metals from circuit boards and these are generally shipped to one of the main European integrated metal smelters or to outside the EU. Various material separation technologies are used to concentrate saleable quantities of material into the manufacturing supply chain. For example, Umicore based in Hoboken, Belgium, has developed a processing technology to separate 17 different elements from circuit board scrap; for electronic waste, PGMs, indium and antimony are refined for reuse.[e] Other elements contained within the circuit board are generally disposed of as slag.

Research is ongoing for new technologies to extract further value from the scrap; Umicore is exploring methods for extraction of REEs from the slag, but these are some way from commercial realisation.[f] There is doubt that the current smelting methods of recycling could effectively recycle the remaining critical elements. Most are highly reactive at the temperatures employed and readily oxidise, ending up in the slag. The relative concentration of these materials is also very low, making extraction of commercially significant quantities difficult. This situation may get worse: the concentration of valuable materials within electronics is reducing because of the drive to use less material within each component. Further separation and collection of products containing critical materials may slow this trend.

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[a] Indium, USGS, 2008

[b] Ruthenium Use: Hard Disks, www.ebullionguide.com/ruthenium-use-hard-disks.aspx, accessed 21/02/2011

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

[d] Platinum Year Book 2009(other metals), Johnson Matthey, 2009

[e] Electronic scrap recycling at Umicore, 3rd China International Metal Recycling Forum, 2007

[f] Personal communication Christian Hagelueken, 2011

As greater collection of WEEE occurs, the amount of waste material available for smelting will increase. There are, however, concerns that there is not sufficient capacity within the EU to reprocess the increased supply. This is difficult to corroborate from either the smelters or the suppliers of scrap, but clearly there is a barrier to entry into this area due to know-how and capital outlay; the amount of WEEE that can be fed into conventional integrated smelters is limited to about 6% of the feedstock.[a]

Flat panel displays

Obtaining the plastics and circuit boards from panels could be achieved in a similar manner to those described above for other types of WEEE. In addition to these materials, most LCD FPDs use a mercury-containing backlight. Due to its fragility, there are valid concerns over the removal of this backlight, although several pilot-scale technologies claim to have overcome this problem using manual separation and possibly through the use of mechanical shredding.[b] However, there was some concern that simple washing of the shredded material did not remove sufficient mercury to make safe the hazardous material.

Recovery of indium from the panel glass does not appear to have been solved. Indeed a study by WRAP[c] that examined the economics of recycling FPD considered the ITO-containing glass as a waste rather than a resource for recycling. The critical material indium is the obvious target for recovery from LCD panels; some 80% of the world's production of indium is used in the manufacture of ITO matrices for flat panels. Smelting is not seen as an attractive option to obtain the indium from these products. The relatively small quantities of indium are dwarfed by the amount of low-value glass substrate, making the economics of recovery less favourable. In addition, smelting would be inefficient with most of the energy focused on melting the glass. A less conventional route appears to be needed to recover this material.[d]

Presently, there does not appear to be any commercially available means to recycle post-consumer ITO from FPDs. This should be seen as a potential target for further research. FPDs should be easily separable from other types of WEEE because they are easily recognisable. This should enable sufficient concentration of material to enable more effective recycling methods to be developed.

Hard disk drives

Although there is an increased use of neodymium magnets in other applications (mainly focused around rotating electrics), their use in hard drives still dominates this market. The potential risk of sensitive data loss for companies has led to targeted services for data destruction from old hard disk drives. Several different practices are used, but the consumer driven separation and identification of these components should help in collecting the neodymium magnets. Most collection and separation techniques for hard disk drives result in the drive being shredded; this serves the dual purpose of enabling extraction of materials for sale and ensuring that sensitive data are destroyed, suggesting that access to these magnets should be relatively easy. There is no evidence that the magnets are recovered for recycling. Indeed the British Metals Recycling Association stated that the current volumes were too low.[e] Also, it is unclear if there is a viable recycling route for these compounds. There is evidence that novel research is on-going: Birmingham University is involved in a project[f] as are Hitachi in Japan.[g,h] Smelting could provide another avenue for recycling neodymium but does not appear to be currently practised, possibly because of the currently low volumes /dispersed nature in the waste stream.

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[a] Using metal-rich WEEE plastics as feedstock / fuel substitute for an integrated metals smelter, Plastics Europe, November 2006

[b] LCD Recycling, http://www.stenatechnoworld.com/sv/Atervinning-av-bildskarmsglas-och-LCD-skarmar/LCD--atervinning/, accessed 17/02/2011

[c] Demonstration of Flat Panel display recycling technologies, WRAP, 2010

[d] Technology challenges to recover precious and epical metals from complex products, R'09 twin world congress and world resources forum, 2009

[e] Recycling Association Gives Evidence at Inquiry into Strategic Rare Earth Metals, Waste Management World, February 2011

[f] Multiple recycling of NdFeB-type sintered magnets, Zakotnik, M and Harris, IR and Williams, AJ, Journal of Alloys and Compounds, 469 (1-2), *2009*, 314-321

[g] Hitachi Launches R&D on Rare Earth Magnet Recycling , http://www.japanfs.org/en/pages/029912.html, accessed 14/02/2011

[h] Hitachi's Involvement in Material Resource Recycling, http://www.hitachi.com/rev/archive/2010/__icsFiles/afieldfile/2010/10/26/r2010_04_110.pdf, accessed 17/02/2011

Relevant policy and legislation

The WEEE Regulations 2006 are UK-wide regulations that transpose the requirements of the WEEE Directive that was adopted by the EC in 2003. They place responsibilities on producers and importers of electrical and electronic equipment for financing collection, treatment and recycling of electrical and electronic wastes. The regulations include targets for the amount of WEEE that will need to be treated, recovered and recycled. Sites that treat, recover and recycle or export WEEE need to be approved.

With the main manufacturing bases located outside the UK (and indeed the EU), the majority of resource efficiency savings will be focused on treatment of electronics at the end of life. Used electronic equipment can be disposed of by one of three ways:

- export for reuse in secondary markets
- export outside the EU for material separation
- material separation within the UK or Europe.

It is important to examine these three disposal routes to identify resource efficiency gains and where materials are lost.

There are official figures for the export of WEEE, but there does not appear to be any official statistics on the export of electronics for reuse, but the number of companies offering to redeploy electronics suggests that there are large quantities of working electronics being exported for reuse in secondary markets. The loss of these products from Europe removes the possibility to recycle them locally. Indeed there are two further problems with this activity:

- covertly exporting WEEE claiming it is destined for reuse
- disposal of the equipment once it reaches the end of its life within the secondary market.

The outcome of both these issues is that serious health and environmental problems are caused in the country where these products are reused if the waste disposal infrastructure is poorer than the equivalent in Europe. Better policing of the exporting companies will prevent WEEE exports under the guise of reuse, whereas there will be a need for investment in waste infrastructure within emerging economies to ensure correct disposal at the end of the electronic product's life. The environmental problems associated with exporting used electronics can also be mitigated through the development, implementation and certification of new standards for selling used electronics, namely PAS141 and BS8887-211.[a]

It should be noted that the disposal and treatment of waste outside the EU is permitted for Approved Exporters. They are allowed to issue evidence notes for the treatment, recovery and recycling of WEEE that takes place outside the UK. They must supply evidence that each overseas treatment or recovery site operates to standards that are equivalent to those required in the EU.[b]

It is important to give an overview of the processes involved in recycling WEEE into raw materials. WEEE is collected and consolidated at Authorised Approved Treatment Facilities. These facilities are permitted to collect and treat WEEE and provide evidence that is has been appropriately disposed of and recycled. There are 156 registered sites in the UK, operated by a number of different waste contractors including ERM and SIMS.[c] These sites generally collate and shred WEEE. Various automated and manual sorting techniques are used to separate the waste into streams such as plastics, ferrous metals, aluminium, inert material and other metal containing waste.[d] This last fraction mainly comprises circuit boards, containing all the critical materials discussed in Section 6.9.1 along with a large amount of copper. These materials are then sold to various recycling facilities either within the UK or abroad for further processing into recycled materials.

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[a] Both these standards are in an advanced draft stage and are due to be published by BSI within the first half of 2011.

[b] What is an approved exporter, www.metalandwaste.com, accessed 15/02/2011

[c] AATF public register, The Environment Agency, 2011

[d] Personal communication, Graeme Corus EMR, 10/02/11

6.9.2 Impact on carbon emissions

Printed circuit boards

No attempt has been made to assess the impact of critical material recovery from PCBs, due to the complexity of these products and complicated manufacturing and recycling processes. Compared with the overall composition of these components, only small quantities of the critical materials are present, which are also dispersed by mixing, making recovery difficult and energy intensive. In addition, much of the impact from using these materials is associated with their processing into the component. For example, in the production of a gallium semiconductor the production of the gallium is estimated to account for less than 2% of overall carbon impact. Therefore the carbon benefits of recovery of the critical materials on a per unit basis are likely to be negligible, and small even on a large scale. Other measures such as reuse are likely to be more favourable using this measure.

Flat panel screens

It is estimated that 1 cm^2 of screen requires 0.07 mg of indium in ITO.[a] A screen size with a diagonal size of 32” has an area of 2,800 cm^2, therefore 0.196 g of indium. The production of this amount of indium has impact of 0.03 $kgCO_2e$, prior to further processing. The corresponding television is estimated to have an overall impact of 756 $kgCO_2e$ for manufacture. Therefore, even with the necessary processing to produce the ITO film from recycle indium, it is unlikely that it would make a significant change to the overall impact of the television.

Hard disk drives

As stated in Section 6.8, the production of the neodymium oxide precursor contributes a significant portion of the carbon impact of materials production. Similarly, the recovery or these materials and recycling or reuse could provide significant carbon benefits in terms due to the saving in primary critical material production.

6.9.3 Recommendations and conclusions

Based on the discussion above, the following opportunities and recommendations can be made:

- There is a research gap for the separation of ITO from flat panel display glass. Research and development of a treatment facility would prevent its disposal to landfill.
- There appears to be a capacity issue within Europe for smelting PCBs; further investment into increasing capacity may be needed.
- There is a growing opportunity requiring investment to separate out neodymium magnets from hard disk drives and determining an appropriate method for recycling them. Separation of these components from waste streams already occurs on a small scale due to data security concerns.
- Separation of many of the critical elements from scrap PCBs is not technically possible as individual materials are usually too disperse within the slags produced from the smelting processes. Separating components into material rich streams may make them more viable targets for recycling.
- There are concerns that the current policing of exported WEEE is leading to illegal dumping of hazardous material in developing countries. Tighter regulation may stop this, but the development and implementation of standards that certify UK exporters of used EEE [NOTE: not WEEE].

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[a] Regaining Indium from e-waste, Elisabeth Walter, CeBIT green IT, Hannover, 2010

Table 23: Conclusions for electronics and IT sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Potential for Increased Recovery	Carbon Benefit
Printed Circuit Boards	A dopant in n-type semi conductors	Antimony	Shredding and WEEE recovery. Post-industrial scrap is currently recycled (largely outside the EU).	Selective segregation and new technologies to extract further material steams. The development of more European capacity for high metal content WEEE scrap	Low	Low
	Beryllium copper alloys for connectors High strength, low density materials used as a support on circuit boards	Beryllium			Low	Low
	Used as gallium arsenide in wireless communication	Gallium			Low	Low
	An alternative to gallium arsenide	Germanium			Low	
	Capacitors and integrated circuits.	PGM			Low (currently high)	Low
	Used extensively in capacitors	Tantalum			Low	Low
Flat Panel Displays	Used as ITO in LCD screens	Indium	Shredding and WEEE recovery	New techniques for removing the ITO from a concentrated waste stream	High	Low
Hard Disk Drives	80% of Ru produced is used in hard disks	PGM (Ru)	Shredding and WEEE recovery – REE are not recycled	Segregation and materials recovery can be more focused on these products.	High	Medium
	Neodymium is used in magnets for HDD	REE			High	Medium

6.10 *Flame Retardants*

Relevant materials: antimony

Antimony is the only critical material used to any extent to assist the flame retardant properties of materials; however this application accounts for 72% of world antimony demand. In this use antimony is present exclusively as antimony trioxide (ATO), and world production of this material is estimated to be 161,000 tonnes, based on 2009 supply figures. Using a three-year average price of antimony metal of $6.6/kg, the value of antimony metal used for this application is $888 million per year. However, the price of antimony has risen considerably in the past few years, and the current price is almost double this and is not expected to fall in the short term.

6.10.1 Antimony trioxide

ATO is not itself a particularly effective flame retardant. Instead it is used as a synergist to improve the performance of other flame retardants or flame retardant materials. This property reduces the quantity of expensive or harmful flame retardants which need to be added to a product to meet fire regulations. It also enables the use of particular plastics in products such as computer casings and TV sets that might otherwise pose considerable fire hazard.

The use of ATO is almost entirely associated with brominated flame retardants (BFRs), and with PVC which has some inherent flame retardant properties. As such it is found in a variety of different applications (Table 24).

Table 24: Common applications of ATO as a flame retardant synergist and in other uses

Use	% Use	Major Applications
Plastics and Rubber (excl. PVC)	47%	Plastics used in electronic and electrical equipment, including ABS, HIPS , PS , PP
PVC	36%	Cabling, flooring
Textiles	7%	Upholstery for furniture and vehicles.
Others	10%	Catalysts, glass additives, paints, pigments, ceramics.

Source: EU Risk Assessment

The quantity of ATO added to products varies considerably, depending on factors such as the type of material, specific flame retardency requirements and cost considerations. For example, plastics typically contain a concentration of ATO around 4-6%[a], though some applications may require up to 25%. In textiles 4-6% by weight is typical.[b]

Other flame retardants are also available and commonly used, hence ATO is not always present in these uses. For example, in applications classified as electronics and electrical items it is estimated that around 41% use BFRs, and consequently contain ATO; the remaining 59% use alternative flame retardant systems.[c]

Recent information suggests that the use of BFRs is reducing within the EU due to changes in legislation, although this is mainly applicable to large electrical items. Manufacturers outside Europe have continued to use BFRs in smaller goods, and their sales have continued to grow, mostly due to demand from China and the Far East.[d] Therefore it is likely that ATO will still be present in end of life products for some time to come. However, there are indications that in the future stronger legislation governing the use and imports of products containing BFRs could be implemented due to environmental and health concerns. For example, the BFR deca-BDE is already effectively banned in the US, through a voluntary agreement between the manufacturers. Therefore, in the longer term the demand for ATO is likely to drop, as BFR systems are replaced by alternatives, particularly those based on phosphorus.

Existing practice and infrastructure

The production of ATO and incorporation into other materials is relatively simple process (Figure 21).

Within Europe ATO is produced from antimony metal, purchased by the ATO manufacturers on the metals exchange.[e] The metal is converted to ATO simply by heating in a furnace, the ATO sublimes and is collected in pure form. When ATO manufacture occurs closer to the primary ore mining, a slightly

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[a] Develop a process to separate brominated flame retardants from WEEE polymer, WRAP, 2006

[b] EU Risk Assessment Report – [Diantimony Trioxide], EU, 2008

[c] End of Life Products Containing Flame Retardants, European Flame Retardants Association, 2006

[d] Develop a process to separate brominated flame retardants from WEEE polymer, WRAP, 2006

[e] EU Risk Assessment Report – [Diantimony Trioxide], EU, 2008

different route is more suitable which uses the ore directly. In these cases the ore is purified to increase the antimony content; this is then smelted to produce crude ATO. Purification again occurs through sublimation to separate out impurities such as arsenic compounds. Once produced, ATO powder is simply added to a plastic during its production; this material then undergoes further manufacturing stages to produce the final product.

Figure 21: Schematic of the ATO supply chain, based on EU practices

China is the largest source of ATO, producing around half of world supply. Other major producers included the US, Europe and Japan. ATO production is fairly well established in Europe: one study estimated that four ATO manufacturing sites in Europe were responsible for 17% of world production in 2006.[e] The EU plastics and textiles industry are also reliant on ATO; the same study indicating that there are 15,000 end users within the EU, most consuming up to 125 tonnes per year. Additional ATO is also imported from China and the US to supply this market.

Significant quantities of ATO also enter the EU and UK in manufactured products, and though the quantity is expected to be significant, no figures are available. Therefore there is no accurate estimate of the quantity of ATO in circulation in the EU or UK.[a]

The fate of ATO typically depends on the product in which it is used, which in turn varies depending on applications and user. An EU report states that the widespread use of ATO means that it is not possible to fully determine how it is disposed of. It is concluded that materials containing ATO are most commonly incinerated or sent to landfill, though this is likely to change due to implantation of WEEE and ELV legislation. The three common sources of ATO in waste, general plastics, PVC and Textiles are described below.

Plastics

The major use of BFRs, and therefore ATO, is in plastics used in electronic and electrical equipment due to the need for good flame retardant properties. This use means the processing of end of life products containing ATO typically follows WEEE treatment.

The WEEE Directive requires that plastics containing BFRs should be separated, which can occur at any point during the recycling process. However, at present there are few commercially viable processes available for this separation, though this has been investigated recently and schemes are coming on line.[b] Therefore the existing practice of mechanical shredding and sorting generates large volumes of mixed plastics, which are often not economically viable to separate fully, though techniques are being researched.[c]

This leaves options for disposal of these plastics as export for recycling outside the EU (where regulations are not as strict), landfill or incineration for energy recovery. These latter two are becoming increasing difficult and costly due to increasing control over these activities.

Where plastics are exported for recycling, anecdotal evidence suggests that flame retardant-containing plastics are separated by hand prior to recycling, and that ATO does not impact on the plastics ability to be recycled. Separation in this way allows the recycled plastic to maintain some fire retardant nature after recycling, as the flame retardants are retained in the plastic. However there are little or no controls

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[a] EU Risk Assessment Report – [Diantimony Trioxide], EU, 2008

[b] Develop a process to separate brominated flame retardants from WEEE polymer, WRAP, 2006

[c] Separation of mixed WEEE plastic, WRAP, 2009

on this process. Therefore it may be the case that ATO is reused through this mechanism, though little certainty can be placed on the efficiency of this process.

If separation of plastics containing BFRs is implemented specifically, several options for ATO recovery are available. A recent study was commissioned by WRAP to investigate the separation and removal of BFRs from WEEE plastic.[a] This demonstrated that pilot-scale processes are available which, through the removal of BFRs, allow recovery of the ATO. It was stated that this recovered metal could be reused by the antimony industry if present in a pure enough form. Within the UK Axion Polymers and Simms recycling were identified as leaders in WEEE plastic recycling.

A further alternative for antimony recovery from WEEE plastics was developed by Umicore.[b] A demonstration was performed to test the impact of addition of general WEEE plastic to an integrated metal smelter for calorific value. It was shown that the plastic could form up to 6% of the overall feed, without impacting the smelter. As a side consequence around 70% of the antimony was recovered and refined to an antimony salt using already established processes. The antimony salt product has industrial applications, though more extensive processing could produce ATO or antimony. However, it should be noted that this process does not allow recycling of the plastic which should also be taken into consideration. If it is assumed that 0.5% of the weight of the WEEE plastic is ATO[c], and that 70% can be recovered, 1 tonne of WEEE plastic would produce $40 worth of antimony, based on today's high prices. If separation of BFR-containing plastics did occur, this concentration would increase to around 6% (weight), making this far more attractive economically.

PVC

In 2000 PVC accounted for around 16% of the UK plastics market, corresponding to 750,000 tonnes.[d] The use of ATO in PVC appears to be less well defined compare to other plastics, however evidences suggests that it is used in flexible PVC, primarily for flooring and cable sheathing. Cabling and flooring together account for 21% of the UK PVC market in close to equal proportions. In these uses ATO is believed to be added at concentrations of 2-8%.[e,f]

The end of life fate of these products is not well characterised, and depends strongly on the end market. Most consumption occurs within the construction industry, where these materials may have a lifetime of 10-50 years, therefore it is likely that a significant proportion of PVC is still held in use. Historically most PVC flooring was sent to landfill, with some recovery of cabling occurring due to copper content.

Recycling of PVC does occur. In the case of flooring this is usually off cuts from industrial trimming (i.e. pre-use), which then are reformed into products such as traffic calming ramps and traffic cones; this accounts for around 7,000 tonnes of waste per year. It is estimated that 130,000 tonnes a year of post-use PVC flooring waste is generated; however the volumes being recycled are minimal. The remainder of this waste is sent to landfill. Around half of this is from large sites in the contract sector, which could be collected comparatively easily; this has been identified as a possible opportunity for PVC recyclers. By contrast smaller uses, such as domestic installations are less viable, due to the smaller more dispersed quantities used.[g]

Cabling waste, pre- and post-use, has been recycled in the UK by Manchester Plastics. Around 35,000 tonnes per annum were recycled, again into products such as traffic cones. However, this operation ceased in around 2001, partly due to lowering quantities of PVC in these waste steams as alternative

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[a] Develop a process to separate brominated flame retardants from WEEE polymer, WRAP, 2006

[b] WEEE plastics with brominated flame retardants – from legislation to separate treatment – thermal processes, Tang. L., Polymer Degradation and Stability, 88, *2005*, 35-40

[c] EU Risk Assessment Report – [Diantimony Trioxide], EU, 2008

[d] Materials and products from UK-sourced PVC-rich waste, WRAP, 2004

[e] Prioritisation of Flame Retardants for Environmental Risk Assessment, Environmental Agency , 2003

[f] Information provided by Recovinyl, www.recovinyl.com

[g] Materials and products from UK-sourced PVC-rich waste, WRAP, 2004

plastics were introduced. Also, operations have started in the Far East and China which can conduct this process more economically; however there is less certainty over the standard of this treatment. Export to other countries currently is the main fate of this waste; this may change if copper prices provide incentive to carry out recovery schemes more locally.

Perhaps most critical to the future of PVC recycling in the EU is Recovinyl, which has been set up as a result of a voluntary agreement made by the PVC industry in 2000.[a] Using their processes most PVC can be recycled to form a further product, and 190,000 tonnes of post-consumer PVC were recycled in the EU in 2009, covering all types of PVC. It is likely that this figure will increase in the future as processes and logistics become more established.

In all these commercial recycling processes ATO is likely to remain held within the plastic as they are physical processes, which shred the plastic then reform it. However, flame retardant properties are not typically required for these secondary uses, therefore this does not constitute reuse of the antimony, rather it is dispersed even more with mixed PVC types during the recycling process.

More advanced chemical based recycling for PVC is being investigated, which may separate out some additives; however these are not commercially viable at present, nor is it clear whether antimony could be extracted or whether they will be implemented on a large scale.[b]

It is clear that recycling in the PVC industry is becoming increasingly important, and focus is on increasing levels and quality of recycled material. However, there may be value in extracting antimony from unmixed PVC waste streams if new technologies are implemented. Based on the information above the ATO content can be assumed to be 5% in flooring. The value of antimony metal associated with this can be estimated to be $275 per tonne of PVC, and just over £12.5 per annum in the UK.[c] As antimony prices are increasing, this may provide an incentive for recovering this material.

Textiles

The use in textiles is typically linked to use in upholstery in furniture and vehicles, where it is either present in the textile or in a backing material to the textile. Therefore ATO is found in products such as mattresses, sofas and automotive seating.

In these uses no recovery or recycling of ATO is known to take place as there is little recycling specifically taking place of furniture, or of these materials in vehicles. Textiles from vehicles typically end up in automotive shredder waste, which can either be sent to landfill or incinerated for energy recovery. ELV regulations have influenced processing, but the quantities and values of other materials means that they are recovered in preference.

The high value and function of furniture means that it is reused as long as is practical, then disposed of to landfill or incineration. The value and weight of antimony contained within these products is likely to be low compared that of other materials.

The relative quantity of antimony used in these applications compared with other materials is typically low, as is the comparative value. Therefore it is unlikely that ATO will be recovered directly. Extending the lifetime of this equipment through reuse seems to present the most suitable option for minimisation of ATO use at present.

Substitution and minimisation

Alternatives flame retardant systems are available for all these uses, such as zinc borate or magnesium hydroxide. However ATO, either on its own in PVC or combined with a BFR, typically presents the most

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[a] Vinyl 2010, http://www.vinyl2010.org/, accessed 17/02/2011

[b] Materials and products from UK-sourced PVC-rich waste, WRAP, 2004

[c] Assuming and exchange rate of 1.6 USD to the Pound.

cost-effective way to meet fire regulations.[a] It is unlikely that alternatives will be used, thus reducing the demand for ATO unless a significant change in prices of materials occurs or legislation changes.

Relevant policy and legislation
Within the UK a host of legislation regarding performance in fires is applicable to different products, for example, the Furniture and Furnishings (Fire)(Safety) Regulations 1988. A variety of different British Standards are also used as the basis for performance, for example, BS2782 (methods of testing plastics). While these do not directly influence the use of ATO, their existence defines the need for flame retardants in the products described above.

Disposal is typically driven by the individual products in which the plastic or textile appears, therefore the WEEE directive and ELV often apply to items containing ATO. For electronic and electrical items Annex II of the WEEE Directive specifies that WEEE plastics containing brominated flame retardants need to be identified and separately treated. As described above, this does not necessarily take place at initial sorting, and may occur abroad. The ELV Directive describes recovery and recycling of materials in general terms, therefore there is nothing which specifically influences ATO. For flooring and furniture there appears to be little specific legislation which influences their disposal.

6.10.2 Impact on carbon emissions

No figures were available for the production of ATO, however, antimony metal has an impact of 12.9 $kgCO_2e$ per kg. For comparatively purposes, the carbon footprints of 1 kg of PVC and ABS without additives or moulding are 2 $kgCO_2e$ and 3.7 $kgCO_2e$ respectively. If it is assumed that the manufacture of ATO has a similar impact to that of pure antimony, the addition of 5% by weight would account for around 25% and 15% of the carbon impact for raw PVC and ABS respectively. Therefore recovery of this material is likely to have an influence on the overall carbon impact of the plastics with which it is mixed.

6.10.3 Overall conclusions for flame retardants

- The use of antimony trioxide is directly linked to the use of PVC and brominated flame retardants used in plastics and textiles.
- Whilst this use can be considered dispersive, the concentration in materials is general high (5-8%), however this is significantly reduced when whole products are considered or when they form part of a mixed waste stream.
- Existing infrastructure is more suited to bulk plastic recovery, or disposal via other means. With the exception of flooring and cabling, extraction of ATO bearing materials is likely to increase the cost of waste separation. Therefore recovery must justify this process.
- Separation of BFR plastics may provide a more concentrated waste stream, and the processing required to extract BFRs may also allow antimony to be collected.
- Increasing prices is likely to mean that alternatives to ATO are sought, which may influence the quantity of ATO appearing in waste stream in the future. However in the short term this may increase the attractiveness of ATO or antimony recovery from waste streams, particularly PVC flooring and cabling which are easily separated.
- Environmental pressures on BFRs will mean an increasing search for substitutes, for example flame retardants based on phosphorus chemistry. This will also negatively affect demand for antimony.
- Overall, the situation around the use of antimony oxide in fire retardants is complex; there are drivers such as the need to recycle more plastics, and WEEE processing which may conflict with the recovery of antimony both from an economic and environmental perspective.

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[a] Prioritisation of Flame Retardants for Environmental Risk Assessment, Environmental Agency , 2003

Table 25: Conclusions for flame retardants sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Increased Recovery Prospect	Carbon Impact
Antimony Trioxide	Flame retardant in plastics	Antimony	Follows fate of plastics	Separation of brominated flame retardant containing plastics may encourage recovery of antimony	Medium	Medium

6.11 Optics

Relevant Materials: gallium, germanium

Optics encompasses the following products:

- optical fibres, lasers and light emitting diodes for use within the communications sector
- specialist lenses for applications in passive infrared detection.

Of the 14 critical materials, two materials have been identified with uses within optics: germanium and gallium. Germanium is used as a dopant which affects the refractive index of silica within a fibre optic cable and is also used to form lenses for infrared detectors and cameras whereas gallium is used in semiconductors in the manufacture of light emitting diodes (LEDs).

6.11.1 Optical equipment

Fibre optics

An optical fibre is a single, hair-fine filament drawn from molten silica glass. These fibres are replacing metal wire as the transmission medium in high-speed, high-capacity communications systems that convert information into light, which is then transmitted via fibre optic cable.[a] They are primarily comprised of high purity silicon dioxide but also contain small amounts of germanium to enhance the optical properties. Fibre optic manufacture was worth £296.8 million to the UK in 2010.[b] The market is set to grow in the foreseeable future as optical broadband is rolled out across the UK. For example, BT are currently laying 50,000 km of fibres across the network.[c]

About 30% of worldwide germanium consumption is used in this sector, for telecommunication optical fibres. Germanium dioxide is doped into common silica fibre optic to about 4% by weight. Globally, 42 tonnes of germanium were used in the production of fibre optics.[d]

There is no evidence of post-consumer fibre optic recycling. Indeed reports of recycling fibre optics have focused on reclaiming the plastic cladding. Tokyo Electric Power recycles the outer jackets and slotted rods (protective layers) in which optical fibres are encapsulated. These are cut up, melted, refined, and moulded into pellets, which are used as a raw material for recycled products such as cable storage drums. Tokyo Electric Power plans to recycle all the cable used by the company in fiscal 2006. About 130 tonnes of waste cable were generated in 2004. If all outer jackets and slotted rods are recycled into drums, it will produce enough material to manufacture about 3,400 drums, while halving the amount of waste material buried as industrial waste.[e]

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[a] Optical Fibre, www.madehow.com, accessed 28/02/2011

[b] Fibre Optic Cable Manufacturing – UK Industry Report, IBIS World, 2010

[c] BT commercial and funded deployment in the UK, G Miller, 15th February 2011

[d] Germanium, USGS, 2004

[e] Tokyo Electric Power Starts Recycling Fiber Optics, http://www.japanfs.org/en/pages/026132.html, accessed 25/02/2011

A possible reason for the lack of recycling this is that the amount of glass within a fibre optic is relatively small compared to the cladding and supporting structures for the fibre. Of the total cable volume, 0.03-2% of the cable is the optical core, of which only 4% is germanium oxide. Based on a fibre diameter of 35 µm, 1 g of germanium oxide will be used in around 2.5 km of optical fibre. It should be noted that in most cabling systems, many optic fibres are bundled together such that the amount of cabling needed is significantly reduced: however, such systems reduce the ratio of silica to packaging material further, requiring more cable.

Lenses

An additional 25% of produced germanium is used for high quality lenses and window material for infrared applications. The ability of germanium oxide glasses and germanium metal to transmit near-IR radiation has been used in passive night vision systems. Germanium is readily machinable into IR windows and lenses, and its high refractive index and low chromatic dispersion allow the use of simple, sometimes uncorrected, lenses in IR imaging systems.[a]

There are strong recycling rates for germanium from post-industrial sources. Approximately 30% of germanium used in manufacture is from post-industrial scrap.[b] However, there appears to be no evidence of recycling optical components from post-consumer scrap. The lenses are usually contained within products that are considered WEEE, which are usually shredded and separated into their constituent materials. It is likely that any germanium lenses are separated off as inert materials and landfilled. There are reports of specialist lenses being recycled from military applications.[c]

Light emitting diodes and lasers

Of the estimated 196 tonnes of gallium produced in 2009, 20% is used for optoelectronic devices such as laser diodes and LEDs in the form of gallium arsenide and gallium arsenide phosphide. The rapidly growing high-brightness LED industry was also a significant driver for GaAs- and GaN-based technologies. The backlighting of computer notebook screens, flat-screen computer monitors, and flat-screen televisions was the driving force for high-brightness LED consumption in 2010.[d] The laser diode market feeds into the telecommunications industry and in particular, the light source for fibre optic communication.

Recycled gallium is a significant source of material for the market. Post-industrial scrap may account for up to half of the supply into the world market. Only 15% of a GaAs ingot is actually used during electronics manufacture, and the remaining 85% can be recycled. Countries that reported gallium production from secondary sources in 2004 were the US, Japan, the UK and Germany. It is probable that there is also significant recycling in China.[e]

At the height of the gallium price boom in 2001, GaAs substrate maker Sumitomo Electric estimated that it was internally recycling 40% of the gallium used for crystal growth. A further 20% was retrieved from GaAs device makers in the form of broken wafers, sludge from wafer thinning and waste from epitaxial source material.[f] The largest refined gallium producer is GEO Gallium (a part of GEO Speciality Chemicals) from its Salindres plant in France. GEO Gallium is the world's only fully integrated gallium producer from extraction in alumina plant to refining.[g]

There has been no reported recycling activity involving of LEDs from post-consumer scrap although there is concern that, that by Californian standards, it should be classified as hazardous waste largely due to the

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[a] Germanium, USGS, 2004

[b] Germanium, USGS, 2011

[c] Germanium, USGS, 2011

[d] Gallium, USGS, 2011

[e] Gallium, Minor Metals Trade Association, http://www.mmta.co.uk/uploaded_files/GalliumMJ.pdf, accessed 25/02/2011

[f] Growth Predicted for Gallium Market, Compound Semiconductor, May 2003

[g] Gallium, Minor Metals Trade Association, http://www.mmta.co.uk/uploaded_files/GalliumMJ.pdf, accessed 25/02/2011

high levels of copper, lead, nickel, or silver present in the leachate. The study also detected gallium and indium leaching from the LEDs.[a] The tiny amounts of material within the LEDs will hamper any attempts to collect and refine post-consumer waste. However, the nascent growth in the use of LEDs in consumer lighting may lead to more attractive concentrations of gallium and indium within the waste stream.

Relevant policy and legislation

From the analysis above it there is little current opportunity for resource efficiency within optics. Post-industrial scrap is readily recycled whereas post-consumer scrap is disperse, in low concentrations, and as yet not entering the waste stream in significant volumes. The UK's data network is still being upgraded and the majority of installed cable is expected remain *in situ* for a long time before it reaches the end of its life in significant quantities. Even then, the amount of germanium available for recovery is less than 0.1% of the total weight, which will be difficult to recycle because it is encased in glass. Recycling IR lenses may be possible in certain applications were there is a concentration of products (for example the military). There does not appear to be any efforts being made towards recycling LEDs, probably because of the dispersive nature of the materials within the technology. This may change as they come into more prevalent used within consumer electronics and as lighting sources.

6.11.2 Carbon impact on emissions

No relevant data could be found to measure the impacts of the critical materials in this sector. The dispersive nature and low concentrations of critical materials used in optical applications means there is unlikely to be a significant carbon benefit for recovery or recycling of these materials.

6.11.3 Overall conclusions and recommendations for optics

The overall conclusions for the optics sector can be found in Table 26. However other than the recycling of post-industrial scrap there are very limited opportunities for increasing recovery. This is because both the germanium and gallium have highly dispersive uses, which prohibits effective sorting and refining for these metals.

Table 26: Conclusions for the Optics sector

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Increased Recovery Prospect	Carbon
Fibre optics	GeO_2 is used as a dopant to alter the extinction coefficient	Germanium	Some recycling of post industrial, no indication of post commercial recycling	Few due to the dispersed nature of the material	Low	N/A
Lenses	Optical components in infrared lenses	Germanium	Some recycling of post industrial and military, no post-consumer	Few due to the dispersed nature of the material, potential for military recycling	Low	N/A
Light emitting diodes	Semi conductors for LED production	Gallium	Good recycling of post-industrial, no recycling of post-consumer	Few due to the dispersed nature of the material	Low	N/A

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[a] LED products billed as eco-friendly contain toxic metals, http://www.scraprevolution.com/scrap/news/recycling-a-waste/770-led-products-billed-as-eco-friendly-contain-toxic-metals-study-finds.html, accessed 25/02/2011

6.12 *Packaging*

Relevant materials: magnesium

The packaging industry is the second largest consumer of magnesium after casting alloys, and uses around 16% or 97,000 tonnes of magnesium production.[a] In the packaging industry magnesium is exclusively used in aluminium based alloys. In this use magnesium helps reduce the volume and weight of packaging materials required, by strengthening the material and making it more ductile allowing it to stretch. Within the packaging sector magnesium alloys are almost entirely used in beverage cans, therefore this is the focus of the discussion below. Other minor uses of these alloys within the packaging sector include aluminium foils, food cans, screw caps and aerosol canisters: these uses will not be covered in this section as their magnesium content is minimal.

Many reviews of aluminium packaging and beverage recycling exist.[b] However these reviews typically focus on the recycling of aluminium with little consideration of other alloyed metals. Within this report the use and recycling of magnesium will be focussed on, as one of the critical materials.

6.12.1 Aluminium beverage cans

Worldwide over 187 billion[c] aluminium cans are produced every year, of which an estimated 7 billion are sold in the UK.[d] Based on typical composition figures, this represents the use over 1,700 tonnes of magnesium. The typical aluminium can is made from two grades of aluminium alloy, with the can body and the can lid/tab containing 1.1% and 4.5% of magnesium respectively. The flat lid is required to be stiffer and stronger than the rest of the can, and this is achieved through the addition of a higher concentration of magnesium.

Although recycling of beverage cans is well known, it is not the only resource efficiency measure being taken to save materials. Aluminium alloys offer certain properties for use as beverage cans in comparison to steel cans because of their light weight. The first aluminium-based beverage cans weighed an average of 21g[e], representing a significant weight saving over equivalent standard steel cans which still weigh as much as 28g.[f] Improvements in design mean that the standard 330ml aluminium beverage can now weigh 14g or less, representing an average weight reduction of 7g (33%) per can.

Supply chain

Figure 22 shows a schematic of aluminium can production and lifecycle. More than 80% of all magnesium is mined and subsequently processed in China. Magnesium metal is produced by variations of two fundamental processes, based on thermic or electrolytic techniques. The thermic, or Pidgeon, process is the most well developed method of these two, and is also the most commonly used production method, particularly in China.[g]

In the production of aluminium alloys, magnesium metal is added to the aluminium melt/smelter at the desired concentration. Once mixed, the alloy flows into a mould, where it is slowly chilled in a number processing steps. The final ingot is then transported to a rolling mill where it is rolled into sheets which are used to produce can bodies, lids and tabs.[h] The cans are then filled and enter the consumer market.

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

[b] Global Aluminium Recycling:A Cornerstone of SustainableDevelopment, The Global Aluminium Recycling Committee,

[c] Cans & Closures, Novelis, 2011

[d] http://www.thinkcans.net/

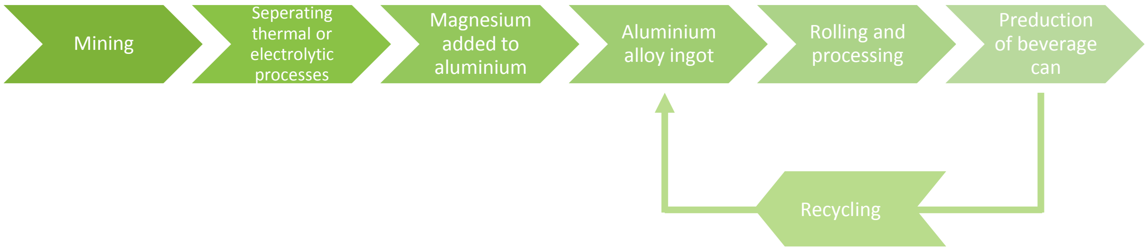
[e] Information from Can Central, http://www.cancentral.com/, accessed 17/02/2011

[f] Steel Cans – Developments in Design and Materials, http://www.azom.com/Details.asp?ArticleID=1693, accessed 17/02/2011

[g] Vulcan T. Magnesium: Behind The Bright Shining Light. Hard Assets, 2010

[h] The Recycling Process, Novelis Recycling, 2008

Figure 22: The manufacturing stages for an aluminium beverage can



When recycling takes place, the used beverage cans (UBCs) are collected after use and then recycled, either in a closed-loop process where the alloy is recycled into cans (Figure 23) or in an open loop for other uses of the alloy. Used aluminium cans be recycled, remade, refilled and returned to store shelves as new cans in as few as 60 days.[a]

Figure 23: Closed-loop system for aluminium can recycling

The recycling process can further be divided into four steps: shredding, de-coating, melting and casting.

Existing practice and infrastructure

Recycling of aluminium alloys in general is well understood, and its commercial and environmental benefits are mainly due to the large energy savings compared to primary production. In addition to this, aluminium alloys can be recycled almost endlessly without degradation of their essential properties. Where recycling of UBCs occurs, the magnesium is not separated from the aluminium alloy. Therefore the recycling of magnesium in aluminium cans is tied to aluminium can recycling in general.

The UK's leading aluminium sheet producer and recycler, Novelis, operates a closed-loop drinks can recycling plant at Warrington. In their processing UBCs are recycled into ingots, which may be processed into new drinks cans.[b] However, due to the different magnesium concentrations present in drinks cans, once melted together the recycled alloys have a magnesium concentration that is between that required for cans bodies or lids. Therefore to achieve maximum efficiency the magnesium concentration is reduced to the desired level by the addition of either virgin aluminium or other scrap which is low in magnesium.

Other recycling plants operate open loop processes which recycle a wider range of aluminium alloy types from a variety of sources, including the construction and automotive sector. The resulting aluminium alloy composition is then re-alloyed to compositions for use in a wide range of end-market uses.

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[a] http://www.recycle.novelis.com/aluminumrecycling/Pages/lifecycle.aspx, accessed 17/2/2011

[b] Personal Communication, Mr Martinelli, Novelis Switzerland

Both methods of recycling preserve the magnesium content of the aluminium alloy, and these recycled alloys are typically of a high specification and can be used again in drink cans or other products, depending on its grade. Therefore the recycling process represents a highly resource efficient method of retaining magnesium, without causing dissipation or loss of function.

According to Beverage Can Makers Europe (BCME), the UK has the industrial capacity to take back all available UBCs. Within the UK there are five major reprocessing facilities and six aluminium can manufacturing plants (Table 27). These companies have their own recovery infrastructure operating collection sites for large scrap around the country: recovery is also supported by a large number of smaller agents which recover and supply scrap. However this activity is not specific to UBCs, and is more suited to general aluminium scrap.

Table 27: Aluminium reprocessors and can manufacturers, UK

Reprocessing	Location	Can Manufacturer	Location
Aleris	Swansea	Ball Packaging Europe	Wrexham
Avon Metals	Gloucester	Ball Packaging Europe	Runcorn
EMR	Multiple	Crown Cork & Seal-Bevcan Europe	Leicester
Novelis Recycling	Warrington	Crown Cork & Seal-Bevcan Europe	Carlisle
Sims Metal Management	Multiple	REXAM	Milton Keynes
		REXAM	Wakefield

Source: BCME

Despite the local and European capacity for recycling, the main issue with the recycling of UBCs is their recovery. An industry estimate indicates that in 2009 only 55% of all UBCs were collected in the UK. Therefore several billion cans go unaccounted for each year, despite the scrap value of aluminium UBCs being around £800 per tonne.[a,b] The growth in kerbside collection of metal packaging, which has reached 90% of UK households[c], has not influenced collection of UBCs as much as it has other materials. However, losses can typically be attributed to consumer usage patterns, as approximately 30% or 30,000 tonnes of cans are consumed 'on-the-go'. These UBCs typically end up in street bins, rather than being taken home to be recycled.[d] Assuming that each can weighs 14g, this represents around 44,000 tonnes of lost aluminium alloy.

Despite improving the collection rates of UBCs from 28% in 1995 to 42% in 2001, and finally 55% in 2009, the UK lags behind many countries in the EU, which have an average recycling rate of 63.1%. The countries with the highest recycling rates are Germany (96%), Belgium, Sweden or Switzerland – all reaching annual recycling rates of 90% or more.[e] Around 1,500 tonnes of magnesium would be recovered if a similar recycling rate were achieved in the UK.

Further improvements in recovery rates are possible, and an industry representative stated that with UK current practices a 65% recycling rate could be achieved by 2020. However, to go beyond this will require significant infrastructure changes to the UK recycling system. For example other countries have introduced deposit schemes for UBCs, these are active in six of the eight EU states with a greater than 90% recovery. In addition many countries have 'on-the-go' recycling, which provides separate bins in public places for different recyclates, including UBCs, allowing consumers to easily sort waste.

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[a] Aluminium Can Recycling Rate Hits Fifty Five per cent, Alupro, July 2010

[b] http://www.wrap.org.uk/businesses/market_information/market_knowledge_portal/materials_markets/metal.html#metalbeverage, accessed 18/02/11

[c] http://www.canmakers.co.uk/industry/recycling.asp, accessed 18/02/11

[d] Making the most of packaging – A strategy for low-carbon economy, Defra, June 2009

[e] UK aluminium can recycling rate lags behind Europe, World Aluminium Market, May 2010

Other resource efficient activities

Both aluminium and magnesium have the potential for high level recycling where old scrap is recovered and recycled into high value products. One example of this is a process called Melt Conditioning by Advanced Shear Technology (MCAST), developed at Brunel University. This process allows the 'upcycling' of aluminium alloys containing magnesium, by reprocessing light alloy scrap into either cast engineering components or feedstock materials. These alloys have equivalent or improved properties compared to currently available primary alloys.[a] One of the main uses for upcycled aluminium can be found in the automotive industry, where it is used as a lightweight material for car frames and automotive body parts. Recycled aluminium cans are a good feedstock for vehicle alloys since average UBC alloy compositions can easily be adjusted for this use by addition of small quantities of magnesium, aluminium or other additives.

Relevant policy and legislation

Within the EU the management of packaging and packaging waste, including UBCs, is enforced by EC Directive 2004/12/EC. This Directive seeks to reduce the impact of packaging on the environment by introducing recovery and recycling targets for packaging waste, and by encouraging minimization and reuse. In the UK this Directive has been implemented through the Producer Responsibility Obligations Regulations and the Essential Requirements Regulations. As part of this legislation, packaging recycling and recovery targets were set for Members to target for December 2008. The UK has exceeded the target rate for recovery of all aluminium packaging. For 2012 the collection rate for aluminium collection target rate is 40%, ensuring that the UK continues to meet EU Directive targets over the next two years. Targets beyond 2012 will be set following the Waste Review, the findings of which are due to be published in spring 2011.

To reach higher recycling rates, Defra has published a new packaging strategy in which it outlines the UK's packaging policy for the next ten years.[b] The overall aim of this strategy is to minimise the environmental impact of packaging. It aims to develop and establish standards which make packaging more sustainable by using as little material as needed to protect the product. These goals are being worked towards by:

- Collaboration between WRAP and the aluminium industry to influence local authorities to improve the rate of kerbside collection.
- Launching campaigns to boost recycling at work (Alupro & WRAP).
- Analysing factors which influence rates of collection, to develop a best practice model to encourage interest from collectors.
- Encouraging individual businesses, such as Coca Cola and Tesco, to invest in 'on-the-go' infrastructure.
- Increasing future aluminium recycling targets. This would unlock additional producer funds for expanding the collection infrastructure.

This strategy also sets out plans to improve the quality of waste packaging collected from domestic recycling streams, with aluminium alloys being one of the materials focussed upon. The intention is to ensure that, over time, the UK achieves a recycling rate similar to the best EU performers.

One further influence on the collection rates of aluminium packaging in general are the weight based reporting mechanisms for landfill diversion. As aluminium is a low density material, these practices offer no incentive to collect it.

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[a] Upcycling of Light Alloys, Innoval Technology, 2010

[b] Making the Most of Packaging, DEFRA, 2009

6.12.2 Impact on carbon emissions

Aluminium alloy recycling is known to reduce the carbon impact of can manufacture significantly. Figures for the benefits of aluminium can recycling are readily available, and it has been estimated that for each tonne of aluminium can scrap recycled, 9 tonnes of CO_2 emissions are avoided.[a] A significant amount of this benefit arises from recycling of the magnesium content, which contributes approximately 8% to the carbon impact of primary alloy manufacturing, despite being only a few percent of the composition (estimated in Section 6.2).

Based on figures in this report, around 98,000 tonnes of aluminium alloy are used in cans for the UK market each year. With the existing recycling rate of 55%, emissions are reduced by 485,000 tonnes CO_2e per annum, compared with alternative primary production. If this level is increased to 90%, to meet the level achieved in other countries, the benefit would increase to 794,000 tonnes CO_2e.

6.12.3 Conclusions and recommendations for packaging

- Within the packaging industry the major use for magnesium is in aluminium alloys for beverage cans. The recycling process for UBCs meets the minimum recycled targets in the UK, and ensures that the alloyed magnesium is recycled. It is also known to significantly lower the environmental impact of beverage cans.
- The nature of the domestic waste stream and common ‘on-the-go’ usage of these cans means that collecting more UBCs maybe more expensive and more difficult than some other waste packaging.
- Despite recent vast improvements, the recovery rate of used aluminium cans in the UK it is still very low (55%) compared to some European countries, which have collection rates of over 90%. Improving this collection rate appears to offer the best method of keeping already produced magnesium in use.
- Improvements could partially be achieved by better kerbside collection of household waste, linked with better collection systems for cans that are used and disposed of ‘on-the-go’.
- The development of ‘on-the-go’ recycling would also lead to a higher recovery rate. For example, the introduction of a deposit scheme would also help to change people’s awareness; this strategy has been successful in other European countries, notably Denmark.

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Increased Recovery Prospect	Carbon Impact
Beverage Cans	Aluminium Alloys	Magnesium	Follows fate of beverage cans	Increasing ‘on-the-go’ collection	High	High

6.13 *Steel and Steel Alloys*

Relevant materials: graphite, fluorspar, magnesium, REEs, (niobium),

Iron and steel manufacturing (part of manufacture of basic metals) in the UK had a turnover of £11.8 billion in 2008, with a gross value added of around £3 billion.[b] The sector encompasses the manufacture of basic iron, steel and ferro-alloys to the manufacture of tubes, pipes, bars and wires. The broader metal manufacturing sector (i.e. including ferrous metals and metal fabrication) accounted for £19.9 billion or 2.2% of UK GVA.

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[a] Making the Most of Packaging, Defra, 2009

[b] Annual Business Inquiry 2008, ONS, 2010

With the exclusion of niobium and tungsten, (which have been discussed within their main market areas Section 6.2 and Section 0 respectively), four critical materials are used within the sector, either during primary production or as alloying elements:

- Graphite raises the carbon content of steel within the steel industry and in foundries, each accounting for 24% of world graphite consumption (i.e. a total of 48%).
- Fluorspar as a specialised flux agent accounts for 20% of world fluorspar consumption.
- Magnesium: desulfurization within iron and steel accounts for 15% of global primary magnesium consumption.
- REEs are used to improve mechanic characteristics, in desulfurization, and to bind stainless steel, accounting for 6% of global rare earth production.

6.13.1 Graphite in steel production

Within the steelmaking industry three major applications for graphite use were identified:

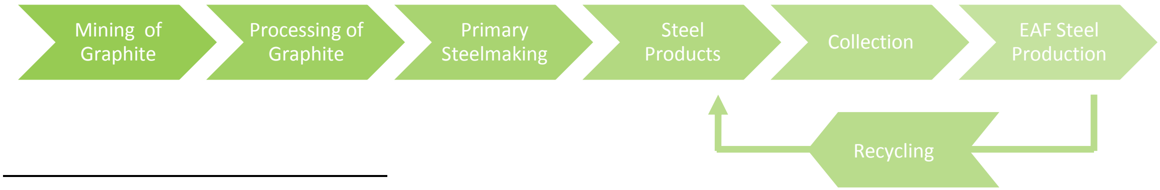
1. Electrodes for electric arc furnaces.
2. Linings for blast furnaces.
3. Raise the carbon content of steel.

For the first two applications, within Europe it is synthetic graphite rather than natural graphite that is used, i.e. not requiring the use of a critical raw material.[a] Information on the supply chain and processing for these applications is available from the European Carbon and Graphite Association (ECGA), but they have not been included here because of the use of synthetic graphite.[b]

Figure 9 outlines the supply-chain map for the major use of natural graphite in steelmaking, i.e. to raise the carbon content. In 2009 China dominated natural graphite production with 71% of world production.[c] Among the world's top 12 producing companies (which collectively account for around half of world supply), six are Chinese including the three largest (Jixi Liumao Graphite Resource, Heilongjiang Aoyu Graphite and Chenzhou Luteng Crystalline Graphite).[d] However, not all the graphite processing takes place in the graphite mining countries; two companies located in Turkey and the Ukraine (where very little graphite mining takes place) both appear in the list for top 12 graphite producing countries. Another aspect of importance is that whilst China is dominant for both the amorphous and flake/crystalline forms of natural graphite, it is only Sri Lanka that commercially mines the rarer vein/lump from of natural graphite. This has the highest carbon content of all the types of natural graphite at 90-96% carbon (compared to 85-89% for flake/crystalline and 70-85% for amorphous), and is used almost exclusively for steelmaking.[e]

It is noteworthy that 70% of natural graphite is used within Asia - much of it linked to steel production[f] - which is mostly the much more abundant amorphous and flake/crystalline forms of natural graphite. In the UK however, Tata Steel report that they use graphite of size 2-10 mm[g], which is a vein/lump grade. Recycling of the steel is typically conducted at an EAF where the secondary steel is remelted.

Figure 24: Supply chain map for natural graphite in steelmaking



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[a] Corina Hebestreit (ECGA), personal communication

[b] ECGA, Graphite in Steelmaking, http://www.carbonandgraphite.org/, 24/02/11

[c] Mineral Commodity Summaries, USGS, 2010

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

[e] The Bright Side of Graphite, IM, July 2010

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

[g] Alun Thomas (Tata Steel), personal communication

Existing practice and infrastructure

Despite the fact that the graphite electrodes are made from synthetic graphite, their recycling from EAFs is nonetheless of relevance with regard to substitution of synthetic for natural graphite. At the end of life of an electrode a sizeable piece of the old electrode remains. This remaining piece is either resized (from several manufacturers) in order to be used by smaller furnaces, or crushed and the resulting powder used to raise the carbon content of the molten steel, substituting for natural graphite.[a]

Where natural graphite is used to raise the carbon content of steel, a chemical bond is formed with metal content of the steel, with carbon representing an alloying component. This is present in the steel product and available at end of life for recycling, with a high recycling rate. Because carbon in included in all types of steels (albeit in varying proportions), the carbon content of the natural graphite is not diluted on recycling and is tightly specified in the production of secondary steel. It is consequently still available for its intended purpose. In the UK in 2008, steel scrap arisings were estimated at 11.1 million tonnes, of which construction, post-consumer (ELV, WEEE etc.) and pre-consumer waste each accounted for around a third of the arisings, i.e. approximately 3.7 million tonnes.[b] The scrap steel industry has a pyramid structure with many small feeder yards and fewer merchants of unfinished and finished scrap. At present the UK is a major exporter of ferrous scrap, exporting 6.6 million tonnes or 59% of the scrap arising. In 2008 over half of this was within Europe (Spain, Turkey, France and Portugal among others), although India and China represent large and growing markets.[c]

Losses of natural graphite however do occur within the production (and recycling) of steel. Some of these losses are unavoidable as some carbon does not bond with the steel and is lost as CO_2.[d] Natural graphite is also contained within the waste generated from steel production, and companies such as Tata Steel can recover and utilise the carbon content. The cache flakes are collected in the back filter of the basic oxygen furnace with the slurry waste for processing. This has a carbon content of around 4.5% and is put into briquettes that are used in the steel manufacturing, principally as a coolant, although any metal content is also recovered.[e]

Relevant policy and legislation

The recycling of scrap steel from a number of products is governed by various regulations such as the ELV and WEEE Directives (see Sections 6.2, 6.8 and 0 for more information).

Conclusions and recommendations

- The recycling of steel is highly efficient in terms of collection and recycling rates. As all steels contain carbon the carbon content of the natural graphite is not diluted upon recycling and is tightly specified in the production of secondary steel. Additionally processes exist for the recovery of the carbon content from the slurry waste produced from the steelmaking.

6.13.2 Other critical raw materials used in steel production

The major application of fluorspar within steel production is as a flux agent to lower the melting point, increase the fluidity of the slag and remove impurities from steelmaking, although this represents a minor market within the UK.[f] The fluorspar reacts with the oxides on the surface of the molten steel to form calcium oxide[g], although a number of substitutes are available such as aluminium smelting dross, borax, calcium chloride, iron oxides, manganese ore, silica sand, and titanium dioxide are already used as

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[a] Matteo Rigamonti (Eurofer), personal communication

[b] The Structure and Outlook for UK Markets in Secondary Steel and Aluminium [unpublished], Oakdene Hollins for WRAP, 2009

[c] HMRC, UK Trade Info, https://www.uktradeinfo.com/, accessed 22/02/11

[d] Corina Hebestreit (ECGA), personal communication

[e] Alun Thomas (Tata Steel), personal communication

[f] Fluorspar Factsheet, BGS, 2010

[g] Matteo Rigamonti (Eurofer), personal communication

substitutes for fluorspar fluxes.[a] A further use of fluorspar within steel production is within hydrofluoric acids used in the surface finishing of stainless steel to remove impurities e.g. oxidisation and stains. China (59%) and to a lesser extent Mexico (18%) dominate world fluorspar production, also for the lower-purity metallurgical grades that are used within steel production. A supply-chain map for fluorspar, and further discussion of hydrofluoric acid, can be found in Section 6.6.

Magnesium is commonly added as a desulfurization agent within iron and steel production, accounting for 15% of global primary magnesium consumption. 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. China is the largest producer of magnesium accounting for 77% of world production in 2010.[b] More details on the processes and a supply-chain map can be found in Sections 6.2 and 0.

REEs have a number of different applications within steel making and are used to improve mechanical characteristics, to bind stainless steel and in desulfurization. The addition of REEs to non-stainless steels has the effect of strengthening and acting as grain refiner: we assume that as there is little information available on this[c] the quantities used are likely to be small. In stainless steels REEs improve the strength and adhesion of the oxide film at high temperatures. From the British Stainless Steel Association (BSSA) website, four grades of austenitic heat-resisting steel were identified that contained cerium, although none exceeded 0.1% of the content, with 0.05% being typical amongst the four grades.[d] Due to its high reactivity, the rare earth alloy mischmetal can be used for purifying steel by removing oxygen and sulphur to very low levels.[e] According to Lynas, the composition of the REEs used for metallurgy excluding batteries, most of which is within iron and steel production, is 52% cerium, 26% lanthanum, 16.5% neodymium and 5.5% praseodymium.[f] This composition corresponds closely to that of mischmetal, which suggests that desulfurization may be the major application of REEs within steelmaking.

Existing practice and infrastructure

Most of these critical raw materials are consumed, i.e. fully reacted with the impurities, within the steelmaking process and end up in the slag, which means that recovery is not feasible. This is the situation for the fluxing agent metallurgical fluorspar, and where magnesium and REEs are used as desulfurization agents; although any iron content is recovered from the slag. It is possible to use the slag itself as substitute for clinker in cement manufacture[g], but this does not allow for the recovery of the critical raw materials themselves. There is very little in-process wastage for these materials due to their high value. For example the magnesium comes in sealed containers and is stored under nitrogen in order to prevent it reacting prematurely.[h] As for the REEs used as minor alloying elements within stainless steel, because of the volumes there is not a specific recycling loop, which means they will be diluted amongst a larger volume of stainless scrap when they are recycled.[i]

Potential opportunity however exists for the recovery of fluorspar from the hydroxide sludges resulting from the finishing (pickling) of stainless steel. These sludges contain complex ions of metals and fluorides, which are currently neutralised and landfilled. In Sweden, the stainless steel producer Outokumpu has developed (patented) and demonstrated a process to recycle and utilise the dry matter contained in the sludges, recovering the metal content for recycling and the fluorspar (50% of the content) for use in its melting shop for flux. Investment in a full scale plant was considered in 2009,

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[a] Mineral Commodity Summaries, USGS, 2010

[b] Mineral Commodity Summaries: Magnesium Metal, USGS, 2010

[c] Matteo Rigamonti (Eurofer), personal communication

[d] BSSA website, http://www.bssa.org.uk/topics.php?article=50, accessed 24/01/11

[e] Rare Earth Metals: Not so Rare, but still Valuable , Hard Assets Investor, 2008

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

[g] Matteo Rigamonti (Eurofer), personal communication

[h] Alun Thomas (Tata Steel), personal communication

[i] Matteo Rigamonti (Eurofer), personal communication

although not implemented at the time.[a] However, an operation is ongoing with around 1,500 tonnes of hydroflux product recovered for use in the Outokumpu melt shop in 2010 (representing around two thirds of the total sludges produced). The profitability of the process is dependent on both the energy cost and the fluorspar price, but discussions are ongoing with suppliers to find a viable and cost effective supply route.[b]

Relevant policy and legislation

A regulation of interest is that relating to End of Waste Criteria. This is an ongoing European initiative that aims to determine procedures that will lead to materials, such as slag materials, no longer being classified as waste but as products after certain processes have been implemented. This would mean that these materials would no longer require prior written notification and consent, and hence would reduce administrative burdens.

Conclusions and recommendations

- Many of the critical raw materials assessed within this section are consumed within the steelmaking process and leave little scope to increase their recovery. However the example of recovering the hydrogen fluoride from sludges from stainless steel for its fluorspar merit has technical and economic merit and should be explored further.

6.13.3 Impact on carbon emissions

As there appears to be little scope for recovering materials, no scenarios have been modelled for this section.

6.13.4 Overall conclusions for steel and steel alloys

The overall conclusions can be found in Table 28.

For the graphite submarket a high level of recycling exists, although there is some prospect to increase recovery. The current practice of steel recycling is highly efficient and, because the carbon content is well controlled in secondary steel, recovery rates of graphite are already high. Opportunities exist to recover graphite losses from slurry waste and utilise these within steel production, and to substitute natural graphite in raising the carbon content of steel with synthetic graphite from end of life electrodes. It is not known how widespread these activities are.

For the other critical raw materials used within steel production the current practice of recovery and potential opportunities are limited. The fluorspar, magnesium and much of the REEs are fully reacted with the impurities, and end up in the slag and cannot be recovered. The REEs used within stainless steel are unlikely to be available for recovery due to their small concentrations. The only opportunity within this submarket is to recovery fluorspar from within the pickling sludges rather than neutralising it and sending it to landfill. Full-scale trials have been conducted for the process, although the economics are dependent on the fluorspar and energy prices.

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[a] Gunnar Ruist (Outokumpu), personal communication

[b] Gunnar Ruist (Outokumpu), personal communication

Table 28: Conclusions for steel & steel alloys

Submarket	Application	Raw Material(s)	Current Practice	Opportunities	Increased Recovery Prospect	Carbon
Steel Production (Graphite)	Raise carbon content of steel	Graphite	Recycled along with steel	Steel recycling highly efficient & carbon content controlled	Low	Low
			Losses recycled from slurry waste	Processes exist for recovery of graphite content	Medium	Low
	Electrodes		End of life (synthetic) electrodes as potential substitute for natural graphite		Medium	Low
Steel Production (Others)	Flux agent	Fluorspar	Fully react with impurities & end up in slag	Can be used as a substitute for clinker in cement	None	Low
	Desulfurization	Magnesium REEs				Medium
	Pickling	Fluorspar	Pickling sludges are neutralised & landfilled	Processes exist, but economics rely on fluorspar & energy prices	Medium	Low
	Stainless	Rare Earths	General stainless steel recycling	Limited, as minor alloying element	Low	Low

6.14 Summary of Opportunities

6.14.1 Opportunities

Over all twelve markets studied, ten applications were identified as having high opportunity to implement critical material recovery for 9 of the 14 critical raw materials listed in Table 1 (Table 29).

Table 29: Summary of 'high' opportunities from all markets, with estimated consumption and value associated with each[a]

Market/ Submarket	Application	Raw Material(s)	Current Total Consumption (Tonnes)	Current Total Consumption ($Millions)	Estimated Carbon Impact	Timeframe
Aerospace	Superalloys	Cobalt	10,639	$126	N/A	Short
		Niobium	4,960	$200		Short
		Tantalum	58	$5		Short
	Landing gear	Beryllium	21	$3	N/A	Short
	Aluminium alloys	Magnesium	54,900	$180	Medium	Short
Portable Batteries	Li-Ion	Cobalt	11,594	$137	Medium	Short
		Graphite	39,776	$41		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 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 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.

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

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 30). These opportunities may still be viable; however, there are greater barriers to implementation, which are discussed within individual market sections.

Table 30: Summary of medium opportunities from all markets, with estimated consumption and value associated for each[a]

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	$24		Short
(H)EV Batteries	Li-Ion/NiMH	Cobalt	1,860	$22	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	$88	Medium	Short
		Tungsten	34,800	$1,076		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	$28	Low	Short
Steel Production (Others)	Pickling	Fluorspar	61,200	$20	Low	Short

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

6.14.2 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 31).

Table 31: 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%	$733	$397
Fluorspar	5,100,000	61,200	1%	$1,683	$20
Gallium	184	4	2%	$92	$2
Germanium	140	0	0%	$161	$0
Graphite	1,130,000	72,320	6%	$1,175	$75
Indium	600	456	76%	$304	$231
Magnesium	610,000	411,750	68%	$2,004	$1,353
Niobium	62,000	4,960	8%	$2,500	$200
PGMs	445	232	52%	$14,172	$7,398
REEs	124,000	53,804	43%	$3,699	$1,605
Tantalum	1,160	58	5%	$103	$5
Tungsten	58,000	34,800	60%	$1,793	$1,076

When the proportion of each raw material associated with the medium and high opportunities is considered, 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). Other measures such as substitution, reuse or elimination may be necessary to reduce the demand for these raw materials in the future.

7 Conclusions and Recommendations

7.1 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:

	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 Hard disk drive 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
- 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.

7.2 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.

7.3 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 plants in Royston and Brimsdown (London) or a few other large sites in the EU, or they are sent to outside of 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.

Annexes

See Separate Document

Annex A – Summary of Critical Materials
Annex B – Best Practice Review Methodology
Annex C – Screening Data

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Would you like to find out more about European Pathway to Zero Waste?

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