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# Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector

## Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies

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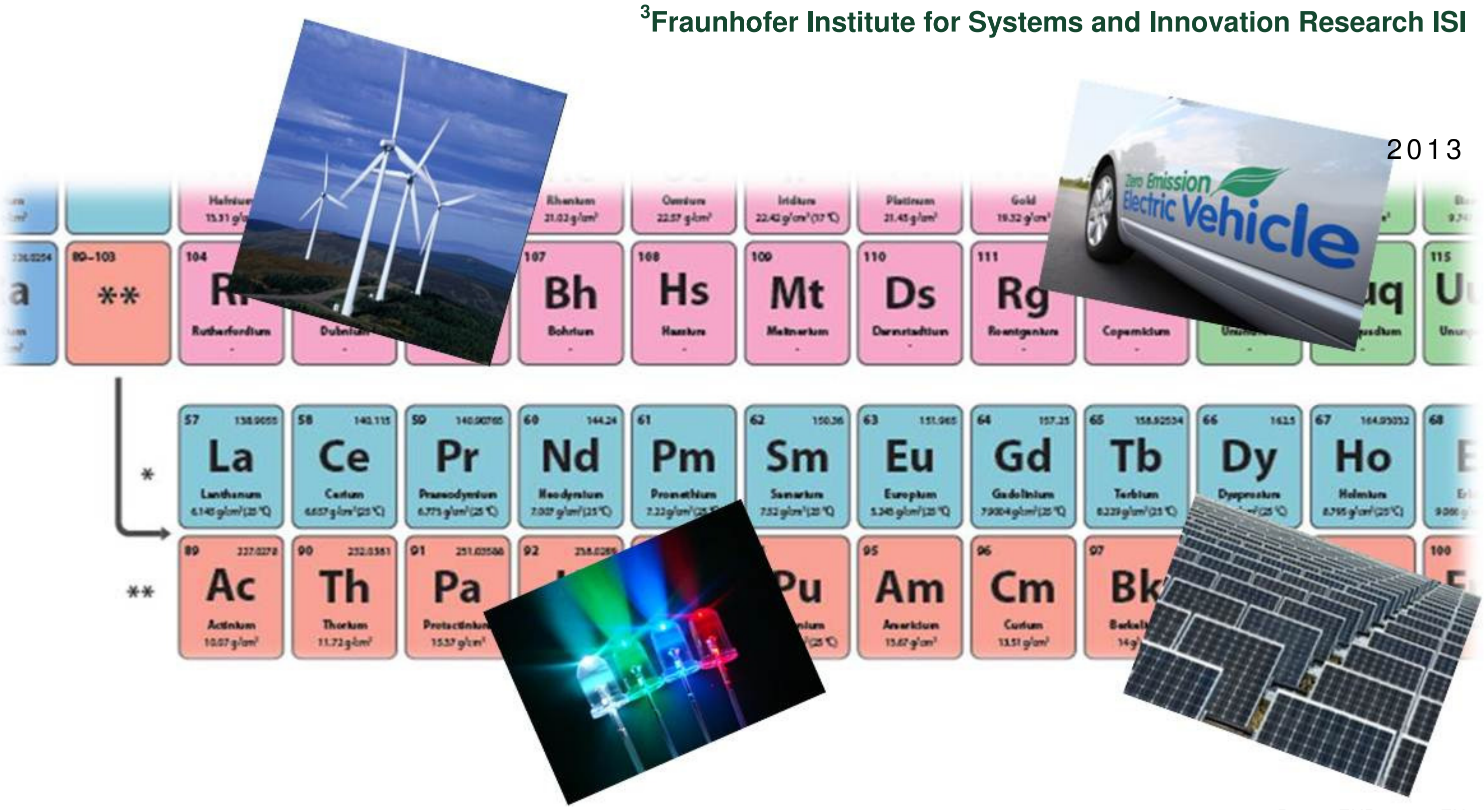

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# Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector

## Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies

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# Abstract

In order to tackle climate change, to increase energy supply security and to foster the sustainability and competitiveness of the European economy, the EU has made the transition to a low-carbon economy a central policy priority. This report builds on the first study conducted by the JRC in 2011 (Critical Metals in Strategic Energy Technologies), where critical metals were identified, which could become a bottleneck to the supply-chain of the low-carbon energy technologies addressed by the Strategic Energy Technology Plan (SET-Plan), namely: wind, solar (both PV and CSP), CCS, nuclear fission, bioenergy and the electricity grid. Fourteen metals were identified to be a cause for concern. After taking into account market and geopolitical parameters, five metals were labelled 'critical', namely: tellurium, indium, gallium, neodymium and dysprosium. The potential supply chain constraints for these materials were most applicable to the deployment of wind and PV energy technologies.

In the follow-up study reported here, other energy and low-carbon technologies are investigated that not only play an important role in the EU's path towards decarbonisation but also may compete for the same metals as identified in the six SET-Plan technologies. Eleven technologies are analysed including fuel cells, electricity storage, electric vehicles and lighting. As in the first report, sixty metals, i.e. metallic elements, metallic minerals and metalloids are considered; only iron, aluminium and radioactive elements (used as fuel in nuclear plants) were specifically excluded. Graphite was also included, reflecting its status as one of the critical raw materials identified by the EU Raw Materials Initiative. Where possible, the study models the implications for materials demand as a result of the scenarios described in the EU Energy Roadmap 2050. Consequently, the results obtained in the first study are updated to reflect the data that has become available in the roadmap.

This second study found that eight metals have a high criticality rating and are therefore classified as 'critical'. These are the six rare earth elements (dysprosium, europium, terbium, yttrium, praseodymium and neodymium), and the two metals gallium and tellurium. Four metals (graphite, rhenium, indium and platinum) are found to have a medium-to-high rating and are classified as 'near critical', suggesting that the market conditions for these metals should be monitored in case the markets for these metals deteriorate thereby increasing the risk of supply chain bottlenecks. The applications, i.e. technologies, of particular concern are electric vehicles, wind and solar energy, and lighting. As in the first report, ways of mitigating the supply-chain risks for the critical metals are considered. These fall into three categories: increasing primary supply, reuse/recycling and substitution.

In addition, a number of topics were identified as possibly meriting further research, but could not be considered within the immediate scope of this study. These include conducting further studies to look at raw materials requirements for hybrid and electric vehicles for a wider range of technology uptake and penetration scenarios; developing new and more detailed scenarios for the uptake and technology mix of options for stationary energy storage; undertaking similar studies in defence and aerospace; improving statistics on the contribution of recycling to world production for a number of metals; and investigating the contribution of greater traceability and transparency to reducing raw materials supply risk.

Finally, it is important not to overstate the bottlenecks due to the risks of raw material shortages for key technologies. This is because there are still many years before the large uptake of some technologies and in the coming years, there are numerous options that will become available to mitigate the identified risks.

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# Glossary

| | |
|---|---|
| A-USC | advanced ultra-supercritical (power gen) |
| AA-CAES | advanced adiabatic CAES |
| AC-DC | alternating current – direct current |
| AFC | acid fuel cells |
| ANL | Argonne National Laboratory |
| BAT | Best available technology |
| BEV | battery electric vehicles |
| CAES | compressed air energy storage |
| CCFL | cold-cathode fluorescent lamp |
| CCGT | combined cycle gas turbines |
| CCS | carbon capture and storage |
| CFB | circulating fluidised bed combustion |
| CFL | compact fluorescent lighting |
| CHP | combined heat and power |
| DC | direct current |
| DD | direct drive |
| DMFC | direct methanol fuel cells |
| DZR | dezincification brass |
| e | equivalent |
| EGS | enhanced geothermal systems |
| EPD | Environmental Product Declaration |
| EV | electric vehicles |
| FCV | fuel cell vehicle |
| HEV | hybrid electric vehicles |
| HTSC | High temperature superconductors |
| HTTS | high temperature thermal storage |
| ICE | internal combustion engine |
| ICT | information and computer technology |
| IEA | International Energy Agency |
| IGCC | integrated gasification combined cycle |
| LCA | life cycle assessment |
| LCD | liquid crystal display |
| LCE | lithium carbonate equivalent |
| LCO | lithium cobalt oxide (battery) |
| LED | light emitting diode |
| LFL | linear fluorescent lighting |
| LFP | lithium iron phosphate (battery) |
| LMS | lithium manganese spinel (battery) |
| LTSC | low temperature superconductors |
| MCFC | molten carbonate fuel cells |
| MED | multi-effect distillation |
| MIGD | million imperial gallons per day |
| MSF | multi-stage flash (distillation) |
| NCA | nickel cobalt aluminium (battery) |
| NCM | nickel cobalt manganese (battery) |
| NEW-IG EU | New Energy World Industrial Grouping in conjunction with the EU |
| NiCd | nickel-cadmium (battery) |
| NiMH | nickel-metal hydride (battery) |
| OTEC | ocean thermal energy conversion |
| OWC | oscillating water column |
| PAFC | phosphoric acid fuel cells |
| PCC | pulverised coal combustion |
| PCM | phase change material |
| PEM | proton exchange membrane |
| PEMFC | polymer electrolyte membrane fuel cells |
| PHES | pumped hydro energy storage |
| PHEV | plug-in hybrid electric vehicles |
| R&D | research and development |
| RD&D | R&D and demonstration |
| RO | reverse osmosis |
| ROR | run-of-the-river |
| SHS | sensible heat storage |
| SMES | superconducting magnetic energy storage |
| SOFC | solid oxide fuel cells |
| STDA | Selenium Tellurium Development Association |
| TES | thermal energy storage |
| toe | tonnes of oil equivalent |
| ULCO | ultra-low $CO_2$ |
| USC | ultra-supercritical (power generation) |
| USGS | United States Geological Survey |
| V system | vanadium system |
| VCD | vapour compression distillation |

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

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# Executive Summary

In order to tackle climate change, to increase energy supply security and to foster the sustainability and competitiveness of the European economy, the European Union (EU) has made the transition to a low-carbon economy a central policy priority. The EU is committed to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050. The European Commission analysed the path towards the 2050 targets and their implications within its EU Energy Roadmap 2050.

## Study Aims

This report presents the results of a study with the aim to identify the metals which could become a bottleneck to the supply-chain of various low-carbon energy technologies. It builds on the existing research conducted by the European Commission's JRC in 2011 (Critical Metals in Strategic Energy Technologies). Where possible, this current study models the implications for materials demand as a result of the scenarios described in the EU Energy Roadmap 2050. The study considers 17 technologies, including fuel cells, electricity storage, electric vehicles and lighting, and the re-addressed six technologies analysed in the first study.

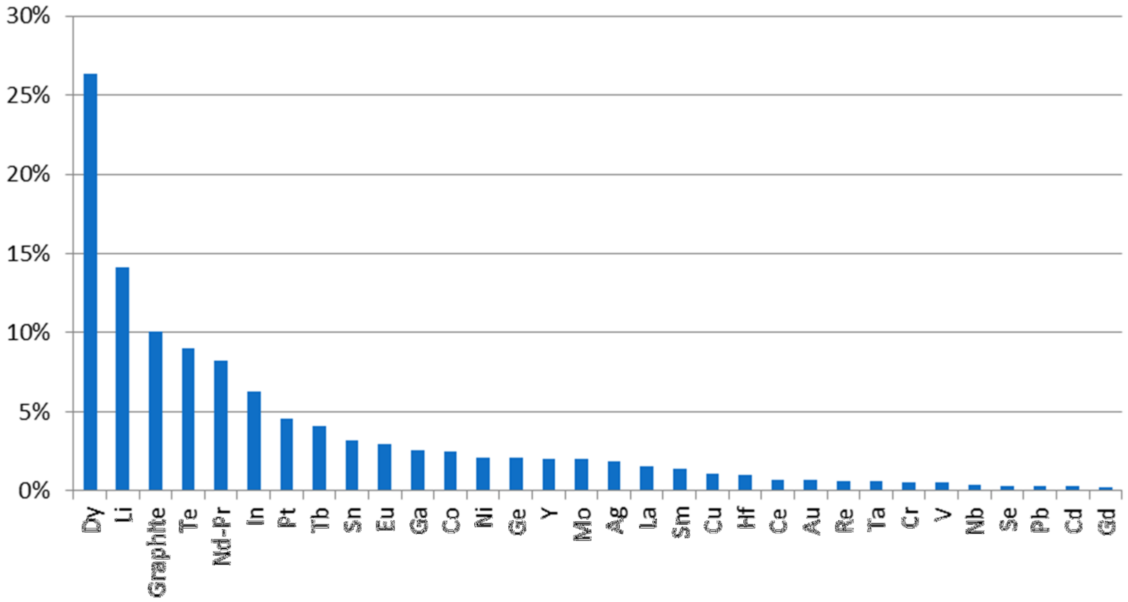
## Methodology

This study uses a bottom-up approach, compiling an inventory of all metals used in each technology. For each technology, an appropriate functional unit (e.g. kg/MW) has been used along with forecasts of demand. Sixty metallic elements, metallic minerals and metalloids were considered; only iron, aluminium and radioactive elements (used as fuel in nuclear plants) were specifically excluded. Graphite was also included, reflecting its status as one of the critical raw materials identified by the EU Raw Materials Initiative. The materials in greatest demand were identified and their uses analysed in depth.

## Results

The results of the metals demand in the EU for the 32 most significant materials, as a percentage of the average supply over the decade 2020-2030, are shown in Figure 1. Dysprosium was identified as being the most ‘at risk’, with the EU requiring over 25% of expected world supply to meet EU demand for hybrid and electric vehicles and wind turbines. Other materials of significance and their associated key technology include: (for hybrid and electric vehicles) lithium, graphite, neodymium, praseodymium and cobalt; (for solar energy) tellurium, indium, tin and gallium; (for fuel cells) platinum; (for lighting) indium, terbium, europium and gallium; (for wind) neodymium and praseodymium; and (for nuclear) indium.

*Figure 1: EU metals demand for energy technologies, as % of average supply 2020-2030*



To assess their criticality further, the 32 materials were analysed according to a combination of market and geopolitical factors, resulting in a reduced list of metals (see Table 1).

Eight metals were given a high criticality rating and therefore classified as 'critical'. These include six rare earth elements (dysprosium, europium, terbium, yttrium, praseodymium and neodymium), as well as gallium and tellurium.

Six materials were given a high-medium rating and classified as 'near critical'. It is suggested the market conditions for graphite, rhenium, hafnium, germanium, platinum and indium are monitored in case these metals markets deteriorate with the effect of posing supply chain bottleneck risks.

*Table 1: Criticality ratings of shortlisted raw materials*

| High | High-Medium | Medium | Medium-Low | Low |
|---|---|---|---|---|
| REE: Dy, Eu, Tb, Y | Graphite | REE: La, Ce, Sm, Gd | Lithium | Nickel |
| REE: Pr, Nd | Rhenium | Cobalt | Molybdenum | Lead |
| Gallium | Hafnium | Tantalum | Selenium | Gold |
| Tellurium | Germanium | Niobium | Silver | Cadmium |
|  | Platinum | Vanadium |  | Copper |
|  | Indium | Tin |  |  |
|  |  | Chromium |  |  |

## Uncertainties and Sensitivity

The above ratings should be regarded as an illustration of the possible supply-chain bottlenecks that could occur under business-as-usual conditions as they are subject to the following uncertainties:

- the demand for low-carbon technologies
- the technology mix between competing sub-technologies
- the materials composition and associated quantities of some components
- the substitutability of key materials in certain technologies
- the projected supply of various metals to 2020 and 2030.

The sensitivity to these sources of uncertainty was investigated in depth for hybrid and electric vehicles and lighting. For hybrid and electric vehicles, this highlighted the sensitivity of the results to widely different demand forecasts. The technology mix between permanent magnet motors and induction systems was also found to be a key sensitivity, as to some extent was the choice of battery chemistry. For lighting, a key sensitivity was found to be the timing and penetration of LED lighting versus phosphor lighting.

## Risk Mitigation

The study considered ways of mitigating the supply-chain risks for the critical metals. These fell into three categories: increasing primary supply, reuse/recycling and substitution, although continued innovation underlies many of these risk mitigation strategies:

- Increasing primary supply: The development of rare earth mines within Europe is in its early stages. The Norra Kärr deposit in Sweden is relatively attractive given its high proportion of heavy rare earths. An alternative option in the short term is to process rare earth concentrates from tailings, by-product sources or from mines opened outside Europe. For gallium and tellurium, the data indicate that Europe already has a degree of self-sufficiency; however, opportunities may exist to create further refineries to boost recovery of these materials.
- Reuse/ recycling and waste reduction: Significant improvements have already been made in the recycling of post-industrial waste streams such as magnet, semi-conductor and photovoltaic scrap. Recycling post-consumer waste streams is more challenging due to issues with collecting, sorting and pre-processing and the long lifetimes of certain product groups. Nevertheless, there

are short term opportunities and initiatives for the recovery of rare earth magnets from hard disc drives and rare earth phosphors from lighting.
- Substitution: The increased price of these materials has resulted in significant reduction in materials intensity for some applications, such as the reduction of dysprosium and neodymium in rare earth magnets, of terbium and europium within rare earth phosphors and the minimisation of the thickness of tellurium within thin film solar panels. Systemic approaches to materials substitution are also being widely considered including alternative motors technologies e.g. asynchronous or switch reluctance; and alternative lighting technologies e.g. LEDs, OLEDs and quantum dots. There are also opportunities to substitute the current use of critical materials from traditional applications where other materials are suitable e.g. eliminate tellurium from steel alloys.

## Possible further research

A number of topics were identified as possibly meriting further research, but could not be considered within the immediate scope of this study. These include:

- A meta-study of the raw materials requirements for hybrid and electric vehicles considering a wider range of technology uptake and penetration scenarios than was not possible within this project.
- The implications of missing or exceeding targets for the uptake of low carbon technologies.
- Research into the implications for raw materials of continued improvements of internal combustion engines, including advanced lead acid batteries and catalytic convertors.
- Development of new and more detailed scenarios for the uptake and technology mix of options for stationary energy storage in particular.
- Similar studies could be undertaken for other sectors such as defence and aerospace.
- An investigation into the location of production of the energy technologies and the stage of the value chain conducted within Europe.
- Improving statistics on the contribution of recycling to world production for a number of metals.
- An assessment of the appropriate scale and location of recycling technologies.
- The purity of the raw materials required for different decarbonisation technologies.
- Contribution of greater traceability and transparency to reducing raw materials supply risk.

## Recommended actions

To conclude, there are numerous risk mitigation strategies available, but ultimately a combination of actions is required by both governments and businesses. Table 2 summarises a list of possible policy actions to mitigate raw materials risk. It is noted that some of these are already underway.

However, it is important not to overstate the risks of raw materials bottlenecks for key technologies. This is because there are still many years before the large uptake of some technologies and there are numerous options available to mitigate the risks identified.

*Table 2: Possible policy actions to mitigate raw materials risks for the EU path to decarbonisation*

| **Type** | **Recommended action** |
|---|---|
| Data collection & dissemination | • Collect better data on the production, use, trade and prices of minor metals including gallium and other by-product metals<br>• Conduct research on product, material flows in the economy, and supply chains such as for the aerospace and defence sectors |
| | • Publish regular studies on supply, demand, prices and outlook for critical metals for materials designated as being critical or near critical for EU decarbonisation<br>• Conduct further research on the contribution of recycling to world metal production |
| | • Improve the traceability and transparency of raw materials supply chains<br>• Disseminate information on material risks and mitigation solutions to SMEs |
| Primary production | • Encourage the development of new mines and refineries in Europe, in particular for heavy rare earth elements, tellurium and gallium<br>• Build greater public acceptance of mining and refining, including the enforcement of appropriate environmental and social standards |
| | • Support RD&D to lower the environmental impact of mining and refining<br>• Raise awareness of valuable by-product metals in mining/refining waste streams, among major mining companies in particular |
| | • Improve geological mapping for critical metals, including revisiting the geological potential of old mines and refineries, urban mines and spoils |
| Resource efficiency | • Investigate recycling potentials for post-industrial waste streams, including improving resource management control procedures within companies<br>• Improve collection rates of WEEE and other end-of-life products in order to indirectly increase the availability of scrap in supply chains |
| | • Develop new mechanical pre-processing techniques for WEEE to effectively dismantle end-of-life products and to minimise/capture fines for recycling<br>• Promote the benefits of reuse and remanufacturing at a EU policy and company level such as by supporting the uptake and certification of reuse standards |
| | • Increase the product lifetimes of key products and components including wind turbines, engineering components and solar photovoltaic |
| Design & innovation | • Promote eco-design practices to better allow disassembly, recycling and reuse<br>• Support RD&D for the development of recycling technologies for CRMs in WEEE, including pre-processing and metallurgical recover techniques |
| | • Continue RD&D for substitution of supply constrained materials such as for heavy rare earths within magnets and lighting phosphors or tellurium within steel alloys<br>• Support research in technologies such as nanotechnologies, with the potential to reduce materials requirements of key technologies such as photovoltaic solar |
| International co-operation | • Continue to collaborate internationally to exchange knowledge<br>• Consider the formation of additional International Metals Study Groups |
| Stockpiling & procurement | • Consider long-term incentives and risk in procurement decisions<br>• Explore possibilities to secure materials supply chain |

# 1 Introduction

## 1.1 Background

In order to tackle climate change, to increase energy supply security and to foster the sustainability and competitiveness of the European economy, the EU has made the transition to a low-carbon economy a central policy priority. To ensure this, the EU created the Strategic Energy Technology Plan (SET-Plan) with the aim to accelerate the development of low-carbon energy technologies throughout the EU in support of their subsequent large-scale deployment by 2020 (European Commission (EC), 2007a; EC, 2007b). The SET-Plan prioritised six technologies: nuclear fission, solar photovoltaics (PV) and concentrated solar power (CSP), wind, bioenergy, carbon capture and storage (CCS) and the electricity grids. The EU also committed itself to reducing greenhouse gas emissions to 80-95% below 1990 levels by 2050. The Commission has since analysed the pathway towards the 2050 targets and their implications within its EU Energy Roadmap 2050 (EC, 2011a; EC, 2011b).

The Roadmap looks at a number of scenarios which explore different routes towards decarbonisation of the energy system, all of which imply major changes such as in fossil fuel prices, energy technologies and electricity networks. A number of scenarios to achieve an 80% reduction in greenhouse gas emissions (implying some 85% decline of energy-related $CO_2$ emissions including from transport) provide illustrative long-term projections. The Roadmap scenarios highlight the following ten structural implications for the transformation of the EU energy system (EC, 2011b):

1. Decarbonisation is possible – and can be less costly than current policies in the long-run.
2. Higher capital expenditure and lower fuel costs are expected.
3. Electricity will play an increasing role in meeting final energy demand.
4. Electricity prices are forecast to rise until 2030 and then decline.
5. Household expenditure on energy and energy-related products will increase.
6. Energy savings throughout the system are crucial.
7. The share of renewables within the energy mix rises substantially.
8. Carbon capture and storage has to play a pivotal role in system transformation.
9. Nuclear energy provides an important contribution.
10. Decentralisation and centralised systems increasingly interact.

To realise the milestones on emission reductions given in the Roadmap, the implementation of the SET-Plan, as outlined above, is of crucial importance. To support the development and implementation of the SET-Plan, a dedicated information system - the Strategic Energy Technologies Information System (SETIS) - was established. SETIS provides a central role in the successful implementation of the SET-Plan by helping to identify energy technology and RD&D objectives, striving to build consensus around the SET-Plan programme, identifying new opportunities and assessing the effectiveness and efficiency of the SET-Plan in delivering energy and climate change policy goals. SETIS is managed and operated by the JRC.

As part of the SETIS activities, JRC/SETIS conducted a study in 2010/11 to investigate the potential role that material supply chains could play in hindering the large-scale deployment of low-carbon technologies addressed within SET-Plan, namely: wind, solar (both PV and CSP), CCS, nuclear fission, bioenergy and the electricity grid (Moss et al., 2011). It identified 14 metals as being a cause for concern with respect to EU SET-Plan needs as a percentage of world supply. Five metals were labelled ‘critical’ after taking into account market and geopolitical parameters: tellurium, indium, gallium, neodymium and dysprosium. The potential supply chain constraints for these materials were most applicable to the deployment of wind and solar (PV) energy technologies.

Two years prior to the first JRC study, the EU Raw Materials Initiative (EC, 2008a) was set-up due to similar concerns on materials shortages that would affect the EU economy in general. An ad hoc Working

Group analysed the economic importance and potential supply risk of various raw materials (EC, 2010a) and identified the following materials to be critical: antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals (PGMs), rare earth elements (REEs), tantalum and tungsten (EC, 2010a). The study also highlighted that the following technologies could be affected: electricity storage (Li-ion batteries), synthetic fuels, solar photovoltaics, fibre optics, displays (TV, monitors), fuel cells, catalysts, permanent magnets, laser technology, micro-capacitors and medical technology.

Likewise, US Department of Energy studies (Bauer et al, 2010 and 2011) - which addressed similarly related issues on the deployment of wind turbines, electrical vehicles, solar cells and energy-efficient lighting - identified the following 14 elements as being ‘critical’: nine rare earth elements (yttrium, lanthanum, cerium, praseodymium, neodymium, samarium, europium, terbium and dysprosium) and indium, gallium, tellurium, cobalt and lithium. Studies elsewhere have identified potential supply-chain risks to catalytic convertors, polishing media, glass additives, etc. There is therefore evidently a worldwide concern about materials supply for a wide spectrum of hi-tech technologies.

## 1.2 Scope and approach

This study builds on the first JRC study and aims to identify the metals, which could be a potential supply-chain bottleneck to other low-carbon energy technologies, as well as other selected critical technologies, for the European economy. It therefore models, where possible, the scenarios of the EU Energy Roadmap 2050 in order to provide an assessment of the risks of supply chain bottlenecks in the pathway to the decarbonisation of the EU energy sector.

This study considers an additional eleven technologies, including fuel cells, electricity storage, electric vehicles, lighting, technologies that improve energy efficiency in industry and buildings and other technologies that may be competing for the same resources. The results from the first JRC study (Moss et al., 2011; Moss et al., 2013) are taken into account and updated to reflect the data that has become available in the Energy Roadmap.

The methodology that has been used for the study is based on a bottom-up approach, i.e. first compiling an inventory of all metals used in each technology, followed by an analysis to identify which metals appear significant (e.g. using criteria based on supply and demand, thereby eliminating ‘safe’ materials from the analysis). For each technology an appropriate functional unit (e.g. kg/MW) has been used to quantify the requirements alongside projections of technology uptake.

The widest selection of metals has been included, encompassing metallic elements, metallic minerals and metalloids. In total, the usage of sixty different elements was considered, with only iron, aluminium and radioactive elements (used as fuel in nuclear plants) specifically excluded. The usage of graphite was also considered, given its identification as a critical raw material (EC, 2010a). More in-depth analyses of the significant metals are presented, including criticality arguments based on market and geopolitical factors. More detailed descriptions of the critical metals are supplied in Appendix 6, which includes relevant background information on sources, supply chain, suppliers, applications (end-users), market price and future availability.

The study complements other relevant analytical work being undertaken at the level of the European Commission (e.g. on stockpiling, material flow analysis, work on analysis of critical raw materials) and provides a useful input which can help the Commission in its implementation and further development of its related policies.

## 1.3 Structure of the report

The structure of the report is the following:

- Chapter 2 introduces each of the low-carbon technologies to be analysed.
- Chapter 3 outlines the calculations for the materials composition of each technology.
- Chapter 4 presents the quantification of the metal requirements. These results are screened by expected supply to identify the list of significant metals, and includes how the results can be influenced by different uptake and technology mix scenarios cited by different sources, in particular the electric vehicle and lighting sectors are analysed.
- Chapter 5 evaluates the market and geopolitical risks associated with the list of significant metals. A further reduced list of metals is identified, with these metals designated as ‘critical’.
- Chapter 6 considers the mitigation strategies available to alleviate potential bottlenecks, including primary production, reuse, recycling and waste management and substitution.
- Chapter 7 provides the report’s conclusions and recommendations.

There are six Appendices. Appendix 1 provides detailed information on each technology that is analysed in the report. The remaining five Appendices provide useful background material for the study:

- Appendix 1: Technology Descriptions
- Appendix 2: Data on the current worldwide use of each metal
- Appendix 3: A graphical illustration of long-term metal production trends
- Appendix 4: Statistics on recycled metals production
- Appendix 5: Political risk ratings for different countries
- Appendix 6: Summaries of each of the critical metals

# 2 Technology Descriptions

The descriptions of all the technologies (apart from road transport efficiency and desalination) are taken primarily from the JRC's 2011 Technology Map (EC, 2011c), which provides a concise and authoritative assessment of the state of the art of each technology, their current and estimated future market penetration and the barriers to their large-scale deployment, as well as the on-going and planned R&D and demonstration efforts to overcome technological barriers. These technological descriptions are supplemented by other sources where appropriate.

Where possible, this current study assesses materials demand as a result of the scenarios described in the EU Energy Roadmap 2050. The study considers 17 technologies, including fuel cells, electricity storage, electric vehicles and lighting (as listed in Table 3), and re-addresses the six technologies analysed in the first study (see Table 4).

Desalination has been included as it is potentially an important technology for the global supply of fresh water. Furthermore, it is important to consider other technologies competing for the same resources, such as in the electronics and information and computer technology (electronics/ICT) sector, so that the relative criticality of a particular metal may be accurately assessed. For example, rare earth magnets are used in wind turbines, but their largest application is in hard disc drives. These technologies are considered within the sector study in Section 4.4. More detailed information on the technology descriptions, where appropriate, is given in Appendix 1.

Table 3: The additional eleven technologies analysed in this second study

| No. | Key decarbonisation technology |
|---|---|
| 1 | Hydropower |
| 2 | Geothermal energy |
| 3 | Marine energy |
| 4 | Co-generation or combined heat and power |
| 5 | Advanced fossil fuel power generation |
| 6 | Fuel cells and hydrogen |
| 7 | Electricity storage in the power sector |
| 8 | Energy intensive industries |
| 9 | Energy efficiency in buildings |
| 10 | Road transport efficiency* |
| 11 | Desalination* |

*Source: EC, 2011c*

**Road Transport Efficiency and desalination were not included in the 2011 Technology Map*

Table 4: The six SET-Plan technologies analysed in the first JRC study

| No. | SET-Plan technology |
|---|---|
| 1 | Nuclear Energy (fission) |
| 2 | Solar energy (PV and CSP) |
| 3 | Wind energy |
| 4 | Bioenergy (including biofuels) |
| 5 | CCS |
| 6 | Electricity (smart) grids |

*Source: EC, 2011c and Moss et al, 2011*

# 3 Materials Composition of the Technologies

## 3.1 Introduction

This chapter outlines the calculations that have been made to estimate the materials composition of each technology. It provides details of the assumptions and references that have been used to quantify the materials requirements in each technology. For example, it provides information on the types of alloys used, their composition and the amounts that are needed per technology.

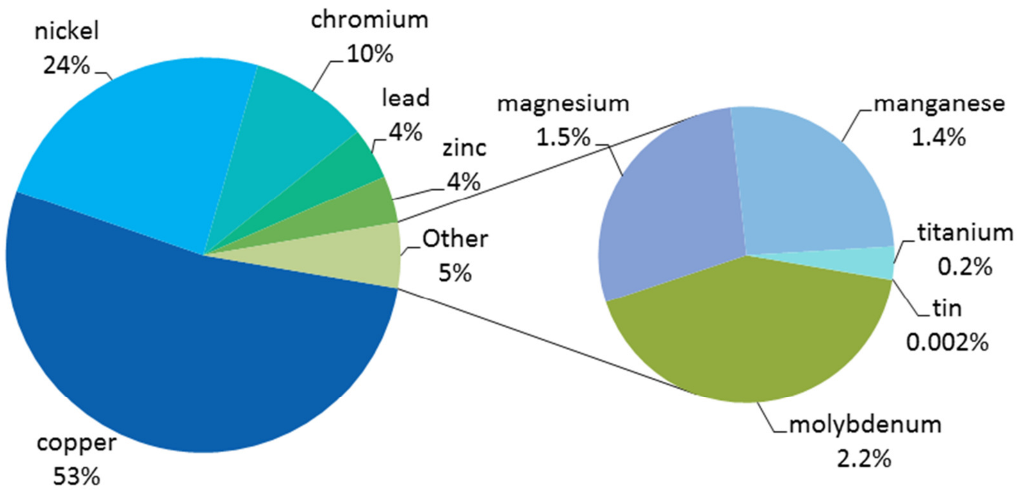
The methodology used is a bottom-up approach, first compiling an inventory of all metals used in each technology using an appropriate functional unit, such as kg/MW. In Chapter 4, the metals demand is determined by scaling up according to the projected uptake of the technology under various scenarios. These results are presented alongside the expected supply figures.

The widest selection of metals has been included, where metals refers throughout the report to metallic elements, metallic minerals and metalloids. In total the usage of sixty different elements was considered, with only iron, aluminium and radioactive elements (used as fuel in nuclear power plants) specifically excluded. Graphite was also included, reflecting its status as one of the critical raw materials identified by the EU Raw Materials Initiative (EC, 2010a).

## 3.2 Hydropower

Three different sources of data were used to assess different types of hydropower. First, data for materials was obtained from an Environmental Product Declaration (EPD) of 14 Nordic hydropower plants owned by Vattenfall power company (Vattenfall AB, 2011). These include hydropower plants ranging in output from less than 5 MW to 590 MW. This life cycle assessment (LCA) provided information on the mass and percentage of materials used per MWh for a single year (see Figure 2). The number of hours used in this calculation was inferred by determining the total power capacity of the 14 hydropower stations, information for which can be found on the individual websites of each hydropower station. Knowing that the average total hydropower per year produced by Vattenfall’s hydroplants is 30.9 TWh, and that this LCA examined 31% of this electricity, it was possible to determine estimates for the mass per unit of power for each material required.

*Figure 2: Use of metals for 14 Vattenfall hydropower stations (excludes steel and aluminium)*



*Source: Vattenfall AB, 2011*

Second, an Environmental Product Declaration (EPD) for Wildegg-Brugg (Axpo Hydro Energy, 2009) run-of-the-river power plant in Switzerland was examined. This plant has a total power output of 50 MW and an average annual generation of 300 GWh. The EPD provides data regarding the mass of a given material needed per MWh (Table 5), which in combination with the power output and annual generation values can be used to estimate the mass of materials required per unit of installed capacity.

For small scale hydropower, an EPD for Au-Schönenberg (Au-Schönenberg hydro power plant, undated) hydropower plant, also in Switzerland, was used. This hydropower plant produces 2.1 MW of power and has an average annual electricity production of around 5.6 GWh. The EPD provided data on the mass of material required per MWh (Table 6). The procedure employed for obtaining the mass of materials per unit of power was similar to those outlined above.

*Table 5: Materials used at the run-of-the-river hydro-power plant at Wildegg-Brugg (Switzerland)*

| Element | g per average net MWh |
|---|---|
| Nickel | 18 |
| Chromium | 4.15 |
| Baryte | 1.23 |
| Copper | 4.76 |
| Magnesite | 5.94 |
| Zinc | 0.117 |
| Zirconium | 0.000,001,9 |

*Source: Axpo Hydro Energy, 2009*

*Table 6: Materials used at the small-scale hydro-power plant at Au-Schönenberg (Switzerland)*

| Element | g per average net MWh |
|---|---|
| Nickel | 34.5 |
| Chromium | 12.8 |
| Baryte | 0.202 |
| Copper | 3.02 |
| Magnesite | 10.4 |
| Zinc | 0.311 |
| Zirconium | 0.000,011 |

*Source: Au-Schönenberg hydro power plant, undated*

Taking into account the above descriptions, the metals requirements for hydropower, are based on the following figures (kg/MW).

*Table 7: Hydropower metals requirements*

| Elements | Materials demand (kg/MW) | Elements | Materials demand (kg/MW) |
|---|---|---|---|
| Ni | 31.0 | Zn | 5 |
| Mo | 2.9 | Mn | 1.7 |
| Cu | 67 | Ti | 0.24 |
| Mg | 1.92 | Sn | 0.003,08 |
| Cr | 12.5 | Zr | 0.000,013 |
| Pb | 5.36 | | |

## 3.3 Geothermal energy

The alloys that are used in well piping contain some of the metals that are of interest to this study, including chromium, molybdenum, nickel and copper. These metals are principally used in alloys for well pipes that must be able to operate under conditions of high temperatures (up to 500°C), high acidity (pH=1), high salinity and gas content ($CO_2$, $H_2S$, $CH_4$).

The data for the materials required for geothermal systems was obtained from an LCA published by Argonne National Laboratory (ANL), (Argonne National Laboratory, 2010). Additional information obtained from Butting[1] regarding typical pipes used in geothermal plant was used in conjunction with the ANL data to infer other possible material usage. In total six types of steel or other alloys were examined

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[1] Conversation with Sylvia Muller, Butting (Sales and marketing), July 2012

for three different geothermal systems. The percentages of constituent elements in these materials are given in Table 8.

*Table 8: Composition of key steel or other alloys used in geothermal plants, % (balance is iron)*

| Steel or other alloy | Ti | Mn | Nb | V | Cr | Cu | Mo | Ni | Co and Ta |
|---|---|---|---|---|---|---|---|---|---|
| K-55 | - | 1.5 | - | - | 0.15 | 0.2 | - | 0.2 | - |
| X-56 | 0.09 | 1.4 | 0.05 | 0.05 | - | - | - | - | - |
| T-95 | - | 0.25 | - | 0.08 | 0.4 | 0.4 | 0.15 | 0.4 | - |
| 316L | - | 2 | - | - | 18.5 | - | 2.5 | 15 | - |
| 625 | 0.4 | - | - | - | 23 | - | - | 58 | 4.15 |
| 825 | 1.2 | 1 | - | - | 23.5 | 3 | 3.5 | 46 | - |

*Source: Industry websites*

For enhanced geothermal systems (EGS), the analysis assumes a medium-sized plant producing 50 MW with 25 wells, each with a depth of 5 km. For binary cycle plants, the analysis assumes a power output of 10 MW with 5 wells, each 1.5 km deep. For the flash steam plant, a power output of 48.4 MW is assumed, with 22 wells, each 2.5 km deep (Argonne National Laboratory, 2010).

Taking into account the above descriptions, the metals requirements for geothermal energy, are based on the following figures (kg/MW):

*Table 9: Geothermal metals requirements*

| Elements | Materials demand (kg/MW) | Elements | Materials demand (kg/MW) |
|---|---|---|---|
| Ta | 64.0 | Nb | 128 |
| Ni | 120,155 | Ti | 1,634 |
| Mo | 7,209 | Cu | 3,605 |
| Cr | 64,405 | Mn | 4,325 |

## 3.4 Marine energy

### 3.4.1 Tidal barrage and tidal current energy

Although the planned tidal power project at the Severn River estuary in the UK has been put on hold by the British government because of high costs, several analyses were made in advance including a life cycle assessment (LCA). As a result of the LCA, an overview was given showing the required quantities of materials for a tidal barrage power plant, with a planned capacity of 8,640 MW (216 turbines at 40 MW each (DECC, 2010) with an estimated energy output of 16.8 TWh annually. Huge quantities of materials are required for the construction of a tidal barrage. Concrete, consisting of coarse and fine aggregate as well as cement, and reinforcement bars account for the bulk of the material (Sustainable Development Commission, Black & Veatch, 2007; Kelly et al., 2012). Moreover, metallic raw materials are needed for turbines and embankments. In the LCA study of (Kelly et al., 2012), it is assumed that the turbines consist of about 10% copper and 90% steel.

*Table 10: Estimated quantities of metals for the turbines of the Severn Tidal Barrage (Kelly et al., 2012)*

| Element | Quantity (tonnes) | Tonnes per MW | Tonnes per MWh |
|---|---|---|---|
| Copper | 43,200 | 5 | 2.6 |
| Steel | 388,800 | 45 | 23.1 |

A more detailed listing of the turbine composition can be found in (DECC, 2010) where percentage shares are given for the relevant materials of a 40MW Alstom turbine, which was taken into consideration for the Severn tidal power plant.

The Seagen turbine is representative of maritime turbines which are driven by (tidal) currents. The device considered here has a capacity of 1.2 MW and weighs 465 tonnes. Similar materials requirements are expected for other turbines. Its main components are a tall tower with a platform on top (over the ocean's surface) and the crossbar carrying the turbines. For these three components, which represent 89% of the total mass, steel is the main material used. Therefore steel is the most important material under consideration (Douglas et al., 2008). Steel and other relevant materials are shown below.

*Table 11: Relative composition of a hydro turbine*

| Element | Percentage (mass) |
|---|---|
| Carbon Steel | 76 |
| Stainless Steel | 4 |
| Special Alloys | 4 |
| Silicon Steel | 11 |
| Copper | 5 |
| Insulation | 0 |
| Other | <1 |

*Source: DECC, 2010*

*Table 12: Materials for the Seagen turbine*

| Element | Quantity (tonnes) | Kilograms per MW |
|---|---|---|
| Steel | 412.9 | 344 |
| Stainless steel | 2.8 | 2.3 |
| Iron | 33.9 | 28.3 |
| Copper | 4.7 | 3.9 |
| Composites | 9.3 | 7.8 |
| Other | 1.4 | 1.2 |

*Source: Douglas et al., 2008*

### 3.4.2 Wave energy

The Wave Dragon is an example of a technology for harvesting energy from ocean waves. It is an overtopping device, which means that a reservoir above sea level is filled by waves and then the water is released back to sea level, driving a turbine on its way down (Soerensen et al., 2012). Raw materials inventory analyses were made for the Wave Dragon's generator and electrical transformer: the results are shown in the tables below (Soerensen and Naef, 2008). Another wave energy converter is the Pelamis wave power plant. For the prototype mostly steel was used, but it is assumed that in the future more specialized materials will be used, such as concrete or glass-reinforced plastic (Parker et al., 2007).

*Table 13: Materials for the generator of the Wave Dragon*

| Element | Quantity (kg) | kg/MW |
|---|---:|---:|
| Ferronickel, 25% Ni | 1,500 | 214 |
| Copper, at regional storage | 5,800 | 829 |
| Cast iron | 10,900 | 1,557 |
| Steel, electric, un- and low-alloyed | 10,000 | 1,429 |
| Polypropylene, granulate | 20 | 3 |
| Glass fibre | 280 | 40 |

*Source: Soerensen and Naef, 2008*

*Table 14: Materials for the electrical transformer of the Wave Dragon*

| Element | Quantity (kg) | kg/MW |
|---|---:|---:|
| Copper, at regional storage | 3,500 | 500 |
| Aluminium, production mix, at plant | 100 | 14 |
| Reinforcing steel, at plant | 9,000 | 1,286 |
| Synthetic rubber, at plant | 9,000 | 1,286 |
| Polypropylene, granulate, at plant | 400 | 57 |
| Silicone product, at plant | 6,800 | 971 |
| Steel, electric, un- and low-alloyed, at plant | 7,000 | 1,000 |

*Source: Soerensen and Naef, 2008*

### 3.4.3 Ocean thermal energy conversion

Ocean thermal energy conversion typically consists of two main components: the intake pipes in which the cold water is pumped up from the depth, and a heat exchanger for vaporising the working fluid. Currently the materials for the cold water pipes are the focus of research. In 2011 Lockheed Martin was developing a composite material with fibreglass as its main component (Millera et al., 2012). Therefore it is assumed that mineral raw materials are needed, mostly for the heat exchanger. Investigations regarding possible materials for OTEC heat exchangers began in the 1980s. As a result of this work, titanium became the material of choice due to its favourable corrosion properties, followed by stainless steel which has the advantage of being less expensive than titanium. Copper-nickel alloys are not suitable because they are susceptible to corrosion in an ammonia-rich environment. Aluminium alloys are of interest but the problem here is the shorter lifetime compared to stainless steel and titanium (Darby, 1984; Kapranos and Priestner, 1987). Quantitative data of the required materials in relation to the installed capacity are not available.

### 3.4.4 Osmotic power

According to (Skilhagen et al., 2007), osmotic power generating systems are very similar to conventional desalination plants (see Section 3.12).

### 3.4.5 Overall metals demand

Taking into account the above descriptions, the metals requirements for marine energy, are based on the following figures (kg/MW):

*Table 15: Marine energy metals requirements*

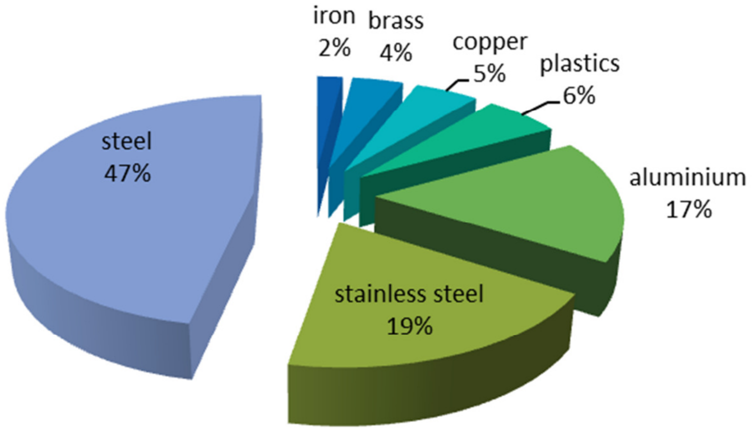
| Elements | Materials demand (kg/MW) |
|---|---|
| Cu | 5.00 |
| Mo | 0.05 |
| Ni | 0.22 |
| Cr | 0.31 |
| Ti | 0.01 |

## 3.5 Co-generation or combined heat and power (CHP)

Material requirements for district heating CHP and micro-CHP were obtained. The materials for district CHP were obtained from an academic paper examining the life cycle of a district CHP for 240 dwellings (Oliver-Solà et al., 2009). The combined heating and electric power was 0.84 MW, including a supplementary peak boiler unit, and the materials examined included the infrastructure for transporting hot water to the homes and heat exchangers installed in the homes.

The materials for the micro-CHP system were taken from a life cycle analysis of a micro-CHP system with a Stirling engine (Gazis and Harrison, 2011). This system has an output of 24 kW of heat and 1 kW of electricity, resulting in a total power output of 25 kW. The mass per unit power is calculated using this value. For components made of stainless steel, type 43 steel was employed as a typical material for the purposes of estimating quantities of elements. For the iron-neodymium magnets contained within this CHP a typical composition of $N_{32}Fe_{14}B$ was used. For the composition of the brass components, dezincification (DZR) brass was examined. The composition of the main materials for this system is illustrated in Figure 3.

*Figure 3: Materials composition of a micro-CHP system incorporating a Stirling engine*



*Source: Gazis and Harrison, 2011*

Other types of micro-CHP system are also available or are likely to become available in the near future. These include systems that use fuel cells, which are dealt with in a separate section. Materials requirements for CHP used in large-scale power plants proved difficult to obtain. Such systems require piping to carry away hot water to locations near the plant where it may be used for heating. Suitable piping does not require unusual alloys and is therefore unlikely to impact on supplies of critical metals.

Taking into account the above descriptions, the metals requirements for co-generation, are based on the following figures (kg/MW):

*Table 16: Cogeneration metals requirements*

| Elements | Materials demand (kg/MW) |
|---|---|
| Cu | 44,448 |
| Sn | 168 |
| Ni | 541 |
| Cr | 1,033 |
| Mn | 108 |
| Zn | 9.0 |
| Pb | 0.5 |

## 3.6 Advanced fossil fuel power generation

### 3.6.1 Materials required for ultra-supercritical (USC) and advanced ultra-supercritical (A-USC) coal power plants

The overall plant efficiency is influenced by the internal efficiency of the steam turbine more than any other component. In addition further net efficiency gains can be achieved by enhancing boiler efficiency and reducing auxiliary consumption. Consequently, the focus here will be on materials for turbines, boilers and pipes which allow for higher steam temperatures hence increasing energy efficiency.

***Materials for boilers and pipework***

The materials used for boilers and pipework are dependent on the conditions employed. In general, steam conditions of up to 610°C are achieved using steels with around 12% chromium content. By using coatings on Ni-chrome steel it is possible to push the steam conditions up to around 640°C. The materials requirements for different steam conditions are summarised in Table 13.

In order to achieve advanced ultra-supercritical steam conditions, furnaces, pipework and other components which come in contact with high temperature steam will need to be built from high-performance materials such as nickel-based super alloys. Compared to the chromium steels which are currently used, nickel-based alloys are more expensive and more difficult to weld. The nickel materials required cost around 20 times more than those for the current state-of-the-art technology boilers. However, due to the increased efficiency the payback period is expected to be around 12 months. Over the past decade, a significant amount of research has been devoted to developing the necessary materials for advanced ultra-supercritical power plants. To date these materials have not been used in power plant applications, test plants are currently under construction in India and China. Commercial 700°C steam power plants are not expected to be in commercial operation in Europe until 2020.[2]

*Table 17: Materials for boilers, pipes, headers for different steam conditions*

| Steam conditions | Metal alloy | Commercial time frame |
|---|---|---|
| 600/620°C 25-30 MPa | NF616, T91, T92 | 2009-2017 |
| Up to 650°C | Austenite, Ni-chrome steels with coating | 2017-2020 |
| 700/720°C up to 35 MPa | Ni super alloys | 2020-2030 |

*Source: IEA, Clean Coal Centre, 2011*

There are currently around five nickel super-alloys under consideration for use in pipes and furnaces in 700°C steam power plants. They are: for thin sections, Inconel 740, Haynes 282 and Inconel 617; for thick sections, Inconel 740H and Nimonic 263. Most of these materials were developed for the aerospace industry, except for Inconel 740H which has been developed especially for the power generation industry. A typical 800 MWe power plant will require around 1,000 tonnes of Ni-based materials for the furnaces and piping alone. However, it is hoped that with improvements in design this figure will come down to around 500 tonnes.

*Table 18: Boiler materials for 700°C power plants (%)*

| | Nimonic 263 | Inconel 740H | Inconel 740 | Haynes 282 | Inconel 617 |
|---|---|---|---|---|---|
| Ni | 52 | 48 | 48 | 57 | 44.5 |
| Co | 20 | 20 | 20 | 10 | 12.5 |
| Cr | 20 | 25 | 25 | 20 | 22 |
| Mo | 6 | 0.5 | 0.5 | 8.5 | 9 |
| Mn | 0.6 | 0.3 | 0.3 | 0.3 | 1 |
| Ti | 2.4 | 1.35 | 1.8 | 2.1 | 0.6 |
| Al | 0.6 | 1.35 | 0.9 | 1.5 | 1.15 |
| Nb | | 1.5 | 2 | | |
| Cu | 0.2 | | | | |
| Fe | 0.7 | | 1.1 | | |

*Source: VGB PowerTech, 2005, Advances in Materials Technology for Fossil Power Plants,2010 for Inconel 740H*

To model the materials demands for pipes and furnaces in 700°C steam power plants, Inconel 740 and 740H have been used, as these are materials are the most promising. Inconel 617 was excluded because of problems experienced with this material during the Comtes 700 project.

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[2] Personal communication with Doosan Power Systems (August 2012)

*Table 19: Metals requirements for boilers and pipework for current best technology*

| | kg/MW |
|---|---|
| Ni | 2.5 |
| Cr | 111.25 |
| Mo | 5 |
| Mn | 6.25 |
| Fe | 1091.25 |
| W | 18.75 |
| Nb | 0.75 |
| V | 2.5 |

*Assumptions – T92 alloy is used*

*Table 20: Metals requirements for boilers and pipework for A-USC 700°C power plants*

| | kg/MW |
|---|---|
| Ni | 656.25 |
| Co | 187.50 |
| Cr | 281.25 |
| Mo | 56.25 |
| Mn | 3.75 |
| Ti | 21.56 |
| Nb | 9.38 |

*Assumptions – Inconel 740H used for thick sections and Inconel 740 used for thin sections*

### 3.6.2 Materials requirements for gas and steam turbines

Gas and steam turbines are complex pieces of machinery and accordingly have far from trivial materials requirements. A typical gas turbine contains over 1,000 precision cast parts, made from a range of different metal alloys, aluminium, titanium and ferritic and austenitic steels (Rolls Royce, 2008). It is expected that the technology for steam turbines for A-USC power plants can be adapted from gas turbines and compared to boilers and pipes fewer technological advances are required.

***Materials requirements for steam turbines for A-USC power plants***

A large steam turbine for a 700°C steam coal power plants will require around 100 tonnes of nickel super alloys. The composition of the alloy will depend on the specific component, and the different alloys used are 263, 617 and 625. The compositions of these alloys can be found in Table 21.[3] The metals requirements for steam turbines for A-USC power plants are shown in Table 22. It is assumed that equal amounts of all three Ni-alloys are used. Components of the turbine which do not require the use of Ni-alloys have not been considered.

***Materials requirements for gas turbine blades***

Due to the temperatures that turbine blades are exposed to, they have the most demanding materials requirements of any turbine component. Turbine blades are required to withstand very high centrifugal forces whilst operating at temperatures in excess of the melting point of the alloy. Consequently, research in this area has been focused on increasing temperature capabilities of the material used.

Ni-based super alloys are the predominant material for turbine blades of modern land-based gas turbines. These alloys are limited to metal temperatures of 900°C to 927°C: for higher energy efficiency materials with higher temperature capabilities are required. Turbine blades are exposed to high centrifugal stress and very high temperatures during service; this puts great demands on the materials required for the blades (Martinsson, 2006).

A step change in temperature capability was realised by the introduction of single crystal superalloys. Single crystal superalloys have been developed for use in aerospace applications and have been selected for development for industrial turbine applications. Rhenium is used in single crystal super alloys to stop them becoming micro-structurally unstable, thus improving creep strength and longevity. Single crystal superalloys contain 3 to 6% rhenium; however, it is anticipated that for industrial turbine applications a lower proportion of rhenium is favoured due to cost. The composition of the second generation single crystal used for gas turbine blades is presented in Table 23 (Bhangu and Ford, 2011). The metals requirements for turbine blades in the current best technology industrial gas turbines are presented in Table 24 (it is assumed that CMSX-4 alloy is used).

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[3] Personal communication with Skoda Power (August 2012)

*Table 21: Nickel superalloys used for steam turbines (%)*

| | Nimonic 263 | Inconel 617 | Haynes 625 |
|---|---|---|---|
| Ni | 52 | 44.5 | 59 |
| Co | 20 | 12.5 | 1 |
| Cr | 20 | 22 | 21 |
| Mo | 6 | 9 | 9 |
| Mn | 0.6 | 1 | 0.5 |
| Ti | 2.4 | 0.6 | 0.4 |
| Al | 0.6 | 1.15 | 0.4 |
| Nb | - | - | 2.5 |
| Ta | | | 1.2 |
| Cu | 0.2 | - | - |
| Fe | 0.7 | - | 5 |

*Nb+Ta is 3.7, it has been assumed that 1/3 of this is Ta and 2/3 is Nb*

*Table 22: Metals requirements for A-USC turbines*

| | kg/MW |
|---|---|
| Ni | 64.79 |
| Co | 13.96 |
| Cr | 26.25 |
| Mo | 10.00 |
| Mn | 0.88 |
| Ti | 1.42 |
| Al | 0.90 |
| Nb | 1.03 |
| Ta | 0.51 |
| Fe | 2.38 |

*Table 23: Composition of second generation single crystal nickel-based superalloys (%)*

| | CMSX 4 | PWA 1484 | Rene N5 |
|---|---|---|---|
| Ni | 61.7 | 59.3 | 61.6 |
| Co | 9.0 | 10.0 | 8.0 |
| Cr | 6.5 | 5.0 | 7.0 |
| Mo | 0.6 | 2.0 | 2.0 |
| Ti | 1.0 | | |
| W | 6.0 | 6.0 | 5.0 |
| Ta | 6.5 | 9.0 | 7.0 |
| Al | 5.6 | 5.6 | 6.2 |
| Re | 3.0 | 3.0 | 3.0 |
| Hf | 0.1 | 0.1 | 0.2 |

*Table 24: Metal requirements for gas turbine blades*

| | kg/MW |
|---|---|
| Ni | 0.617 |
| Co | 0.090 |
| Cr | 0.065 |
| Mo | 0.006 |
| Ti | 0.010 |
| W | 0.060 |
| Ta | 0.065 |
| Re | 0.030 |
| Hf | 0.001 |

*Assuming that a 200MW turbine requires 200kg of weld alloy for the blades*
*Source: Alstom Thermal Power, 2012*

To date, the single crystal nickel alloys used in industrial gas turbines have all been developed for aerospace applications. However, this does not necessarily make them suitable for industrial gas turbine applications, where the environment is often more corrosive due to the choice of fuels. These applications require alloy compositions with high levels of chromium to protect against corrosion. Alloys containing around 12-15% chromium have been developed and are expected to be used in turbine blades for industrial gas turbines in the future (Caron and Lavigne, 2011).

### 3.6.3 Gas fired power plants

For gas fired power plants, such as a Combined Cycle Gas Turbine (CCGT) plant and Integrated Gasification Combined Cycle (IGCC) plant, it is expected that the materials advances required for increased energy efficiency will be for gas turbines. LCA data has been used to determine the material compositions and requirements of a combined cycle gas power plant (Ataei et al., 2012). Nickel alloys are required for some of the gas turbine components due to the high temperatures which they are exposed to in this form of power generation. It is assumed that IGCC power plants have similar metals requirements to CCGT plants.

*Table 25: Metal inventory of a 400MW CCGT power plant*

| Metal | Amount (kg) | kg/MW |
|---|---|---|
| Aluminium | 440,000 | 1,100 |
| Copper | 440,000 | 1,100 |
| Chromium steel | 1,800,000 | 4,500 |
| Nickel | 6,300 | 15.75 |
| Chromium | 976 | 2.44 |
| Cobalt | 720 | 1.8 |

## 3.7 Fuel cells and hydrogen

Fuel cells that operate at low temperatures require catalysts to accelerate electrochemical processes, and the usual choice of catalyst is platinum. Other metals such as ruthenium may also be employed. High temperature fuel cells do not generally require platinum catalysts. Information regarding the constituent elements in fuel cells was found for solid oxide fuel cells (SOFCs), proton exchange membrane fuel cells (PEMFCs) and direct-methanol fuel cells (DMFCs).

***SOFCs***

SOFCs operate at high temperatures and therefore do not require noble metal catalysts such as platinum. The electrically active parts of SOFCs are mainly made of ceramics or of a mixture of ceramics and metals (a 'cermet'). The anode, for example, is typically made of a cermet which includes the elements nickel, oxygen and zirconium. The most common electrolyte is YSZ, which is made of yttrium, oxygen and zirconia ($Y_2O_3/Zr_2$) and the cathode is usually made of lanthanum, samarium, magnesium and oxygen (LSM) in the form $La_xSr_yMn0_3$. For SOFCs material usage was obtained from a Sixth Framework Programme project providing life cycle assessment (LCA) of fuel cells (NEEDS, 2008). The SOFCs analysed here were stationary systems consisting of a stack, a heat exchanger, an inverter, an air and fuel supply and a reformer and burner. For the purposes of our analysis only the materials in the stack were examined since the uses examined would not require the additional components. The data for SOFCs was presented in terms of the requirements in 2008 and the predicted requirements for 2025. To obtain values for 2020 material requirements, the mean of values for 2008 and 2025 were used: for 2030 the value for 2025 was employed.

This LCA includes only the main structural materials used to create the fuel cells, however, and does not supply information on the electrolytes or anodes. Further information was also obtained from a review of critical materials in SOFCs (J. Thijssen, LLC, 2011), which provided data such as the mass of material required per unit volume (Table 26). Using the combination of this data with the NEEDS project data, it was possible to estimate the mass required of a given material per MW (Table 29).

*Table 26: Metal content of electrically active components of SOFC*

| Element | Typical critical metal content for SOFC (mg/cm$^2$) |
|---|---|
| Lanthanum | 4 |
| Yttrium | 10 |
| Cerium | 1 |
| Gadolinium/samarium | <0.3 |
| Cobalt | 0.5 |

*Source: J. Thijssen, LLC, 2011*

***PEMFCs***

PEMFCs operate at low temperatures, and therefore require platinum as a catalyst on both the cathode and the anode. For PEMFCs the materials usage was obtained from the same NEEDS project referenced above, where the system examined included materials for the balance of plant and for a reformer. For the analysis here only the stack was examined. The materials usage includes chromium steel 18/8, for which 18% is chromium and 8% is nickel. The data for PEMFCs was presented in terms of the requirements in

2008 and the predicted requirements for 2025 (Table 27). To obtain values for 2020 material requirements the mean of values for 2008 and 2025 were used: for 2030 the value for 2025 was employed.

*Table 27: The chromium steel and platinum requirements for PEMFCs*

| Material | kg/kW (2008) | kg/kW (2025) |
|---|---|---|
| Chromium steel 18/8 plant | 0.1 | 0.02 |
| Platinum, at regional storage | 0.000,75 | 0.000,22 |

*Source: NEEDS, 2008*

***DMFCs***

For DMFCs the important materials for this analysis are those used as catalysts. Information regarding typical state-of-the-art loadings was obtained following discussion with an expert in this field, Martin Hogarth. Average values for the loading of platinum and ruthenium at the anode were estimated to be 2 mg/cm$^2$ and 1 mg/cm$^2$ respectively. At the cathode only platinum is used, the estimated loading of which was 1 mg/cm$^2$. Such a combination of loadings would provide around 90 mW/cm$^2$. From this data it is possible to calculate the mass required per unit of power for both platinum and ruthenium.

*Table 28: Typical loading of platinum and ruthenium of a DMFC*

| Element | Typical loading at cathode (mg/cm$^2$) | Typical loading at anode (mg/cm$^2$) |
|---|---|---|
| Platinum | 1 | 2 |
| Ruthenium | - | 1 |

*Source: Conversation with Martin Hogarth, fuel cells expert (July 2012)*

Taking into account the above descriptions, the metals requirements for co-generation, are based on the following figures (kg/MW):

*Table 29: Fuel cells and hydrogen metals requirements*

| Elements | Materials demand (kg/MW) | Elements | Materials demand (kg/MW) |
|---|---|---|---|
| Pt | 67.9 | La | 38.0 |
| Ru | 22.0 | Gd | 1.2 |
| Cr | 48,323.2 | Sm | 1.2 |
| Ni | 282.0 | Ce | 8.0 |
| Y | 8.4 | Co | 10.8 |

## 3.8 Electricity storage in the power sector

Different options for power storage are at different levels of technological maturity and face different constraints for their (more extensive) deployment. Moreover, energy storage is a costly option and the need for energy storage can be reduced through upgrades in the electricity networks, flexible generation, demand side management or curtailment of regenerative energy production. A recent publication (summarised in Table 67) compared the different technologies available on various terms (Evans et al., 2012). Due to the reliability requirements for grid applications, it is reasonable to expect that proven technologies are more likely to see the largest increase in deployment in the short- to mid-term. However, costs and technological maturity are not the only factors affecting deployment. For example, geographical constraints limit the use of pumped hydro storage and underground CAES, and large-scale underground hydrogen storage is tied to local geology (Genoese and Wietschel, 2011).

*Table 30: Key features of selected power storage technologies*

| | Capacity (MW) | Runtime | $/kW | $kWh | Maturity |
|---|---|---|---|---|---|
| Mechanical storage | | | | | |
| CAES underground | 5-400 | 1 to 24+ h | 800 | 50 | Commercial |
| CAES above ground | 50 | 2 to 4 h | 2,000 | 100 | Developed |
| Pumped hydro | 100-5,000 | 1 to 24+ h | 600 | 100 | Mature |
| Flywheels | 0.25 | ms to 15 m | 350 | 5,000 | Demonstration |
| Electrical storage | | | | | |
| Supercapacitors | 0.3 | ms to 60 m | 300 | 2000 | Developed |
| SMES | 0.1-10 | ms to 8 s | 300 | 10,000 | Developed |
| High-temperature thermal storage | | | | | |
| | 0-60 | 1 to 24+ h | | 60 | Developed |
| Chemical storage | | | | | |
| Lead-acid | 0-40 | s to h | 300 | 400 | Mature |
| Sodium-sulphur | 0.05-8 | s to h | 3,000 | 500 | Commercial |
| Nickel-cadmium | 0-40 | s to h | 1,500 | 1,500 | Commercial |
| Lithium-ion | 0.1 | m to h | 4,000 | 2,500 | Demonstration |
| Fuel cells | 0-50 | s to 24+ h | 10,000 | | Developing |

*Source: Evans et al., 2012*

## 3.8.1 Mechanical storage

In the different strategies for mechanical energy storage, electrical energy is converted into kinetic or potential energy and then back into electrical energy. This implies that the basic technology needed is essentially the same as conventional power generation technologies where electricity is obtained by means of a generator.

Pumped storage hydropower
Pumped storage hydropower has essentially the same raw materials requirements as hydropower stations (Oertel, 2008), including iron, nickel, copper, chromium and aluminium (Axpo Hydro Energy, 2012).

*Table 31: Specific metal requirements at the Löntsch storage plant*

| Element | g/MWh | kg/MW |
|---|---|---|
| Iron | 500 | 1000 |
| Nickel | 30 | 60 |
| Chromium | 10 | 20 |
| Aluminium | 10 | 20 |
| Copper | 30 | 60 |

*Notes: The Löntsch storage plant used a drop of 370 m to produce 60 MW of power.*
*The average yearly energy production amounts to 120 million kWh (120 GWh),*
*with an equivalent operation time at maximum load of 2000 hours.*
*Source: after Axpo Hydro Energy, 2012, rounded*

***Compressed air energy storage (CAES)***
Generating electricity from compressed air using current technology, involves driving a turbine with the compressed air together with the combustion products of natural gas. The burning of natural gas is necessary to prevent freezing. The temperature is close to 700°C (Oertel, 2008), which is lower than that in normal gas turbines – implying less stringent material requirements, as materials do not have to keep their properties at such high temperatures. In adiabatic facilities, where the heat of compression is stored

and used to compensate for the cooling during rapid expansion, the conditions that the turbine must withstand are milder.

*Table 32: Metal inventory of a CAES facility with 2 MW for 10 hours*

| Element | tonnes/MW | tonnes/MWh |
|---|---|---|
| Steel (includes construction) | 320 | 32 |
| Aluminium | 2.5 | 0.25 |
| Copper | 5 | 0.5 |

*Source: Klobasa et al., 2008, rounded; MWh for a single charge-discharge cycle.*

***Flywheels***

Flywheels themselves may be made out of steel, aluminium-manganese-magnesium alloys or titanium (low speed), or of glass or carbon fibre reinforced plastics (high speed). Table 33 shows an overview of key properties of these materials. Due to the combination of low material density and high tenacity yield, the higher energy density / light flywheels (e.g. out of carbon fibre reinforced plastic) rotating at high speeds are preferred over heavier and slower metal-based flywheels.

*Table 33: Key properties of selected flywheel materials*

| Element | Density ($kg/m^3$) | Tenacity ($MN/m^2$) | Theoretical maximum energy density (Wh/kg) |
|---|---|---|---|
| Steel (AISI 4340) | 7,800 | 1,800 | 32 |
| Al-Mn-Mg-alloy | 2,700 | 600 | 31 |
| Titan (TiAl6Zr5) | 4,500 | 1,200 | 37 |
| Glass fibre reinforced plastics | 2,000 | 1,600 | 111 |
| Carbon fibre reinforced plastics | 1,500 | 2,400 | 222 |

*Source: Oertel, 2008; Notice that a low density combined with high tenacity lead to higher energy densities.*

### 3.8.2 Chemical and electrochemical storage

***Hydrogen***

When considering power storage in the form of hydrogen, it is necessary to realize that several different components are necessary to (a) produce hydrogen from electricity via electrolysis, (b) store it (underground storage or high pressure storage in 70 MPa tanks or liquid storage or metal hydrides), and (c) produce electricity from the stored hydrogen, for example by using a fuel cell (Wietschel and Ball, 2009). The raw material requirements for a sample hydrogen storage facility were analysed in an internal Fraunhofer project considering different concepts for stationary storage (Klobasa et al., 2008). Performance and material data for a sample hydrogen storage system using proton exchange membrane (PEM) electrolysis for hydrogen production, pressure vessels for storage and a gas engine for electricity production are shown below (Table 34).

***Lead-acid batteries***

Batteries in general and particularly lead-acid batteries are mostly designed for specific applications, leading to a large number of different designs. The design of the electrode must provide both mechanical support for the active material and electronic conductivity for the collected current. The most common plate design is the grid plate or pasted plate. A network of lead wires is filled with pellets of active material. The grid itself may be produced by casting lead or lead alloys or by expanding or punching sheet metal.

The basic material for positive and negative active material usually is ‘gray oxide’, a fine powder consisting of about 70–80% lead oxide (PbO) and the remainder lead. This powder is mixed with water and sulphuric acid to form a paste, which is applied to the grid by pasting machines. The selection of appropriate alloying additives is of immense importance, since the rate of grid corrosion is influenced by the composition of the grid alloy. In particular, antimony improves the cycle stability of the active mass in the positive electrode, but its addition must be limited (to <2%) to reduce the production of hydrogen (Berndt and Spahrbier, 2001).

*Table 34: Composition for an exemplary hydrogen storage system*

| | | Unit | Hydrogen (ND PEM with gas engine) | |
|---|---|---|---|---|
| Plant details | Power | kW | 2,000 | |
| | Max. operating time per cycle | hours | 10 | |
| | Capacity | kWh | 20,000 | |
| Materials | Al | kg | 600 | 0.471% |
| | Resin | kg | 1,200 | 0.943% |
| | Ir | kg | 4 | 0.003% |
| | Cu | kg | 2,250 | 1.768% |
| | Pt | kg | 4 | 0.003% |
| | PVC | kg | 500 | 0.393% |
| | Steel | kg | 122,400 | 96.167% |
| | Viton | kg | 320 | 0.251% |

*Table 35: Composition of a representative lead-acid battery*

| Material | Percentage | g/kWh[1] |
|---|---|---|
| Lead | 25 | 5.2 |
| Lead oxides | 35 | 7.2 |
| Polypropylene | 10 | 2.1 |
| Sulphuric acid | 10 | 2.1 |
| Water | 16 | 3.3 |
| Glass | 2 | 0.4 |
| Antimony | 1 | 0.2 |

*Note 1: estimated from a lead-acid battery, Varta type E12V75N with 12 Volt, 80 Ah, 19.8 kg*

*Source: Gaines et al., 2010*

A further vital factor is the addition of metals that achieve a fine structure in the hardened material (fine grain alloys). Otherwise, alloys with such low antimony content cannot be cast flawlessly. The addition of small amounts of selenium (approx. 200 g/tonne) is especially effective. Selenium forms fine lead selenide (PbSe) particles in the molten alloy, which act as nucleants during the solidification process causing the formation of a great number of crystals, thus attaining the desired fine grain structure (Varta, 2012). Lead batteries with these types of alloy lose water so slowly that, for standby applications under normal conditions, the refilling intervals are longer than five years. At the same time, the residual antimony content stabilizes the cycling performance to such an extent that more than 1,000 charging/discharging cycles are possible. Starter batteries in motor cars, based on such a design, do not have to be refilled during their normal service life of approximately five years when used under normal operating conditions.

### *Nickel-cadmium (NiCd) batteries*

As shown in Table 36, the nickel content of NiCd batteries is generally between about 20% and 25%, but there may be as little as 15% or as much as 40% cadmium. The energy content based on the specific material requirements of NiCd batteries for Ni is in the range of 4-5.5 g/Wh and for Cd 3-5 g/Wh. A NiCd battery has only half of the energy density of a nickel metal hydride (NiMH) battery. They are also less durable and also more affected by memory effect. Also as NiMH batteries do not need the toxic heavy metal cadmium, it is expected that NiCd batteries will pushed from the market. There might be some exception in some smaller market segments, due to the advantages NiCd batteries have over NiMH batteries such as better cycle stability, greater maximum charge/discharge, better (low) temperature resistance and better mechanical robustness and insensitivity against inferior charges and total discharge (BatteryUniversity.com, 2012, RWTH Aachen University, 2012).

Table 36: Average material content of different NiCd batteries

| Material (weight-%) | Portable battery | | | | 3 types of batteries | | | 2 types of AA batteries | | EV | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Literature** | **a)** | **b)** | **c)** | **d)** | **e)** | | | **f)** | | **g)** | **h)** | **i)** |
| Al | | | | 0.019 | 0.01 | 0.02 | 0.03 | | | | | |
| Cd | 16.4 | 15 | 15-25 | 15-20 | 39.4 | 35.3 | 28.4 | 33.17 | 34.2 | 24.6 | 25 | 15 |
| Co | 0.5 | | | 0.6 | 2.08 | 2.56 | 1.43 | | | 1.4 | | |
| Cu | | | | | 0.03 | | | | | 2.05 | 2 | |
| Cr | | | | 0.017 | | | | | | | | |
| Fe | | 40 | | 29-40 | 0.01 | 0.03 | 0.04 | 12.92 | 27.7 | | | 35 |
| Li | | | | | 0.05 | 0.07 | 0.04 | | | | | |
| Mn | | | | 0.083 | | 0.01 | | | | | | |
| Ni | 20.5 | 22 | 20-25 | 15-20 | 14.3 | 19.8 | 33.3 | 24.32 | 26.4 | 31.22 | 30.8 | 22 |
| Zn | | | | 0.06 | 0.9 | 0.01 | 0.03 | | | | | |
| Hydroxide | 8.1 | | | | | | | | | 6.38 | 6.2 | |
| $H_2O$ (demin.) | 8 | | | | | | | | | 11.48 | 12 | 5 |
| KOH (30%) | 3.5 | 2 | | | | | | | | | | |
| KOH (clean) | | | | | | | | | | 5.22 | 5 | |
| LiOH (clean) | | | | | | | | | | 0.7 | | |
| Steel | 39.2 | | | | | | | | | 13.8 | 14 | |
| Plastic | | 5 | | | | | | | | 3.1 | 3 | 10 |
| PA | 2.6 | | | | | | | | | | | |
| PVC | 1.1 | | | | | | | | | | | |
| Rubber | 0.3 | | | | | | | | | | | |
| Other | | 16 | | | | | | | | 0.1 | 2 | 13 |

*Sources: a) Rydh and Karlström, 2002; b) Vassura et al., 2009; c) Lankey and McMichael, 1999; d) Rydh and Svärd, 2003; e) Mantuano et al., 2006; f) Rudnik and Nikiel, 2007; g) Cuenca et al., 2009; h) Sullivan and Gaines, 2012; i) Fisher et al., 2006*

Table 37: Specific material use of different types of NiCd batteries

| Material | Specific material use [g/Wh] | | |
|---|---|---|---|
| | Portable battery$^a$ | Portable battery$^b$ | Electro car battery$^c$ |
| Steel | 9.8 | | 2.40 |
| Cd | 4.09 | 3-5 | 4.30 |
| Cu | | | 0.36 |
| Fe | | | |
| Ni | 5.11 | 4-5 | 5.46 |
| Hydroxide | 2.03 | | 1.12 |
| $H_2O$ (demin.) | 2.00 | | 2.01 |
| KOH (30%) | 0.86 | | |
| KOH (pure) | | | 0.91 |
| LiOH (pure) | | | 0.12 |
| Plastic | | | 0.54 |
| PA | 0.65 | | |
| PVC | 0.26 | | |
| Co | 0.12 | | 0.24 |
| Rubber | 0.06 | | |
| Other | | | 0.02 |

*a) Rydh and Karlström, 2002; b) Lankey and McMichael, 1999; c) Cuenca et al., 2009*

### *Redox-flow batteries*

Different types of redox-flow batteries have been studied over the years. In the 1970s, the focus was on the iron-titanium system in which titanium was later replaced by chromium. In the meantime, vanadium redox couples have been shown to be a particularly interesting variant of redox flow batteries, with the systems vanadium bromide and zinc bromide more recently coming into development. An overview of the various systems is given in Table 38 and their specific material requirements in Table 39 (Angerer et al., 2009).

*Table 38: Key figures of different redox flow batteries*

| System | Iron/ Chromium | Vanadium/ Vanadium | Vanadium/ Bromine | Zinc/ Bromine |
|---|---|---|---|---|
| Voltage [V] | 1.2 | 1.3 | 1.4 | 1.8 |
| Capacity [Ah/l] | 33.5 | 21.4 | 26.8 | 54.0 |
| Energy density [Wh/l] | 40.2 | 27.9 | 37.5 | 96.0 |

*Table 39: Comparison of raw materials requirements for redox flow batteries*

| System | Iron/ Chromium | | Vanadium/ Vanadium | Vanadium/ Bromine | | Zinc/ Bromine | |
|---|---|---|---|---|---|---|---|
| | **Fe** | **Cr** | **V** | **$V^{3+}$** | **$V^{4+}$** | **Zn** | **Zn** |
| Specific required amount [kg/kWh] | 3.47 | 3.23 | 2.92 | 1.36 | 1.36 | 0.34 | 1.02 |

*Source: (Angerer et al., 2009)*

***Lithium-ion battery***

Lithium ion batteries contain metal oxides, for example cobalt oxide, carbon as graphite, lithium which enables the electricity transport in the cell interior, a water-free organic solvent, which is mixed with conducting salts, copper and aluminium for the electrodes and other materials that are part of the manufacturers trade secret. Table 40 shows average material contents for portable Li-ion batteries and Table 41 shows shares of recyclable materials (lithium, cobalt and nickel).

*Table 40: Average material content of portable Li-ion batteries*

| Battery component | Product data sheets in mass-% |
|---|---|
| Casing | ~20–25 |
| Cathode material ($LiCoO_2$) | ~25–30 |
| Anode material (graphite) | ~14–19 |
| Electrolyte | ~10–15 |
| Copper electrode foil | ~5–9 |
| Aluminium electrode foil | ~5–7 |
| Separator | - |

*Source: Georgi-Maschler et al., 2012*

*Table 41: Shares of selected recyclable materials in weight of lithium-ion battery systems (in weight-%).*

| | **Li-Ion-$LiCoO_x$** | | **Li-Ion-$LiNiO_x$** | |
|---|---|---|---|---|
| | **a)** | **b)** | **a)** | **b)** |
| Lithium | 4.7 | 2.7 | | 3 |
| Cobalt | 22 | 23.3 | | 18 |
| Nickel | | | 22 | |

*a) Angerer et al., 2009; b) Noll et al., 2012*

***Sodium-sulphur (NaS) batteries***

NaS batteries are characterized by the low cost and wide availability of the raw materials used. As shown in Table 42, the sodium content of NaS batteries is about 8% if the entire system is considered. In a single cell it is significantly larger and lies between approximately 14% and 18%. The sulphur content is approximately 1.5 times the sodium content: 12% with respect to the total battery unit and between 21% and

29% with respect to the individual cell. The high specific material requirements amount to 0.8 g/Wh for sodium and 1.2 g/Wh for sulphur (Cuenca et al., 2009).

*Table 42: Material requirement of various NaS batteries*

| **Materials** | **Share (weight-%)** | | | |
|---|---|---|---|---|
| | **Total battery$^{a)}$** | **Total battery$^{b)}$** | **2 single cells$^{c)}$** | |
| Al | 22.7 | | 15.3 | 36.4 |
| C (Graphite) | 2 | | 2.5 | |
| Cu | 3.4 | | 4.2 | |
| Na | 8 | 8 | 17.8 | 13.8 |
| S | 12.5 | 12 | 29.4 | 21.6 |
| α-$Al_2O_3$ | 2.3 | | 1 | 3.9 |
| β-$Al_2O_3$ | 10.2 | | 2.7 | 17.7 |
| Steel | 12.8 | <60 | 13 | 0.3 |
| Polypropylene | 8 | | 7.7 | |
| Glass | 4.3 | | 1.4 | |
| Ceramics | | 20 | | |
| Sand | 15.2 | | | |
| Other | 8.7 | | | |

*Sources: a) Sullivan and Gaines, 2010; b) Cuenca et al., 2009; c) Sullivan and Gaines, 2012*

### 3.8.3 Electrical and electromagnetic storage

***Supercapacitors***

In supercapacitors, mostly materials with extremely high surface areas are used as electrode materials, among which carbon based materials - for example various forms of activated charcoal - are the most common. Other forms of high-surface carbon such as graphene, carbon nanotubes, or aerogel are currently being investigated. Other supercapacitors use polymers, such as polypyrrole or polyaniline, or certain metal oxides, i.e. $RuO_2$, $Fe_3O_4$, or $MnO_2$, as electrode materials.

A variety of electrolytes can be used in supercapacitors ranging from aqueous solutions of various inorganic salts and acids (e.g. KOH and $H_2SO_4$) to organic solvents (e.g. acetonitrile) with quaternary salts of ammonia or alkyl ammonia salts. To avoid the formation of a galvanic cell, the same material (mostly Al) is usually used for the supercapacitor’s casing, current collectors and power connectors. Additionally, a thin, porous and chemically inert material is required to mechanically separate the electrodes and to prevent a short circuit, e.g. paper, porous plastic foils or ceramic materials (Schneuwly and Gallay, 2000; Halper and Ellenbogen, 2006; Wang et al., 2012).

*Table 43: Material compositions of various supercapacitor technologies*

| **Material** | **Fraction (w%)** | **Specific Demand$^{a)}$ [kg/kWh]** |
|---|---|---|
| Activated charcoal | 45-50 | 45-100 |
| Electrolyte [e.g. KOH$^{a}$ or $H_2SO_4$$^{a}$, or acetonitrile] | 30 | 30-60 |
| Al foil | 20 | 20-40 |
| Plastic foil | 1 | 1-2 |
| Al power connectors | 4-5 | 4-10 |

*Note a: Based on energy density of 5-10 Wh/kg*
*Source: Trapp, 2012*

***Superconducting coils***

Utilizing superconductive properties of special compound materials superconducting magnetic energy storages (SMES) are suitable to act as short-term storages in power systems. Such materials can be classified by the critical temperature where the superconducting state is reached: High temperature superconductors (HTSC) with critical temperatures ($T_c$) less than 77 K (temperature of liquid nitrogen) and low temperature superconductors (LTSC) with lower critical temperatures. LTSC require coolants such as liquid helium at 4.2 K or super fluid helium at 1.8 K.

A broad spectrum of high temperature superconducting compound materials has been discovered. However, in the field of SMES, mainly niobium (LTSC) and yttrium (HTSC) compounds as well as magnesium diboride (HTSC) are used. Beside the demand for the superconducting material copper is required as a stabilizer.

*Table 44: Material compositions of various superconductor cables*

| Material | Fraction [%] | Reference |
|---|---|---|
| Cu<br>Nb<br>Ti | 80<br>10.6<br>9.4 | (Hartikainen, 2005) |
| Cu + Ni-Alloy<br>Ag | 95<br>3 | (Lehner, 2011) |
| Cu + Ni-Alloy<br>Rare Earth-BaCuO-HTS | ca. 97<br>1 | (Selvamanickam, 2011) |

### 3.8.4 Thermal storage

One of the latest studies concerning life cycle assessment of thermal heat storage devices was executed by Oró et al. (2012) where both sensible and latent heat storage schemes were taken into consideration.

Sensible heat storage (SHS)

As there are different designs of SHS devices, a LCA was made for a solid as well as for a molten salt energy storage system. The solid system is based on high temperature concrete and with a maximum operating temperature of 390°C it has a capacity of 350 kWh. Table 39 gives an overview of the materials used in total and per kilowatt hour.

*Table 45: Materials for high temperature concrete heat storage for 350 kWh*

| Element | kg | kg/kWh |
|---|---|---|
| Tubes of steel | 1,516 | 56.6 |
| High temperature concrete | 26,757 | 4.3 |
| Metalsheets | 173 | 76.5 |
| Rockwool | 403 | 0.5 |

*Source: Oró et al. 2012*

The molten salt device considered here uses 3,300 tonnes of $KNO_3$ and 2,200 tonnes of $NaNO_3$. These 5,500 tonnes of salt lead to a capacity of 600 MWh. The required quantities of salt and other materials are shown in Table 46.

Another example for a raw materials inventory analysis is given by (Heath et al., 2009), where two different approaches of molten salt storage systems are examined. The first system consists of a hot salt tank and another tank for cold salt, whereas for the second system only one tank is needed to generate a thermal gradient. Both systems have the same capacity of 300 MWh (see Table 47).

*Table 46: Materials for molten salt heat storage with a capacity of 600 MWh*

| Element | Tonnes | kg/kWh |
|---|---|---|
| $KNO_3$ | 3,300 | 5.50 |
| $NaNO_3$ | 2,200 | 3.67 |
| Stainless steel | 18 | 0.03 |
| Firebricks | 1,270 | 2.12 |
| Carbon steel | 555 | 0.92 |
| Ceramic fibre | 10 | 0.02 |
| Aluminium sheet | 4 | 0.01 |
| Sand | 418 | 0.70 |
| Foamglas | 4 | 0.01 |

*Source: Oró et al. 2012*

*Table 47: Materials for different molten salt heat storage devices with a capacity of 300 MWh*

| Element | tonnes (2-tank) | kg/kWh (2-tank) | tonnes (thermocline) | kg/kWh (thermocline) |
|---|---|---|---|---|
| Thermal mass | | | | |
| Silica sand | | | 17,900 | 59.67 |
| $KNO_3$ | 10,240 | 34.13 | 3,072 | 10.24 |
| $NaNO_3$ | 15,360 | 51.20 | 4,608 | 15.36 |
| Heat exchanger | | | | |
| Calcium Silicate | 78 | 0.26 | 38 | 0.13 |
| Stainless Steel | 411 | 1.37 | 179 | 0.60 |
| Storage tank | | | | |
| Calcium Silicate | 51 | 0.17 | 26 | 0.09 |
| Carbon Steel | 885 | 2.95 | 456 | 1.52 |
| Mineral Wool | 283 | 0.94 | 158 | 0.53 |
| Stainless Steel | 6 | 0.02 | 3 | 0.01 |

*Source: Heath et al. 2009*

***Latent heat storage***

For the latent heat storage $KNO_3$ and $NaNO_3$ are used as well, although in a slightly different mixture consisting of 54% $KNO_3$ and 46% $NaNO_3$. The heat storage system has a latent heat of fusion of 100 kJ/kg and with the reported 2,100 kg of the phase change material ($KNO_3$ and $NaNO_3$) about 58 kWh of energy can be stored Oró et al. (2012).

*Table 48: Material requirements for a sample latent heat storage facility*

| Element | kg | kg/kWh |
|---|---|---|
| Concrete | 6,600 | 113.79 |
| Tubes of steel | 202 | 3.49 |
| Metalsheets | 427 | 7.37 |
| KNO3 | 1,134 | 19.55 |
| NaNO3 | 966 | 16.66 |
| Metalsheets | 81 | 1.39 |
| Rockwool | 50 | 0.86 |
| Foamglas | 69 | 1.20 |

*Source: Oró et al. 2012*

## 3.9 Energy-intensive industries

The EU is aiming for a 20% cut in Europe's annual primary energy consumption by 2020, where in 2010, 25% (292 Mtoe) was by industrial users (EC Eurostat, 2012). The work of the SETIS Technology Map on energy efficiency and $CO_2$ reduction in industry has to date been to focus specifically on three energy-intensive industries, which between them accounted for almost 43% of the EU-27's final energy consumption within industry in 2010: cement, iron & steel, and pulp & paper.

Each of these industries has now developed a roadmap modelling different scenarios as to how to increase energy efficiency and reduce $CO_2$ emissions with reference to best available technologies and in comparison to high efficiency reference plants:

- For the cement industry, the results show that, by implementing technological improvements available, a thermal energy improvement of around 10% is possible between 2006 and 2030. This corresponds to a decrease of about 4% in $CO_2$ emissions from clinker manufacture. However, the results are relatively insensitive to higher $CO_2$ and fuel prices, indicating the large number of economically feasible retro-fits already available (EC, 2010b).
- For the iron and steel industry, the modelling identified large improvements possible for both primary and secondary steel production routes. For primary steel a reduction of 14-21% of $CO_2$ emissions is possible, with a reduction of around 11% available within secondary steel production. These equate to an energy reduction of around 10%. Higher $CO_2$ and fuel prices could motivate further reductions to some extent (EC, 2012a).
- For pulp and paper, the results of the modelling show that a reduction of 50-60% of $CO_2$ emissions is possible by 2050 - given the right circumstances regarding investment patterns and available and emerging technologies. However, to achieve an 80% reduction in $CO_2$ emissions, breakthrough technologies will have to be developed and available for implementation by 2030 (CEPI, 2011).

The following sub-sections provide a summary of the initiatives and interventions available for each industry. Many of these include retro-fits, site specific interventions, alternative fuels and materials, and emerging technologies, which are not currently available. Due to the more piecemeal nature of these interventions, and consequently the lack of an appropriate scenario to model, the results are more descriptive than quantitative. Nonetheless the research conducted did not identify a reliance on critical or scarce materials. Instead the technologies appear to be making use of more common materials such as aluminium, copper, stainless steel, plastics etc. Many of these materials have been identified in other technologies and have therefore been captured elsewhere in the analysis.

### 3.9.1 Cement industry

For the cement industry, the main processes identified include:

- decrease of the proportion of clinker in cement
- use of alternative fuels
- site-specific energy efficiency measures
- deployment of CCS
- fluidised bed technologies.

The first two processes are defined as co-processing, i.e. utilising waste products within the cement production process. The benefits of this are reducing the raw material and fuel requirements of cement production and reducing the associated emissions; as well as improving the competitiveness of the industry. On the substitution towards alternative fuels and materials, CEMBUREAU the European Association reports the following progress (Table 49):

- On alternative fuels, the European cement industry used the energy equivalent of approximately 26Mt of coal in 2006 for the production of cement. This represented a substitution rate of 18%

across Europe away from fossil fuels (CEMBUREAU, 2009). A significant proportion of these alternative fuels were waste materials that might otherwise have been destined for incineration of landfill. By incorporating these alternative fuels the calorific value of the waste is utilised in the production process, as well as being effectively decomposed through the high burning conditions. In addition, the ash generated can be used as an alternative raw material in the production of clinker. If current trends continue for the use of alternative fuels these could amount to $CO_2$ reductions of 18Mt $CO_2$ by 2020 and 23.5 Mt of $CO_2$ by 2030 (EC, 2011c).

- On alternative raw materials an estimated 14.5Mt per year were utilised in the production of cement, representing a substitution rate of approximately 5% of the total raw materials (CEMBUREAU, 2009). These alternative raw materials include contaminated soil, coal fly ash and blast furnace slag. The effect of using these raw materials is to reduce the need for the quarrying of traditional raw materials such as clay, shale and limestone; hence reducing the environmental footprint of these activities. On the reduction of clinker content within cement, the JRC technology map estimates that if these trends continue these could amount to $CO_2$ reductions of 4.7 MT $CO_2$ by 2020 and 8.0 MT of $CO_2$ by 2030 (EC, 2011c).

As for site-specific energy efficiency measures these incorporate a wide range of possible activities, (EC, 2010c) some of which will include improved process control, alternative fuels and raw materials (covered above), co-generation or combined heat and power (see Section 3.5) and carbon capture and storage (also covered elsewhere). Fluidised bed technology is currently being researched as a potential breakthrough technology, although it is possible deployment is considered to be relatively far in the future.

*Table 49: EU cement co-processing*

| Type of co-processing | Average EU substitution rate |
|---|---|
| Alternative fuels | 18% |
| Alternative raw materials | 5% |
| Alternative constituents | 12% |

*Source: CEMBUREAU, 2009*

This review of energy efficiency in the cement industry therefore did not identify any particular role for critical metals, but rather a continuation of best practice in the industry.

### 3.9.2 Iron and steel industry

For the iron and steel industry, the main sub-technologies identified include:

- integrated production – dissemination of BAT
- electric arc furnaces, direct-reduced iron and smelting reduction
- ultra-low $CO_2$ steelmaking (ULCOS).

The dissemination of BATs for integrated steel production focuses in the following areas:

- Improved and optimised systems to achieve smooth and stable processing by using:
    - process control optimisation including computer-based automatic control systems
    - modern, gravimetric solid fuel feed systems
    - preheating, to the greatest extent possible, considering the existing process configuration.
- Recovering excess heat from processes, especially from their cooling zones.
- Optimised steam and heat management e.g. CHP, insulation and heat recovery.
- Applying process integrated reuse of sensible heat as much as possible.

Alternative production processes such as electric arc furnaces have significantly lower energy use (by around 80%); however, their adoption is limited by the availability of scrap. In 2011 42% of steel production in Europe was from electric arc furnaces (up from 40% in 2007), (EUROFER, 2012). Worldwide post-consumer steel recovery rates were at 83% with industry targets steel recovery of 90% for 2050 (Table 50).

*Table 50: Post-consumer steel product recovery rates and targets by sector*

| Sector | Recovery rate 2007 (%) | Recovery rate 2050 (%) | Life cycle in years |
|---|---|---|---|
| Construction | 85 | 90 | 40-70 |
| Automotive | 85 | 90 | 7-15 |
| Machinery | 90 | 95 | 10-20 |
| Electrical & domestic appliances | 50 | 65 | 4-10 |
| Weighted global average | 83 | 90 | N/A |

*Source: World Steel Association, 2012*

The European steel industry has embarked on a co-operative R&D initiative to enable drastic reduction of at least 50% carbon dioxide emissions from steel production. Four processes are currently being demonstrated, although commercial deployment in not expected until the late 2020s (World Steel Association, 2012):

- **ULCOS-BF process** – top gas recycling in combination with CCS: Blast furnace top gas recycling relies on separation of the top gas so that the useful components can be recycled into the furnace as a reducing agent. The $CO_2$ is captured and stored.
- **ULCOWIN**: Alkaline electrolysis of iron ore: Electrolysis is commonly used to produce metals other than steel and requires large amounts of electricity. The process would depend on a $CO_2$-lean electricity source such as hydro or nuclear power.
- **ULCORED** - advanced Direct Reduction in combination with CCS: Direct-reduced iron is produced from the direct reduction of iron ore by a reducing gas produced from natural gas.
- **ULCOS** Smelting reduction (HIsarna) in combination with CCS: HIsarna combines a melting cyclone for ore melting and a liquid-bath smelter vessel for final ore reduction and hot metal production. It produces fairly pure $CO_2$, which can be captured allowing for major $CO_2$ reductions. Construction of the HIsarna pilot plant was completed in 2011 and hot commissioning began the same year at Ijmuiden in the Netherlands at an 8 tonne/hour scale.

### 3.9.3 Pulp and paper industry

For the pulp and paper industry, the main sub-technologies identified include:

- CHP generation (covered in Section 3.5)
- use of recycled fibres in integrated paper production
- innovative drying technologies and mechanical pulping optimisation
- bio-route: integrated bio-refinery complexes.

On the use of recycled fibres, recovered paper and board has increased considerably over the past two decades and recovered paper now represents around 44% of the total raw materials in the industry. This corresponds to the increasing EU recycling rates of paper and board, which have increased from 52% in 2000 to a current level of around 70% in 2010. These recycling rates are the highest of any geographic region anywhere in the world (CEPI, 2011).

A number of site-specific type energy-saving measures are possible such as CHP (covered in Section 3.5), innovative drying technologies and mechanical pulp optimisation:

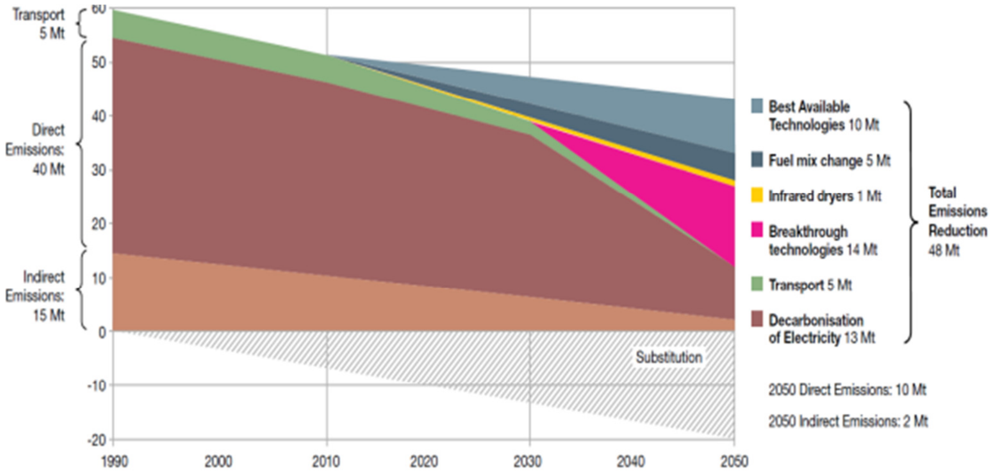
- On CHP, CEPI note that as of 2010 95% of the industry's electricity was generated on-site by CHP.

Electricity consumption has fallen in the industry by 6% since 2010, with direct $CO_2$ emission having fallen by 20% and indirect emissions by a third over the same period.

- Leading machine supplier, Metso, advertise various energy saving techniques for installation (Metso, 2012):
    - Process optimizer for the automation of mechanical pulping with the effect of reducing fibre property variation, increasing production volumes and an energy saving of up to 5%
    - PowderDry dryers designed for high drying capacity. These high intensity and energy efficient air dryers can lead a reduction of 50% in energy consumption
    - New generation refiners for paper and board stock preparation to replace two existing traditional refiners and deliver 40% savings in electrical energy.

Figure 4 shows the industry pathway for $CO_2$ emissions reduction by 2050. Much of the immediate reductions are based on the interventions mentioned above. After 2030, breakthrough technologies such as integrated bio-refinery complexes are expected to make a contribution.

*Figure 4: EU pulp and paper industry $CO_2$ emissions reduction projection 1990 - 2050 (in million tonnes)*



*Source: CEPI, 2011*

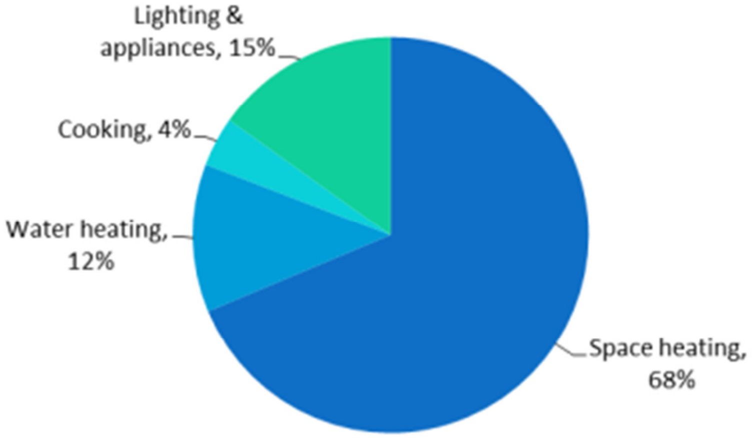
## 3.10 Energy efficiency in buildings

### 3.10.1 Introduction

As an introduction to energy efficiency in buildings, it is useful to provide data on the relative proportion of energy consumption associated with different uses. Approximately 40% of final energy consumption in the EU is within buildings; 27% is within residential buildings and 13% within the services sector.

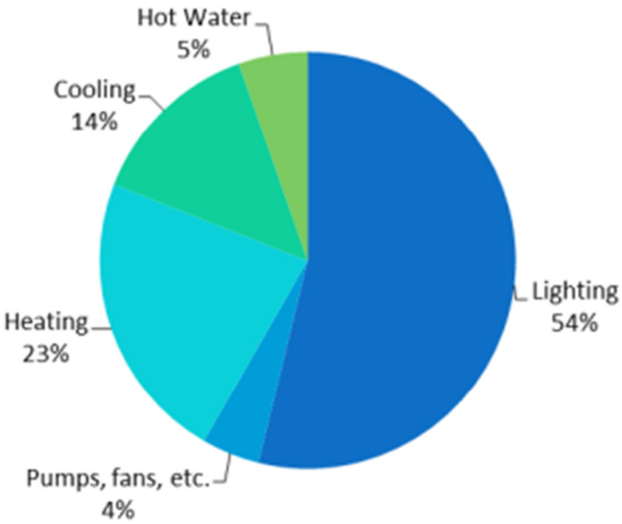
For household energy consumption the dominant use is for space heating, accounting for around two thirds of household energy consumption (Figure 5). Water heating, lighting and appliances make up most of the remainder. For offices the pattern of energy use differs somewhat, with lighting accounting for over half of typical energy consumption (Figure 6). Heating and cooling are the other contributors to total energy consumption. This data is used as a guide in covering the main aspects associated with energy efficiency in buildings in this chapter.

*Figure 5: Household energy consumption in the EU, 2009 (%)*



*Source: Enerdata, 2011*

*Figure 6: Annual energy consumption in a typical office building (%)*

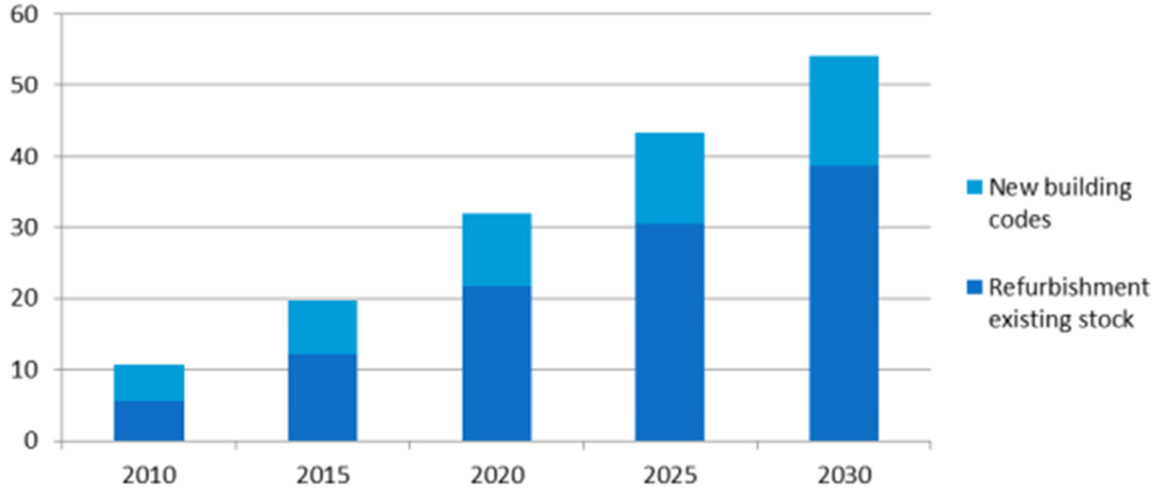


*Source: EC, 2011e*

### 3.10.2 Construction materials

A key aspect for determining the overall energy efficiency of a building is its design and the materials from which it was originally constructed. The results of scenario modelling on potential energy efficiency improvements associated with residential buildings identifies that a 45% improvement in useful energy demand is achievable under a high policy intensity scenario by 2030. This includes refurbishment rates of around 2.5% per year for existing buildings, as well as new building. In total this could lead to a reduction of 54 Mtoe by 2030 against a baseline scenario. The refurbishment of existing housing stock accounts for 70% of the total improvement (Figure 7). Comparable results are found for the tertiary sector (27 Mtoe energy efficiency savings by 2030, of which 80% is from refurbishment).

*Figure 7: Energy efficiency potentials from existing and new buildings, high policy scenario (EU-27 Mtoe)*

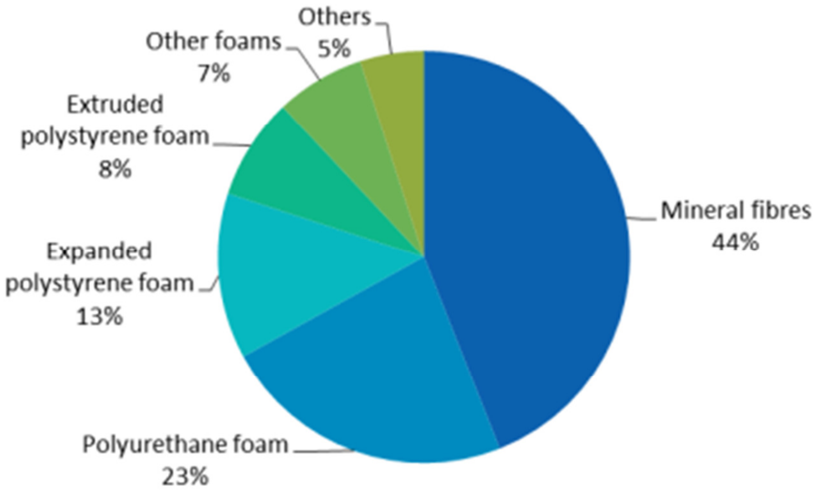


*Source: EC, 2009*

***Refurbishment of existing stock***

A key part of the refurbishment of existing housing stock is the installation of insulation materials for walls, roofs, floors and windows. The main types of insulation are mineral fibres and polyurethane or polystyrene foams (Figure 8). Other types of insulation include those derived from textiles. The main materials involved are therefore rock, slag and glass (mineral wool) and plastics; no metal requirements are identified.

*Figure 8: Insulation types broken down by market value (%)*



*Source: Market Transformation Programme, 2007*

For windows, this includes the installation of double glazing and the associated frame and roller blinds; none of which has specific metals requirements of interest. One emerging technology of interest, however, is the increasing use of metal coatings to improve the energy efficiency of glass. There are three main types to consider with respect to energy performance:[4]

- Reflective coatings, which work by reflecting heat away from buildings, and hence reduce the need for cooling and ventilation. These include gold- and silver-containing alloys, typically with tin, of a thickness of around 3 nm. Alternative reflective coatings are titanium nitride and vanadium nitride.

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[4] Pilkington Glass, personal communication (July 2012)

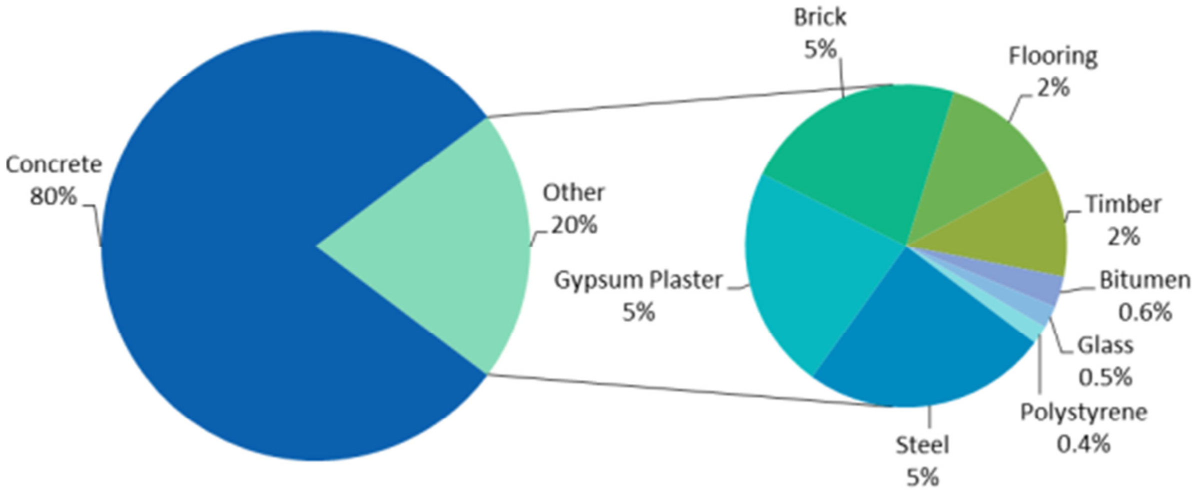
- Low emissivity coatings, which operate by keeping heat inside a building, and therefore reduce the need for heating. The main material used is fluorine doped tin oxide at around 100-200 nm thickness. Other materials that are potentially suitable include indium tin oxide and gallium or antimony zinc oxides. None of these latter materials is currently used commercially.
- Thermo-chromic coatings, which are temperature sensitive, combining both the above properties by reflecting heat away at high temperatures and keeping heat inside at lower temperatures. The main material considered for this purpose is vanadium dioxide at a thickness of 100-200 nm.

It is expected that the use of energy efficient coatings will become more widespread over time, as they become more commercially available and as building codes and regulations encourage greater energy efficiency within buildings. However, given the thickness of these different types of coatings, their contribution to the overall demand for these metals is expected to be relatively limited.

***New buildings***

For new buildings a review of the typical composition of an office building highlights concrete as the dominant material representing 80% of the construction materials (Figure 9). Other bulk materials such as steel, gypsum plaster and brick make up most of the remaining materials. Similar construction materials, albeit in differing proportions, will be typical for the construction of residential property. This analysis does not therefore identify any specific metals requirements for further consideration.

*Figure 9: Construction materials for a generic office building (% of weight)*



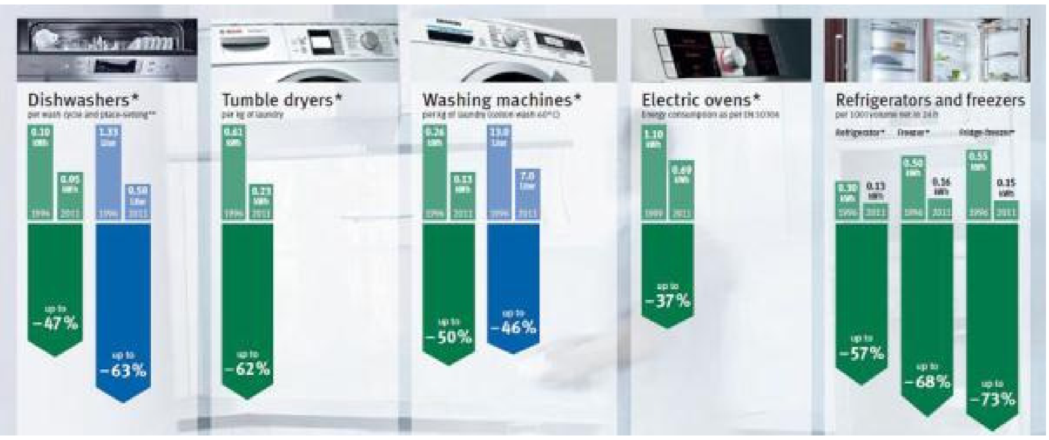
*Source: EC, 2011e*

### 3.10.3 Lighting and electrical appliances

For electrical appliances the evidence highlights that large improvements in energy efficiency have already been achieved for a large number of products (Figure 10). For many product categories, improvements of greater 50% in energy efficiency have been achieved between 1996 and 2011.

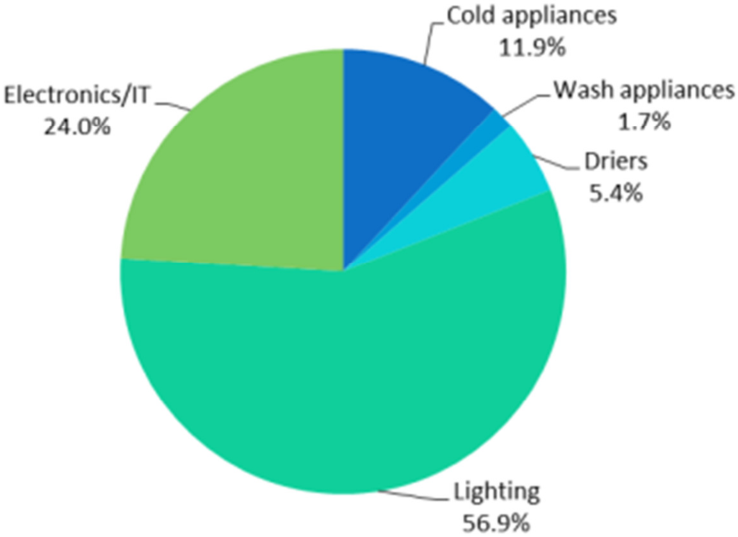
However, the evidence from energy efficiency scenario modelling suggests that further improvements are possible. Under a high policy intensity scenario, i.e. much higher LED penetration (up to 90% in 2030), savings of nearly 11 Mtoe across the EU-27 by 2030 are thought to be achievable. This represents a 27.8% reduction against the baseline scenario. Over half of the estimated energy efficiency savings are associated with lighting (Figure 11). Approximately a quarter of the savings relate to electronics and IT (televisions, computers etc.), with the remainder covering electrical appliances such as fridges, freezers, washing machines, dishwashers and tumble driers. The key question to consider with respect to this study, however, is the extent to which particular materials enable greater energy efficiency of these appliances.

*Figure 10: Increases in energy efficiency of household appliances*



*Source: BOSCH, 2012*

*Figure 11: Contribution of different types of electrical appliances to energy efficiency (%)*



*Source: EC, 2009*

***Lighting***

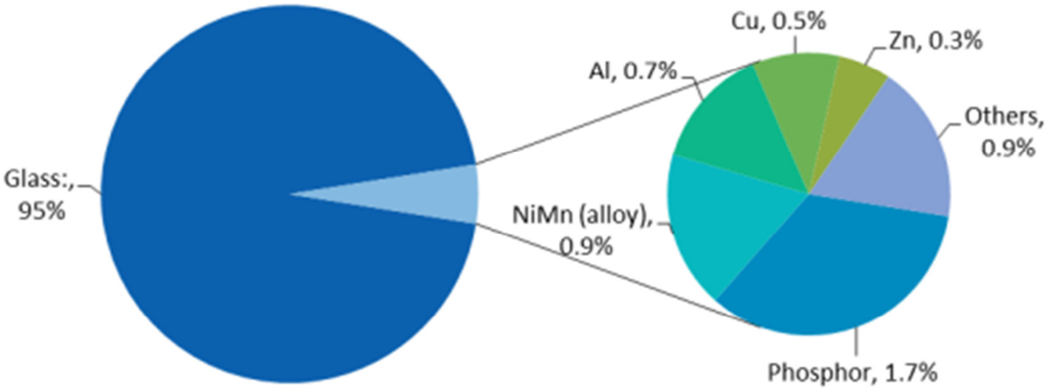
For lighting this involves the shift away from incandescent and halogen lamps towards compact fluorescent lamps (CFLs) (now largely complete) and the later shift to LED technology. Details can be found below on the material composition. Ceramic halide lighting has been excluded from this study due to its small share of the lighting market.

***Fluorescent lighting***

For fluorescent lighting the composition of a typical linear fluorescent lamp (LFL) in the EU is shown in Figure 12, courtesy of data provided by the European Lamp Companies Federation. The majority of weight of fluorescent lighting is glass (95%), as well as various metal components, including 1.7% of tri-band phosphor. Other materials include resins and hard paper. The weight of a linear fluorescent lamp (LFL) is assumed to be 120 g (European Lamp Companies Federation, 2012).

For CFLs the materials composition differs somewhat, including 55% of glass by weight and 20% of both electronics and plastics within a typical 120 gram bulb (European Lamp Companies Federation, 2012). Metal content is approximately 3% (copper, aluminium, tin and manganese), with around 0.75% of tri-band phosphor.

*Figure 12: Quantitative estimates of the weight of fluorescent lamp composition*



*Source: European Lamp Companies Federation, personal communication (Dec 2012)*

Of particular interest is the content of the tri-band phosphor. Rare earth oxides comprise 65% of the tri-band phosphor, along with various other metals.[5] This represents 1.33 g per LFL and 0.59 g per CFL. This compares to 0.66 g estimated by US Department of Energy in their critical materials strategy (Bauer et al., 2010). As for the composition of rare earths within phosphors slightly different estimates exist, as shown in Table 51. This partly reflects the diversity of compositions used by different types and brands. Here the Lynas combined estimates have been used.

*Table 51: Estimates of the composition of rare earth content of phosphors (%)*

| **Element** | **CFL** | **LFL** | **Combined Estimate*** |
|---|---|---|---|
| Lanthanum | 8.5 | 22.0 | 8.5 |
| Cerium | 20.1 | 6.5 | 11.0 |
| Europium | 4.5 | 4.5 | 4.9 |
| Terbium | 5.0 | 5.0 | 4.6 |
| Yttrium | 62.0 | 62.0 | 69.2 |
| Gadolinium | - | - | 1.8 |

*Sources: *Lynas Corporation Ltd, 2010; Bauer et al., 2010*

***LED Lighting***

LED lighting consists of a number of different components, and the market is still undergoing rapid evolution, with many different types of LEDs with differing compositions.

One example material composition is shown in Figure 13, for the Osram Golden Dragon white LED chip (mass of approximately 230 mg). The majority of the weight is copper and polymers. However, there is also significant silver, germanium and tin content, as well as doping of rare earths. The role of the rare earth phosphor (cerium doped yttrium aluminium garnet) is to convert blue light into white light, which remains a considerably cheaper method than to mix the light produced by red, green and blue LEDs.

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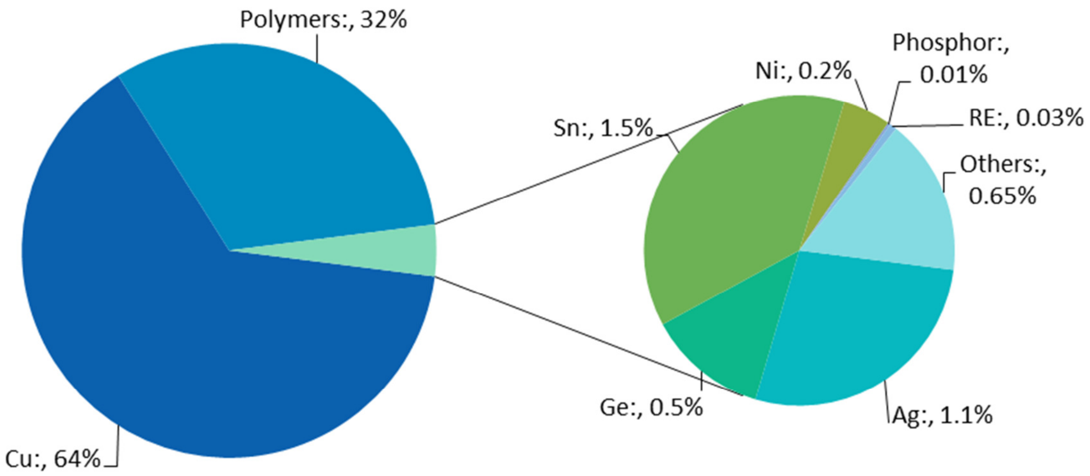
[5] European Lamp Companies Federation, personal communication (Dec 2012)

*Figure 13: Materials composition of white LED chip*



*Source: European Lamp Companies Federation, personal communication (Dec 2012)*

Data is also available from a detailed US study by Lim et al. (2011) who estimated the material content of different types of LEDs, considering 20 separate materials. Here the results of that study have been averaged just for the high brightness LEDs analysed. These results have been rescaled according to chip size[6] and by expert judgement where certain key metals such as indium were not detected because of the study methodology.[7] The key differences between these estimates are the use of indium-doped gallium nitride versus germanium as the choice of semi-conductor, and differing estimates for the content of the base and precious metals contained. Data from both studies have therefore been combined here to reflect the diversity and evolution of different types of LEDs.

Three main applications of LED lighting are considered: bulbs, tubes and street lighting. Each of these has a different number of LEDs (Table 52). In addition to the above metals within the LED itself, there is also some nickel, chromium, copper and zinc as part of the bulb structure (US DOE, 2012).

*Table 52: High brightness LED content by application*

| Lighting type | Number of replacement LEDs |
|---|---|
| Incandescent lamp | 5-12 |
| Compact fluorescent lamp | 5-12 |
| Fluorescent lamp | 40-50 |
| Streetlight | 60-80 |

*Source: Aixtron, 2012*

***Electrical appliances***

For electrical appliances more generally, the main materials used include plastics, glass, steel, aluminium, copper and electronic circuit boards. As many of these materials are relatively generic across a large number of different appliances, an overview of these materials can be found in Section 4.4.

In terms of potential energy efficiency improvements, a review of the eco-design criteria literature (IVF Industrial Research and Development Corporation, 2005; ISIS, 2007; EC, 2008b; bio Intelligence Service, ERA Technology, 2011) for key product categories (televisions, computers, ovens, washing machines/dishwashers, fridges/freezers etc.), reveals the following list of potential energy efficiency im-

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[6] General lighting uses a chip size of 1mm$^2$, material content scales by area. Personal communication, Michael Heuken, Aixtron (July 2012)

[7] Gallium content is approximately eight times of that of indium with the semiconductors (Indium Corporation, 2011).

provements:

- changing the use of stand-by modes
- greater insulation/sealing of doors and windows
- improved temperature and other sensors
- lower temperature functionality
- higher efficiency heat exchanges and motors
- noise reduction.

In general terms these energy efficiency improvements do not appear to be linked to particular metals requirements. For example, many relate to changing the functionality and design of the appliances; and for improved insulation and noise reduction the associated materials are largely plastics and foams. It is therefore assumed that the materials associated with most electrical appliances are similar to those identified in the sector study for electronics/ICT, and no further analysis is required. The electronics/ICT analysis includes a range of materials from the bulk metals such as copper and tin, to minor and precious metals such as tantalum, rare earth elements, gold, silver and PGMs.

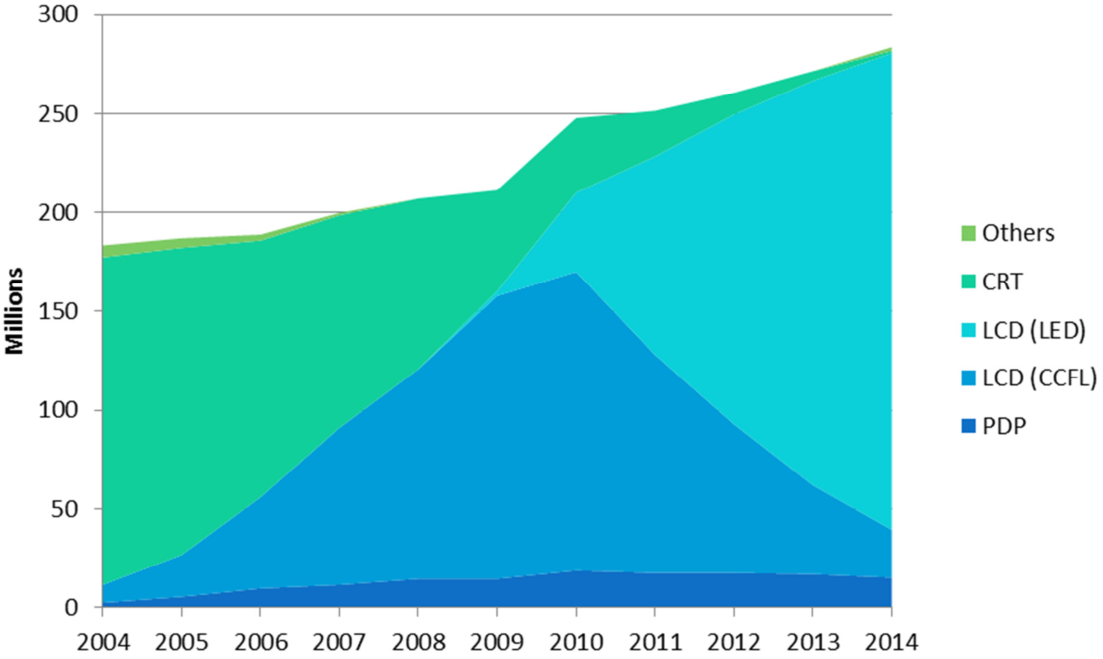
A few examples of specific materials leading to improved energy efficiency of appliances were identified. For washing machines, brushless DC direct drive motors were identified as being able to deliver estimated improvements of around 6% to the motor efficiency (EC, 2007c). These imply the introduction and use of rare earth based permanent magnets within washing machines, which is of interest with respect to this study. The report provided statistics of their uptake at 0.5% market share for 2005. The cost benefit analysis within the report suggested that the payback period for cost of DD motors versus the energy savings would be more than 130 years, and that further increased uptake appears unlikely.

For televisions and computers, one of the enablers for improved energy efficiency is the changing material composition of the screens. Figure 14 shows data for past and forecast sales of different types of televisions. It shows the phasing out of the older and more energy intensive technology - cathode ray tubes - with newer and more energy efficient LCD televisions; which occurred between 2004 and 2008. The television sales data also shows a second shift in television type that is already underway. This is between cold-cathode fluorescent lamp (CCFL) backlit LCD screens to LED backlit screens.

Many of the key materials, such as indium tin oxide, are common to both LCD technologies; however, the shift from CCFL to LED backlights does bring some changes to material composition (see above section on lighting). These include the greater use of gallium, yttrium, gold and silver. However the data shows that this shift has now largely been completed. For example, in 2012 LED backlit TVs are expected to account for 60% of worldwide television sales, increasing to 85% by 2014 (Figure 14). In comparison to lighting, the market for displays (televisions and computer screens) is expected to be much smaller due to the relative size difference in LED chip size. Figure 15 shows how high brightness LED material area is expected to develop up to 2015. This shows associated material demand for displays holding steady at around 20 billion mm$^2$. In terms of material demand, sales of 250 million LED televisions worldwide may equate to around 15% of worldwide demand for yttrium in 2015 (2,700 tonnes), (Metal Pages, 2012).

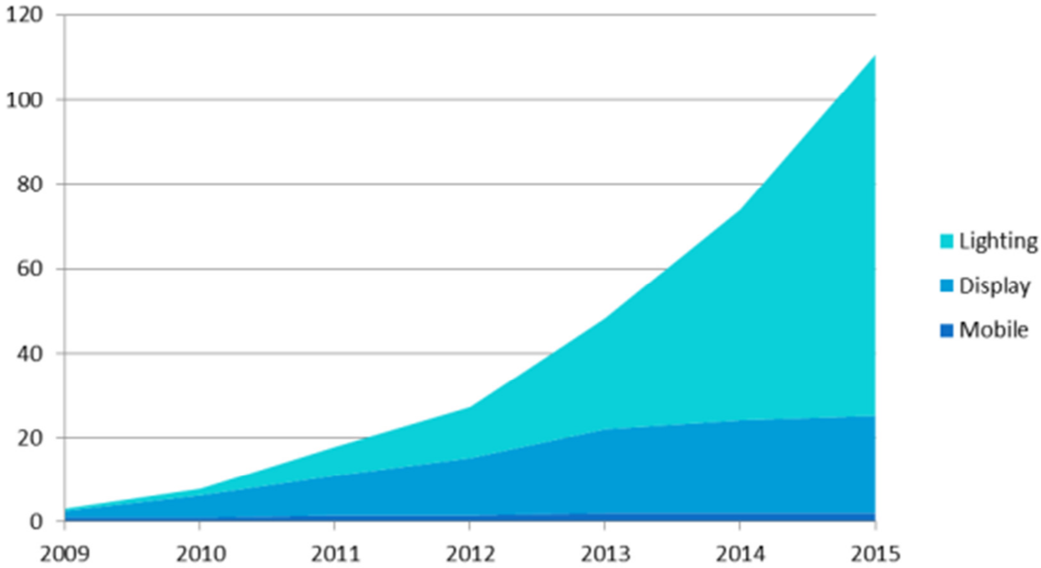
An alternative type of electronic appliance to be considered is smart meters, which offer the potential to reduce energy consumption by providing real-time information to consumers regarding their energy use. A study by the European Smart Metering Alliance identifies that, through encouraging changing consumer behaviour, smart meters can achieve reductions in energy bills of 15-20% (BEAMA, 2010). Very limited information was identified on their material composition, although designs appear to incorporate a combination of plastics, metals and electronic components.

*Figure 14: Worldwide TV forecast by type (millions of units)*



*Source: Indium Corporation, 2012*

*Figure 15: High brightness LED material area by market (square area, billion mm$^2$)*



*Source: Aixtron, 2012*

### 3.10.4 Heating and cooling

Under a high policy intensity scenario (EC, 2009), the scenario analysis for energy efficiency, highlights that significant improvements of up to 50% in thermal energy efficiency are achievable by 2030. A number of appliances and technologies are considered within this section, including high efficiency boilers and water heaters, efficient heat exchange ventilation, solar thermal and aero-thermal energy (see geothermal energy).

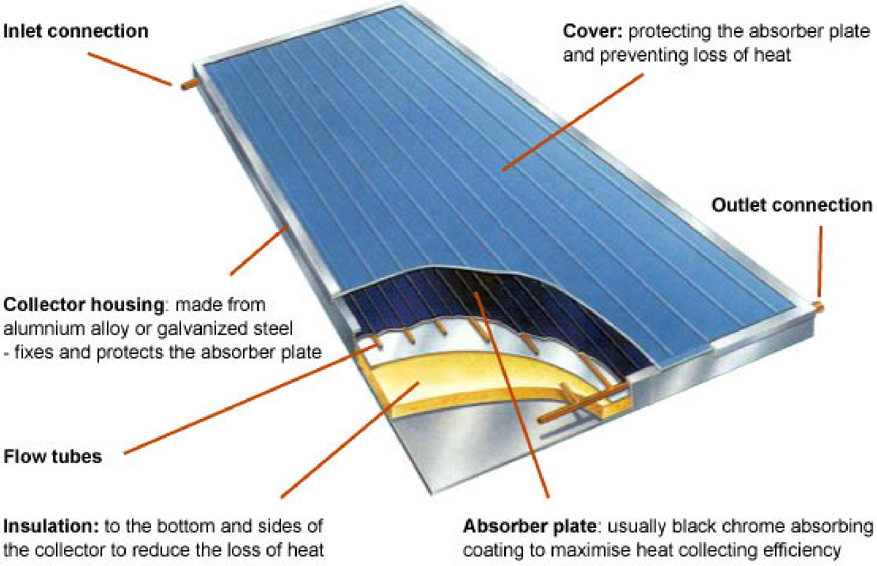
For boilers there are several possible design dimension options to improve energy efficiency; however, none was identified as representing particular metals requirements beyond standard materials such as plastics, glass, steel and base metals. Many of the options represented improved controls, heat exchanges and standby modes (VHK for EC, 2007):

- steady state efficiency and power input
- turndown ratio and standby heat loss
- circulation and electric heat pumps, and fans
- air-fuel ratio, temperature, valve and weather controls.

For ventilation and cooling the eco-design research identified a number of possible changes in design that could offer energy efficiency improvements, as well as identifying the materials involved in achieving them. The analysis of the material composition of current types of ventilation systems identified plastics, steel, aluminium and copper as the major materials. The bill of materials for the modified systems identified the same major materials within the alternative more energy efficient designs (EC, 2008a). The alterations included improvements in motor, fan and air flow design; motor and fan control, heat recovery and noise control.

For solar thermal, Figure 16 shows a diagram for the materials associated with a flat plate collector. In a solar water heating system the collectors are usually installed on the roof of the building, with circulating fluids delivering the solar heat from the collectors to the storage tank. The heat is then transferred to the water in the storage tank via a heat-exchanger. Other system components are the pump and pump controller, temperature display, expansion vessel and valves. The major materials associated are glass, plastic, steel, aluminium and copper; none of which represents major metals requirements.

*Figure 16: Diagram of a flat plate solar thermal collector*



*Source: Greenspec, 2012*

## 3.11 Road transport efficiency

### 3.11.1 Electric vehicles

Critical metals including rare earths are found in many applications within electric vehicles. Examples include cerium and lanthanum in fuel additives and rare earths in LCD screens. In this instance the focus is on the applications where the largest amounts of critical metals can be found, namely the electric drive motor and battery pack. The materials demand for electric vehicles varies depending on the range and type of vehicle and the battery used. A summary of these different materials demands is given in Table 53. To estimate the materials requirements of batteries and motors for the different vehicle types, the vehicle specifications are shown Table 54 (MIT, 2008). The battery types and market shares are shown on the next pages. For graphite, it is noted that very substantial losses occur in the production of spherical battery grade graphite. These losses can be up to 70-75% of the raw material - flake graphite (Industrial

Minerals, 2012) - and the processing waste is not recoverable for use in batteries. To a certain extent there are manufacturing losses associated with all of the technologies and metals. However, as an industrial mineral, the physical properties are as important as the chemical properties, which limit the recycling potential of graphite. In contrast, manufacturing losses for metals are more readily recyclable.

*Table 53: Materials demand for battery- and drive motor-types* in kg per vehicle, by vehicle type*

| Material | BEV | HEV | PHEV-50 | Mild hybrid | FCV |
|---|---|---|---|---|---|
| Li | 4.52-7.81 | 0.09-0.16 | 0.77-1.33 | - | 0.12-0.21 |
| Ni | 0-46.65 | 0-6.67 | 0-7.97 | - | 0-1.26 |
| Co | 0-13.91 | 0-1.16 | 0-2.38 | - | 0-0.38 |
| La | - | 0-1.16 | - | - | - |
| Nd | 2.80 | 0.76-1.12 | 1.46 | 0.36 | 2.91 |
| Pr | - | 0-0.08 | - | - | - |
| Sm | - | 0-0.08 | - | - | - |
| Mn | 0-60.07 | 0-1.25 | 0-10.26 | - | 0-1.63 |
| Cu | 0-71.08 | 0-1.48 | 0-1.93 | - | 0-0.1.93 |
| Ti | 0-38.78 | 0-0.81 | 0-6.63 | - | 0-1.05 |
| Dy | 0.28 | 0.14-0.29 | 0.22 | 0.05 | 0.43 |
| B | 0.09 | 0.03 | 0.04 | 0.01 | 0.09 |
| Graphite | 0-85.94 | 0-1.79 | 0-14.68 | - | 0-2.33 |
| Ce | - | 0-0.77 | - | - | - |

**fuel cell vehicles (FCV), battery electric vehicles (BEV), plug-in electric vehicles (PHEV), mild hybrids (mild HV) and hybrid electric vehicles (HEV).*

*Table 54: Vehicle specifications for different types of electric vehicles*

| | HEV | PHEV-50 | BEV | FCV |
|---|---|---|---|---|
| Motor power (kW) | 25 | 40 | 70 | 90 |
| Battery energy (kWh) | 1.0 | 8.2 | 35 | 1.3 |
| Battery Power (kW) | 28 | 45 | 75 | 40 |
| Specific energy (Wh/kg) | 100 | 135 | 150 | 100 |

*PHEV-30 = plug-in hybrid with a 50 kilometre all electric range.*

***Batteries for electric vehicles***

Improving battery technologies is paramount to lowering overall vehicle costs and improving performance. There are two types of battery which are under consideration; these are nickel metal hydride (NiMH) batteries and lithium-ion (Li-ion) batteries. For HEVs, the market share predictions for battery types from Deutsche Bank are used, as shown in Table 55 (Deutsche Bank Global Markets Research, 2008).

*Table 55: Market share of HEV batteries*

| | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|---|---|
| NiMH | 70% | 65% | 60% | 50% | 40% | 30% | 1% | 0% |
| Li-Ion | 30% | 35% | 40% | 50% | 60% | 70% | 99% | 100% |

***Nickel metal hydride batteries***

NiMH batteries currently dominate the HEV market and have been the battery of choice for the Toyota Prius since it was first introduced. However, for BEVs and PHEVs NiMH cannot compete with Li-ion batteries due to their lower energy density and due to their relatively low deep-cycling capability. Consequently, Toyota has decided to use Li-ion batteries for their new plug-in hybrid model.  As NiMH batteries are not widely used in BEVs or PHEVs, they will only be considered for hybrid electric vehicles. The metals requirements for an HEV NiMH battery are shown in Table 56; it has been assumed that the battery alloy used is AB5.

*Table 56: Metals requirements for NiMH batteries for HEVs in kg per vehicle*

| Metal | HEV |
|---|---|
| Ni | 6.67 |
| Co | 1.16 |
| La | 1.16 |
| Ce | 0.77 |
| Nd | 0.23 |
| Pr | 0.08 |
| Sm | 0.08 |

***Lithium-ion batteries***

The main battery chemistry for the foreseeable future is expected to be Li-ion, and in 2011 they accounted for over 40% of the battery chemistry split; this is expected to rise to over 80% in 2015 (Frost & Sullivan, 2011a). The composition of Li-ion batteries varies depending on the cathode chemistries employed. The amount of lithium varies significantly across the different types, from around 0.2 kg to 10 kg per vehicle. Battery packs found in electric vehicles contain a range of materials, with the active materials typically representing less than 50% of the overall weight. Other materials found include copper for wiring and electrical parts, aluminium and plastics for casings and small amounts of precious metals in printed circuit boards.

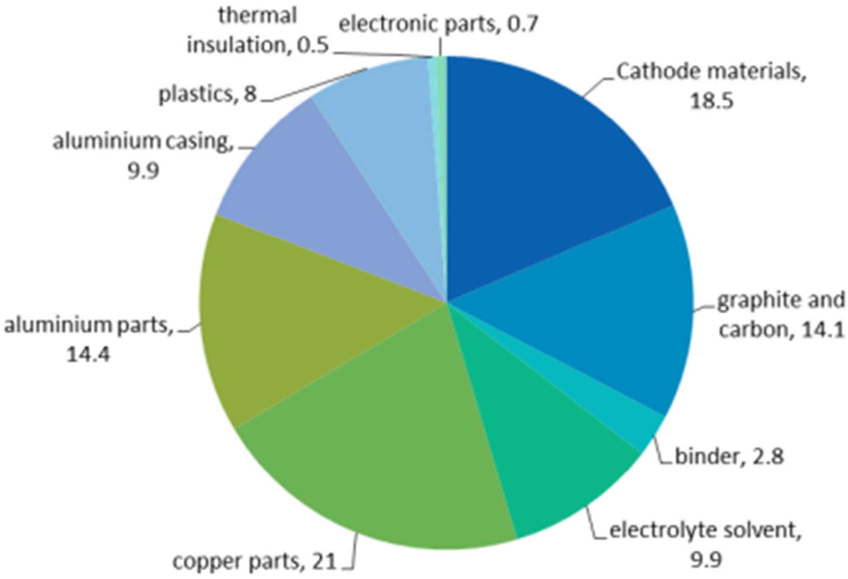
Four different cathode chemistries have been chosen for further investigation, presented in Table 57. Although, there are currently many types of Li-ion batteries in the pipeline, such as lithium air, the focus of this study is on these four battery types as they are likely to be the most widely used for the short-to-medium term. It is expected that these battery types will be optimised for use in EVs in the near term and in the longer term, new battery chemistries with higher energy densities will be developed (IEA, 2011a). All of these battery chemistries are currently in commercial use in electric vehicles and are therefore well characterised. It is worth noting that the exact compositions of cathode chemistries vary with supply, and it is possible to have dual composite cathodes where two different active materials are used.

*Table 57: Characteristics of different Li-ion batteries* by cathode chemistry (Saft Groupe SA, 2009)*

| | NCA | LFP | LMS-titanate | NMC |
|---|---|---|---|---|
| Energy (Wh/kg) | Good | Average | Poor | Good |
| Power | Good | Good | Good | Average/good |
| Calendar life | Very good | Poor above 30°C | Poor | Good |
| Cycle life | Good | Good | Average | Good |
| Safety (per kWh) | Poor | Good | Average | Poor |
| Cost | High | Average | Average | High |
| Maturity | High | Low | High | Medium |

**nickel cobalt aluminium (NCA), lithium iron phosphate (LFP), lithium manganese spinel (LMS), nickel cobalt manganese (NCM)*

*Figure 17: Battery pack component breakdown by weight (%)*



*Source: Gaines et al., 2010*

Nickel cobalt aluminium (Li $Co_{0.15}Al_{0.05}O_2$) battery types (NCA) are similar to lithium cobalt oxide ($LiCoO_2$) which are commonly used in laptop batteries and mobile phones. The advantages of NCA batteries are that they have good energy and power densities; however, they are expensive compared to other battery types. Toyota's plug-in Prius uses NCA batteries (Committee on Climate Change, 2012).

*Table 58: Materials requirements in kg per vehicle for NCA battery types*

| Material | BEV | HEV | PHEV-50 | FCV |
|---|---|---|---|---|
| Li | 6.23 | 0.13 | 1.06 | 0.17 |
| Ni | 46.65 | 0.97 | 7.97 | 1.26 |
| Co | 8.44 | 0.18 | 1.44 | 0.23 |
| Al | 1.35 | 0.03 | 0.23 | 0.04 |
| Graphite | 72.19 | 1.50 | 12.33 | 1.96 |
| Cu (anode) | 66.82 | 1.39 | 11.41 | 1.81 |

Lithium iron phosphate ($LiFePO_4$) based batteries (LFP) have superior thermal and chemical stability compared to other Li-ion technologies. However, phosphate batteries have lower energy densities than cobalt batteries (Axeon, undated). They are used in electric vehicles manufactured by BYD, who also manufacture LFP cells (Axeon, undated; CreditSuisse, 2009a).

*Table 59: Materials requirements in kg per vehicle for LFP battery types*

| Material | BEV | HEV | PHEV-50 | FCV |
|---|---|---|---|---|
| Li | 4.52 | 0.09 | 0.77 | 0.12 |
| Fe | 39.08 | 0.81 | 6.68 | 1.06 |
| Graphite | 85.94 | 1.79 | 14.68 | 2.33 |
| Cu (anode) | 79.54 | 1.66 | 13.59 | 2.15 |

Lithium manganese spinel oxide batteries (LMS) provide a higher cell voltage and are more thermally stable than cobalt-based batteries. An advantage of this cell chemistry is that it is based on manganese which is relatively non-toxic and inexpensive. In this instance they are considered with a lithium titanate oxide anode instead of a graphite anode, as these are often used in conjunction with each other. Compared to graphite anodes, lithium titanate anodes offer better power and rate capability (Axeon, n.d.).

*Table 60: Materials requirements in kg per vehicle for LMS-titanate battery types*

| Material | BEV | HEV | PHEV-50 | FCV |
|---|---|---|---|---|
| Li | 7.81 | 0.16 | 1.33 | 0.21 |
| Mn | 60.07 | 1.25 | 10.26 | 1.63 |
| Cu (anode) | 71.08 | 1.48 | 12.14 | 1.93 |
| Ti | 38.78 | 0.81 | 6.63 | 1.05 |

Nickel cobalt manganese ($LiNi_xCo_yMn_zO_2$) batteries (NCM) offer a compromise of cost and electrochemical performance, and in terms of energy density they are superior to LFP batteries. NCM batteries can be found in many consumer electrical goods and in EV prototypes (Committee on Climate Change, 2012).

*Table 61: Materials requirements in kg per vehicle for NCM battery types*

| Material | BEV | HEV | PHEV-50 | FCV |
|---|---|---|---|---|
| Li | 4.64 | 0.10 | 0.79 | 0.13 |
| Ni | 14.43 | 0.30 | 2.46 | 0.39 |
| Co | 13.91 | 0.29 | 2.38 | 0.38 |
| Mn | 12.88 | 0.27 | 2.20 | 0.35 |
| Graphite | 53.08 | 1.11 | 9.07 | 1.44 |
| Cu (anode) | 49.13 | 1.02 | 8.39 | 1.33 |

***Electric drive motors***

Permanent rare earth magnets are the dominant technology used for motors in all types of electric vehicles. A few exceptions, such as the Tesla Roadster and the Mini-E, use induction motors (Bauer et al., 2011). Hybrid and electric drive train applications typically use 8.7% dysprosium (by weight) in their magnets (Bauer et al., 2010). The materials composition of the permanent magnet motors used for the different vehicle types is shown in Table 62.

*Table 62: Magnet composition (%) of drive motor by vehicle type*

| | HEV (2012) | HEV (2020-) | PHEV-50 | BEV | FCV | Mild Hybrid |
|---|---|---|---|---|---|---|
| Nd | 22.5 | 27.0 | 27.0 | 27.0 | 27.0 | 27.0 |
| Fe | 66.0 | 66.0 | 66.0 | 66.0 | 66.0 | 66.0 |
| Dy | 8.5 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| B | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

The majority of electric vehicles use NdFeB permanent magnet technology for their drive motor, however some EVs currently on the market use induction motors and to reflect this, these have been included into our model. Induction motors do not require permanent magnets and therefore rare earth elements, instead they use copper coils to produce a magnetic field. Consequently, their requirements for copper are relatively high, for instance a typical induction motor for a fully electric BEV requires 80kg of copper.

*Table 63: Metals requirements for electric drive motors in kg per vehicle*

| Motor Type | Material | HEV (2012) | HEV (2020-) | PHEV | BEV | FCV | Mild hybrid |
|---|---|---|---|---|---|---|---|
| Permanent magnet | Nd | 0.76 | 0.91 | 1.46 | 2.55 | 2.92 | 0.36 |
| | Fe | 2.25 | 2.25 | 3.6 | 7.65 | 8.1 | 0.90 |
| | Dy | 0.29 | 0.14 | 0.22 | 0.38 | 0.38 | 0.05 |
| | B | 0.025 | 0.025 | 0.04 | 0.085 | 0.09 | 0.01 |
| Induction | Cu | 25 | 25 | 40 | 70 | 80 | 10 |

## 3.12 Desalination

A key material need in desalination plants of any type is for corrosion resistant materials. The choice of material is a compromise between investment and operating costs, performance and durability. The required characteristics for the corrosion resistant materials vary depending on the type of desalination plant (multi-stage flash distillation-MSF, multiple-effect distillation-MED, reverse osmosis-RO) and the corrosive conditions in different sections of the desalination plant (e.g. tubing, valves, pumps or evaporation chambers). The most severe conditions are found in MSF plants followed by MED plants. Conditions in RO plants are much less severe as they operate at low temperatures (< 70°C; Malik and Kutty, 1992; Richaud-Minier et al., 2007)

### 3.12.1 Thermal plants

Different metals and alloys are used in different sections of thermal desalination plants. In addition, due to choices for each section that also have to do with raw material pricing in addition to technical characteristics, the raw material profile of different thermal plants of the same type is also different. For example, MSF plants in Saudi Arabia at the turn of the century used mostly steel, stainless steel, copper-nickel alloy and titanium for parts such as (Malik and Kutty, 1992; Hamed et al., 2001):

- Brine heaters – shell made from carbon steel and tubes made from 70/30 or 90/10 Cu-Ni alloy, but with exceptions (Ti tubing). It is worth noting that heat exchanger tubes are the single largest procurement item in an MSF plant and at the same time account for 70% of corrosion failures.
- Flash chambers – carbon steel with and without cladding of some or all of the chambers; cladding in some plants is made out of stainless steel or 90/10 Cu-Ni alloy.
- Heat rejection tubes – mostly made from Ti but with exceptions (90/10 Cu-Ni).

Generally, Ti is used for the parts most at risk of corrosion and copper alloys for the less critical parts (Richaud-Minier et al., 2007). However, due to high costs for Ni and Ti, high alloy steels with up to 29% Cr (Richaud-Minier et al., 2007; Richaud-Minier, 2008) have become competitive both in performance and costs. Duplex stainless steel (21.5-25% Cr, 1.5-7% Ni, 0.3-4% Mo) can be used for critical components in both MSF and MED plants (Outokumpu, 2010, 2012a, 2012b). For MED and MSF facilities, the most relevant metals for desalination technologies are Fe, Cr, Ni and Mo for stainless steel, Cu-Ni alloys, and Ti (also with Pd as an alloying element; Angerer et al., 2009). Examples of stainless steel requirements for MED and MSF facilities are Marafiq in Saudi Arabia with 10,000 tonnes stainless steel and 800,000 $m^3$/d capacity and Shuweihat 2 in the United Arab Emirates with 5,800 tonnes stainless steel and 100 MIGD capacity, yielding metal requirements of the order of 3 kg Cr, 1 kg Ni and 0.5 kg Mo per $m^3$/d of capacity (Outokumpu, 2012a, 2012b).

### 3.12.2 Reverse osmosis plants

In the case of RO plants, components like pumps, valves and pipes as well as the casings for the membrane modules need to be resistant to corrosion. As the conditions are less severe than in thermal desalination plants, lower Cr contents are acceptable (> 15% Cr; Oldfield and Todd, 1986; Malik and Kutty, 1992; Malik and Andijani, 2005); for example, stainless steel type 1.4571/316Ti[8] which is considered of 'marine grade' but is not resistant to warm sea water (aalco, 2012; Saravia, 2012).

## 3.13 SET-Plan technologies

The first JRC study addressed the six SET-Plan technologies (wind, solar - both photovoltaics and concentrated solar power, carbon capture and storage, nuclear fission, bioenergy and the electricity grid) (Moss et al., 2011). The first study compared demand figures to the known supply figures in 2010. Furthermore, demand was based on the available scenarios at the time. The results are therefore re-assessed using the

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[8] Containing 16-18% Cr, 2-3% Mo, 10-14% Ni, up to 0.7% Ti depending on the content of C and N

same methodology as above, i.e. the results are now compared to expected supply figures rather than current supply estimates, and the scenarios take into account the latest projections in the EU Energy Roadmap 2050 (EC, 2011b). The technology descriptions are essentially unchanged but the uptake mix of the different types of technologies within a sector can vary. These are presented here. The metals requirement figures are presented in Chapter 4.

### 3.13.1 Wind energy

Recent developments have highlighted a trend to a higher share of permanent magnet electricity generators (PMG) in the future market of wind turbines. Three major items suggest this trend:

- analysis of turbine prototypes introduced or announced to be introduced in the period 2011 - 2013
- the approximately 10-year commercial life of a wind turbine
- the reduction of the prices of rare earths along with the projections of abundant supply from 2014 (Nd) and 2017 (Dy).

Between 2000 and 2004, PMG had an average share of 5% of all turbine prototypes. However, since 2007 this share has grown to 35%. In absolute numbers whereas PMG were included in one or two turbine prototypes per year in 2000-03; since 2010 they have been included in 11-13 turbine prototypes.

The share between low-speed, direct-drive (DD) PMG and medium- and high-speed (MS/HS) PMG is approximately equal. However, the analysis of the turbine models presented suggests that for the offshore turbine prototypes, DD-PMG will prevail over MS/HS-PMG.

Furthermore, based on the projections of the future energy system, it is expected that DD-PMG models will gain an increasing market share of future (2015-20) installations, for examples: Alstom's Haliade 150, Siemens SWT-6.0-154 and XEMC-Darwind / Vensys-Goldwind. These machines are likely to have a growing market share because of the contracts already signed in Europe (Alstom, Siemens) and the prospects for cost reduction from Chinese manufacturers (XEMC, Goldwind).

Significant, non-DD prototypes offshore are represented by Vestas, Gamesa, Bard, REpower, Mitsubishi, Sinovel and Areva. For onshore, it is still the prototypes with electromagnets that prevail, represented by General Electric, Vestas, Alstom, Enercon, REpower, Nordex, Suzlon, and Sinovel. PMG turbines onshore are already significant at world level and therefore it is expected that the penetration of PMG onshore will continue.

### 3.13.2 Solar energy

A number of new scenarios for the solar energy uptake and technology mix have been identified, as well as the EU Energy Roadmap 2050 (EC, 2011b), but also recent IEA roadmaps for both photovoltaic solar and concentrated solar power (IEA, 2011b, 2011c). Analysis of the IEA scenarios showed that the projections were relatively similar to those modelled in the first JRC study (Moss et al., 2011). In contrast the EU Energy Roadmap 2050 scenarios were deemed to be too pessimistic.

### 3.13.3 Carbon capture and storage

The results for CCS from the first JRC study highlighted vanadium and niobium as representing important materials requirements for the implementation of the EU SET-Plan. Here the results have simply been rescaled against projected supply, although it is noted that the EU Energy Roadmap 2050 scenarios (EC, 2011b), are significantly more pessimistic on the uptake of CCS before 2030.

### 3.13.4 Smart electricity grids

For smart electricity grids, the first JRC study modelled the metals requirements associated with ENSTO-E's list of projects of European Significance to 2020 (ENTSO-E, 2010). No more up-to-date appropriate scenarios have been identified.

### 3.13.5 Biofuels

For biofuels, the first JRC study identified that the same catalysts currently used for fossil fuels would be used, and therefore there would not be any additional materials requirements. The reference scenario of the EU Energy Roadmap 2050 (EC, 2011b) is used.

### 3.13.6 Nuclear energy

For nuclear energy it is clear that the aftermath of the Fukushima events in Japan during 2011 have led to a number of countries that use nuclear energy to reconsider their energy policies. The vast majority of countries, however, remain firmly committed to their nuclear power programmes and – as after any major industrial accident – committed to learning lessons and improving safety. Nevertheless, some governments have turned against nuclear power and seek to implement alternatives. Within Europe, these countries are Germany, Belgium, Switzerland and Italy (World Nuclear Association, 2012):

- Germany had 17 operational reactors prior to the Fukushima accident, but following the accident the government decided to immediately and permanently shut down the seven oldest units and to forbid the one undergoing upgrades to restart. It has also re-instated a previously held phase-out policy that, if maintained, will see the last German reactor cease operations by 2022.
- Belgium has decided to reverse a 2009 policy that would have seen reactors operate for about 50 years, and instead shut them down 10 years earlier, with some now due to close by 2015.
- Switzerland opted to veto the replacement of nuclear generating capacity, which means that, based on 50-year operating lifetimes, nuclear power generation in the country would cease in 2034.
- Italy had been looking at starting a nuclear energy programme, but has now cancelled these plans.

As a result of these major policy changes, it is therefore appropriate to model a scenario that assumes a significantly lower implementation of nuclear energy in Europe. The chosen scenario for this is the reference scenario of the EU Energy Roadmap 2050 scenarios (EC, 2011b), which has fairly constant net capacity up to 2030.

# 4. Metal Requirements of Technologies

## 4.1 Introduction

This chapter presents the quantitative results of calculating the materials requirements of energy technologies deployed during the path to the decarbonisation of the EU energy sector, building on the previous chapter in which the materials composition of each technology was determined.

The approach taken in the last chapter was a bottom-up approach to compile an inventory of all metals used in each technology using an appropriate functional unit, such as kg/MW. In this chapter the estimates of the material composition of each technology are scaled up, according to the projected uptake of the technology under various scenarios - although where possible and depending on which technology, the most extreme scenario of the EU Energy Roadmap 2050 has been used (EC, 2011b). Likewise, the results from the first JRC study (Moss et al., 2011) are re-assessed using the data from the Energy Roadmap 2050, which was not available in 2011.

At the end of the chapter a reduced list of metals is derived representing the most significant materials requirements associated with the path to the decarbonisation of the EU energy sector. These are based upon the proportion of expected world supply that is estimated to be required within the EU. As projected supply has been used in the analysis, a lower cut-off value has been used than in the first study (ca. 0.3% of world supply rather than 1%). Attention is also given to use of the materials within the electronics/ICT and automotive sectors, as these sectors are in competition with the energy sector for the same resources.

## 4.2 Expected supply of metals

To get a sense of scale of the EU material demand estimates, it is important to provide the context of metals supply estimates. The latest available data for metals supply estimates is for 2011. The EU materials demand estimates can also be compared against long term supply projections for 2020 and 2030. This aims to provide a more dynamic measure of materials availability.

There is potentially a total of 60 materials of relevance to analyse (Table 64), so it is not practical to produce a detailed forecast for each of them. The approach therefore needs to be relatively generic and to apply largely a common data source and methodology. The length of the projections is around 20 years – 2011 to 2030. However, due to the volatility that is inherent in many commodity markets - particularly those for many minor metals - a long-term forecast cannot be considered reliable. Indeed, even for the base metals (i.e. copper, lead, nickel, steel, tin and zinc) for which the markets are much more transparent and less volatile than the minor metals, most forecasts are only for a period of around 2-5 years. It is therefore clear that the projections here should not be regarded as forecasts. Table 64 does not include the platinum group metals and the rare earth elements. These special groups are assessed in Sections 4.2.1 and 4.2.2 respectively, using additional data (Johnson Matthey, 2012; IMCOA in US DOE, 2011) to identify the supply of the individual metals within each group.

The main source of data used for the long term supply projections is historical supply data provided by the USGS Mineral Commodity Specialists for around 90 mineral commodities (US Geological Survey (USGS), 2011a). Long term supply trends have then been linearly extrapolated to form the supply projections to 2030. Some supplementary data has been included for particular metals where additional data was felt to be useful in providing further details or was missing from USGS data. More detail is given in Table 64 and in Appendix 3, where historical and predicted production data are illustrated graphically. For many metals an allowance has been made for supply from recycled content as indicated by (UNEP, 2011) and other references (see Appendix 4).

*Table 64: Current estimates and future projections of annual metal production for various metals (tonnes)*

| **Metal** | **Symbol** | **Production Type** | **2011** | **2020** | **2030** | **Compound Annual Growth Rate (CAGR) over 20 years** |
|---|---|---|---|---|---|---|
| Antimony[#] | Sb | Mine | 198,800 | 261,580 | 317,000 | 2.49% |
| Arsenic | As | Trioxide | 52,000 | 59,400 | 62,800 | 1.00% |
| Barytes* | Ba | Mine | 7,800,000 | 9,112,000 | 10,331,300 | 1.49% |
| Beryllium[#] | Be | Mine | 300 | 322 | 405 | 1.59% |
| Bismuth | Bi | Mine | 8,500 | 11,040 | 14,230 | 2.75% |
| Boron | B | All forms | 4,300,000 | 4,835,600 | 5,498,500 | 1.30% |
| Cadmium[#] | Cd | Refinery | 30,700 | 33,600 | 37,000 | 0.99% |
| Chromium[#] | Cr | Mine | 9,145,000 | 12,823,600 | 16,911,000 | 3.29% |
| Cobalt[#] | Co | Mine | 130,700 | 227,000 | 336,700 | 5.11% |
| Copper[#] | Cu | Mine | 19,777,000 | 23,159,000 | 27,386,000 | 1.73% |
| Gallium[#1] | Ga | Refinery | 288 | 450 | 630 | 4.21% |
| Germanium[#] | Ge | Refinery | 197 | 319 | 433 | 4.25% |
| Gold[#] | Au | Mine | 4,310 | 5,780 | 7,140 | 2.69% |
| Graphite* | C | Mine | 925,000 | 1,178,000 | 1,311,740 | 1.86% |
| Hafnium[2] | Hf | Refinery | 85 | 112 | 142 | 2.74% |
| Indium[#1] | In | Refinery | 1,360 | 1,900 | 2,500 | 3.26% |
| Lead[#] | Pb | Mine | 9,656,000 | 12,588,000 | 15,846,500 | 2.64% |
| Lithium[3] | Li | Li Content | 20,800 | 28,250 | 36,500 | 3.01% |
| Magnesium[#] | Mg | Primary | 1,114,300 | 1,545,900 | 2,018,400 | 3.18% |
| Manganese[#] | Mn | Mine | 20,895,500 | 29,720,500 | 39,295,000 | 3.38% |
| Mercury | Hg | Mine | 1,930 | 2,375 | 2,875 | 2.12% |
| Molybdenum[#] | Mo | Mine | 333,300 | 483,210 | 648,340 | 3.56% |
| Nickel[#] | Ni | Mine | 2,686,500 | 3,752,000 | 5,065,500 | 3.39% |
| Niobium[#] | Nb | Mine | 78,750 | 131,212 | 180,985 | 4.48% |
| Rhenium[#] | Re | Mine | 65 | 89 | 111 | 2.81% |
| Scandium[4] | Sc | Refinery | 10 | 30 | 50 | 8.84% |
| Selenium[4] | Se | Refinery | 2,650 | 3,940 | 4,970 | 3.36% |
| Silver[#] | Ag | Mine | 32,050 | 36,600 | 43,075 | 1.57% |
| Strontium | Sr | Mine | 380,000 | 590,100 | 641,100 | 2.79% |
| Tantalum[#] | Ta | Mine | 988 | 1,301 | 1,820 | 3.27% |
| Tellurium[#1] | Te | Refinery | 742 | 1,255 | 1,826 | 4.86% |
| Thallium | Tl | Mine | 10 | 10 | 10 | 0.00% |
| Tin[#] | Sn | Mine | 334,150 | 415,750 | 482,600 | 1.95% |
| Titanium[5] | Ti | $TiO_2$ Content | 6,000,000 | 6,940,900 | 7,986,400 | 1.52% |
| Tungsten[#] | W | Mine | 120,000 | 146,600 | 181,600 | 2.20% |
| Vanadium | V | Mine | 60,000 | 73,800 | 88,400 | 2.06% |
| Zinc[#] | Zn | Mine | 15,500,000 | 19,353,500 | 23,758,000 | 2.27% |
| Zirconium | Zr | Mine | 1,410,000 | 1,928,200 | 2,486,500 | 3.03% |

*Source: USGS, 2012 & UNEP, 2011, for 2011 unless stated above; Oakdene Hollins projections thereafter*

*#: Supply estimates include an allowance for production from recycled content as indicated by (UNEP, 2011) or other references.*

*See Appendix 5 for further details on data sources and the methodology that has been used.*

** Barytes and Graphite are both technically defined as industrial minerals rather than as metals*

*1: Gallium, Indium & Tellurium 2011 data from (Bauer et al., 2011)*

*2: Hafnium 2011 data from (Moss et al., 2011)*

*3: Lithium 2010 Li content data from (British Geological Survey (BGS), 2012a)*

*4: Scandium and selenium 2011 data from (International Study Group for Nickel, 2012)*

*5: Titanium 2010 $TiO_2$ content data from (BGS, 2012a)*

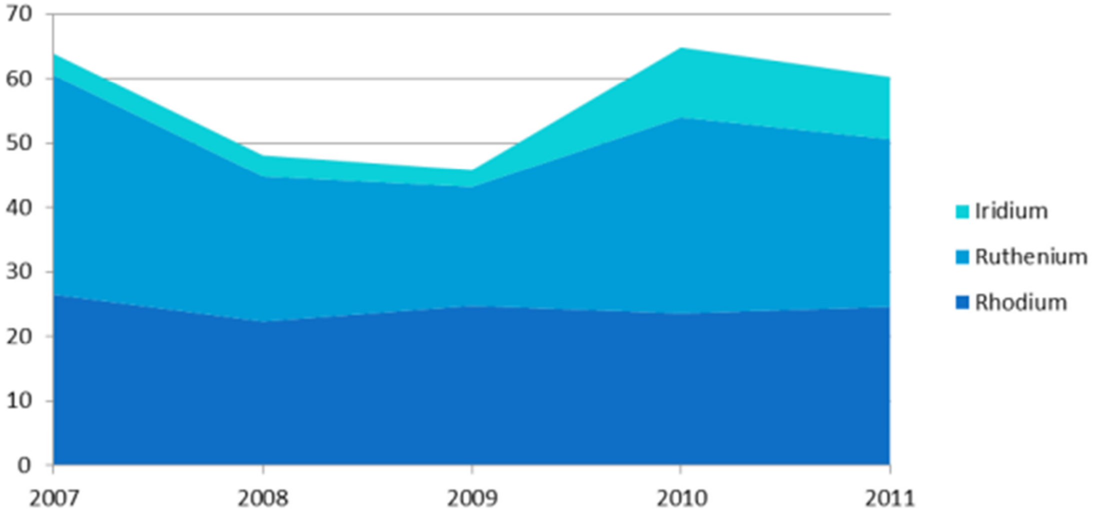
### 4.2.1 Platinum group metals

For the platinum group metals, the USGS provides historical data on the production of platinum, palladium and 'other platinum group metals' (USGS, 2011b). This data shows that the production ratios have remained fairly constant over time, with platinum and palladium production each accounting for just over 40% of total supply of platinum group metals.

Detailed supply data for the individual metals within 'other platinum group metals' is not published. However, Johnson Matthey does publish demand estimates for rhodium, ruthenium and iridium (Figure 18). Some demand volatility is observable in the data; however, the supply of each of these metals will be closely linked to that of the host metals due to the relative concentrations in the ores. Supply data has therefore been averaged and used to disaggregate the category 'other platinum group metals'. Production of osmium is an order of magnitude smaller. The USGS reports imports of just 76 kg of osmium in 2010 or 0.2% combined imports of rhodium, ruthenium, iridium and osmium (USGS, 2011b).

In addition, an estimate of world production from recycled sources has been included using data provided within (Johnson Matthey, 2012) and (UNEP, 2011). Based on these data sources, Table 65 provides supply projections of the individual platinum group metals for 2020 and 2030.

*Figure 65: Demand for rhodium, ruthenium and iridium (tonnes)*



*Source: Johnson Matthey, 2012*

*Table 59: Current estimates and future projections of annual metal production for individual platinum group metals (tonnes)*

| **Metal** | **Symbol** | **2011** | **2020** | **2030** |
|---|---|---|---|---|
| Platinum# | Pt | 259 | 337 | 414 |
| Palladium# | Pd | 277 | 368 | 463 |
| Rhodium# | Rh | 40 | 50 | 60 |
| Ruthenium# | Ru | 67 | 81 | 92 |
| Iridium# | Ir | 9 | 11 | 12 |
| Osmium | Os | 0.1 | 0.2 | 0.2 |
| **Platinum Group Metals** | **PGMs** | **652** | **847** | **1,041** |

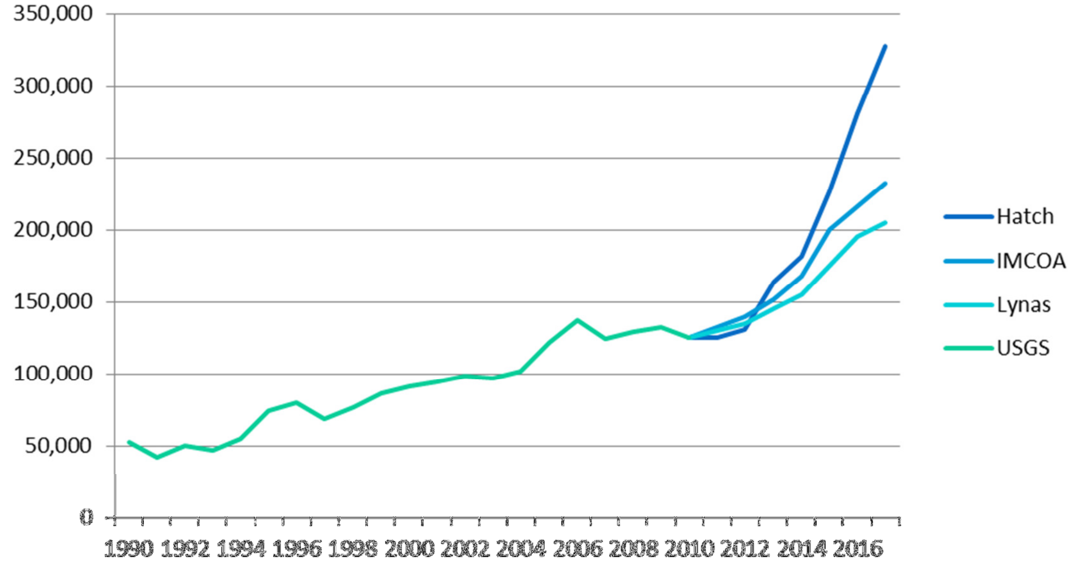
*Source: Compositional and trend data derived from (USGS, 2011b; Johnson Matthey, 2012)*
*#: Supply estimates include an allowance for production from recycled content as indicated by (Johnson Matthey, 2012) or (UNEP, 2011).*
*See Appendix 5 for further details on data sources and the methodology that has been used.*

### 4.2.2 Rare earth elements

The USGS provides historical data on the total world production of rare earth oxides, but there are various different projections of future supply of rare earth elements (Figure 19). The most conservative forecast is by junior mining company, Lynas, which predicts rare earth supply of 155,000 tonnes for 2014 when there is a significant cut in production from Southern Chinese clays. IMCOA's forecast, contained within the US Department of Energy Critical Materials Strategy, is for 200,000 tonnes of rare earth production capacity for 2015. Tech Metals Research, (Hatch, 2011), is much more optimistic, putting 2017 supply at 327,000 tonnes in its average scenario.

For this study, the middle view - of IMCOA - has been selected as the baseline. This is in part because this is an independent forecast which has already been scrutinised by experts at the US Department of Energy, but also because of the considerable experience that IMCOA has in assessing the viability of future rare earth mine prospects. In contrast, the Tech Metals Research scenario is believed by the authors to be too optimistic, underestimating the difficulties of bringing new rare earth supply to the market. The Lynas scenario is relatively conservative, and highlights some of the risks should there be a significant cut in rare earth production in China.

*Figure 19: Estimates and projections of annual metal production for rare earth elements (tonnes)*



*Sources: USGS, 2012 data till 2010, interpolation and extrapolation of Lynas Corporation Ltd, 2010 IMCOA in US DOE, 2011 and Hatch, 2011.*

However, for the purposes of this study, detailed supply data is required on each of the individual rare earth elements. The composition of world rare earth supply is not presumed to remain constant over time, and is dependent on the composition of exactly which mines commence production. Figure 20 illustrates this using IMCOA data (IMCOA in US DOE, 2011), which shows the composition of world 2010 rare earth supply, of which the share of heavy rare earth elements[9] is approximately 15%. The addition of light rare earth[10] dominant mines such Mountain Pass, Mount Weld and Nolans Bore takes the heavy rare earth fraction of world supply down to around 10% in 2015.

It is hard to predict how rare earth supply will develop further into the future, as there are some advanced rare earth projects[11] with significant heavy rare earth content, as well as those that do not (Technology Metals Research, n.d.). The projections used in this study do not assume further reduction in the

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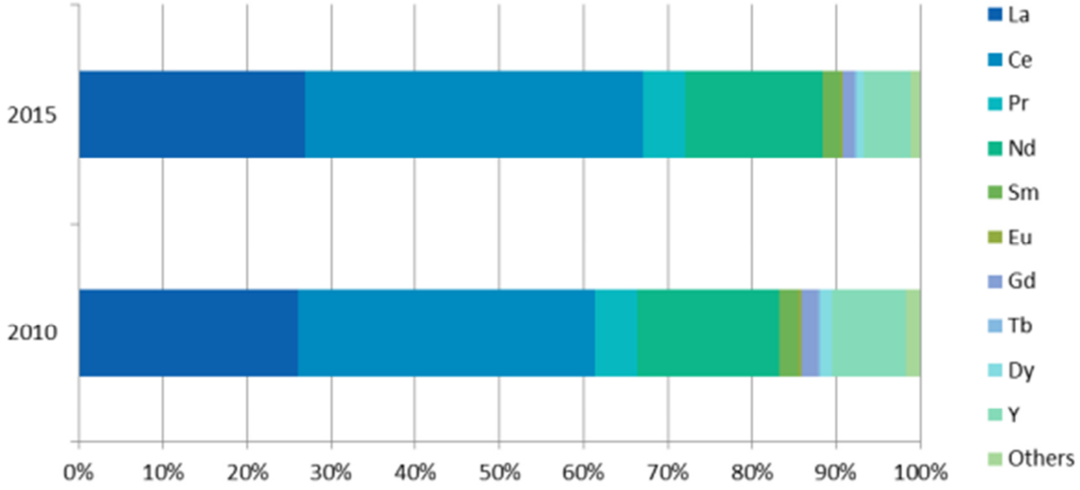
[9] Heavy rare earth elements typically include: europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium

[10] Light rare earth elements typically include: lanthanum, cerium, praseodymium, neodymium and samarium

[11] Advanced projects are defined as where either the mineral resource or reserves have been formally defined or where the project has been subject to past mining campaigns for which reliable historic data is available

share of heavy rare earths as a fraction of total supply beyond 2015, but a continuation of the 2015 rare earth supply composition. This therefore implicitly assumes a mix of different types of rare earth deposits that commence production. Table 66 shows the results of the projections assumed in this study for the individual rare earth elements. This highlights the relative difference assumed in increases of supply growth rates for light versus heavy rare earth elements. A five-percent recycled content has also been assumed for certain rare earth elements, based upon (UNEP, 2011).

*Figure 20: Forecast changes in the composition of world rare earth supply*



*Source: IMCOA in US DOE, 2011*

*Table 66: Estimates & projections of annual metal production for individual rare earth elements (tonnes)*

| **Metal** | **Symbol** | **2011** | **2020** | **2030** | **Implied CAGR** |
|---|---|---|---|---|---|
| Lanthanum[#] | La | 35,680 | 79,135 | 124,355 | 6.79% |
| Cerium[#] | Ce | 48,340 | 118,705 | 186,535 | 7.37% |
| Praseodymium[#12] | Pr | 6,790 | 14,510 | 22,800 | 6.58% |
| Neodymium[#] | Nd | 23,020 | 48,360 | 75,995 | 6.49% |
| Samarium | Sm | 3,060 | 5,570 | 8,750 | 5.68% |
| Europium | Eu | 405 | 765 | 1,200 | 5.90% |
| Gadolinium | Gd | 2,625 | 4,180 | 6,560 | 4.94% |
| Terbium | Tb | 350 | 515 | 810 | 4.51% |
| Dysprosium[#] | Dy | 1,840 | 2,490 | 3,915 | 4.05% |
| Pm-Er-Ho-Tm-Yb-Lu | - | 2,190 | 3,200 | 5,030 | 4.48% |
| Yttrium | Y | 11,480 | 15,730 | 24,720 | 4.12% |
| Rare Earth Elements | REE | 135,780 | 293,160 | 460,670 | 6.64% |

*Source: Compositional and trend data from (IMCOA in US DOE, 2011) projections thereafter*
*#: Supply estimates include an allowance for production from recycled content as indicated by (UNEP, 2011).*
*See Appendix 5 for further details on data sources and the methodology that has been used.*

## 4.3 Metal requirements per technology

The following pages and tables present the results of the scenario modelling for each technology. Each provides the full list of metals and the amounts required in tonnes for the EU in 2020 and 2030. This is then compared to the expected supply, as given in the previous sections, for the respective years. Unless otherwise stated, the derived figures are calculated using scenarios in the EU Energy Roadmap 2050. The full results are summarised in Section 4.5 where the reduced list of metals is also presented.

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[12] In the report praseodymium and neodymium (didymium) are treated together, as they are often not separated from each other

### 4.3.1 Hydropower

For hydropower, the metals requirements are shown in Table 67, based upon modelling the high RES scenario of the EU Energy Roadmap 2050 (EC, 2011b). In comparison to expected world supply, these metals requirements are very modest.

*Table 67: Hydropower metals requirements*

| Technology | Elements | Materials demand (kg/MW) | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|---|
| | | | 2020 | 2030 | 2020 | 2030 |
| Hydropower | Ni | 31.0 | 23.72 | 15.87 | <0.1% | <0.1% |
| | Mo | 2.9 | 2.22 | 1.48 | <0.1% | <0.1% |
| | Cu | 67 | 51.26 | 34.30 | <0.1% | <0.1% |
| | Mg | 1.92 | 1.47 | 0.98 | <0.1% | <0.1% |
| | Cr | 12.5 | 9.56 | 6.40 | <0.1% | <0.1% |
| | Pb | 5.36 | 4.10 | 2.74 | <0.1% | <0.1% |
| | Zn | 5 | 3.83 | 2.56 | <0.1% | <0.1% |
| | Mn | 1.7 | 1.30 | 0.87 | <0.1% | <0.1% |
| | Ti | 0.24 | 0.18 | 0.12 | <0.1% | <0.1% |
| | Sn | 0.00308 | 0.00 | 0.00 | <0.1% | <0.1% |
| | Zr | 0.000013 | 0.00 | 0.00 | <0.1% | <0.1% |

### 4.3.2 Geothermal energy

For geothermal energy, the metals requirements are shown in Table 68, based upon modelling the high RES scenario of the EU Energy Roadmap 2050 (EC, 2011b). This analysis highlights the usage of tantalum and nickel, within some of the speciality high temperature alloys, as representing relatively modest material requirements.

*Table 68: Geothermal energy metals requirements*

| Technology | Elements | Materials demand (kg/MW) | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|---|
| | | | 2020 | 2030 | 2020 | 2030 |
| Geothermal | Ta | 64.0 | 2.50 | 7.68 | 0.2% | 0.4% |
| | Ni | 120,155 | 4,686 | 14,419 | 0.1% | 0.3% |
| | Mo | 7,209 | 281 | 865 | 0.1% | 0.1% |
| | Cr | 64,405 | 2,512 | 7,729 | <0.1% | <0.1% |
| | Nb | 128 | 4.99 | 15.36 | <0.1% | <0.1% |
| | Ti | 1,634 | 64 | 196 | <0.1% | <0.1% |
| | Cu | 3,605 | 141 | 433 | <0.1% | <0.1% |
| | Mn | 4,325 | 169 | 519 | <0.1% | <0.1% |

### 4.3.3 Marine energy

Of the sub-technologies considered for marine energy, only tidal barrages (akin to conventional hydropower plants) can be considered as a mature technology. Despite their track record, however, the installation of tidal barrages is costly and tied to specific locations. Wave energy has the greater potential, as outlined in the SETIS forecast for 2020 and 2030 (EC, 2011c), which is based on the forecast provided by the EOEA in its Ocean Energy Roadmap (EOEA, 2010). However, wave energy is not expected to have a large impact on the overall EU ocean energy production.

No scenario for marine energy is explicitly identified in the 2050 roadmaps. The modelling here is therefore based upon scenarios from DG Energy's "EU Energy Trends to 2030", where marine energy is explicitly listed as tidal etc. Based on this scenario, none of the metals requirements for marine energy are significant (Table 69).

*Table 69: Marine energy metals requirements*

| Technology | Elements | Materials demand (kg/MW) | Expected EU demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|---|
| | | | 2020 | 2030 | 2020 | 2030 |
| Tidal | Cu | 5.00 | 250 | 350 | <0.1% | <0.1% |
| | Mo | 0.05 | 2 | 3 | <0.1% | <0.1% |
| | Ni | 0.22 | 11 | 15 | <0.1% | <0.1% |
| | Cr | 0.31 | 15 | 21 | <0.1% | <0.1% |
| | Ti | 0.01 | 1 | 1 | <0.1% | <0.1% |

### 4.3.4 Co-generation or combined heat and power (CHP)

The metals requirements for CHP are shown in Table 70, based on modelling the low nuclear scenario of the EU Energy Roadmap 2050 (EC, 2011b). However, these scenarios do not provide a breakdown of the increase in power generation required for different types of CHP. In the absence of knowledge regarding CHP in power stations, an assumption has been made that district CHP will account for 50% of uptake, while micro-CHP using Stirling engines will account for a further 25% of uptake, with the remaining 25% being supplied by fuel cell (SOFC) micro-CHP.

This analysis highlights that the use of copper in heat exchangers in the next decade represents a relatively modest material requirement.

*Table 70: Combined heat and power metals requirements*

| Technology | Elements | Materials demand (kg/MW) | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|---|
| | | | 2020 | 2030 | 2020 | 2030 |
| Combined Heat and Power | Cu | 44,448 | 116,898 | 51,915 | 0.5% | 0.2% |
| | Sn | 168 | 442 | 196 | 0.1% | <0.1% |
| | Ni | 541 | 1,423 | 632 | <0.1% | <0.1% |
| | Cr | 1,033 | 2,717 | 1,207 | <0.1% | <0.1% |
| | Mn | 108 | 284 | 126 | <0.1% | <0.1% |
| | Zn | 9.0 | 24 | 11 | <0.1% | <0.1% |
| | Pb | 0.5 | 1 | 1 | <0.1% | <0.1% |

### 4.3.5 Advanced fossil fuel power generation

The share of fossil fuel power generation is expected to decrease in Europe. However, new fossil power plants will be built to replace decommissioned power plants. The capacity for European power generation from solids is expected to decrease in the long term, due to increasing carbon prices. Consequently, gas will gain an increasing share of fossil fuel generation.

According to the JRC's 2011 Technology Map, between 510 GW and 635 GW of new fossil fuel power plant capacity is required by 2030 (EC, 2011c). To gain an estimate of the new installed capacity per year, an average of this figure coupled with the reference scenario for gas and coal power generation capacity from the EU Energy Roadmap to 2030 is used.

To allow for retrofitting of fossil fuel power stations, a figure of 5% of the total capacity by fuel per year has been assumed. Based on power plants currently under construction, the short term trends show an increase in natural gas fired Combustion Turbine/Combined-Cycle (CTCC) plants and a decrease in coal powered capacity (Capros et al., 2009). In Germany there are plans for 29 gas- and 17 coal-fired power stations - a combination of new builds and retrofits - by 2020 (Bloomberg, 2012). Capacity additions for coal power plants are expected to be 18.1 GW between 2011 and 2015, and 12.1 GW between 2016 and 2020 (Frost & Sullivan, 2012a).

The metals requirements for advanced fossil fuel power generation are shown in Table 71, based on the reference scenario from DG Energy's "EU Energy Trends to 2030".

This analysis highlights that the use of cobalt, rhenium and tantalum, within some of the superalloys, represents the greatest material requirement.

*Table 71: Advanced fossil fuel power generation metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| Advanced fossil fuel power generation | Co | 1.8 | 2,123 | <0.1% | 0.6% |
| | Re | 0.6 | 0.6 | 0.7% | 0.6% |
| | Ta | 1.3 | 7.2 | 0.1% | 0.4% |
| | Ni | 44.3 | 7,435 | <0.1% | 0.1% |
| | Mo | 64.2 | 636 | <0.1% | 0.1% |
| | Nb | 9.6 | 106 | <0.1% | 0.1% |
| | Cr | 1,428 | 3,182 | <0.1% | <0.1% |
| | Hf | 0.0 | 0.0 | <0.1% | <0.1% |
| | Ti | 0.2 | 244 | <0.1% | <0.1% |
| | W | 242 | 1.3 | 0.2% | <0.1% |
| | Mn | 80.1 | 42.4 | <0.1% | <0.1% |
| | V | 32.1 | 0.0 | <0.1% | <0.1% |

### 4.3.6 Fuel cells and hydrogen

The metals requirements for fuel cells and hydrogen are shown in Table 72.

The scenarios employed here for SOFCs were all obtained from New Energy World Industrial Grouping in conjunction with the EU (NEW-IG EU). For trucks, the average power output was taken to be 5 kW; for planes a value of 225 kW was assumed and for maritime uses the power output was 20 kW. The average power output value for micro-CHP was assumed to be 2.5 kW, and it was assumed that 25% of the total CHP uptake would come from this system. As outlined in the co-generation section (3.5), the other 25% would be provided by micro-CHP using a Stirling engine.

For PEMFCs, the scenario employed for fuel cell electric vehicles is taken from the HyWays project. The scenario assumes that platinum catalysts will not be replaced with cheaper alternatives. The scenario employed for fuel cells in materials handling is taken from NEW-IG EU and assumes that 50% of such devices will use PEMFCs. The scenario for PEMFCs in combined heat and power units was also obtained from NEW-IG EU. To model the requirements for materials in fuel cell backup units a NEW-IG EU scenario was used, and it was assumed that PEMFCs would be used in 100% of these devices.

For DMFCs the scenarios are again taken from NEW-IG EU, with the assumption that 50% of fuel cells used in materials handling devices will be DMFCs and that 100% of fuel cells in portable devices will be DMFCs.

This analysis highlights that platinum use within fuel cells represents an important material requirement for the decarbonisation of EU energy sector. The modelling results in an estimate that approximately 7% of the world's platinum supply in 2030 could be required for fuel cells in the EU.

*Table 72: Fuel cells and hydrogen metals requirements*

| **Technology** | **Elements** | **Materials demand (kg/MW)** | **Annual EU Demand (tonnes)** | | **Annual EU Demand / World Supply** | |
|---|---|---|---|---|---|---|
| | | | **2020** | **2030** | **2020** | **2030** |
| Fuel Cells | Pt | 67.9 | 5.5 | 28.9 | 1.6% | 7.0% |
| | Ru | 22.0 | 0.0 | 0.1 | <0.1% | 0.1% |
| | Cr | 48323.2 | 1,185 | 1,599 | <0.1% | <0.1% |
| | Ni | 282.0 | 59.2 | 216.0 | <0.1% | <0.1% |
| | Y | 8.4 | 0.2 | 0.2 | <0.1% | <0.1% |
| | La | 38.0 | 0.8 | 0.9 | <0.1% | <0.1% |
| | Gd | 1.2 | 0.0 | 0.0 | <0.1% | <0.1% |
| | Sm | 1.2 | 0.0 | 0.0 | <0.1% | <0.1% |
| | Ce | 8.0 | 0.2 | 0.2 | <0.1% | <0.1% |
| | Co | 10.8 | 0.2 | 0.3 | <0.1% | <0.1% |

### 4.3.7 Electricity storage in the power sector

Estimates of the necessity or demand for large-scale electricity storage vary from one study to the next. Unfortunately, studies exist only for a few countries or regions, and most often cover only one or few storage technologies. In consequence, no comprehensive data exists with serious estimates as to the distribution of technologies that could meet that storage requirement. Recent modelling work points to a slow build-up of storage capacity with run-times of several hours, with essentially no new capacity being installed until 2020 but increasing to up to a total of 5 GW (or 40 GWh daily if it runs for 8 hours) by 2030, for the EU-27 plus Switzerland and Norway (Pfluger, 2012).[13]

The estimates shown below (Tables 73 - 76) are based on these figures and using the materials requirements described in section 3.8. The entire possible demand is allotted to each sub-technology (i.e. total expected demand is not the sum of the possible demand shown for the sub-technologies). Furthermore,

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[13] These are interim results from the FP7 Project Responses (http://www.responsesproject.eu/). This scenario results in a high penetration of intermittent renewable energy by imposing a $CO_2$ cap and assuming strong increases in electricity demand and no use of CCS. These results reflect the optimum power storage capacity needed for the assumed simulation and optimization conditions. They do not take into account feasibility of installation.

because the modelling results are cumulative, the possible demand is also cumulative for the years 2021-2030 in the tables below. It is important to note that in the case of mature technologies, secondary metals can cover a substantial share of the demand, e.g. secondary lead from lead-acid batteries. Some factors, such as a failure to speed up the expansion of the grid infrastructure necessary for integrating fluctuating renewable energies, could increase the demand for storage technologies significantly. As for the distribution of technologies, it is noted that because of the low specific investment costs, high efficiency and proven track record, pumped hydro storage plants are currently the technology of choice for large-scale energy storage but they nonetheless suffer from a scarcity of suitable sites for new facilities (Höflich et al., 2010).

*Table 73: Possible compressed air energy storage metals requirements*

| Technology | Elements | Materials demand (tonnes/MWh) | Possible Demand (tonnes) | |
|---|---|---|---|---|
| | | | 2020 | 2021-2030 |
| CAES | Cu | 0.50 | 0 | 20,000 |
| | Steel | 32.0 | 0 | 1,280,000 |

*Table 74: Possible pumped hydro storage metals requirements*

| Technology | Elements | Materials demand (kg/MWh) | Possible Annual Demand (tonnes) | |
|---|---|---|---|---|
| | | | 2020 | 2021-2030 |
| Pumped hydro storage | Ni | 0.03 | 0 | 300 |
| | Cr | 0.01 | 0 | 100 |
| | Cu | 0.03 | 0 | 300 |

*Table 75: Possible lead acid batteries metals requirements*

| Technology | Elements | Materials demand (tonnes/MWh) | Possible Annual Demand (tonnes) | |
|---|---|---|---|---|
| | | | 2020 | 2021-2030 |
| Lead-acid batteries | Pb | 5.20 | 0 | 208,000 |
| | Sb | 0.20 | 0 | 8,000 |

*Table 76: Possible NaS batteries metals requirements*

| Technology | Elements | Materials demand (tonnes/MWh) | Possible Annual Demand (tonnes) | |
|---|---|---|---|---|
| | | | 2020 | 2021-2030 |
| NaS batteries | Cu | 3.40 | 0 | 136,000 |

These results are summarised in Table 77. As the possible demand estimates are for the whole decade 2012-2030, these results have been divided by cumulative expected world supply for each of the metals concerned. None of the metals require more than 0.3% of expected supply over the decade 2021-2030.

*Table 77: Maximum possible power storage metals requirements*

| Technology | Elements | Cumulative World Supply (tonnes) | Possible Demand (tonnes) | Annual EU Demand / Cumulative World Supply |
|---|---|---|---|---|
| | | 2021-2030 | 2021-2030 | 2021-2030 |
| Power Storage – Summary | Pb | 59,615,850 | 208,000 | 0.3% |
| | Sb | 2,482,650 | 8,000 | 0.3% |
| | Cu | 202,712,100 | 156,300 | 0.1% |
| | Ni | 29,980,000 | 300 | <0.1% |
| | Cr | 120,574,100 | 100 | <0.1% |

### 4.3.8 Energy intensive industries

As described in Section 3.9, no specific metals requirements were identified for energy efficiency and $CO_2$ emissions reduction in industry.

### 4.3.9 Energy efficiency in buildings – lighting

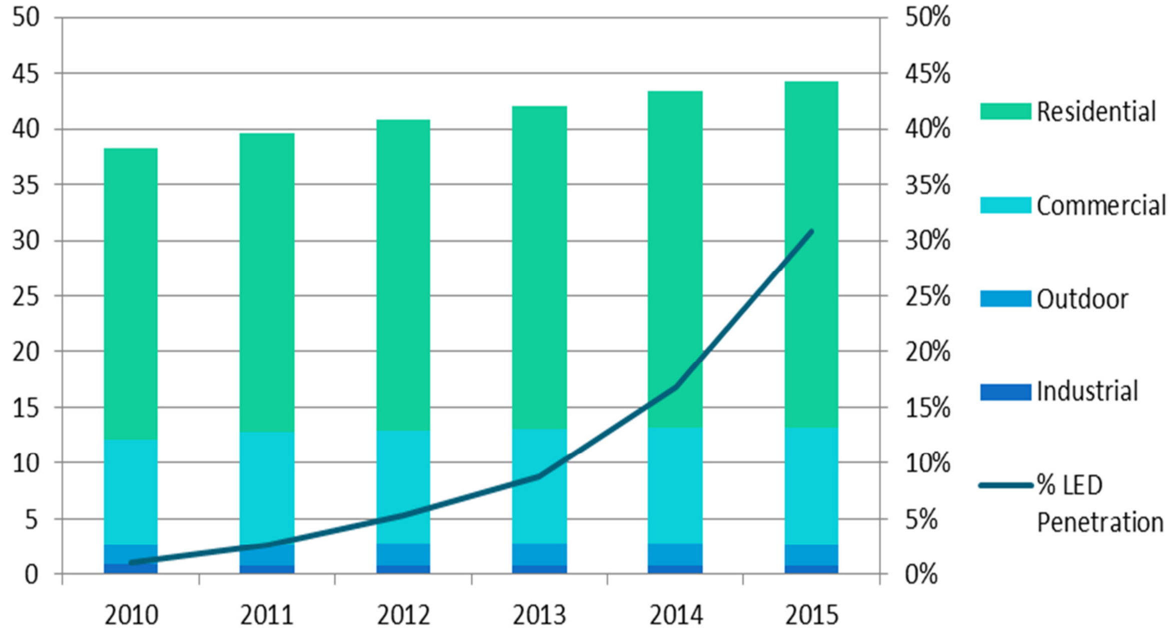
No comprehensive scenarios already published for the sales and penetration of different lighting types have been identified by this study; as a consequence, scenarios have been constructed from various sources. A key driver on the type of lighting sales is regulation, such as the phase-out of incandescent lamps. Based on proposed regulatory changes, the IEA forecasts annual CFL sales of around 630 million within the EU, assuming that the phase-out is steady rather than fast (International Energy Agency (IEA), 2010a).

In addition to CFLs, LFLs must be considered in the study. Analysis of PRODCOM EU production data and EU trade statistics puts annual EU consumption at approximately 350 million LFLs for 2010.

Street lighting should also be considered, as it is seen as an important market for LED lighting. The installed stock of streetlights in EU-25 was estimated at 56.1 million units in 2007 (EC, 2007c). Under the assumption that bulbs are replaced every three years, and that the EU market has expanded with the admission of two further countries into the EU, annual sales may be approximately 20 million bulbs per year.

As can be shown (Figure 21), some growth in annual lighting sales is anticipated over time; it is forecast at 3% per year globally. Annual growth rates for a more mature market such as the EU might be expected to be lower than for the world as a whole. For this study, EU annual light sales growth is modelled at a more modest 1.84% per year, as indicated by forecasts from McKinsey for the growth of the general lighting markets to 2020 (McKinsey, 2012).

*Figure 21: Global lighting sockets (billion units)*



*Source: Aixtron, 2012*

A further parameter within the scenario concerns the penetration of LED lighting onto the market. Whilst neither the US Department of Energy nor IEA consider this technology shift in their studies, the lower manufacturing costs and the benefits offered by its higher energy efficiency mean that large scale adoption is possible. For example, forecasts show LED penetration reaching 30% of the total lighting market by 2015 (Figure 21). Higher rates of uptake are possible, with McKinsey forecasting 46% LED penetration by 2016, and 72% for 2020 within Europe (McKinsey, 2012). However, for modelling purposes in this study, LED penetration is assumed to be 5% for 2011, 30% for 2020 and 60% for 2030. This represents average uptake over the entire decade, although higher rates of LED uptake are discussed in section 4.6.3.

The metals requirements for 'energy efficiency in buildings – lighting' are shown in Table 78. This analysis highlights the usage of heavy rare earth elements (yttrium, terbium and europium), germanium and gallium as representing important material requirements for implementing the path for decarbonising the EU energy sector. For the heavy rare earth elements their usage is mainly within fluorescent lamps, which are expected to be gradually replaced by LEDs over time. Nonetheless metals requirements for terbium and europium within EU lighting are estimated to represent nearly 10% of current global supply in 2011.  Yttrium is also used in fluorescent lighting with requirements of around 5% for 2011. Yttrium is also used to a small extent within LED lighting. For gallium and germanium, requirements within LED lighting are expected to grow to around 2.5% of total supply in 2030.

*Table 78: Lighting metals requirements*

| **Technology** | **Elements** | **Annual EU Demand (tonnes)** | | | **Annual EU Demand / World Supply** | | |
|---|---|---|---|---|---|---|---|
| | | **2011** | **2020** | **2030** | **2011** | **2020** | **2030** |
| Lighting | Tb | 36.5 | 32.3 | 22.1 | 10.4% | 6.3% | 2.7% |
| | Ge | 0.6 | 4.6 | 11.0 | 0.3% | 1.4% | 2.5% |
| | Ga | 0.8 | 5.9 | 14.3 | 0.3% | 1.3% | 2.3% |
| | Eu | 38.9 | 34.4 | 23.6 | 9.6% | 4.5% | 2.0% |
| | Y | 547.7 | 484.8 | 333.3 | 4.8% | 3.1% | 1.3% |
| | Au | 3.4 | 24.7 | 59.2 | 0.1% | 0.4% | 0.8% |
| | Ag | 9.6 | 69.1 | 165.8 | <0.1% | 0.2% | 0.4% |
| | Gd | 14.6 | 12.9 | 8.9 | 0.6% | 0.3% | 0.1% |
| | In | 0.1 | 0.7 | 1.8 | <0.1% | <0.1% | 0.1% |
| | Cu | 1,852.0 | 5,271.0 | 10,714.0 | <0.1% | <0.1% | <0.1% |
| | La | 66.9 | 59.2 | 40.6 | 0.2% | 0.1% | <0.1% |
| | Ce | 85.7 | 75.8 | 52.0 | 0.2% | 0.1% | <0.1% |
| | Sn | 39.7 | 59.3 | 87.9 | <0.1% | <0.1% | <0.1% |
| | Ni | 203.4 | 292.7 | 421.3 | <0.1% | <0.1% | <0.1% |
| | Sr | 85.9 | 75.9 | 52.1 | <0.1% | <0.1% | <0.1% |
| | Zn | 156.7 | 372.3 | 712.2 | <0.1% | <0.1% | <0.1% |
| | Mg | 85.2 | 75.3 | 51.7 | <0.1% | <0.1% | <0.1% |
| | Zr | 85.2 | 75.3 | 51.7 | <0.1% | <0.1% | <0.1% |
| | Sb | 0.1 | 0.5 | 1.3 | <0.1% | <0.1% | <0.1% |
| | Mn | 209.5 | 185.3 | 127.0 | <0.1% | <0.1% | <0.1% |
| | Cr | 1.3 | 9.2 | 22.0 | <0.1% | <0.1% | <0.1% |
| | W | 0.0 | 0.1 | 0.2 | <0.1% | <0.1% | <0.1% |
| | Pb | 0.0 | 0.1 | 0.3 | <0.1% | <0.1% | <0.1% |

### 4.3.10 Road transport efficiency

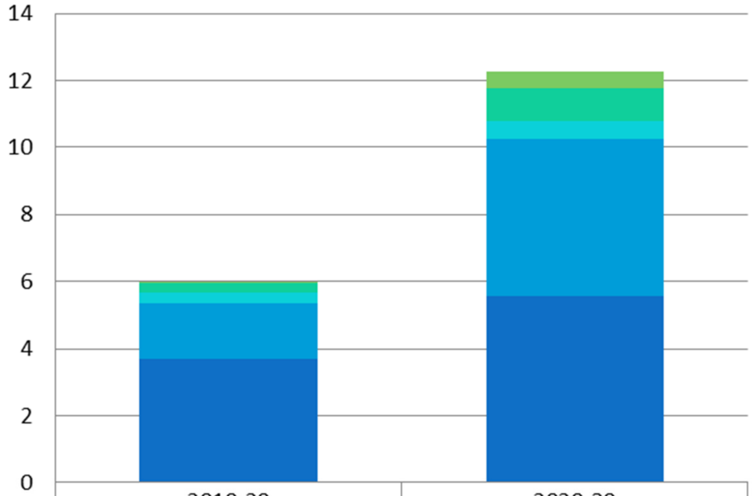
No suitable or detailed EU scenario for road transport efficiency is provided in the 2050 roadmap. Therefore models are based on the forecasts produced by Deutsche Bank (Deutsche Bank Global Markets

Research, 2009). These forecasts provide detailed projections for the uptake of four different types of vehicles (mild hybrid, full hybrid, plug-in hybrid, battery electric vehicle). The scenarios modelled for fuel cell vehicle motor drive scenarios are compatible with those used in the fuel cell scenarios. Figure 22 shows the uptake of low-carbon vehicles in the EU for fuel cell vehicles (FCV), battery electric vehicles (BEV), plug-in electric vehicles (PHEV), mild hybrids (mild HV) and hybrid electric vehicles (HEV).

Assumptions have also been made on the size and type of motor drives, and the choice of batteries (NiMH versus Li-ion, including specific Li-ion chemistry options). Due to the magnitude and sensitivities associated with the modelling results for this technology, data and scenarios have been extensively verified in consultation with industry stakeholders.

Various other forecasts and scenarios are available for road transport efficiency, both for its uptake and its possible technology mix. Other scenarios considered include those by: IEA, 2011a; McKinsey, 2010; J.D. Power and Associates, 2010; Roland Berger Strategy Consultants, 2010; Boston Consulting Group, 2011; Credit Suisse, 2009b; and CE Delft, 2011. A useful summary is provided by Pasaoglu et al. (2012). Further discussion and the modelling of these alternative scenarios are provided in Section 4.6.2.

*Figure 22: Uptake of low-carbon vehicles for the EU under the Deutsche Bank scenario*



| | 2010-20 | 2020-30 |
|---|---|---|
| ■ FCV | 0.0 | 0.5 |
| ■ BEV | 0.3 | 1.0 |
| ■ PHEV | 0.3 | 0.6 |
| ■ Mild HV | 1.7 | 4.7 |
| ■ HEV | 3.7 | 5.6 |

*Source: Deutsche Bank Global Markets Research, 2009*

Using the Deutsche Bank forecasts, the material requirements for hybrid and electric vehicle batteries and drive motors are shown in Table 79. There are a number of important materials requirements for the implementation of the path for the decarbonisation of EU energy sector:

- For drive motors, the focus is on three rare earth elements; dysprosium and neodymium-praseodymium.[14] The supply is notably tighter for the heavy rare earth element, dysprosium, where around 25% of world supply is required. Demand for neodymium-praseodymium is lower, at 7% of expected world supply.

- For batteries, there is a split between NiMH, which has been the battery of choice for many

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[14] In the report praseodymium and neodymium (didymium) are treated together, as they are often not separated from each other

hybrid vehicles; and the adoption of Li-ion. For 2011, in percentage terms, the materials requirements for NiMH batteries (lanthanum, cerium, praseodymium and samarium) are comparable to those for Li-ion batteries (lithium, cobalt and graphite) at around 1-2% of current world supply. However, the uptake of electric vehicles to 2030 and the shift to exclusively Li-ion batteries places the highest materials requirements on lithium (19%), graphite (15%) and cobalt (2%).

*Table 79: Road transport efficiency materials requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | | Annual EU Demand / World Supply | | |
|---|---|---|---|---|---|---|---|
| | | 2011 | 2020 | 2030 | 2011 | 2020 | 2030 |
| (H)EV batteries and drive motors | Dy | 123 | 566 | 980 | 6.7% | 22.7% | 25.0% |
| | Li | 314 | 2,214 | 6,939 | 1.5% | 7.8% | 19.0% |
| | Graphite | 8,575 | 60,464 | 189,471 | 0.9% | 5.1% | 14.4% |
| | Nd-Pr | 702 | 4,425 | 6,803 | 2.4% | 7.0% | 6.9% |
| | Co | 1,196 | 4,412 | 7,390 | 0.9% | 1.9% | 2.2% |
| | La | 894 | 2,279 | 707 | 2.5% | 2.9% | 0.6% |
| | Sm | 59 | 150 | 47 | 1.9% | 2.7% | 0.5% |
| | Ni | 5,966 | 18,931 | 22,327 | 0.2% | 0.5% | 0.4% |
| | Cu | 3,607 | 25,703 | 79,708 | <0.1% | 0.1% | 0.3% |
| | Ce | 597 | 1,522 | 472 | 1.2% | 1.3% | 0.3% |
| | Mn | 987 | 6,961 | 21,814 | <0.1% | <0.1% | 0.1% |
| | B | 125 | 724 | 1,883 | <0.1% | <0.1% | <0.1% |
| | Ti | 57 | 879 | 2,205 | <0.1% | <0.1% | <0.1% |

### 4.3.11 Desalination

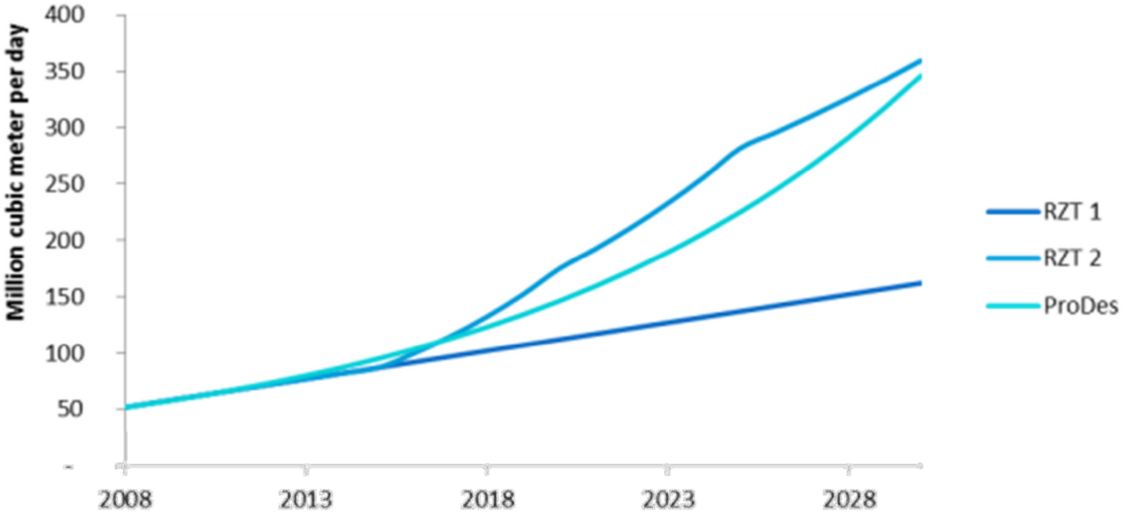
Though large desalination plants are generally thermal plants operating with waste heat from a neighbouring thermal power plant, reverse osmosis plants nowadays account for most of the new installed capacity, resulting in less stringent material specifications due to milder conditions (Khawaji et al., 2008; Frost & Sullivan, 2010a).

The global capacity of operating desalination plants (drinking water) was estimated to be approximately 52 million $m^3$ per day in 2008 (ProDes Consortium, 2010). A total desalination capacity of 155- 220 million $m^3$ per day in 2030 has been proposed (as a conservative projection) based on recent and projected rates of increase in installed capacity (Angerer et al., 2009). Assuming a doubling in the installed capacity by 2016 compared to 2008 implies a yearly growth rate of 9% which, if extrapolated to 2030, leads to a total installed capacity of around 345 million $m^3$ (Figure 23).

In the most material-intensive case, the expansion in capacity would be covered by thermal facilities (MSF and MED). However, the current trend points to most of the additional capacity being due to RO facilities requiring less corrosion resistant materials. Over 90% of newly-built desalinisation plants are based on RO (Frost & Sullivan, 2010a).

Nonetheless, this analysis highlights that the use of molybdenum, nickel and chromium within corrosive resistant alloys represents the greatest material requirements for implementing the path for decarbonising the EU energy sector.

*Figure 23: Extrapolation of desalination capacity to 2030 based on three different growth assumptions*



*Source: (RZT1 and RZT2 after Angerer et al., 2009 with an updated starting value; ProDes extrapolates from ProDes Consortium, 2010).*

*Table 80: Desalination metals requirements*

| **Technology** | **Elements** | **Annual EU Demand (tonnes)** | | | **Annual EU Demand / World Supply** | | |
|---|---|---|---|---|---|---|---|
| | | **2011** | **2020** | **2030** | **2011** | **2020** | **2030** |
| Desalination | Mo | 0.0 | 7,561 | 9,470 | <0.1% | 1.6% | 1.5% |
| | Ni | 0.0 | 37,497 | 46,968 | <0.1% | 1.0% | 0.9% |
| | Cr | 0.0 | 52,397 | 65,631 | <0.1% | 0.4% | 0.4% |
| | Ti | 0.0 | 2,084 | 2,610 | <0.1% | <0.1% | <0.1% |

### 4.3.12 Rescaling results of the first study

For the SET-Plan technologies, the results from the first JRC study (Moss et al., 2011) are shown here and compared in order to provide an overall assessment of the supply chain bottlenecks risks for the decarbonisation of the EU energy sector. It should be noted that limited new analysis has been conducted here.

However, there has been one major change in methodology, as the results have now been compared to expected supply figures rather than current supply estimates. In addition, some of the scenarios have been amended to take into account the latest projections in the EU Energy Roadmap 2050 (EC, 2011b). Therefore the percentages of world supply shown in these tables may be very different to those in the first JRC study.

#### *Wind energy*

In Europe, the 2020 projections based on the National Renewable Energy Action Plans (NREAPS) suggest that offshore installations will increase significantly more (from 2.6 to 44 GW, a 15-fold increase) than onshore (from 82 to 169 GW, a 2-fold increase). The industry expects 230 GW by 2020 of which 40 GW offshore, and 400 GW by 2030 of which 150 GW offshore, and track records show that in Europe the projections of the wind industry have proved more accurate. The scenario of electricity generation technologies that therefore results from those changes is shown in Table 81.

*Table 81: Uptake and technologies mix modelled for wind energy*

| Wind Turbine Type | EMG-geared | EMG-DD | HTS | MS/HS-PMG | DD-PMG | Installations per year (GW) |
|---|---|---|---|---|---|---|
| Market share in 2020 | 33% | 15% | 1% | 24% | 27% | 14 |
| Market share in 2030 | 0% | 10% | 18% | 29% | 43% | 13 |

*Source: Personal communication, Roberto Lacal Arantegui, European Commission (EC), JRC IET, October 2012*

The results from the first JRC study, in terms of kg/MW for each of the separate sub-technologies have been remodelled, using the scenario above. The results are shown in Table 82. This analysis highlights the metals requirements associated with rare earth elements (dysprosium and neodymium-praseodymium)[15]. These metals requirements have increased compared to the first JRC study, due to the change in the technology mix identified. Other metals representing significant usage to albeit to a lesser extent include molybdenum and nickel.

*Table 82: Wind energy metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| Wind | Dy | 58 | 84 | 2.3% | 2.2% |
| | Nd-Pr | 845 | 1,222 | 1.3% | 1.2% |
| | Mo | 1,801 | 1,603 | 0.4% | 0.2% |
| | Ni | 8,711 | 7,726 | 0.2% | 0.2% |
| | Cr | 12,020 | 10,776 | 0.1% | 0.1% |
| | Cu | 16,000 | 14,857 | 0.1% | 0.1% |
| | Mn | 867 | 641 | <0.1% | <0.1% |

***Solar energy***

The results have been rescaled against projection supply only, although the scenario presented here is the 'high scenario' from the first JRC study rather than that from the significance screening. That scenario was deemed to be more realistic as it gives a steady uptake of solar PV in both decades rather just within the second decade. The results highlight the metals requirements associated with tellurium, indium, gallium and tin and to a lesser extent silver, cadmium and selenium, as representing important materials requirements.

*Table 83: Solar energy metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| Solar PV | Te | 150 | 126 | 12.0% | 6.9% |
| | In | 145 | 121 | 7.6% | 4.9% |
| | Sn | 14,913 | 12,505 | 3.6% | 2.6% |
| | Ag | 619 | 519 | 1.7% | 1.2% |
| | Ga | 4 | 3 | 0.8% | 0.5% |
| | Se | 15 | 13 | 0.4% | 0.3% |
| | Cd | 109 | 91 | 0.3% | 0.2% |
| | Cu | 70,650 | 59,241 | 0.3% | 0.2% |
| | Pb | 8,672 | 7,272 | 0.1% | <0.1% |
| CSP | Ag | 19 | 19 | 0.1% | 0.1% |

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[15] In the report praseodymium and neodymium (didymium) are treated together, as they are often not separated from each other

### *Carbon capture and storage*

The results for CCS from the first JRC study highlighted vanadium and niobium as representing important materials requirements. Here the results have been rescaled against projected supply only, although it is noted that the more recent EU Energy Roadmap 2050 scenarios (EC, 2011b), are significantly more pessimistic on the uptake of CCS before 2030.

*Table 84: Carbon capture and storage metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| CCS | V | 80 | 730 | 0.1% | 0.8% |
| | Nb | 80 | 730 | 0.1% | 0.5% |
| | Ni | 926 | 8,336 | <0.1% | 0.2% |
| | Mn | 3,011 | 27,380 | <0.1% | 0.1% |
| | Cu | 559 | 5,034 | <0.1% | <0.1% |
| | Co | 6 | 55 | <0.1% | <0.1% |
| | Cr | 261 | 2,373 | <0.1% | <0.1% |
| | Mo | 6 | 55 | <0.1% | <0.1% |

### *Smart electricity grids*

The first JRC study modelled the metals requirements associated with ENSTO-E's list of projects of European Significance to 2020 (ENTSO-E, 2010). No more up-to-date appropriate scenarios have been identified. The results highlight the metals requirements associated with copper and lead, as representing important materials requirements.

*Table 85: Smart electricity grids metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| Smart Grids | Cu | 78,700 | | 0.3% | |
| | Pb | 19,200 | | 0.2% | |

### *Biofuels*

The first JRC study identified that the same catalysts currently used for fossil fuels would be used and therefore there would not be any additional materials requirements. The results shown in Table 86 should therefore be considered as illustrative; the use of ruthenium is of particular note. This modelling has rescaled the results against the reference scenario of the EU Energy Roadmap 2050 (EC, 2011b) and also against projected supply figures.

*Table 86: Biofuels metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| Biofuels | Ru | 0.4 | 0.4 | 0.4% | 0.5% |
| | Co | 18 | 21 | <0.1% | <0.1% |

***Nuclear energy***

Due to the major policy changes of some European countries, it is appropriate to model a scenario that assumes a significantly lower implementation of nuclear energy in Europe. The chosen scenario for this is the reference scenario of the EU Energy Roadmap 2050 (EC, 2011b), which has fairly constant net capacity up to 2030. However the scenario implicitly assumes the opening of 51 GW of new capacity up to 2030 to replace some plants, which here has been equally distributed over the period. The updated results are shown in Table 87, which are significantly lower than those from the first JRC study. Nonetheless the results still identify the metals requirements associated with hafnium and indium, as being important.

*Table 87: Nuclear energy metals requirements*

| Technology | Elements | Annual EU Demand (tonnes) | | Annual EU Demand / World Supply | |
|---|---|---|---|---|---|
| | | 2020 | 2030 | 2020 | 2030 |
| Nuclear | Hf | 1.1 | 1.4 | 1.0% | 1.0% |
| | In | 3.6 | 4.5 | 0.2% | 0.2% |
| | Ag | 19 | 24 | 0.1% | 0.1% |
| | Mo | 162 | 204 | <0.1% | <0.1% |
| | Ni | 586 | 737 | <0.1% | <0.1% |
| | W | 11 | 14 | <0.1% | <0.1% |
| | Cr | 978 | 1,232 | <0.1% | <0.1% |
| | Y | 1.1 | 1.4 | <0.1% | <0.1% |
| | Cd | 1.2 | 1.5 | <0.1% | <0.1% |
| | Zr | 70 | 88 | <0.1% | <0.1% |
| | Nb | 4.6 | 5.8 | <0.1% | <0.1% |
| | Sn | 10 | 13 | <0.1% | <0.1% |
| | V | 1.4 | 1.7 | <0.1% | <0.1% |
| | Cu | 137 | 172 | <0.1% | <0.1% |
| | Pb | 10 | 12 | <0.1% | <0.1% |
| | Ti | 3.4 | 4.3 | <0.1% | <0.1% |
| | Co | 0.0 | 0.0 | <0.1% | <0.1% |

## 4.4 Sector studies

In addition to the energy technologies, other technologies are considered that may be competing for the same resources and thus limit the availability of certain materials from use in low-carbon technologies in the EU. The competing sectors of particular interest are the automotive and electronics/ICT sectors:

- The automotive sector in Europe is estimated to employ 12.6 million people directly or indirectly, producing a total of 15.1 million vehicles or 22% of worldwide motor vehicle sales in 2010 (ACEA, 2011).

- The electronics/ICT sector accounted for 8.5% of total business value added in the EU and 3% of total business sector turnover (EC, 2012b). Europe’s share of worldwide electronics and ICT turnover is estimated at around 18% for 2010 (Deloitte, 2010).

There is clearly some overlap with that for road transport efficiency. To avoid any double counting, therefore, the sector study does not include material requirements associated with hybrid and electric vehicle batteries or motors; nor with fuel cells. The analysis focuses predominantly on existing vehicle technologies such as catalytic convertors, lead acid batteries, and steel and aluminium alloys.

There is also potentially some overlap with respect to electronics and ICT, as many low-carbon technologies will contain circuit boards and batteries. As these have not been effectively quantified for specific technologies, there is, however, little risk of double counting here.

The approach taken was to review the current applications for each of the metals identified. This highlights where other technologies currently compete for the same resources. This can consequently be considered as part of the screening process. Full details of the data sources and detailed information on other competing applications can be found in Appendix 2. Some further sources of information have been used to disaggregate uses of batteries, steel and alloys to these categories.

The results of the sector study are shown in Table 88, providing both the worldwide share of demand and the EU's estimated share. Metals highlighted in this analysis as being of particular importance to these sectors include antimony, beryllium, cadmium, copper, gallium, germanium, indium, lead, magnesium, platinum group metals, tantalum and tin.

*Table 88: Results of the sector study, share of metal demand (%) - numbers rounded down*

| **Metal** | **Worldwide** | | **EU Share** | | **EU Total** |
|---|---|---|---|---|---|
| | **Electronics/ICT** | **Automotive** | **Electronics/ICT** | **Automotive** | |
| PGM: Rhodium | 1 | 79 | 0 | 17 | 17 |
| PGM: Palladium | 14 | 62 | 3 | 13 | 16 |
| Indium | 80 | 0 | 15 | 0 | 15 |
| Cadmium | 76 | 0 | 14 | 0 | 14 |
| Lead | 1 | 60 | 0 | 13 | 13 |
| Germanium | 65 | 0 | 12 | 0 | 12 |
| PGM: Ruthenium | 62 | 0 | 11 | 0 | 11 |
| Tantalum | 60 | 0 | 11 | 0 | 11 |
| Magnesium | 0 | 50 | 0 | 11 | 11 |
| Antimony | 36 | 19 | 7 | 4 | 11 |
| Gallium | 58 | 0 | 11 | 0 | 11 |
| PGM: Iridium | 55 | 0 | 10 | 0 | 10 |
| Copper | 41 | 10 | 7 | 2 | 10 |
| Tin | 52 | 0 | 9 | 0 | 9 |
| Beryllium | 40 | 10 | 7 | 2 | 9 |
| PGM: Platinum | 3 | 41 | 1 | 9 | 9 |
| REE: Dysprosium | 42 | 0 | 8 | 0 | 8 |
| REE: Neodymium | 34 | 1 | 6 | 0 | 6 |
| REE: Praseodymium | 32 | 2 | 6 | 0 | 6 |
| Chromium | 17 | 14 | 3 | 3 | 6 |
| Niobium | 0 | 28 | 0 | 6 | 6 |
| REE: Samarium | 31 | 0 | 6 | 0 | 6 |
| Silver | 30 | 0 | 5 | 0 | 5 |
| Tellurium | 30 | 0 | 5 | 0 | 5 |
| REE: Gadolinium | 29 | 0 | 5 | 0 | 5 |
| Nickel | 16 | 11 | 3 | 2 | 5 |
| Cobalt | 27 | 0 | 5 | 0 | 5 |
| Vanadium | 0 | 20 | 0 | 4 | 4 |
| Zinc | 0 | 20 | 0 | 4 | 4 |
| REE: Cerium | 4 | 16 | 1 | 3 | 4 |
| Lithium | 20 | 0 | 4 | 0 | 4 |
| Molybdenum | 2 | 14 | 0 | 3 | 3 |
| Tungsten | 17 | 0 | 3 | 0 | 3 |
| Graphite | 16 | 0 | 3 | 0 | 3 |
| Manganese | 2 | 10 | 0 | 2 | 3 |
| Barytes | 3 | 6 | 1 | 1 | 2 |
| REE: Lanthanum | 7 | 1 | 1 | 0 | 1 |
| Bismuth | 7 | 0 | 1 | 0 | 1 |
| Gold | 7 | 0 | 1 | 0 | 1 |
| Rhenium | 0 | 5 | 0 | 1 | 1 |
| Selenium | 5 | 0 | 1 | 0 | 1 |
| REE: Terbium | 5 | 0 | 1 | 0 | 1 |
| Boron | 0 | 0 | 0 | 0 | 0 |
| Hafnium | 0 | 0 | 0 | 0 | 0 |
| REE: Europium | 0 | 0 | 0 | 0 | 0 |
| REE: Yttrium | 0 | 0 | 0 | 0 | 0 |
| Scandium | 0 | 0 | 0 | 0 | 0 |
| Titanium | 0 | 0 | 0 | 0 | 0 |
| Zirconium | 0 | 0 | 0 | 0 | 0 |

*Source: see Appendix 2*

## 4.5 Reduced list of metals

The results of the previous sections have identified the materials that have significant usage in the path towards the decarbonisation of the EU energy sector, as well as the needs in the electronics/ICT and automotive sectors that might be competing for the same supply.

The approach taken in the first JRC study to screen the list of metals was to impose a cut-off at 1% demand within SET-Plan technologies as a percentage of current world supply estimates. However, as projected supply has been used in this analysis, it makes sense to apply a lower cut-off value. To ensure consistency with the first study this has been set at around 0.3% of projected supply, with the effect of including the 14 elements previously identified as significant retained in this analysis.

On this basis 32 materials are identified as being significant and are retained on the reduced list of metals for further investigation with respect to supply chain risk (see Chapter 5). Table 89 summarises the reduced list of metals, identifying the key associated decarbonisation technology.

It is apparent that the greatest magnitude and number of materials is associated with vehicles. Solar, wind, fuel cells and lighting are each associated with at least one of the materials with a requirement above 5% of world supply. Several of the metals identified (Table 83) within the sector study (e.g. indium, lead, tantalum, gallium, copper, tin and rare earth elements) are included on the reduced list.

*Table 89: Reduced list of 32 materials with the associated key decarbonisation technology*

1. Dysprosium (vehicles, wind)
2. Lithium (vehicles)
3. Graphite (vehicles)
4. Tellurium (solar)
5. Neodymium-Praseodymium (vehicles, wind)
6. Indium (solar, lighting, nuclear)
7. Platinum (fuel cells)
8. Terbium (lighting)
9. Tin (solar)
10. Europium (lighting)
11. Gallium (lighting, solar)
12. Cobalt (vehicles, fossil fuels)
13. Nickel (desalination, vehicles, geothermal)
14. Germanium (lighting)
15. Yttrium (lighting)
16. Molybdenum (desalination, wind)
17. Silver (solar, lighting)
18. Lanthanum (vehicles)
19. Samarium (vehicles)
20. Copper (CHP, solar, vehicles, grids)
21. Hafnium (nuclear)
22. Cerium (vehicles)
23. Gold (lighting)
24. Rhenium (fossil fuels)
25. Tantalum (geothermal, fossil fuels)
26. Chromium (desalination)
27. Vanadium (CCS)
28. Niobium (CCS)
29. Selenium (solar)
30. Lead (grids, storage)
31. Cadmium (solar)
32. Gadolinium (lighting)

The reduced list of metals are summarised in descending order in Table 90 and presented graphically in Figure 24. From these illustrations the following observations are clear:

- Dysprosium represents by far the most significant material requirement, with the EU requiring just over 25% of expected average supply for 2020-2030.
- Lithium, graphite, tellurium, neodymium-praseodymium, indium, platinum and terbium all have materials requirements within the EU at around 6-10% for at least one period.
- Tin, europium, gallium, cobalt, nickel, germanium, yttrium and molybdenum all have requirements of the order 2-3%.
- Silver, lanthanum, samarium, copper and hafnium all have requirements of the order 1-2%.
- A further eleven metals have material requirements at or above 0.3% within the EU.

*Figure 24: Annual EU metals demand from decarbonisation technologies, % of expected supply 2020-2030*

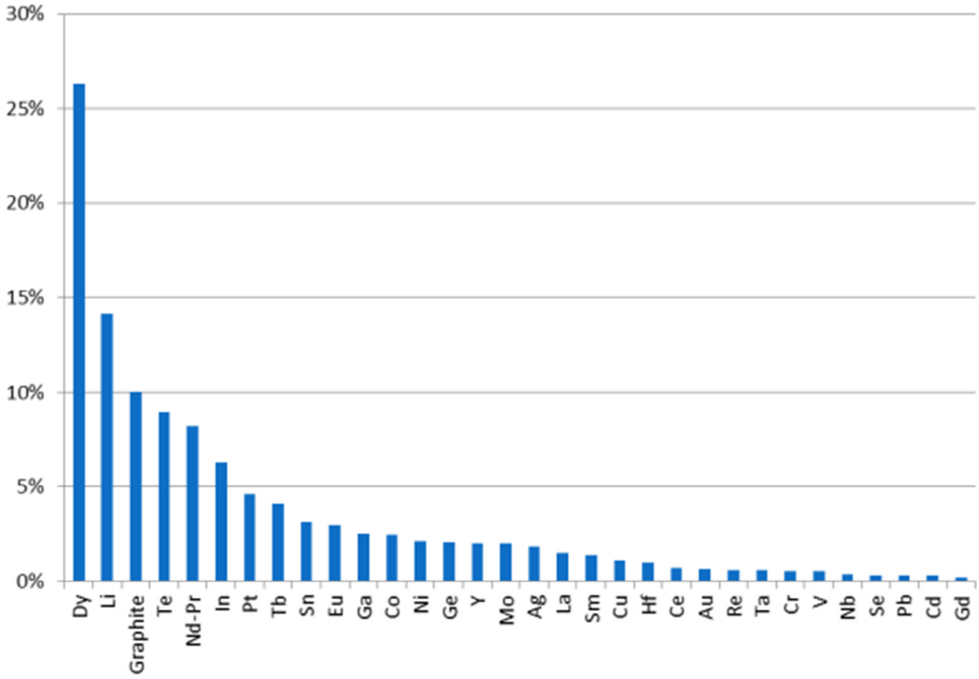


*Table 90: EU metals demand from decarbonisation technologies as % of expected supply*

| **Material** | **Annual EU SET Plan Demand / World Supply** | | **Annual EU demand from other technologies / World Supply** | | **Total Annual EU Demand / World Supply** | | |
|---|---|---|---|---|---|---|---|
| | **2020** | **2030** | **2020** | **2030** | **2020** | **2030** | **Average** |
| Dy | 2.3 | 2.2 | 22.7 | 25.0 | 25.1 | 27.2 | 26.4 |
| Li | <0.1 | <0.1 | 7.8 | 19.0 | 7.8 | 19.0 | 14.1 |
| Graphite | <0.1 | <0.1 | 5.1 | 14.4 | 5.1 | 14.4 | 10.1 |
| Te | 12.0 | 6.9 | <0.1 | <0.1 | 12.0 | 6.9 | 9.0 |
| Nd-Pr | 1.3 | 1.2 | 7.0 | 6.9 | 8.4 | 8.1 | 8.2 |
| In | 7.8 | 5.0 | <0.1 | 0.1 | 7.8 | 5.1 | 6.3 |
| Pt | <0.1 | <0.1 | 1.6 | 7.0 | 1.6 | 7.0 | 4.6 |
| Tb | <0.1 | <0.1 | 6.3 | 2.7 | 6.3 | 2.7 | 4.1 |
| Sn | 3.6 | 2.6 | 0.1 | 0.1 | 3.7 | 2.7 | 3.1 |
| Eu | <0.1 | <0.1 | 4.5 | 2.0 | 4.5 | 2.0 | 2.9 |
| Ga | 0.8 | 0.5 | 1.3 | 2.3 | 2.2 | 2.8 | 2.5 |
| Co | <0.1 | <0.1 | 1.9 | 2.8 | 1.9 | 2.8 | 2.5 |
| Ni | 0.3 | 0.4 | 1.7 | 1.8 | 2.0 | 2.2 | 2.1 |
| Ge | <0.1 | <0.1 | 1.4 | 2.5 | 1.4 | 2.5 | 2.1 |
| Y | <0.1 | <0.1 | 3.1 | 1.3 | 3.1 | 1.4 | 2.0 |
| Mo | 0.4 | 0.3 | 1.6 | 1.7 | 2.0 | 2.0 | 2.0 |
| Ag | 1.8 | 1.3 | 0.2 | 0.4 | 2.0 | 1.7 | 1.8 |
| La | <0.1 | <0.1 | 3.0 | 0.6 | 3.0 | 0.6 | 1.5 |
| Sm | <0.1 | <0.1 | 2.7 | 0.5 | 2.7 | 0.5 | 1.4 |
| Cu | 0.7 | 0.3 | 0.6 | 0.6 | 1.4 | 0.9 | 1.1 |
| Hf | 1.0 | 1.0 | <0.1 | <0.1 | 1.0 | 1.0 | 1.0 |
| Ce | <0.1 | <0.1 | 1.3 | 0.3 | 1.3 | 0.3 | 0.7 |
| Au | <0.1 | <0.1 | 0.4 | 0.8 | 0.4 | 0.8 | 0.6 |
| Re | <0.1 | <0.1 | 0.7 | 0.6 | 0.7 | 0.6 | 0.6 |

| Material | Annual EU SET Plan Demand / World Supply | | Annual EU demand from other technologies / World Supply | | Total Annual EU Demand / World Supply | | |
|---|---|---|---|---|---|---|---|
| | 2020 | 2030 | 2020 | 2030 | 2020 | 2030 | Average |
| Ta | <0.1 | <0.1 | 0.3 | 0.8 | 0.3 | 0.8 | 0.6 |
| Cr | 0.1 | 0.1 | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 |
| V | 0.1 | 0.8 | <0.1 | <0.1 | 0.2 | 0.8 | 0.5 |
| Nb | 0.1 | 0.5 | <0.1 | 0.1 | 0.1 | 0.6 | 0.37 |
| Se | 0.4 | 0.3 | <0.1 | <0.1 | 0.4 | 0.3 | 0.32 |
| Pb | 0.2 | <0.1 | <0.1 | 0.3 | 0.2 | 0.4 | 0.30 |
| Cd | 0.3 | 0.3 | <0.1 | <0.1 | 0.3 | 0.3 | 0.29 |
| Gd | <0.1 | <0.1 | 0.3 | 0.1 | 0.3 | 0.1 | 0.20 |
| Sb | <0.1 | <0.1 | <0.1 | 0.3 | <0.1 | 0.3 | 0.16 |
| Mn | <0.1 | 0.1 | <0.1 | 0.1 | <0.1 | 0.2 | 0.11 |
| W | <0.1 | <0.1 | 0.2 | <0.1 | 0.2 | <0.1 | 0.08 |
| Ru | <0.1 | <0.1 | <0.1 | 0.1 | <0.1 | 0.1 | 0.07 |
| Ti | <0.1 | <0.1 | <0.1 | 0.1 | <0.1 | 0.1 | 0.06 |
| B | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 0.03 |
| Sr | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 0.01 |
| Zr | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | 0.01 |
| Mg | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.01 |
| Zn | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.01 |

## 4.6 Market penetration and technology-mix scenarios

### 4.6.1 Introduction

In the above sections, future metal requirements for a range of low-carbon energy technologies have been identified under optimistic deployment scenarios. The metals with the highest risk for future supply-chain bottlenecks were identified. These bottleneck metals are further assessed here with a focus on the assumptions about the speed and extent of European market penetration and the technology mix.

This is important because these assumptions are subject to considerable uncertainty and, as this section will demonstrate, in many cases have a large potential impact, both on the future demand for individual bottleneck metals and on the time for demand peaks to occur. This section focuses on two technologies in detail: electric vehicles and lighting. These two technologies have been chosen, firstly because this is where many of the bottleneck metals are extensively used (see Table 89), and secondly because of uncertainty associated with the future battery technology mix within the European electric vehicle market and the lamp-type mix in the lighting sector.

### 4.6.2 Electric vehicles

#### 4.6.2.1 Uptake

In section 4.3.10, the future metals demand for electric vehicles was estimated using an uptake scenario from Deutsche Bank and an equal technology mix for the different Li-ion cathode chemistries. The DB Scenario was selected for its completeness and inclusion of the four different electric vehicle types in focus (Deutsche Bank Global Markets Research, 2009).  Selecting a suitable uptake scenario for electric vehicles in Europe was far from trivial.

There are a number of studies which focus on the deployment of alternative vehicles in Europe. However there is rarely any detail of assumptions and quantitative analyses. Moreover, the projections for market penetration are not always in agreement. Scenarios under consideration for this report include those by: IEA, 2011a; McKinsey, 2010; J.D. Power and Associates, 2010; Roland Berger Strategy Consultants, 2010; Boston Consulting Group, 2011; Credit Suisse, 2009b; Deutsche Bank Global Markets Research, 2009 and CE Delft, 2011. The market shares of different vehicle types for 2015 and 2020 for some of these scenarios are presented in Table 91.

*Table 91: Comparison of different market penetration scenarios for low-carbon vehicles for 2015 and 2020*

| | | **Deutsche Bank** | **Boston Consulting Group** | **Roland Berger** | **JD Power and Associates** | **CE Delft - Reference** | **CE Delft – EV breakthrough** |
|---|---|---|---|---|---|---|---|
| HEV | 2015 | 7.0% | n/a | 1.0% | 2.3% | n/a | n/a |
| | 2020 | 15.0% | 17.0% | 1.0% | 4.1% | n/a | n/a |
| BEV | 2015 | 1.0% | n/a | 2.0% | 1.7% | <0.1% | <0.1% |
| | 2020 | 3.0% | 2.7% | 15.0% | 3.1% | 1.0% | 2.0% |
| PHEV | 2015 | 2.0% | n/a | 2.0% | n/a | 1.0% | 1.0% |
| | 2020 | 2.0% | 3.0% | 15.0% | n/a | 3.0% | 6.0% |

Due to the uncertainty of the European market for EVs, a different uptake scenario is used in order to identify any further potential bottlenecks. In this instance the EV breakthrough scenario from the CE Delft report "Impacts of Electric Vehicles" has been used as the alternative uptake scenario (ICF, Ecologic, 2011). Unfortunately, not all the vehicle types studied in this report are featured in this scenario; accordingly only the results for BEVs and PHEVs have been presented. The requirements of the bottleneck metals in both scenarios are presented in Tables 92 - 95.

*Table 92: Comparison of uptake scenarios for metal requirements of BEVs to 2020*

| **EU 2020 Metal Demand for BEVs (tonnes)** | | | | |
|---|---|---|---|---|
| | **Deutsche Bank Scenario** | | **EV Breakthrough Scenario** | |
| | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply |
| Li | 1,688 | 6.0 | 957 | 3.4 |
| Co | 1,626 | 0.7 | 922 | 0.4 |
| Graphite | 46,089 | 3.9 | 26,138 | 2.2 |
| Nd-Pr | 520 | 0.8 | 1,029 | 1.6 |
| Dy | 77 | 3.1 | 62 | 2.5 |

*Table 93: Comparison of uptake scenarios for metal requirements of BEVs to 2030*

| **EU 2030 Metal Demand for BEVs (t)** | | | | |
|---|---|---|---|---|
| | **Deutsche Bank Scenario** | | **EV Breakthrough Scenario** | |
| | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply |
| Li | 5,707 | 15.6 | 10,462 | 28.6 |
| Co | 5,498 | 1.6 | 10,077 | 3.0 |
| Graphite | 155,846 | 11.9 | 285,671 | 21.8 |
| Nd-Pr | 1,255 | 1.3 | 4,601 | 4.7 |
| Dy | 186 | 4.8 | 682 | 17.4 |

*Table 94: Comparison of uptake scenarios for metal requirements of PHEVs to 2020*

| EU 2020 Metal Demand for PHEVs (t) | | | | |
|---|---|---|---|---|
| | Deutsche Bank Scenario | | EV Breakthrough Scenario | |
| | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply |
| Li | 318 | 1.1 | 600 | 2.1 |
| Co | 306 | 0.1 | 578 | 0.3 |
| Graphite | 8,682 | 0.7 | 16,373 | 1.4 |
| Nd-Pr | 327 | 0.5 | 882 | 1.4 |
| Dy | 49 | 2.0 | 131 | 5.3 |

*Table 95: Comparison of uptake scenarios for metal requirements of PHEVs to 2030*

| EU 2030 Metal Demand for PHEVs (t) | | | | |
|---|---|---|---|---|
| | Deutsche Bank Scenario | | EV Breakthrough Scenario | |
| | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply |
| Li | 555 | 1.5 | 4,764 | 13.0 |
| Co | 535 | 0.2 | 4,589 | 1.4 |
| Graphite | 15,162 | 1.2 | 130,079 | 9.9 |
| Nd-Pr | 408 | 0.4 | 7,008 | 7.1 |
| Dy | 61 | 1.6 | 1,038 | 26.5 |

#### 4.6.2.2 Technology-mix scenarios

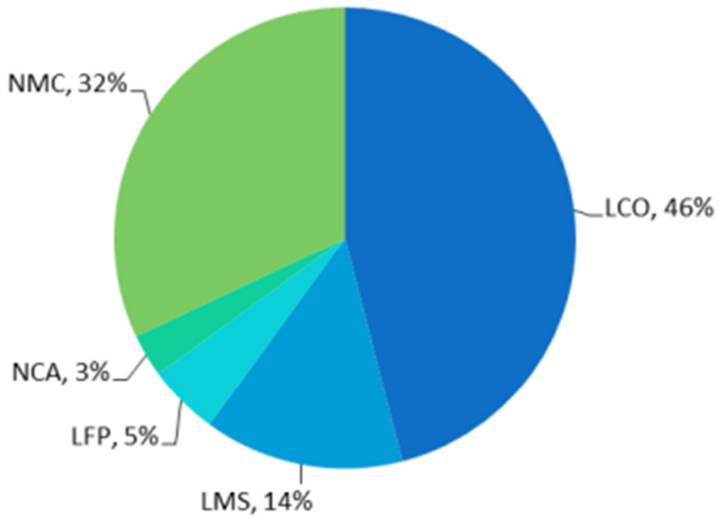
***Battery chemistries***

As identified in section 3.11.1, there are several competing Li-ion cathode chemistries for electric vehicle batteries, each of which has a different metals requirement associated with it. Li-ion battery technology is developing rapidly and it is not clear what the dominant cathode chemistry will be. In section 3.11.1, it was assumed that there would be equal uptake of each of the four sub-technologies chosen.

In order to check the sensitivity of different market shares of the different cathode chemistries, two further technology mixes have been developed: a preference for lower cost batteries and the uptake of market trends from consumer electronic equipment (Committee on Climate Change, 2012).

The market shares for the different Li-ion battery chemistries are shown in Figure 25. Lithium cobalt oxide (LCO) battery chemistries have been excluded, as these are not common for vehicle batteries due to cost. These technology mixes are shown in Tables 96-99, with their respective market shares and forecast volumes per annum for BEVs.

*Figure 25: Li-ion battery chemistry market share for all applications in 2010*



*Source: Committee on Climate Change, 2012*

*Table 96: Effect of technology mix in Li-ion batteries for BEVs on yearly demand up to 2020*

| **EU 2020 Lithium-ion batteries for BEVs Metal Demand** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Technology mix** | **Equal share** | | | | | **Low cost technologies** | | | | |
| Li-ion chemistry | NCA | LFP | LMS | NCM | % of world supply | NCA | LFP | LMS | NCM | % of world supply |
| Market share (%) | 25 | 25 | 25 | 25 | | 5 | 45 | 45 | 5 | |
| Forecast '000 BEVs per year | 72.7 | 72.7 | 72.7 | 72.7 | | 14.5 | 131 | 131 | 14.5 | |
| Li (t) | 453 | 329 | 569 | 337 | 6.0 | 91 | 591 | 1,023 | 67 | 6.3 |
| Co (t) | 614 | - | - | 1,012 | 0.7 | 123 | - | - | 202 | 0.1 |
| Graphite (t) | 15,753 | 18,753 | - | 11,583 | 3.9 | 3,150 | 33,756 | - | 2,316 | 3.3 |

*Table 97: Effect of technology mix in Li-ion batteries for BEVs on yearly demand up to 2030*

| **EU 2030 Lithium-ion batteries for BEVs Metal Demand** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Technology mix** | **Equal share** | | | | | **Market trends from portable Li-ion batteries** | | | | |
| Li-ion chemistry | NCA | LFP | LMS | NCM | % of world supply | NCA | LFP | LMS | NCM | % of world supply |
| Market share (%) | 25 | 25 | 25 | 25 | | 5 | 45 | 45 | 5 | |
| Forecast '000 BEVs per year | 246 | 246 | 246 | 246 | | 49.2 | 442.7 | 442.7 | 49.2 | |
| Li (t) | 1,533 | 1,111 | 1,923 | 1,141 | 15.6 | 91 | 591 | 1023 | 67 | 16.4 |
| Co (t) | 2,076 | - | - | 3,422 | 1.6 | 306 | 2,000 | 3,461 | 228 | 0.3 |
| Graphite (t) | 53,267 | 63,413 | - | 39,167 | 11.9 | 415 | - | - | 684 | 10.1 |

*Table 98: Effect of Technology mix in Li-ion batteries for BEVs on yearly demand up to 2020*

| EU 2020 Lithium-ion batteries for BEVs Metal Demand | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Technology mix** | **Equal share** | | | | | **Market trends from portable Li-ion batteries** | | | | |
| Li-ion chemistry | NCA | LFP | LMS | NCM | % of world supply | NCA | LFP | LMS | NCM | % of world supply |
| Market share (%) | 25 | 25 | 25 | 25 | | 5 | 10 | 25 | 60 | |
| Forecast ‘000 BEVs per year | 72.7 | 72.7 | 72.7 | 72.7 | | 14.5 | 29.1 | 72.7 | 174.5 | |
| Li (t) | 453 | 329 | 569 | 337 | 6.0 | 90 | 131 | 569 | 810 | 5.7 |
| Co (t) | 614 | - | - | 1012 | 0.7 | 123 | - | - | 2429 | 1.1 |
| Graphite (t) | 15,753 | 18,753 | - | 11,583 | 3.9 | 3,151 | 7,501 | - | 27,799 | 3.3 |

*Table 99: Effect of technology mix in Li-ion batteries for BEVs on yearly demand up to 2030*

| EU 2030 Lithium-ion batteries for BEVs Metal Demand | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Technology mix** | **Equal share** | | | | | **Market trends from portable Li-ion batteries** | | | | |
| Li-ion chemistry | NCA | LFP | LMS | NCM | % of world supply | NCA | LFP | LMS | NCM | % of world supply |
| Market share (%) | 25 | 25 | 25 | 25 | | 5 | 10 | 25 | 60 | |
| Forecast ‘000 BEVs per year | 246 | 246 | 246 | 246 | | 49.2 | 98.4 | 246 | 590.3 | |
| Li (t) | 1,533 | 1,111 | 1,923 | 1,141 | 15.6 | 307 | 444 | 1,923 | 2,737 | 14.8 |
| Co (t) | 2,076 | - | - | 3,422 | 1.6 | 415 | - | - | 8,212 | 2.6 |
| Graphite (t) | 53,267 | 63,413 | - | 39,167 | 11.9 | 10,653 | 25,365 | - | 93,999 | 9.9 |

***Motor technologies***

Although permanent magnet motors are the dominant technology for electric vehicle drive motors, they are not the only technology in use for this application. With increasing rare earth prices, some vehicle manufacturers are choosing to adopt rare earth free motors such as induction motors. In order to check the sensitivity of different market shares for motor technologies, it was decided to introduce two further technology mixes, as shown in Table 100.

*Table 100: Market share of rare earth permanent magnet motors in EVs*

| | **2012** | **2020** | **2030** |
|---|---|---|---|
| High substitution | 95% | 50% | 30% |
| Medium substitution | 95% | 70% | 50% |
| Low substitution | 95% | 90% | 70% |

From conversations with industry experts, the medium scenario was taken as the most likely and thus was adopted in the previous chapters for determining the materials demand of electric vehicles.

*Table 101: Effect of technology mix variation in drive motors for 2020*

| 2020 Drive Motors Metal Demand for all Electric Vehicle Types | | | | | | |
|---|---|---|---|---|---|---|
| | **High Substitution** | | **Medium Substitution** | | **Low Substitution** | |
| | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply |
| Dy | 404 | 16.2 | 566 | 22.7 | 727 | 29.2 |
| Nd-Pr | 3,161 | 5.0 | 4,425 | 7.0 | 5,690 | 9.1 |

*Table 102: Effect of technology mix variation in drive motors for 2030*

| 2030 Drive Motors Metal Demand for all Electric Vehicle Types | | | | | | |
|---|---|---|---|---|---|---|
| | **High Substitution** | | **Medium Substitution** | | **Low Substitution** | |
| | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply | Annual EU Demand (tonnes) | % of world supply |
| Dy | 588 | 15.0 | 980 | 25.0 | 1,372 | 35.0 |
| Nd-Pr | 4,082 | 4.1 | 6,803 | 6.9 | 9,525 | 9.6 |

It is clear from the results that the materials demand is sensitive to the technology mix of drive motors employed. For a high rate of rare earth permanent magnet motor substitution, the demand for Dy and Nd-Pr are effectively halved when compared to the low substitution scenario.

#### 4.6.2.3 Summary

For electric vehicles the results of the technology scenario modelling show that the demand for bottleneck metals varies considerably according to the technology mix and uptake. Overall the EV breakthrough scenario forecasts the most optimistic uptake of PHEVs and BEVs, however in comparison to the Deutsche Bank scenario, it predicts a slower uptake of BEVs up to 2020. The most significant differences can be seen for PHEVs, where the optimistic scenario predicts almost nine times the metals demand up to 2030. It is apparent that the technology mix has an impact on the materials demand; for instance, a greater uptake of LMS batteries could significantly decrease the demand for graphite and cobalt.

### 4.6.3 Lighting

#### 4.6.3.1 Technology mix

For lighting, the key sensitivity in determining the metal requirements is the penetration rate of LED lighting in place of fluorescent lighting. As a fairly mature market, the overall sales and installation of lighting is expected to grow steadily at 2% sales growth per year. In 2011, sales of bulbs, tubes and street-lights in Europe totalled nearly 1 billion units, of which 630 million were bulbs and 350 million were tubes (Figure 26).

In section 4.3.9, a relatively steady rate was assumed for the penetration of LEDs: 30% for 2020 and 60% for 2030. In this chapter an alternative and more rapid LED penetration scenario is modelled assuming LED penetration in lighting of 60% for 2020 and 90% for 2030 (see discussion in Section 4.3.9). Figure 26 illustrates this difference. Table 103 provides a comparison of the relative materials requirements under both scenarios. The high scenario results in a significant increase in gallium and germanium use (up 50% for 2030) and a reduction in terbium, europium and yttrium use (of around 75% in 2030).

*Figure 26: Scenarios for the installation of lighting and LED penetration in Europe (millions per year)*

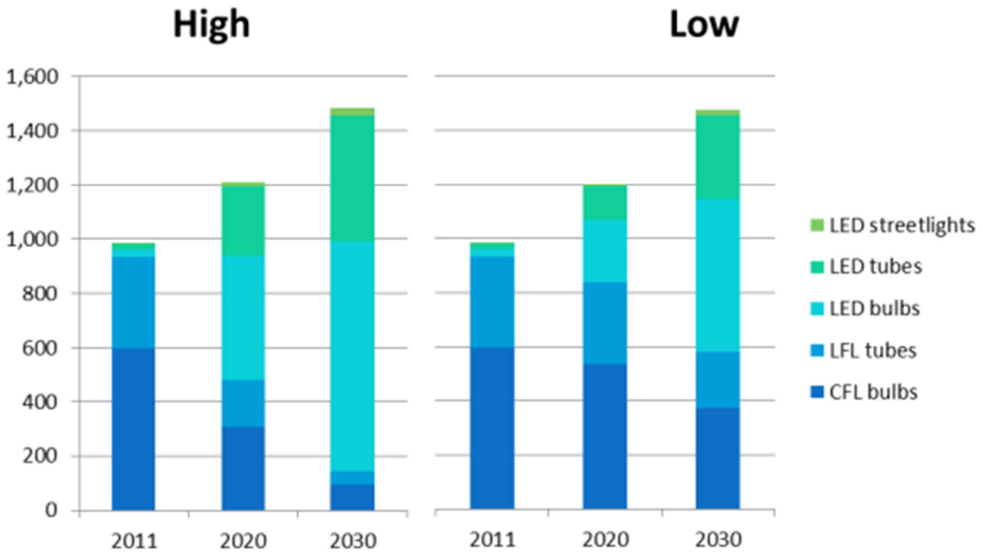


*Table 103: Metal requirements for lighting, high versus low LED penetration*

| Technology | Elements | High EU LED Annual Demand / World Supply | | | Low EU LED Annual Demand / World Supply | | |
|---|---|---|---|---|---|---|---|
| | | 2011 | 2020 | 2030 | 2011 | 2020 | 2030 |
| Lighting | Ge | 0.3% | 2.9% | 3.8% | 0.3% | 1.4% | 2.5% |
| | Tb | 10.4% | 3.6% | 0.7% | 10.4% | 6.3% | 2.7% |
| | Ga | 0.3% | 2.6% | 3.4% | 0.3% | 1.3% | 2.3% |
| | Eu | 9.6% | 2.6% | 0.5% | 9.6% | 4.5% | 2.0% |
| | Au | 0.1% | 0.9% | 1.2% | 0.1% | 0.4% | 0.8% |
| | Y | 4.8% | 1.8% | 0.3% | 4.8% | 3.1% | 1.3% |
| | Ag | 0.0% | 0.4% | 0.6% | 0.0% | 0.2% | 0.4% |
| | Gd | 0.6% | 0.2% | 0.0% | 0.6% | 0.3% | 0.1% |
| | In | 0.0% | 0.1% | 0.1% | 0.0% | 0.0% | 0.1% |

# 5 Criticality Analysis

## 5.1 Introduction

The findings of Chapter 4 demonstrate that the decarbonisation technologies rely on a wide variety of metals. The results further show that a number of metals are required in significant quantities relative to projected production volumes.

The aim of this chapter is to provide an assessment of the risk of supply disruptions to occur for each of these metals. This analysis includes both market and geopolitical factors. Based on the ranking and combination of risks, a reduced list of metals is derived and presented in section 5.4. The reduced list of metals shall be regarded as 'critical'. A number of the metals identified in this study were assessed for their criticality in the previous JRC study (Moss et al., 2011). These criticalities are not reassessed within this report. Nevertheless the analyses are brought together to form one overall criticality ranking.

The structure of this chapter is as follows:

- Review of the methodologies and criteria that have been used to assess the criticality of raw materials such as by the European Commission and United States Government.
- Description of the indicators and assessment criteria to be used in this study.
- Overall summary of the results of the criticality assessment.
- Commentary on the market situation for each of the metals considered.

## 5.2 Review of existing criticality studies

There has been a range of criticality-type studies carried out in recent years (Congressional Budget Office, 1983; Committee on Critical Mineral Impacts on the US Economy et al., 2008; Resource Efficiency Knowledge Transfer Network, 2008; DECC, 2010; EC, 2010a; Buijs and Sievers, 2011; Erdmann and Graedel, 2011; Hatch, 2011; Graedel et al., 2012); thereby revealing the considerable interest from policy makers, businesses and academics alike in the field of critical raw materials. However, as can be expected from the diversity in types of organisations, a wide variety of methodologies, criteria and data have been applied to assess critical raw materials. It is therefore not particularly surprising that differing results are sometimes obtained with respect to the same raw materials. This to a certain extent reflects a question of audience, namely: for whom are the raw materials considered to be critical? Nonetheless it is certainly reasonable that the raw material risks of different countries and companies could be quite different (as discussed e.g. in Graedel et al., 2012).

Inspection of the studies at the national level to date reveals that the choice of indicators used to assess materials risks concerns more than just physical and geological scarcity. Commonly used indicators include production and consumption data, political risk associated with the concentration of production and a sense of the 'importance of the materials'. A summary of indicators used in a selection of previous studies is shown in Table 104. Many of these indicators form part of the criticality assessment used in this study and that the 'importance of the materials' has largely been considered in the analysis of Chapter 4. From the list in Table 104, the studies on raw material needs for strategic and green energy technologies (Bauer et al., 2010; Moss et al., 2011) are of particular relevance and more details are given below.

Unlike most criticality studies where the economic relevance of a raw material is derived from its overall importance for the target national economies, the analysis presented here and in similar studies (Bauer et al., 2010; Moss et al., 2011) is driven by interest in particular energy technologies (in this aspect, they are similar to the work of Angerer et al., 2009, which also includes technologies other than energy technologies). The technologies considered in the Bauer and Moss studies are presented in Table 105. Notice that there is overlap both between the two studies (wind and solar energy) and between the US DoE study and the technologies considered here (lighting).

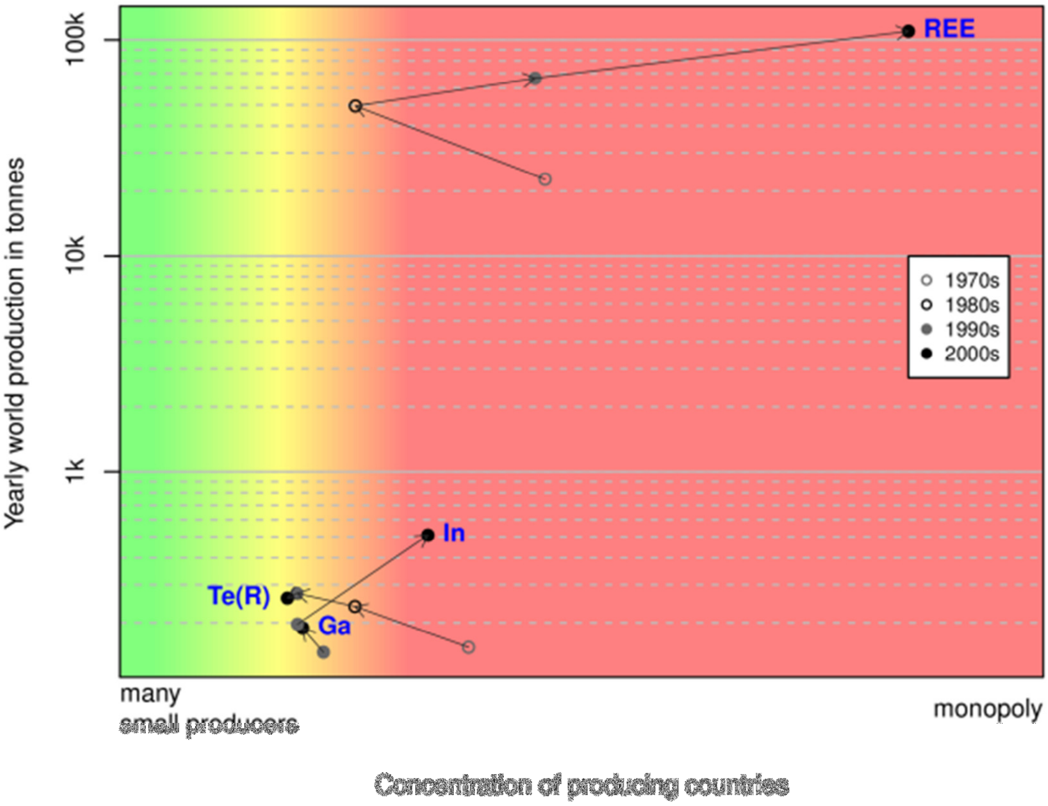
*Table 104: Selection of studies identifying critical non-energy raw materials*

| **Study** | **Criteria** | **Critical minerals** |
|---|---|---|
| Graedel et al., 2012 | Depletion times (reserves)<br>Companion metal fraction<br>Policy potential index<br>Human development index<br>Worldwide governance indicators: Political stability<br>Global supply concentration<br>National economic importance<br>Percentage of population utilizing<br>Substitute performance & their availability<br>Environmental impact ratio<br>Net import reliance ratio<br>Global innovation index<br>LCA cradle-to-gate: 'human health' & 'ecosystems' | Example ranking for the 'copper family' to the USA:<br>Arsenic = Gold (equal criticality)<br>> Silver (less critical)<br>> Selenium ≈ Copper<br>> Tellurium |
| Moss et al., 2011 | Limitations to expanding world supply<br>Concentration of supply (country level)<br>Political risk related to major suppliers<br>Likelihood of rapid demand growth | Dysprosium, neodymium, tellurium, gallium, indium (high risk) |
| EC, 2010a | Concentration of supply<br>Governance rating of producing countries (alternatively environmental performance)<br>Substitutability<br>Recycling rate<br>Value added of end use sectors | Antimony, beryllium, cobalt, fluorspar, gallium, germanium, graphite, indium, magnesium, niobium, platinum group metals, rare earths, tantalum, tungsten |
| Bauer et al., 2010 | Basic availability<br>Competing technology demand<br>Political, regulatory and social factors<br>Co-dependence on other markets<br>Producer diversity<br>Demand for clean energy<br>Substitutability | Dysprosium, neodymium, terbium, europium, yttrium, indium |
| Committee on Critical Mineral Impacts on the U.S.Economy et al., 2008) | US consumption (value)<br>Substitutability<br>Emerging uses<br>US import dependence<br>Ratio of world reserves to production<br>Ratio of world reserve base to production<br>World by-product production compared to total primary production<br>US secondary production from old scrap compared to consumption | Indium, manganese, niobium, platinum group metals, rare earths |
| (Resource Efficiency Knowledge Transfer Network, 2008) | Global consumption levels<br>Lack of substitutability<br>Global warming potential<br>Total material/ environmental requirement<br>Physical scarcity<br>Monopoly supply<br>Political instability<br>Climate change vulnerability | Gold, rhodium, platinum, strontium, silver, antimony, tin |

*Source: from Buijs et al., 2012, with additions)*

Further similarities between the Bauer and Moss studies, is their attempt to assess risks along the supply chain of the technologies considered and the use of scenarios to introduce a dynamic component into the analyses. The lack of dynamics in many criticality studies is a key weakness that has only been partially addressed to date (Buijs et al., 2012). The importance of considering changing market conditions may be illustrated by considering the changes in production and the concentration of production over the past decades, as shown in Figure 27 for the raw materials considered of high risk in both studies.

*Figure 27: Dynamics of the supply of high risk raw materials in the past decade*



*REE = rare earth elements, In = indium, Te(R) = tellurium (refined production), Ga = gallium*
*Note that average values are used for each decade to improve readability and REE are included as a group because of data limitations*
*Source: Fraunhofer ISI based on data provided by German Federal Institute for Geosciences and Natural Resources, 2011*

*Table 105: Technologies considered in recent criticality studies for energy technologies*

| **(Bauer et al., 2010)** | **(Moss et al., 2011)** |
|---|---|
| | Nuclear energy (fission) |
| Solar cells (PV films)<br>Wind turbines | Solar energy<br>Wind energy |
| | Bioenergy<br>Carbon capture and storage (CCS)<br>Electricity grids |
| Vehicle (magnets and batteries)<br>Lighting | |

*Source: (Bauer et al., 2010; Moss et al., 2011)*

## 5.3 Description of assessment criteria

A number of insights are apparent from the review of the various existing criticality studies. These are useful in forming the development and application of assessment criteria in this study. With respect to audience for this study, the focus is for European policymakers and the supply chain for low-carbon energy technologies. However it is noted that the research will also be of interest for technologies that compete for the same resources, as well as EU Member States and other national governments around the world.

A key distinction that emerges between different types of criticality studies is whether the assessment is based upon current data or whether a more dynamic approach is taken. The danger of using solely current data is that the results may lack predictive power. Studies of this nature therefore may accurately assess current risks, but may be considered as only providing a snapshot of the state of the market. The alternative approach utilises data across a number of years, with particular use of forecasts. The aim of this is to make the study more forward looking and help predict future rather than just current materials risks. This is challenging to do, due to the error and assumptions that are inherent in producing reliable forecasts, especially for volatile markets such as minor metals.

For this study, which has a definite focus on predicting future material supply risks, a dynamic approach to assessing criticality is considered to be more suitable. The analysis conducted in Chapter 4 for the calculation of material requirements for low-carbon technologies is almost entirely forward looking, so it would seem to be sensible to take a similar approach for assessing criticality by using market forecasts. This is not to understate the role of different types of studies, nor to be unaware of the potential pitfalls of this approach. Rather it is to take a consistent approach and methodology throughout this study.

The approach builds on that undertaken in the first study from 2011 (Moss et al., 2011). It considers both market and geopolitical factors:

1. Market factors:
    - Limitations to expanding supply capacity
    - Likelihood of rapid global demand growth.
2. Geopolitical factors:
    - Cross-country concentration of supply
    - Political risk related to major supplying countries.

The analysis uses a mixture of both quantitative and qualitative data. Clearly it is important to use the quantitative data that exists for production and use of each of the metals. This data is summarised for each of the metals in turn in section 5.4, with further data available in the Appendices. The quantitative approach adds to the transparency and ability of others to replicate its findings. However its limitation is driven the availability of data and the extent to which the variables included capture all of the relevant dimensions that influence materials criticality. The benefit of a slightly more qualitative approach is that it allows a greater degree of judgement and consideration of information of factors that are not always well quantified, particularly with the range of metals being considered.

For each metal, each of these risk factors is evaluated with a view on the next five to ten years and then scored as low, medium or high. The use of a simple ordinal risk scale, instead of a numeric composite indicator, avoids the misleading impression of a precise quantitative assessment of the future. This mirrors the difficulty involved in the complex set of dynamics, as well as the difficulty in measuring individual factors and the high degree of uncertainty surrounding their future development. This risk profile is then combined into an overall low, medium or high risk assessment for each metal, in a manner that is described in greater detail below.

### 5.3.1 Market factors

The interaction between supply and demand is a large determinant of the price of a given metal. The price of the key metals in turn affects its availability and suitability for use in the low-carbon energy technologies. Market factors are considered to be more important than political largely because the opportunity to implement political interventions hinges upon conditions that may exist in the market.

On the supply side the key issue is the extent to which metals supply is able to respond to increases in market demand. Economists refer to this as the elasticity of supply. It is a simple concept to explain in theory, although in practice it is difficult to measure accurately. The approach that is used here, therefore, is to assess the relative limitations that exist for expanding global production capacity in the short-to-medium-term. There are many dimensions that are relevant including utilisation rate of current capacity, by-product metal dynamics, exploration pipeline for new production, secondary supply sources (i.e. recycling), and availability of geological reserves. On the demand side, where global demand for a metal is forecast to increase rapidly it creates upward pressure on prices, depletes inventories and stretches existing supplies. In the present study, the likelihood of rapid global demand growth over the coming decade is estimated for individual metals as low, medium or high, based on the extensive analysis of available demand forecasts by producers and industry experts. Certain aspects, such as the theoretical potential for substitutability, are not measured here directly; although demand forecasts do tend implicitly to consider these factors.

By considering the interaction of these two risk criteria, an overall measure for the market risk can be obtained. Note that the study does not add or average the two criteria in some way, but rather considers their combination. This is because by themselves, either the likelihood of rapid global demand growth or limitations to rapidly expanding capacity may give only relatively minor risks for bottlenecks. For example, demand might be forecast to expand rapidly but if supply is likely to keep pace then the potential risk is actually quite low. Similarly in the case where supply is judged to be slow to adjust, this would not represent a bottleneck if demand growth itself is also expected to be slow. The market risks are therefore greatest where there is a rapid expansion of demand while the price elasticity of supply is low in the short-to-medium-term. A significant amount of uncertainty remains in the data, especially where the demand for a metal is driven by a few new applications with an uncertain future. However nonetheless clear differences emerge between metals for which global demand is projected to expand at rapid pace versus those for which relatively slow growth is expected.

### 5.3.2 Political factors

In addition to market dynamics, political factors can sometimes exacerbate risks for future supply-chain bottlenecks. The cross-country concentration of supply is a crucial indicator in this regard, because only where the structure of supply is monopolistic or dominated by only a few players, individual large supplier countries have sufficient market power to affect global price levels and aggregate supply through policy decisions. If supply is diversified, other producers are easily able to expand their capacity in response to an individual producer raising prices or reducing export or output.

If supply is significantly concentrated, a range of political dynamics can potentially affect markets. Evaluating political risk related to major supplying countries is therefore important in evaluating risk for future supply-chain bottlenecks. Broader political instability or internal conflicts in a major supplying country may reduce or delay investments or disrupt production and can have significant impact on global production capacity. Political disputes around the licensing, ownership or environmental permitting of large-scale mining operations in major supplying countries might have a similar effect. Further, states can intervene in production and pricing decisions, for example, in an effort to maximise revenue over time or to gain a larger share of valuable downstream industries. Such interventions can take the form of trade restrictions that limit or tax exports of certain metals, perhaps to favour domestic processing industries or for international strategic bargaining. The approach taken here to measure political risk follows the criticality study of the European Commission, focusing on composite indicators measuring 'good governance' and political stability, such as the World Bank Governance Indicator (World Bank, 2011) and the

Failed State Index (Fund for Peace, n.d.). Details can be found in Appendix 6. These political risk ratings have been averaged and scaled between 0 and 100, with a higher score denoting a higher risk.

### 5.3.3 Overall scores

Table 106 provides an overview of each of the factors used to evaluate the risk for future supply chain bottlenecks for individual metals and the rationale for using the factor. The third and fourth column provide an overview of the type of data that has been used to evaluate the individual risk factors and short explanation on what basis the high, medium and low scores have been assigned to each metal. The overall bottleneck risk for each metal is assessed as low, medium or high on the basis of these data. Market risks are determined through the interaction of demand and supply forecasts in the short or medium term. As has been explained above, political interventions are only likely to impact bottleneck risks under tight market conditions. Therefore, market risks are considered as dominant in the evaluation of risks for supply chain bottlenecks, and political risks are given less weight in the overall assessment. In evaluating political risks, concentration of supply is considered to be dominant, with the political risk factor only contributing to overall bottleneck risk if concentration of supply is medium or high.

*Table 106: Bottleneck criteria used in this study*

| **Criterion** | **Rationale** | **Basis** | **Scoring criteria** |
|---|---|---|---|
| Likelihood of rapid global demand growth | Greater risks persist if demand is expected to grow rapidly over the coming years. | Analysis of demand structure and demand forecasts | High: Industry forecasts expect rapid demand growth from several applications (e.g. close to double-digit growth)<br>Medium: Industry forecasts expect moderate and steady demand growth<br>Low: Industry forecasts expect slow or stable demand from mature applications |
| Limitations to expanding supply capacity | Risk are higher if suppliers are unable to expand output relatively easily in the short-to-medium term in response to demand and price increases | Reserve estimates, supply forecasts and evaluation by-product dependencies | High: There is a strong by-product dependency with little opportunity to increase extraction rates or low reserves.<br>Medium: There is a by-product dependency or severe underinvestment.<br>Low: Sufficient reserves and mining as primary product. |
| Concentration of supply | If supply is fairly concentrated within a few countries, the risk of possible supply disruptions increases, together with the ability of individual players to restrict access for political or economic advantage | Production statistics | High: Most of supply is concentrated in one country<br>Medium: Most of supply is concentrated in two or three countries<br>Low: Supply is dispersed among a number of countries |
| Political risk of major supplying countries | Greater political risk in the main supplying countries increases the likelihood of supply disruptions and the likelihood that individual suppliers will seek to restrict access. | Political risk indicators ('Failed States Index' and 'Worldwide Governance Index') | High: The major producing countries have a high score for political risk (>60)<br>Medium: The main producing countries have mixed scores for political risks<br>Low: The main producing countries have low political risk scores (<40) |

## 5.4 Assessment of risks for individual metals

In this section, the supply risks are evaluated for each metal that is used in significant quantities in the decarbonisation technologies. Note that because projected supply has been considered, a lower cut-off value has been used versus the first JRC study (at around 0.3% of world supply rather than 1%).

The methodology and assessment criteria that have been applied are consistent to those applied in the first JRC study. The three-step graduation used in the first study (high, medium and low) is refined further here into five categories (to now include medium-low and low-medium).

A commentary of the market situation for each metal is provided, as well as the results of the assessment.

### 5.4.1 Cadmium

Cadmium is a toxic metal and must be extracted as a by-product during the zinc refining process. World refinery production is estimated at around 22,000 tonnes per year (Table 107). However, industry estimates suggest that the actual total could be significantly higher, as there are reports that cadmium is now being stored in bunkers rather than being sold to the market due to a lack of market demand (International Study Group for Nickel et al., 2012). China is the world's leading producer of cadmium, with around a third of world refinery production; hence cadmium production is relatively dispersed, but has a moderate political risk rating.

*Table 107: Cadmium production concentration and political risk*

| **Country** | **Refinery production (2011)** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| China | 7,500 | 34 | 92,000 | 65 |
| South Korea | 2,500 | 11 | — | 24 |
| Japan | 2,000 | 9 | — | 14 |
| Kazakhstan | 1,800 | 8 | 35,000 | 60 |
| Mexico | 1,500 | 7 | 48,000 | 57 |
| Canada | 1,300 | 6 | 18,000 | 8 |
| India | 660 | 3 | 130,000 | 61 |
| United States | 600 | 3 | 39,000 | 16 |
| Netherlands | 580 | 3 | — | 8 |
| Poland | 550 | 2 | 16,000 | 26 |
| Germany | 400 | 2 | — | 13 |
| Peru | 400 | 2 | 45,000 | 57 |
| Russia | 700 | 3 | 21,000 | 68 |
| Australia | 380 | 2 | 61,000 | 8 |
| Other countries | 1,300 | 6 | 130,000 | 48 |
| **World total** | **21,500** | **—** | **640,000** | **53** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

Market supply for cadmium is not particularly restricted. Potential supply is expected to increase due the increases expected in world zinc production, and the necessity to recover cadmium due to its toxicity. As for demand, over the last decade global cadmium consumption experienced a slow but steady decline. Both in the US and in the EU, concerns over cadmium toxicity ushered in several rounds of increasingly restrictive regulations on cadmium use. The market share of NiCd batteries has also been visibly eroded by more advanced technologies such as NiMH and Li-Ion batteries. Overall, industry experts expect the decline in demand for cadmium to continue (Moss et al., 2011). Overall the criticality risks for cadmium are rated as low (Table 108).

*Table 108: Cadmium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Cadmium | Low | Low | Low | Medium | Low |

## 5.4.2 Chromium

Chromium is the hardest of all known metal elements in the periodic table. Its main use is in the metallurgical industry for the production of ferrochromium for the steel industry. Chromite ore mine production in 2011 totalled 24 million tonnes, of which 46% originated in South Africa (Table 109). Other important chromite mining countries include Kazakhstan, India and Turkey. All of these countries have moderate to high political ratings.

World production of ferrochromium is dominated by four countries: South Africa, China, Kazakhstan and India. Between them these countries accounted for nearly 90% of world ferrochromium production in 2010 (KPMG, 2012). China has very little domestic mined production of chromite ore and is hence dependent on imports from the ore from South Africa for its own consumption.

*Table 109: Chromite ore production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | tonnes | Percentage | | |
| South Africa | 11,000,000 | 46 | 200,000,000 | 46 |
| Kazakhstan | 3,900,000 | 16 | 220,000,000 | 60 |
| India | 3,800,000 | 16 | 54,000,000 | 61 |
| Turkey | 1,700,000 | 7 | — | 54 |
| Other countries | 3,600,000 | 15 | NA | 57 |
| **World total** | **24,000,000** | **—** | **>480,000,000** | **53** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

The demand profile for chromium is dominated by that for steel, and stainless steel grades in particular. Demand for stainless steel is expected to remain strong in China and other Asian markets, as infrastructure projects continue to be built. However, demand in other parts of the world is much more subdued. Overall a world growth rate comparable to that of nickel, at around 5% per year, might be considered reasonable (Moss et al., 2011).

In terms of the supply of chromium, the industry is running at relatively low operating rates of 80-90%, meaning that there is scope to meet this increased consumption with existing capacity. Whilst there have not been many new mines that have opened over the past five years, there are now a considerable number of development and exploration projects in the pipeline (KPMG, 2012). KPMG identify more than 20 major chrome projects underway, many of which are at an advanced stage in exploration or currently under construction. Consequently the supply constraints for chromium are judged to be relatively low.

Overall the criticality risks for chromium are rated as medium (Table 110).

*Table 110: Chromium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Chromium | Low | Medium | Medium | Medium | Medium |

### 5.4.3 Cobalt

Cobalt is mainly produced as a by-product metal, from both nickel and copper, with around 10% arising from primary cobalt operations. However cobalt is an important revenue stream for its producers, representing 15-30% of a miner's revenues (International Study Group for Nickel et al., 2012).

The major source of cobalt is Congo (Kinshasa), which has a high political risk rating. In 2011 Congo (Kinshasa) accounted for just over half of the world's mined production, although other mine production was relatively dispersed (Table 111). It should be noted, however, that the geographic location of refined cobalt differs significantly to that of mine production, with Chinese and European refiners among the leading market players.

*Table 111: Cobalt production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | Tonnes | Percentage | | |
| Congo (Kinshasa) | 52,000 | 53 | 3,400,000 | 95 |
| Canada | 7,200 | 7 | 130,000 | 8 |
| China | 6,500 | 7 | 80,000 | 65 |
| Russia | 6,300 | 6 | 250,000 | 68 |
| Zambia | 5,700 | 6 | 270,000 | 65 |
| Australia | 4,000 | 4 | 1,400,000 | 8 |
| Cuba | 3,600 | 4 | 500,000 | 62 |
| Morocco | 2,500 | 3 | 20,000 | 59 |
| New Caledonia | 2,000 | 2 | 370,000 | 15 |
| Brazil | 1,700 | 2 | 87,000 | 46 |
| United States | — | — | 33,000 | — |
| Other countries | 7,000 | 7 | 990,000 | 59 |
| **World total** | **98,000** | **—** | **7,500,000** | **73** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

On the demand side, considerable growth is forecast by some commentators for cobalt's use, at around 7% between 2008 and 2013; the most significant growth is predicted for batteries, catalysts, super-alloys and carbide tooling applications (The Cobalt Development Institute, 2011). However, there is growing evidence that cobalt's use in batteries is gradually being reduced and replaced by other cheaper materials (Avicenne Development in Darton Commodities, 2010). On this basis the demand growth risk is rated as medium.

On the supply side planned capacity expansions at existing or new mines is expected to double mine production capacity between 2010 (Bauer et al., 2011). Due to the oversupply that appears to be likely, supply constraints are rated as low.

Overall risks for cobalt are therefore rated as medium (Table 112).

*Table 112: Cobalt criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Cobalt | Low | Medium | Medium | High | Medium |

### 5.4.4 Copper

Copper has a large market with annual mined production of 16 million tonnes, with a further 3 million tonnes of originating from recycled scrap. Chile is the largest producing country with approximately a third of world mine production in 2011 (Table 113). Copper production in the rest of the world is highly dispersed with the next dozen countries between them accounting for around half of mined copper production. Some of these countries have medium-to-high political risk, however the political risk rating of Chile is adjudged to be very low.

*Table 113: Copper production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| Chile | 5,420,000 | 34 | 35,000,000 | 19 |
| Peru | 1,220,000 | 8 | 86,000,000 | 57 |
| China | 1,190,000 | 7 | 7,000,000 | 65 |
| United States | 1,120,000 | 7 | 190,000,000 | 16 |
| Australia | 940,000 | 6 | 30,000,000 | 8 |
| Zambia | 715,000 | 4 | 20,000,000 | 65 |
| Russia | 710,000 | 4 | 28,000,000 | 68 |
| Indonesia | 625,000 | 4 | 7,000,000 | 65 |
| Canada | 550,000 | 3 | 38,000,000 | 8 |
| Congo (Kinshasa) | 440,000 | 3 | 90,000,000 | 95 |
| Poland | 425,000 | 3 | 26,000,000 | 26 |
| Mexico | 365,000 | 2 | 30,000,000 | 57 |
| Kazakhstan | 360,000 | 2 | 20,000,000 | 60 |
| Other countries | 2,000,000 | 12 | 80,000,000 | 56 |
| **World total** | **16,100,000** | **—** | **690,000,000** | **39** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

In terms of market dynamics, the size of the market and relative maturity of its end markets means that future demand growth will be steady, at a rate of around 4% per year to 2018. Some substitution of copper to aluminium within cables is also possible (CRU Presentation, 2012) so the demand growth risk is rated low.

On the supply side, the small market deficit that currently exists in copper markets is expected to be closed by 2012. Long-term supply projections of supply do not anticipate a supply gap until at least 2020. This is based upon expected supply from scrap, existing mines, probable and possible projects, prospects and new exploration (CRU Presentation, 2012). Therefore the supply constraints are rated as low.

Overall risks for copper are therefore rated as low (Table 114).

*Table 114: Copper criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Copper | Low | Low | Low | Low | Low |

### 5.4.5 Gallium

Gallium is produced as a minor by-product metal from alumina. Primary production for gallium was estimated by the USGS at 216 tonnes in 2011, although data for its geographic breakdown was not provided. A further 94 tonnes of gallium is estimated to be produced from secondary (recycled) sources (USGS, 2012). Quantitative estimates of reserves are not published.

USGS data is, however, available on primary production capacity for 2010, of which just over half was located in China (Table 115). Other important producers include a number of OECD and CIS countries. Comparison of this data with that provided by a commercial producer showed that it can be considered representative of actual primary production (Indium Corporation, 2010). Whilst the political risk rating for China and the CIS countries is moderately high, it is somewhat offset by production in the OECD countries.

*Table 115: Gallium production capacity concentration and political risk*

| **Country** | **Primary production capacity, 2010** | | **Political Risk Rating** |
|---|---|---|---|
| | **tonnes** | **%** | |
| China | 141 | 54 | 65 |
| Germany | 35 | 13 | 13 |
| Kazakhstan | 25 | 10 | 60 |
| South Korea | 16 | 6 | 24 |
| Ukraine | 15 | 6 | 61 |
| Japan | 10 | 4 | 14 |
| Russia | 10 | 4 | 68 |
| Hungary | 8 | 3 | 29 |
| **World total** | **260** | **—** | **51** |

*Source: USGS, 2010a & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

Due to its low concentration within bauxite, gallium can contribute only a small portion of revenue to alumina refineries. Gallium supply therefore depends on the willingness of these refineries to engage in what can appear to be a small and volatile market. However there are significant opportunities to expand production should it be required. Industry estimates suggest that currently only 10% of alumina refineries extract gallium. On balance, based upon both of these aspects, the supply constraints are judged to be of medium risk.

On the demand side, strong growth is expected for the use of gallium in two emerging energy-related applications: LED lighting and photovoltaic solar. Demand for gallium from these markets is expected to exceed 20% per year between 2011 and 2016. Growth in the other main market for gallium – semiconductors - is in comparison relatively modest at around 6% per year (Indium Corporation, 2011). Nonetheless it is clear that the demand growth for gallium will be very high.

Overall risks for gallium are therefore rated as high (Table 116).

*Table 116: Gallium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Gallium | Medium | High | High | Medium | High |

### 5.4.6 Germanium

Germanium is produced mostly as a by-product of zinc refining, but can account for up to 3% of a refiner's total revenues (International Study Group for Nickel et al., 2012). Approximately a quarter of world germanium is recovered from fly ash from coal-fired power stations in China. World virgin refinery production totalled 120 tonnes in 2011, although it should be noted that recycling of secondary germanium added a further 80 tonnes to world supply.

The USGS does not provide quantitative estimates for germanium reserves, except for the United States where estimated reserves contained in zinc amount to 450 tonnes. A study by the BGR estimates worldwide germanium resources at 35,600 tonnes, of which 24,600 tonnes is from coal and the remainder from lead/zinc (BGR, 2012).

In terms of the main producing countries, China accounts for around two thirds of world refinery production (Table 117). However, China's moderate-to-high political risk rating is somewhat offset by those for Canada, United States and Finland; the next three largest producers. Geographic concentration for germanium is therefore rated as high, with moderate political risk.

*Table 117: Germanium production concentration and political risk*

| Country | Refinery production, 2011 | | Political Risk Rating |
|---|---|---|---|
| | tonnes | % | |
| China | 78 | 65 | 65 |
| Canada | 18 | 15 | 8 |
| United States | 14.4 | 12 | 16 |
| Finland | 6 | 5 | 1 |
| Russia | 3.6 | 3 | 68 |
| **World total** | **120** | **—** | **47** |

*Source: Indium Corporation, 2011 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

In terms of germanium demand, stronger growth in the optical fibre, solar and electronics markets is offset by more modest market growth for germanium in other segments. Germanium's use within PET catalysts in Japan has been in long-term decline, and its use within infrared products can now be considered a relatively mature market for germanium (International Study Group for Nickel et al., 2012).

On the supply side, considerable opportunity exists among zinc refiners to improve their recovery of germanium, both in terms of the recovery efficiency and for other zinc refiners to install new equipment. There therefore seems to be reasonable potential for suppliers to respond to higher prices if required (International Study Group for Nickel et al., 2012). In the light of this evidence, both market risks are rated as medium.  Significant reserves of germanium within coal deposits also exist.

Overall risks for germanium are therefore rated as medium to high (Table 118).

*Table 118: Germanium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Germanium | Medium | Medium | High | Medium | Med-High |

### 5.4.7 Gold

Gold is produced from a wide range of sources including alluvial deposits, hard-rock mines and as a by-product of base metal production. The structure of world gold production is therefore very fragmented with around one hundred separate producing countries listed by the USGS. In 2011 the largest world producer, China, had a market share of 13%. The top ten world gold producers account for only around two thirds of world mine production, although the political risk of some of them is moderate to high (Table 119). In addition to mined production it is worth noting that a significant proportion of world supply originates from recycled sources.

*Table 119: Gold production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | tonnes | Percentage | | |
| China | 355 | 13 | 1,900 | 65 |
| Australia | 270 | 10 | 7,400 | 8 |
| United States | 237 | 9 | 3,000 | 16 |
| Russia | 200 | 7 | 5,000 | 68 |
| South Africa | 190 | 7 | 6,000 | 46 |
| Peru | 150 | 6 | 2,000 | 57 |
| Canada | 110 | 4 | 920 | 8 |
| Ghana | 100 | 4 | 1,400 | 48 |
| Indonesia | 100 | 4 | 3,000 | 65 |
| Uzbekistan | 90 | 3 | 1,700 | 81 |
| Mexico | 85 | 3 | 1,400 | 57 |
| Papua New Guinea | 70 | 3 | 1,200 | 71 |
| Brazil | 55 | 2 | 2,400 | 46 |
| Chile | 45 | 2 | 3,400 | 19 |
| Other countries | 630 | 23 | 10,000 | 60 |
| **World total** | **2,700** | **—** | **51,000** | **48** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

The demand for gold has two main market segments: fabrication (mostly jewellery) and investment. Data from the World Gold Survey highlights a long term downward trend in fabrication demand, which has continued since the late 1990s. Demand for physical bar investment has, however, risen considerably since 2007 amid the financial and economic uncertainty affecting many countries (Thomson Reuters GFMS, 2012).

On the supply side the current price of gold has stimulated a raft of exploration activity. Intierra, in their review of pipeline projects, identified 16 Moz (435 tonnes) of mine capacity due to come on stream between 2011 and 2014 (Objective Capital Conferences, 2011a), which suggests the supply risks are relatively low.

Overall risks for gold are therefore rated as low (Table 120).

*Table 120: Gold criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Gold | Low | Low | Low | Medium | Low |

### 5.4.8 Graphite

Graphite is an industrial mineral, an allotrope of the element carbon and has properties of both metal and non-metals such as electrical and thermal conductivity. The majority of graphite originates from natural sources, although technologies do exist to synthetically produce graphite from oil-based feed stocks.

Natural graphite exists in three varieties: vein graphite (1% market share), flake graphite (38% market share) and microcrystalline or amorphous graphite (61% market share). For industrial purposes flake graphite is the most prized, due to the large volumes required in the metallurgical industry (EPOW, 2011).

China is the world's largest producer of natural graphite, with 65% of world production in 2011. China has a high political risk rating, as does India - the world's second largest producer (Table 121).

*Table 121: Graphite production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **Tonnes** | **Percentage** | | |
| China | 600,000 | 65 | 55,000,000 | 65 |
| India | 140,000 | 15 | 11,000,000 | 61 |
| Brazil | 76,000 | 8 | 360,000 | 46 |
| North Korea | 30,000 | 3 | 30,000 | 87 |
| Canada | 25,000 | 3 | # | 8 |
| Romania | 20,000 | 2 | # | 42 |
| Sri Lanka | 8,000 | 1 | 8 | 69 |
| Mexico | 7,000 | 1 | 3,100,000 | 57 |
| Ukraine | 6,000 | 1 | # | 61 |
| Madagascar | 5,000 | 1 | 940,000 | 70 |
| Norway | 2,000 | 0 | # | 2 |
| Other countries | 6,000 | 1 | 6,400,000 | — |
| **World total** | **925,000** | **—** | **77,000,000** | **61** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*
*#indicates included within other countries*

There has been some concern regarding the possible growth rate in demand for graphite with Li-ion batteries, which could reach 1 million tonnes per year by 2035 (Industrial Minerals, 2010). This equates to an annual growth rate for this market of 12.6% per year; albeit from a relatively small base. However given the diversity of uses for natural graphite in mature markets, overall demand growth may be relatively steady at 3% per year.

On the supply side, due to the differing types of natural graphite deposits, there could be some supply constraints for the flake graphite required for lithium ion batteries.

Overall the risks for graphite are rated as medium to high (Table 122).

*Table 122: Graphite criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Graphite | Medium | Low | High | High | Med-High |

### 5.4.9 Hafnium

Hafnium is a rare metal, which is found along with zirconium in the mineral zircon and to a smaller degree in baddeleyite. Commercial production of hafnium arose from the need to produce hafnium-free zirconium metal for use in nuclear reactors. As hafnium is chemically very similar to zirconium, separating the two elements from each other is very difficult. Most zircon (and, therefore, hafnium) is mined from titanium-rich, heavy-mineral sand deposits, notably in Australia and South Africa. Quantitative reserve estimates for hafnium are not available.

The majority of world hafnium production comes from the hafnium-free zirconium production for nuclear-reactor applications. Two companies dominate world production: Cezsus in France and Wah Chang in the United States, who together produce 60 tonnes out of a total of 64 tonnes, which represents the majority of world production (Table 105). Other producers are known to exist in India and China (for domestic use only). Westinghouse in the United States does not produce added-value hafnium by-products during zirconium sponge production (Lipmann Walton & Co, 2012). Hafnium production is therefore highly concentrated, although within countries of low political risk (Table 123).

*Table 123: Hafnium production concentration and political risk*

| Country | Refinery production, 2011 | | Political Risk Rating |
|---|---|---|---|
| | tonnes | Percentage | |
| France | 30 | 47 | 15 |
| United States | 30 | 47 | 16 |
| Ukraine | 2 | 3 | 61 |
| Russia | 2 | 3 | 68 |
| **World total** | **64** | **—** | **19** |

*Source: Lipmann Walton & Co, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

Supply for refined hafnium is highly constrained, as it is limited by the demand for high purity zirconium in the nuclear industry. As indicated in Section 4.3.12, a number of countries are reconsidering their nuclear programmes, which will affect future hafnium availability for other industries. A further complication relates to the hafnium production process and the purity of the output. Approximately half of world supply is of high purity, produced from the Van Arkel process, which is used in the superalloy industry.

On the demand side, market statistics currently indicate a market imbalance, with demand exceeding supply by perhaps 10 tonnes per year. As the nuclear industry is both the producer and also a consumer of hafnium, it is likely to be shielded from this deficit. For high-purity hafnium for superalloys the market is approximately in balance, but is relatively volatile. Over the longer term, demand growth is expected to be relatively modest, at perhaps 4% per year (Moss et al., 2011).

Overall the risks for hafnium are rated as medium to high (Table 124).

*Table 124: Hafnium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Hafnium | High | Low | High | Low | Med-High |

### 5.4.10 Indium

Although indium is produced as a by-product of zinc refining, it can account for up to 3% of a refiner's total revenues (International Study Group for Nickel et al., 2012). World virgin refinery production totalled 640 tonnes in 2011, while reclaimed indium added a further 900 tonnes to world supply. The USGS does not provide quantitative estimates for indium reserves, although a study by a commercial producer estimates 50,000 tonnes of reserves within zinc and copper concentrates at existing mines (Indium Corporation, 2012).

In terms of the main producing countries, China accounts for around half of world refinery production (Table 125). However, China's moderate-to-high political risk rating is somewhat offset by those for South Korea, Japan and Canada; the next three largest producers. It is worth noting however that relatively higher risk Peru and Bolivia are sources of the mined concentrates from which indium is refined. Nonetheless, political risk is rated on balance as being medium.

*Table 125: Indium production concentration and political risk*

| **Country** | **Refinery production, 2011** | | **Political Risk Rating** |
|---|---|---|---|
| | **tonnes** | **%** | |
| China | 340 | 53 | 65 |
| South Korea | 100 | 16 | 24 |
| Japan | 70 | 11 | 14 |
| Canada | 65 | 10 | 8 |
| Belgium | 30 | 5 | 14 |
| Brazil | 5 | 1 | 46 |
| Russia | NA | NA | — |
| Other countries | 30 | 5 | 19 |
| **World total** | **640** | **—** | **42** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

*NA indicates not available*

In terms of indium demand, the largest market - flat panel displays - is now relatively mature, with slow-to-steady growth expected. More rapid expansions for indium use are expected in the photovoltaic solar industry and LEDs, although both are growing fast from a relatively slow base. An overall rate of demand growth close to around 5% per year is anticipated (Indium Corporation, 2011).

On the supply side, considerable opportunity exists among zinc refiners to improve their recovery of indium, both in terms of recovery efficiency and for other zinc refiners to install new equipment. There therefore seems to be reasonable potential for suppliers to respond to higher prices if required (International Study Group for Nickel et al., 2012). In the light of this evidence, both market risks are rated as medium.

Overall risks for indium are therefore rated as medium to high (Table 126).

*Table 126: Indium criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Indium | Medium | Medium | High | Medium | Med-High |

### 5.4.11 Lead

Lead as a base metal has an annual mined production of 4.5 million tonnes. Global production of refined lead is much higher than this, however, at an estimated 10.4 million tonnes (ILZSG, 2012a). This in part represents the importance of recycling lead acid batteries to world supply of lead. China is the largest lead-producing country, with almost half of world mine production in 2011 (Table 113).

Estimates for refined lead indicate a similar degree of dominance by China. Other important producing countries include Australia, the United States, Latin American countries, India and Russia. As with a number of other metals the high political risk rating of the dominant producer China is important. However, this is to some extent offset by lower political risk in Australia and the United States, giving an overall political risk rating of medium.

*Table 127: Lead production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | Tonnes | Percentage | | |
| China | 2,200,000 | 49 | 14,000,000 | 65 |
| Australia | 560,000 | 12 | 29,000,000 | 8 |
| United States | 345,000 | 8 | 6,100,000 | 16 |
| Peru | 240,000 | 5 | 7,900,000 | 57 |
| Mexico | 225,000 | 5 | 5,600,000 | 57 |
| India | 120,000 | 3 | 2,600,000 | 61 |
| Russia | 115,000 | 3 | 9,200,000 | 68 |
| Bolivia | 85,000 | 2 | 1,600,000 | 68 |
| Canada | 75,000 | 2 | 450,000 | 8 |
| Sweden | 70,000 | 2 | 1,100,000 | 3 |
| South Africa | 55,000 | 1 | 300,000 | 46 |
| Ireland | 50,000 | 1 | 600,000 | 8 |
| Poland | 40,000 | 1 | 1,700,000 | 26 |
| Other countries | 340,000 | 8 | 5,000,000 | 57 |
| **World total** | **4,500,000** | **-** | **85,000,000** | **49** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

Recent statistics indicate a growing market surplus for lead. World lead mine production is expected to rise by more than 10% in 2012, driven by further mine expansions in China, as well as the re-opening of facilities such as La Oroya in Peru.

Demand growth, however, is steadier at 3.3%-3.4% forecast for 2012-13, with stronger growth in China offset by more modest growth elsewhere. Market surpluses are expected to be108,000 tonnes for 2012, increasing to 174,000 tonnes in 2013 (ILZSG, 2012b), and it is noteworthy that metal stocks of lead were reported to be 622,000 tonnes at the end of 2011. Market risks for lead therefore appear low.

The overall risks for lead are therefore rated as low (Table 128).

*Table 128: Lead criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Lead | Low | Low | Medium | Medium | Low |

### 5.4.12 Lithium

Lithium is an industrial mineral that can be produced from a variety of sources including brines, and hard and soft rock deposits. Currently the brine operations in Chile, Argentina and China dominate world lithium supply due to their lower operating cost compared to the hard rock deposits of Australia. Collectively these four countries accounted for 96% of the world supply of lithium in 2011 (Table 129).

The political risk rating for with lithium is relatively low. This is due to the low risk associated with production in Chile and Australia, the world's two largest producers which currently supply 70% of the world market.

*Table 129: Lithium production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **Tonnes** | **Percentage** | | |
| Chile | 12,600 | 37% | 970,000 | 19 |
| Australia | 11,300 | 33% | 64,000 | 8 |
| China | 5,200 | 15% | 7,500,000 | 65 |
| Argentina | 3,200 | 9% | 3,500,000 | 44 |
| Portugal | 820 | 2% | 10,000 | 17 |
| Zimbabwe | 470 | 1% | 38,000 | 95 |
| Brazil | 160 | 0% | 23,000 | 46 |
| United States | W | W | 850,000 | — |
| **World total** | **34,000** | **—** | **13,000,000** | **26** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*
*W indicates withheld to avoid disclosing company proprietary data*

Demand forecasts for lithium do vary significantly according to the rate of uptake and penetration assumed for electric vehicles. The International Lithium Institute in their review of market forecasts considers the following to be reasonable. It estimates world demand at 190,500 tonnes per year of lithium carbonate equivalent (LCE) for 2015, rising to 254,300 tonnes by 2020 (Objective Capital Conferences, 2011b). This compares to USGS's estimates of current production of 150,000 tonnes of LCE in 2010 (Bauer et al., 2011). This therefore implies a demand growth rate of around 5% per year for the coming decade.

On the supply side there are a large number of projects underway, which are expected to comfortably meet these increases in lithium demand. These include expansions of existing projects by the world's big four lithium producers of the order 75,000-80,000 tonnes per year of LCE by 2015. Pipeline projects could add a further 220,000 tonnes per year LCE production by 2015 (Objective Capital Conferences, 2011b), although it can probably be assumed that not all will be successful. Nonetheless the risk for lithium appears to be that of excess production capacity rather than insufficient.

The overall risks for lithium are therefore rated to be medium to low (Table 130).

*Table 130: Lithium criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Lithium | Low | Medium | Medium | Low | Low-Med |

### 5.4.13 Molybdenum

Molybdenum production occurs from two main sources: as a by-product of copper and through primary molybdenum mining. The world mine production of molybdenum of some 250,000 tonnes per year is split almost equally between these two sources (Roskill, 2010a).

The three most important producing countries are China, United States and Chile, which collectively accounted for nearly 80% of world mine production in 2011 (Table 131). Overall the political risk rating of these countries is rated as medium; with the higher political risk rating of China offset by lower ratings for the United States and Chile.

*Table 131: Molybdenum production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **Tonnes** | **Percentage** | | |
| China | 94,000 | 38 | 4,300,000 | 65 |
| United States | 64,000 | 26 | 2,700,000 | 16 |
| Chile | 38,000 | 15 | 1,200,000 | 19 |
| Peru | 18,000 | 7 | 450,000 | 57 |
| Mexico | 12,000 | 5 | 130,000 | 57 |
| Canada | 8,300 | 3 | 220,000 | 8 |
| Armenia | 4,200 | 2 | 200,000 | 57 |
| Russia | 3,800 | 2 | 250,000 | 68 |
| Iran | 3,700 | 1 | 50,000 | 80 |
| Mongolia | 2,000 | 1 | 160,000 | 50 |
| Uzbekistan | 550 | 0 | 60,000 | 81 |
| Kazakhstan | 360 | 0 | 130,000 | 60 |
| Kyrgyzstan | 250 | 0 | 100,000 | 77 |
| **World total** | **250,000** | **—** | **10,000,000** | **43** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

The major markets for the molybdenum are as an alloying element in steel alloys (e.g. stainless steel, full alloy steel), which collectively account for three quarters of its usage. However, this end-use is split across several industries, with none accounting for more than 20% of total use. Strong demand growth in emerging markets, such as in power generation, is expected to be offset by weak demand in developed markets, giving an overall annual growth rate of 3.6% per year to 2020 (IMOA, 2011).

On the supply side, an analysis of some 120,000 tonnes of molybdenum exploration and expansion projects between 2010 and 2014 is expected to increase the current slight market surplus (Roskill, 2010a). Overall the criticality of molybdenum is rated to be medium to low (Table 132).

*Table 132: Molybdenum criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Molybdenum | Low | Low | Medium | Medium | Low-Med |

### 5.4.14 Nickel

Nickel is a base metal with mine production at 1.8 million tonnes in 2011. The largest market for nickel is in stainless steel, which accounts for 70% of the annual use of nickel. The recycling of stainless steel scrap contributes additional supply to the market. World supply of nickel is well diversified with the top five producing countries accounting for just under two thirds of world mine production.

The political risk associated with the top three countries (Russia, Indonesia and Philippines) is rated as high, although that for Canada and Australia is much lower.

*Table 133: Nickel production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | tonnes | percentage | | |
| Russia | 280,000 | 16 | 6,000,000 | 68 |
| Indonesia | 230,000 | 13 | 3,900,000 | 65 |
| Philippines | 230,000 | 13 | 1,100,000 | 68 |
| Canada | 200,000 | 11 | 3,300,000 | 8 |
| Australia | 180,000 | 10 | 24,000,000 | 8 |
| New Caledonia | 140,000 | 8 | 12,000,000 | 15 |
| Brazil | 83,000 | 5 | 8,700,000 | 46 |
| China | 80,000 | 4 | 3,000,000 | 65 |
| Cuba | 74,000 | 4 | 5,500,000 | 62 |
| Colombia | 72,000 | 4 | 720,000 | 64 |
| South Africa | 42,000 | 2 | 3,700,000 | 46 |
| Botswana | 32,000 | 2 | 490,000 | 41 |
| Madagascar | 25,000 | 1 | 1,600,000 | 70 |
| Dominican Republic | 14,000 | 1 | 1,000,000 | 62 |
| Other countries | 100,000 | 6 | 4,600,000 | 51 |
| **World total** | **1,800,000** | **—** | **80,000,000** | **47** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

Demand growth for nickel is expected to be reasonably strong, estimated at around 5% per year between 2010 and 2020. This will primarily be driven by demand growth in the largest market - stainless steel consumption in China (Moss et al., 2011).

On the supply side, the nickel market currently indicates a market surplus, and there are a large number of additional mid-large size nickel projects in the pipeline. The surplus is expected to continue until at least 2015, and thereafter the market should remain approximately in balance (Moss et al., 2011).

Overall the criticality of nickel is rated to be low (Table 134).

*Table 134: Nickel criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Nickel | Low | Medium | Low | Medium | Low |

### 5.4.15 Niobium

Niobium is a non-ferrous metal mainly used as an alloying element within the steel industry, as ferro-niobium. Niobium is found in the minerals pyrochlore (the main commercial source for niobium) and columbite. Estimates of world reserves are large at 3 million tonnes.

World production of niobium is highly concentrated (Table 135), with a single company (CBMM in Brazil located near Araxá), accounting for over 80% of world production. Anglo American is a second, if significantly smaller, Brazilian niobium producer. Most of the remaining 8% comes from the third biggest niobium mine located in Canada, with a number of other small African producers. Brazil, the dominant niobium producer, has a moderate political risk rating. In summary, niobium is given a high geographic concentration and a medium political risk rating.

*Table 135: Niobium production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | tonnes | percentage | | |
| Brazil | 58,000 | 92 | 2,900,000 | 46 |
| Canada | 4,400 | 7 | 200,000 | 8 |
| Other countries | 600 | 1 | NA | 81 |
| **World total** | **63,000** | **—** | **3,000,000** | **44** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

*NA indicates not available*

Future niobium demand will be driven by the growing consumption of ferro-niobium (FeNb) in advanced metallurgical applications, notably high strength alloy steel (HSLA) for construction and large infrastructure projects. Forecasts for the demand of high strength steel vary somewhat, but a long term compound annual growth rate of 8% per year is considered to be reasonable (Moss et al., 2011). Demand growth is therefore rated as high.

To meet such increasing demand, existing niobium producers – most importantly the Brazilian company CBMM – have declared they will be able to gradually expand their production capacity. The niobium industry already has some excess capacity, and increasing niobium prices are likely to make new projects economical (Moss et al., 2011). It is therefore expected that production capacity will be able to keep pace with demand growth, and it is noted that world reserves are very large compared to annual production.

Overall the criticality of niobium is rated as medium (Table 136).

*Table 136: Niobium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Niobium | Low | High | High | Medium | Medium |

### 5.4.16 Platinum

Platinum is a precious metal, the main source of which is production from low concentration primary deposits in South Africa, Zimbabwe and elsewhere. Approximately three quarters of platinum world mine production comes from the Bushveld complex in South Africa from these PGM-dominant deposits (Table 137). The other main source of platinum mine production is as a by-product of nickel-copper production, notably in Russia. However, in contrast to the South African deposits, the content of those in Russia are palladium-rich rather than platinum-rich (International Study Group for Nickel et al., 2012).

A considerable proportion of world platinum supply originates from recycled sources, notably autocatalysts and jewellery. The political risk of the dominant platinum producing country, South Africa, is rated as moderate. For the other main countries, the higher risk associated with production from is offset by that from Canada and the United States.

*Table 137: Platinum production concentration and political risk*

| Country | Mine production, 2010 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| South Africa | 139 | 73 | 63,000 | 46 |
| Russia | 26 | 14 | 1,100 | 68 |
| Canada | 10 | 5 | 310 | 8 |
| Zimbabwe | 9 | 5 | # | 95 |
| United States | 3.7 | 2 | 900 | 16 |
| Colombia | 1 | 1 | # | 64 |
| Other countries | 2.5 | 1 | 800 | — |
| **World total** | **192** | **—** | **63,000** | **49** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

*#indicates included within other countries*

In terms of demand, the two main uses of platinum are for autocatalysts and jewellery, which represent 75% of total usage. The remainder is split between various industrial applications. Platinum demand within autocatalysts will to some extent track global (diesel) vehicle sales, although some substitution towards cheaper palladium is on-going. Strong growth in vehicle sales in emerging markets are being offset by weaker growth in developed markets. GFMS notes that the platinum market is still in recovery, with usage in 2011 still 25% below 2007 levels (Thomson Reuters, 2012). Investment demand arising due to uncertainties in the world economy, however, continues to provide support for the platinum price. Steady long-term demand growth for platinum, at 2-3% per year, may therefore be considered reasonable.

On the supply side the platinum market is estimated to be currently in surplus, by around 9% of annual supply (Thomson Reuters, 2012). However historical trends highlight the slow growth in supply growth that has been witnessed over the past decades.

Overall the risks for platinum are rated as medium to high (Table 138).

*Table 138: Platinum criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Platinum | Medium | Low | High | Medium | Med-High |

### 5.4.17 Rare earths

As is now widely known, rare earth production is highly concentrated in China. In 2011 China had over 95% of the world's mine production (Table 139). The political risk for China is considered to be high.

*Table 139: Rare earths production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| China | 130,000 | 97 | 55,000,000 | 65 |
| India | 3,000 | 2 | 3,100,000 | 61 |
| Brazil | 550 | 0 | 48,000 | 46 |
| Malaysia | 30 | 0 | 30,000 | 46 |
| CIS | NA | NA | 19,000,000 | — |
| Australia | — | — | 1,600,000 | — |
| United States | — | — | 13,000,000 | — |
| Other countries | NA | NA | 22,000,000 | — |
| **World total** | **130,000** | **—** | **110,000,000** | **64** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

***NA indicates not available***

In terms of the outlook for rare earth elements, a key distinction can be made between the more abundant light rare earth elements and the scarcer heavy rare earth elements (Lynas Corporation Ltd, 2010):

- Of the major expansions in world rare earth capacity, both Mountain Pass in California and Mount Weld in Western Australia are dominant in the light rare earths, lanthanum and cerium.
- Of current rare earth supply, many of the heavy rare earth rich mines in Southern China are having their supply severely restricted due to environmental reasons.

In terms of market demand, the strongest growth is forecast for magnet materials (praseodymium and neodymium) and phosphor materials (heavy rare earth elements). Some substitution and demand reduction strategies may be possible, but market supply is expected to remain tight till at least 2016. For the light rare earth elements oversupply is expected as some of the distortionary effects to the Chinese export quotas unwind and surplus stocks are sold (Kingsnorth, IMCOA, 2012). Based on this analysis the supply and demand constraints for the light rare earths are considered to be relatively low, whereas for the heavy rare earths the constraints are much higher.

The overall risks for rare earths are therefore broken down into three categories (Table 140):

- the heavy rare earth elements have the highest risk profile
- praseodymium and neodymium have a slightly lower risk profile, but are still rated as high overall
- other light rare earth elements plus gadolinium are judged to have a medium overall risk profile.

*Table 140: Rare earths criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Dy, Eu, Tb, Y | High | High | High | High | High |
| Pr, Nd | Medium | High | High | High | High |
| La, Ce, Sm, Gd | Low | Medium | High | High | Medium |

### 5.4.18 Rhenium

Rhenium is a rare metal with world mine production of approximately 50 tonnes per year, the majority of which is produced as a by-product of copper-molybdenum deposits. It is this status as a by-product of another by-product that drives the market dynamics for rhenium – sales of rhenium may represent only 0.3% of a copper refinery's total revenues (International Study Group for Nickel et al., 2012).

Molymet in Chile dominates world rhenium supply with around half of world mine production, due to the molybdenum concentrates and roasts produced on behalf of other companies. However, the political risk for Chile is rated as low (Table 141).

*Table 141: Rhenium production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| Chile | 26 | 53 | 1,300 | 19 |
| United States | 6.3 | 13 | 390 | 16 |
| Peru | 5 | 10 | 45 | 57 |
| Poland | 4.7 | 10 | NA | 26 |
| Kazakhstan | 3 | 6 | 190 | 60 |
| Canada | 1.2 | 2 | 32 | 8 |
| Armenia | 0.6 | 1 | 95 | 57 |
| Russia | 0.5 | 1 | 310 | 68 |
| Other countries | 1.5 | 3 | 91 | |
| **World total** | **49** | **—** | **2,500** | **27** |

Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores
NA indicates not available

Roskill, in their market forecast for rhenium demand, predict annual growth of around 5% per year (Roskill, 2010b). This rate of growth is attributed to strong annual sales growth for airline engines at 4% per year, and a rise in the rhenium content of the superalloys in their turbine blades between the first and second generation. With approximately 60% of world rhenium demand in aerospace superalloys and an additional 20% in other applications of superalloys, this market is key to understanding rhenium demand prospects.

On the supply side, rhenium is highly supply constrained. Mine production has remained at around 50 tonnes per year since 2005. There are relatively few projects in the pipeline, although several molybdenum roasters are considering installing rhenium recovery circuits. To meet this growing demand recycling has become considerably more efficient. Nonetheless engine manufacturers are in the process of developing superalloys with lower rhenium content in response to perceived supply constraints (International Study Group for Nickel et al., 2012).

The overall risks for rhenium are considered to be medium to high (Table 142).

*Table 142: Rhenium criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Rhenium | High | Medium | High | Low | Med-High |

### 5.4.19 Selenium

Selenium is a metalloid, mostly produced as a by-product from refining copper sulphide ores and to a lesser extent from lead ores. World reserves within copper deposits are estimated at 93,000 tonnes in countries such as Russia, Peru, Chile and the United States (USGS, 2012).

A range of estimates exist for total world production of selenium such as from the US Geological Survey, International Copper Study Group (ICSG) and other industry sources. Here the ICSG estimates are quoted (Table 143) as they are the most detailed and complete, although at 2,600-2,700 tonnes per year they are more conservative than the 3,000-3,500 tonnes quoted by the USGS (USGS, 2008). The location of production is relatively diverse: the world's leading producers, China and Japan, are each attributed to approximately 20% of world production. Overall the political risk for selenium is moderate.

*Table 143: Selenium production concentration and political risk*

| Country | Refinery production, 2011 | | Political Risk Rating |
|---|---|---|---|
| | tonnes | Percentage | |
| China | 500 | 19 | 65 |
| Japan | 480 | 19 | 14 |
| Germany | 250 | 10 | 13 |
| United States | 170 | 7 | 16 |
| Russia | 160 | 6 | 68 |
| Belgium | 150 | 6 | 14 |
| India | 140 | 5 | 61 |
| Canada | 120 | 5 | 8 |
| Norway | 100 | 4 | 2 |
| South Korea | 100 | 4 | 24 |
| Other countries | 500 | 15 | 58 |
| **World total** | **2,670** | **—** | **44** |

*Source: International Study Group for Nickel et al., 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

All selenium is produced as a by-product of the mining and processing of base metals, and selenium revenues comprise a negligible share of a refiner's overall revenue (International Study Group for Nickel et al., 2012). Supply can therefore be relatively constrained and unresponsive to market demand and price movements.

The consensus is that the market for selenium is broadly in balance, and the diversity of applications for selenium has helped to provide stability to prices. In the major markets - manganese production, glass and feed - no major demand increases are expected and, in the short term, industry observers hope that demand will remain level (International Study Group for Nickel et al., 2012). However, there is some discussion in the industry regarding the long-term substitutability or reduction of selenium in its main market - electrolytic manganese in China.

The overall risks for selenium are considered to be medium to low (Table 144).

*Table 144: Selenium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Selenium | Medium | Low | Low | Medium | Low-Med |

### 5.4.20 Silver

Silver is a precious metal produced in at least 50 different countries worldwide, and from a diverse range of sources. The main source is currently as a by-product of lead and zinc ores (37%), with 21% produced as a by-product of copper and 13% produced as a by-product of gold. Approximately 30% is produced from primary silver mines (Silver Institute & GFMS, 2012). World reserves for silver exceed 500,000 tonnes.

World mine production of silver for 2011 is estimated at 23,800 tonnes, with the three largest producers accounting for just over 50% of world production (Table 145). Although Mexico, China and Peru all have moderate to high political risk ratings, the overall political risk for silver is somewhat offset by Australia and Chile as significant producers. This results in a medium political risk for silver.

*Table 145: Silver production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | 2011 | pecentage | | |
| Mexico | 4,500 | 19 | 25,000 | 57 |
| China | 4,000 | 17 | 69,000 | 65 |
| Peru | 4,000 | 17 | 22,000 | 57 |
| Australia | 1,900 | 8 | 7,000 | 8 |
| Chile | 1,400 | 6 | 70,000 | 19 |
| Russia | 1,400 | 6 | 43,000 | 68 |
| Bolivia | 1,350 | 6 | 37,000 | 68 |
| Poland | 1,200 | 5 | 120,000 | 26 |
| United States | 1,160 | 5 | 85,000 | 16 |
| Canada | 700 | 3 | NA | 8 |
| Other countries | 2,200 | 9 | 50,000 | 50 |
| **World total** | **23,800** | **—** | **530,000** | **48** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

*NA indicates not available*

Silver has a variety of key applications including jewellery, silverware, electronics, photography, mirrors and catalysts. The market is forecast to remain roughly in balance, despite strong growth in new applications (solar, food hygiene and wound care) because of the stability of demand in traditional applications such as photography and jewellery (Moss et al., 2011). The likelihood of rapid demand growth over the coming decade is therefore assessed as low.

Reserve levels for silver are large relative to current production, although most of this is not in primary silver ores. Due to these by-product dependencies, the overall limitations to expanding supply are scored as medium. However, should silver supply from co-product and by-product sources (gold, lead/zinc and copper) track the forecast production for these minerals, supply is expected to keep pace with demand.

The overall risks for silver are considered to be medium to low (Table 146).

*Table 146: Silver criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Silver | Medium | Low | Low | Medium | Low-Med |

### 5.4.21 Tantalum

Tantalum is a minor metal generally produced as a by-product or co-product of tin and/or tungsten (Brazil and Africa) or lithium (Australia). World production statistics do also highlight considerable volatility year-on-year in world tantalum mine production.

World mine production for tantalum was estimated at 790 tonnes for 2011. This was split between Brazil, Australia and four different countries in Africa (Table 147). However while the geographic concentration is relatively low, the political risk of five of these top six countries is considered to be moderate to high.

*Table 147: Tantalum production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| Brazil | 180 | 23 | 65,000 | 46 |
| Congo (Kinshasa) | 140 | 18 | NA | 95 |
| Mozambique | 120 | 15 | 3,200 | 62 |
| Rwanda | 110 | 14 | NA | 65 |
| Ethiopia | 95 | 12 | NA | 81 |
| Australia | 80 | 10 | 51,000 | 8 |
| Canada | 25 | 3 | NA | 8 |
| Nigeria | 20 | 3 | NA | 85 |
| Burundi | 16.4 | 2 | NA | 86 |
| **World total** | **790** | **—** | **120,000** | **61** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*
*NA indicates not available*

The main market driver for tantalum demand is electronics, with some 60% of world tantalum consumption estimated to be for capacitors. Other important markets include cemented carbides and aerospace superalloys. Whilst the growth for electronics is expected to continue, it is growth realising that tantalum capacitors do compete with ceramic, aluminium and other types of capacitors (AVX Presentation, 2011). Trend growth for tantalum demand is approximately 5% per year, although some other estimates are more conservative and some more optimistic (EPOW, 2011).

On the supply side for tantalum, it is clear that some excess capacity exists. In a matter of months in 2008, 40% of world capacity was put onto ‘care and maintenance’ in response to low prices (Roskill, 2009). It is not clear whether and when this will return to production. In addition to the currently mothballed mine capacity there are also large development projects in Mozambique and Egypt. There are some risks of shortages in the short run, but sufficient supply should be available in the medium-to-long run.

Overall the risk evaluation for tantalum is rated as medium (Table 148).

*Table 148: Tantalum criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Tantalum | Low | Medium | Low | High | Medium |

### 5.4.22 Tellurium

Tellurium is a metalloid, mostly produced as a by-product from the refining of copper sulphide ores, and to a lesser extent from lead ores. World reserves within copper deposits are estimated at 24,000 tonnes in countries such as United States, Peru and Canada (USGS, 2012).

A range of estimates exist for total world production of tellurium such as from the USGS, International Copper Study Group (ICSG) and other industry sources. Here the ICSG estimates are quoted (Table 149) as they are the most detailed and complete, although at 450-470 tonnes per year they are more conservative than the 500-550 tonnes quoted by the USGS (USGS, 2008). The location of production is relatively diverse, with China, Japan and Belgium the world's leading producers each reckoned to have 15-20% of world production. Overall the political risk for tellurium is moderate.

*Table 149: Tellurium production concentration and political risk*

| Country | Refinery production, 2011 | | Political Risk Rating |
|---|---|---|---|
| | tonnes | Percentage | |
| China | 80-100 | 19 | 65 |
| Japan | 65 | 15 | 14 |
| Belgium | 60 | 14 | 14 |
| Germany | 30-35 | 8 | 13 |
| Canada | 25 | 6 | 8 |
| Russia | 25 | 6 | 68 |
| Kazakhstan | 20 | 5 | 60 |
| Philippines | 20 | 5 | 68 |
| South Korea | 20 | 5 | 24 |
| Sweden/Finland | 20 | 5 | 3 |
| Indonesia | 15 | 4 | 65 |
| India | 10-12 | 3 | 61 |
| Other countries | 50 | 5 | 45 |
| **World total** | **450-477** | **—** | **45** |

*Source: International Study Group for Nickel et al., 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

All tellurium is produced as a by-product of the mining and processing of base metals, and revenues comprise a negligible share of a refiner's overall revenue (International Study Group for Nickel et al., 2012). This means that supply can be relatively constrained and unresponsive to market demand and price movements. There is also some concern regarding the shift towards SX-EW copper refining, which may affect tellurium recovery in the future.

Demand in tellurium is expected to increase rapidly over the coming decade, especially due to solar PV applications, which is now the main market for tellurium. Likelihood of rapid demand growth over the coming decade is therefore scored as high.

Overall the risk evaluation for tellurium is rated as high (Table 150).

*Table 150: Tellurium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Tellurium | High | High | Low | Medium | High |

### 5.4.23 Tin

Tin is a base metal, and has a relatively large market at 270,000 tonnes of mine production. Secondary tin accounts for around 20% of world supply, putting tin smelter production at nearer 350,000 tonnes per year. Global tin reserves are estimated at 4.8 million tonnes.

China is the world's leading tin producer with 42% of world production, with Indonesia and Peru representing important tin producing countries. All of these countries, as well as a number of other leading tin producing countries, have high political risk ratings. The geographical concentration of production is designated as moderate.

*Table 151: Tin production concentration and political risk*

| **Country** | **Mine production, 2011** | | **Reserves (tonnes)** | **Political Risk Rating** |
|---|---|---|---|---|
| | **tonnes** | **Percentage** | | |
| China | 110,000 | 42 | 1,500,000 | 65 |
| Indonesia | 51,000 | 19 | 800,000 | 65 |
| Peru | 34,600 | 13 | 310,000 | 57 |
| Bolivia | 20,700 | 8 | 400,000 | 68 |
| Australia | 19,500 | 7 | 180,000 | 8 |
| Brazil | 12,000 | 5 | 590,000 | 46 |
| Vietnam | 6,000 | 2 | NA | 63 |
| Congo (Kinshasa) | 5,700 | 2 | NA | 95 |
| Malaysia | 2,000 | 1 | 250,000 | 46 |
| Russia | 1,000 | 0 | 350,000 | 68 |
| Portugal | 100 | 0 | 70,000 | 17 |
| Thailand | 100 | 0 | 170,000 | 60 |
| Other countries | 2,000 | 1 | 180,000 | 79 |
| **World total** | **270,000** | **—** | **4,800,000** | **61** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

*NA indicates not available*

Tin demand is dominated by solder and tinplate and is likely to keep growing at a slow but steady pace driven mainly by applications in the electronics industry (Moss et al., 2011). The likelihood of rapid demand growth over the coming decade is therefore scored as low.

Reserves for tin are large relative to current production. However, while new supply is expected to come on the market in several years, global tin output is currently constrained by years of under-investment (Moss et al., 2011). Supply constraints in the short-to-medium term are therefore scored as medium.

Overall the risk evaluation for tin is rated as medium (Table 152).

*Table 152: Tin criticality evaluation*

| **Metal** | **Supply Constraints** | **Demand Growth** | **Geographic Concentration** | **Political Risk** | **Overall** |
|---|---|---|---|---|---|
| Tin | Medium | Low | Medium | High | Medium |

### 5.4.24 Vanadium

Vanadium is a non-ferrous metal mainly used as an alloying element within the steel industry. It comes from a range of different sources including ores, concentrates and vanadiferous slags. Vanadium is usually recovered as a by- or co-product. Approximately 56% of vanadium is obtained from slag processing, with another 43% of vanadium production from vanadium containing minerals.

Vanadium production is dominated by China, South Africa and Russia. Together they produced over 95% of global vanadium supply in 2011 (Table 153). All of these countries have moderate or high political risk ratings, resulting in a high score for political risk. World reserves are relatively abundant at 14 million tonnes, although the majority is located within the same three countries.

*Table 153: Vanadium production concentration and political risk*

| Country | Mine production, 2011 | | Reserves (tonnes) | Political Risk Rating |
|---|---|---|---|---|
| | 2011 | percentage | | |
| China | 23,000 | 38 | 5,100,000 | 65 |
| South Africa | 20,000 | 33 | 3,500,000 | 46 |
| Russia | 15,000 | 25 | 5,000,000 | 68 |
| Kazakhstan | 1,000 | 2 | NA | 60 |
| United States | 500 | 1 | 45,000 | 16 |
| Japan | 500 | 1 | NA | 14 |
| **World total** | **60,000** | **—** | **14,000,000** | **58** |

*Source: USGS, 2012 & World Bank, 2011, Fund for Peace, n.d. for Political Risk Scores*

*NA indicates not available*

Vanadium demand is expected to experience robust growth based on growing steel production and an increasing share of high-strength steels. Long term demand projections are put at 6% average annual growth for steel and 8% average annual growth for high-strength steel (Moss et al, 2011). New applications for vanadium have been recently discovered, such as batteries, and non-metallurgical usage of vanadium is now rising at the same rate as GDP. Therefore the demand growth rates are rated as high.

Considerable reserves are available and supply is expected to grow substantially over the next few years, driven by expanding capacity of existing suppliers as well as new market entrants. There is a number of promising vanadium development projects in progress and, should these come on-stream, supply is expected to keep pace with increasing demand (Moss et al., 2011). However, history suggests that temporary spikes are possible, as witnessed in early 2005 and again in 2008, and might occur if demand and supply do not match up smoothly.

Overall the risk evaluation for vanadium is rated as medium (Table 154).

*Table 154: Vanadium criticality evaluation*

| Metal | Supply Constraints | Demand Growth | Geographic Concentration | Political Risk | Overall |
|---|---|---|---|---|---|
| Vanadium | Low | High | Medium | High | Medium |

## 5.5 Overview of the bottleneck screening

Eight metals have been given a high criticality rating and are therefore classified as 'critical'. These include six rare earth elements (dysprosium, europium, terbium, yttrium, praseodymium and neodymium), gallium and tellurium. Available mitigation strategies to alleviate potential supply chain bottleneck risks from these eight metals are discussed in Chapter 6.

Six materials have been given a medium-to-high rating and therefore could be considered to be 'near critical'. It is suggested that the market conditions should be monitored for graphite, rhenium, hafnium, germanium, indium and platinum in case the markets for these metals deteriorates with the effect of posing supply chain bottleneck risks. A further ten metals have a medium risk rating.

*Table 155: Summary of the high-, medium-high- and medium-rated metals with their associated technology*

| Element | Rating | Associated Technology |
|---|---|---|
| Rare Earths: Dy, Pr, Nd | High | vehicles, wind |
| Rare Earths: Eu, Tb, Y | High | lighting |
| Gallium | High | lighting, solar |
| Tellurium | High | solar |
| Graphite | Medium-High | vehicles |
| Rhenium | Medium-High | fossil fuels |
| Hafnium | Medium-High | nuclear |
| Germanium | Medium-High | lighting |
| Platinum | Medium-High | fuel cells |
| Indium | Medium-High | solar, lighting, nuclear |
| Rare Earths: La, Ce, Sm | Medium | vehicles |
| Rare Earth: Gd | Medium | lighting |
| Cobalt | Medium | vehicles, fossil fuels |
| Tantalum | Medium | geothermal, fossil fuels |
| Niobium | Medium | CCS |
| Vanadium | Medium | CCS |
| Tin | Medium | solar |
| Chromium | Medium | desalination |

# 6 Mitigation Strategies

## 6.1 Introduction

The first part of this report has focused on the metals which are of importance and critical for a wide range of key technologies for the decarbonisation of the EU energy sector. The analysis of Chapters 3 and 4 identified which metals, and how much of them, are required within the different technologies. These estimates were then modelled against 2020 and 2030 uptake scenarios (largely drawn from the EU 2050 energy roadmaps) and compared to projected world supply. As a result, a reduced list of some thirty metals of interest was compiled for further investigation.

Chapter 5 sought to trim down this list further to identify specific risks associated with particular materials. To achieve this, analysis of market and political risk factors was conducted in order to identify those materials with the greatest supply chain risks. The results of the first JRC study were taken into account in this study to provide an overall assessment of the supply chain bottlenecks risks for the decarbonisation of the EU energy sector.

Eight metals have been given a high criticality rating and are classified as ‘critical’. These are:

- six rare earth elements (dysprosium, europium, terbium, yttrium, praseodymium and neodymium)
- gallium
- tellurium.

The following sections investigate what can be done to mitigate the supply chain risks for the critical metals within the EU. The following three principal mitigation strategies are considered:

- increasing primary supply
- encouraging reuse, recycling and waste reduction
- considering substitution options.

All relevant technical aspects are considered, including: data availability, geological, processing, refining, collection, technological, cost.

## 6.2 Primary supply

Increasing the primary supply of the critical metals is important to mitigating supply-chain bottlenecks. In principle, expanding global supplies helps to alleviate risks for supply chain bottlenecks for all users of the metals, including those in the EU path to the decarbonisation of the energy sector. However, this section focuses on expanding European output for the bottleneck metals as this would give added benefits of security of supply. In addition, European policymakers can obviously more easily influence European than global developments.

### 7.2.1 Rare earths

Following the decision of the Chinese government to reduce its export quotas for rare earth elements in 2009 and 2010 and the large subsequent price rises, there has been a race amongst junior mining companies to open rare earth mines outside China; notably in the US, Australia and Canada.

While the European rare earths industry is currently small it is by no means non-existent. In fact, most steps in the rare earths supply chain are either currently performed in Europe or have been taken place there in the recent past (Schuler et al., 2011). This includes:

- separation of rare earths (by Silmet in Estonia, previously also by Rhodia in France)
- production of alloys (LCM in the UK)
- production of bonded as well as sintered permanent magnets, e.g. Vacuumschmelze in Germany, Magnet Applications in the UK or Goudsmit in the Netherlands
- production of phosphors and catalysts (by Rhodia in France and Treibacher in Austria).

There are currently no active rare earth mines in Europe, although several deposits have potential. It should also be noted that, compared to production of light rare earths (such as neodymium), there are additional challenges facing the establishment of European production of heavy rare earths (such as dysprosium, yttrium, terbium and europium). First, not all rare earth deposits contain significant amounts of dysprosium. More importantly, however, dysprosium and heavy rare earths require their own complex separation procedure and would require additional investments.

***New rare earth mines***

While the European geology is generally not very rich in rare earths, they are known to exist in Scandinavia and Greenland (which has a special relationship with the EU through its links with Denmark). Figure 28 shows the work of the geological mapping FP7 PROMINE for rare earths, and shows that there are significant rare earth deposits in Norway, Sweden, Finland and the Russian Kola Peninsula. Rare earths were actually discovered in Sweden and were mined in relatively small quantities during the 1960s in Finland as by-products of lead.[16] Other smaller deposits are shown in various countries across Europe.

Several deposits are currently being explored by junior mining companies. Two of the most promising projects are the Kvanefjeld deposit in Greenland and the Norra Kärr project in Sweden, which are currently being developed by Greenland Energy and Minerals and Tasman Metals respectively. The resource estimates for the advanced rare earth projects[17] in Europe and Greenland are shown in Table 156, alongside that of Mountain Pass in the United States by way of comparison.

All of these projects can be considered relatively low grade rare earths deposits: Sarfartoq owned by Hudson Resources has the highest grade at 1.72%, with the three Greenland Minerals and Energy Projects at a grade of 1.0-1.2% and Norra Kärr in Sweden owned by Tasman metals with a grade of 0.59% (for comparison, Mountain Pass has a grade of 6.57%.) In terms of total rare earth oxides contained, the three Greenland Minerals and Energy resources are very large, approaching 10 million tonnes between the three deposits.

*Table 156: Resource estimates for advanced rare earth projects in Europe, Greenland vs Mountain Pass*

| Project | Cut-off Grade (wt%) | Resource Size (t) | TREO Grade (wt%) | TREO Contained (t) |
|---|---|---|---|---|
| Norra Kärr (SWE) | 0.17% | 58,100,000 | 0.59 | 342,720 |
| Kvanefjeld (GRL) | 0.015% $U_3O_8$ | 619,000,000 | 1.06 | 6,546,900 |
| Sørensen (GRL) | 0.015% $U_3O_8$ | 242,000,000 | 1.10 | 2,662,000 |
| Zone 3 (GRL) | 0.015% $U_3O_8$ | 95,300,000 | 1.16 | 1,106,338 |
| Sarfartoq (GRL) | 1.0% | 8,343,000 | 1.72 | 143,245 |
| Mountain Pass (USA) | 3.0-5.0 | 31,552,000 | 6.57 | 2,072,037 |

*Source: Technology Metals Research, n.d. [Accessed 18th September 2012]*

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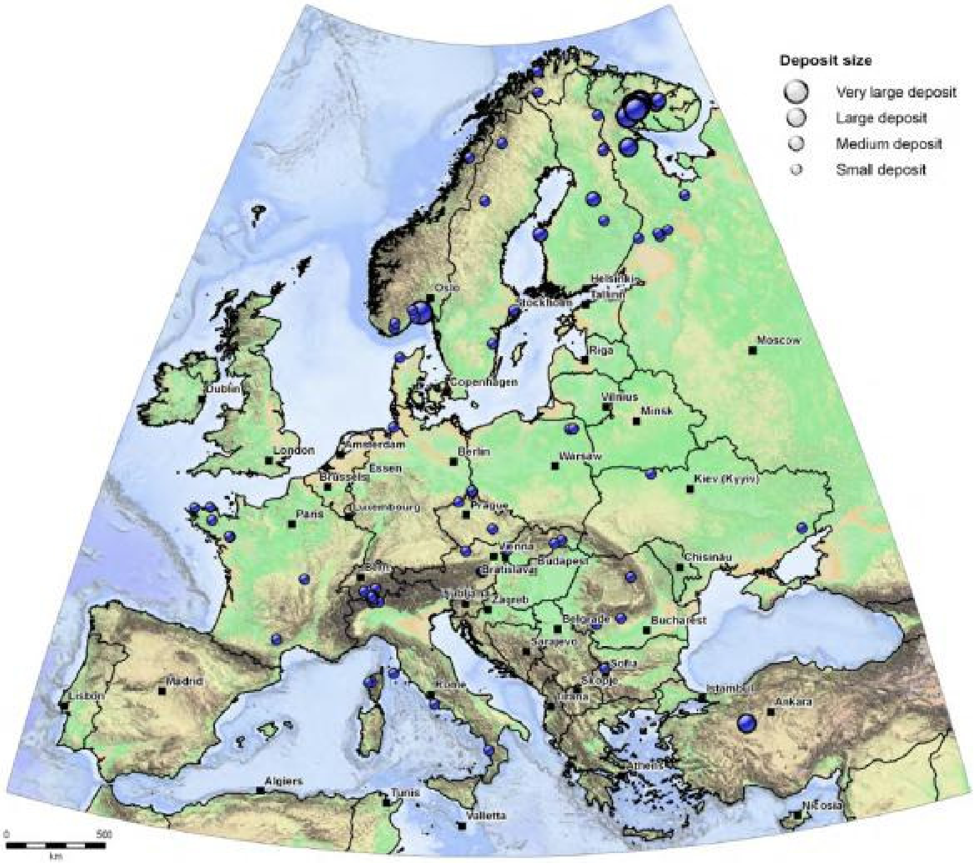
[16] Cassard, Daniel. BRGM PROMINE database , personal communication (September 2012)

[17] Advanced projects are defined as where either the mineral resource or reserves have been formally defined or where the project has been subject to past mining campaigns for which reliable historic data is available

*Figure 28: Rare Earths geological mineral resource potential modelling across Europe*

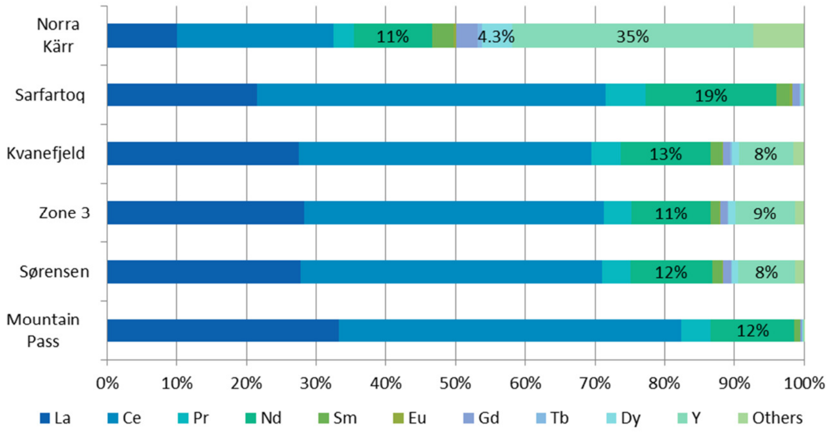


| Legend | Very Large | Large | Medium | Small |
|---|---|---|---|---|
| Rare Earths | >1,000,000t | >100,000t | >10,000t | >1,000t |

*Source: PROMINE Database*

The composition of rare earths contained in these deposits is shown in Figure 29. The rare earth composition of the Greenland deposits is similar to that of Mountain Pass, with only slight differences. The three deposits owned by Greenland Minerals and Energy contain 8-9% yttrium, and the Sarfartoq deposit has higher neodymium content at 19%. Norra Kärr in Sweden, however, has a very different composition of rare earths, which may compensate for its relatively low grade. Lanthanum and cerium represent only one third of the deposit, which is significantly enriched in heavy rare earths with 4.3% dysprosium, 35% yttrium, as well as elevated europium and terbium content.

*Figure 29: Composition estimates for rare earth projects in Europe and Greenland vs Mountain Pass*



*Source: Technology Metals Research, n.d. [Accessed 18th September 2012]*

Exploration is more advanced at Kvanefjeld, Sarfartoq and Norra Kärr, where approximately 70% of the resources are 'indicated' rather than just 'inferred', offering greater certainty to the resource estimate due to the number of holes drilled. However none of these resources have the 'measured' status applied to projects such as Mountain Pass.

A particular challenge for the Greenland Minerals and Energy Projects, such as Kvanefjeld, is their environmental management due to the presence of radionuclides in some mine tailings (El-Dine et al., 2011). A recent report by the German Öko-Institute, for example, raises the concern that obtaining the necessary environmental permits would pose a significant hurdle for realizing a European rare earth mining project (Schuler et al., 2011). As shown in Table 156 all of these resources are estimated against a cut-off grade with respect to uranium rather than rare earths, so these deposits should be considered to be uranium mines, with rare earths produced as a valuable by-product. Their fate is dependent on the uranium market and therefore upon that of nuclear power generation. An unfavourable location in Greenland, with comparably more difficult more logistics and a harsher environment, is also worth considering.

The development time from resource to bankable feasibility study and ultimately production can be 5-12 years (Kingsnorth, IMCOA, 2012). As each ore-body is different, the processing routes are project-specific. IMCOA suggest that there are ten key steps involved on the road to commercial production of rare earths:

1. Prove resource/reserve.
2. Define process.
3. Pre-feasibility study.
4. Beneficiation pilot plant.
5. Extraction of rare earths pilot plant.
6. Separation of individual rare earths pilot plant.
7. Obtain environmental approval.
8. Letters of intent.
9. Bankable feasibility study.
10. Construction and start-up.

Kvanefjeld has recently completed step 3: pre-feasibility study (Greenland Minerals and Energy Ltd., 2012). Norra Kärr is slightly further behind having recently completed its preliminary economic assessment - step 1 (Pincock, Allen & Holt, 2012). Tech Metals Research, in their projections of rare earth production, estimates that Kvanefjeld may realise 44,000 tonnes of rare earths production from 2016, and Norra Kärr 5,000 tonnes from 2017 (Kingsnorth, IMCOA, 2012), although these may prove optimistic if the projects should encounter particular challenges and experience delays. Significant investments - in the range of several hundred million euros - would be necessary to bring these mines into production and to concentrate the ores. Costs for constructing a separation facility from scratch are considerably above the costs of the actual mining and concentration facilities: for example the budgeted capital costs of the Lynas Phase 1 separation plant (for 11,000 tonnes per year of rare earths) is around €200 million, or over three times the cost of the concentration plant (Lynas Corporation Ltd, 2011). IMCOA estimates that in terms of capital intensity, costs greater than $50,000 per tonne of annual capacity can be considered reasonable.

However, unlike rare earth projects currently being developed in Canada or Australia, such projects could benefit from the modification of existing European separation capacities instead of having to rely on extremely costly greenfield investments. It is not known what the costs would be to re-open the European separation facilities, and the complexity of modifying them to deal with the specificities of different ore bodies is likely to be significant but nonetheless below those of constructing a new facility. Norra Kärr's strategy appears to be to sell rare earth concentrate, rather than to separate individual rare earth oxides. The preliminary economic assessment suggests that this may result in a 38% reduction in sales prices compared to the pure oxides; nonetheless capital costs are estimated at $290 million and total operating costs at nearly $11,000 per tonne of rare earth concentrate (Pincock, Allen & Holt, 2012). However, other junior mining companies, such as Great Western Minerals and Molycorp, have rejected this strategy arguing that the greatest value added in the rare earths supply chain is in magnet production, and that intermediate rare earth products such as concentrates and chlorides are hardly saleable.

As a mitigation measure, the European rare earths potential certainly merits further exploration, even if the ultimate commercial viability of these deposits still needs to be established. However, it is clear that there may not be significant production until at least five years hence, and alternative options need to be considered in the short term at least. These might include processing rare earths from tailings (e.g. of tin and titanium) or from by-product sources; or to import rare earth concentrates from another mine opened outside Europe for further processing in Europe.

***Rare earths processing***

There are three main rare earths processing operations in Europe that are noteworthy: Silmet (Estonia), Less Common Metals (UK) and Rhodia (France).

For many years Silmet in Estonia has been the only operating European rare earths separation facility, with an annual production capacity of around 3,000 tonnes of rare earth oxide (around 2% of world annual production). Historically Silmet has been fed from the Russian rare earth mines in the Kola Peninsula. However it has been unable to produce at capacity in the recent past due to limited access to rare earth concentrates on international markets.

In April 2011 Molycorp acquired a controlling stake (90%) in Silmet at a cost of $89 million (Reuters, 2011). Molycorp commented that it offers the company a European base of operations as well as a larger global customer base (Molycorp, 2011). Effectively the purchase doubled the company's rare earth production capacity, and it would immediately begin sourcing rare earth feedstocks for production of its products from Molycorp's rare earth mine and processing facility in Mountain Pass, California. Silmet's products will include rare earth oxides and metals, including didymium metal (used in the manufacture of neodymium-iron-boron permanent rare earth magnets).

Confronted by similar problems regarding the access of rare earth materials, the British alloy producer Less Common Metals (LCM) has sought to vertically integrate with Canadian junior rare earths mining company, Great Western Minerals Group (GWMG). Although GWMG owns several rare earths deposits, it has focused its attention on re-opening the high-grade (16.85%) - if small (28,000 tonne) - Steenkampskraal mine in South Africa. Production may commence from 2013, initially at 2,700 tonnes per year of rare earth oxide, rising to 5,000 tonnes once fully operational (Great Western Minerals Group Ltd., 2012).

Hypothetical projections from a recent investor presentation indicate that nearly all of the magnet materials (praseodymium, neodymium and dysprosium) may be sent to LCM for magnet production (1,034 tonnes in total). GWMG reports that 60% of LCM's sales are within the EU, such as Vacuumschmelze in Germany. The facility is currently undergoing significant expansion with the addition two new 'flake'-type furnaces to double the capacity from 1,100 tonnes to just over 2,000 tonnes per year (Great Western Minerals Group Ltd., n.d.). Other rare earths, such as yttrium, are likely to be sold to off-takes (Table 157).

The French company Rhodia has operated a heavy rare earths separation facility in the past, with similar processes to those currently used only in China. It is noted that even new separation facilities currently under construction in Australia and the US will be unable to separate heavy rare earths. They might be used to process heavy rare earths such as those that could be mined from Norra Kärr in Sweden, or from recycled sources such as rare earth phosphors from lighting (see Section 7.3.2). Rhodia reports that up to the end of 2011, only 4 of its 18 separation units (SX batteries) were operational. However, the company plans to progressively reopen all 18 units by January 2013 (Rhodia, 2012).

*Table 157: Hypothetical consumption of REO from GWMG's Steenkampskraal mine in South Africa*

| Rare Earth Oxides | Production (Tonnes) | To LCM (Tonnes) | To off-takes (Tonnes) |
|---|---|---|---|
| Lanthanum | 1,084 | 77 | 1,007 |
| Cerium | 2,334 | 2 | 2,332 |
| Praseodymium | 250 | 166 | 84 |
| Neodymium | 834 | 834 | 0 |
| Samarium | 125 | 74 | 51 |
| Dysprosium | 34 | 34 | 0 |
| Yttrium | 250 | 0 | 250 |
| Others | 105 | 0 | 105 |
| **Total** | **5,016** | **1,185** | **3,831** |

Source: Great Western Minerals Group Ltd., n.d.

***Summary***

Apart from the mine stage, potentially all the building blocks for a rare earths supply chain exist in Europe, although it is noted that these are owned by different companies and would require collaboration and the complexities of re-opening separation facilities could be high.

Rare earth deposits in Europe do exist and although their development is still in the early stages, they do merit further exploration. However, like many other rare earth projects around the world they must overcome significant challenges before they can go into production, including demonstrating commercial viability and obtaining the relevant environmental permitting. European mining of REEs could help provide a long-term perspective and supply security to European downstream processors of REEs, and reduce risks for the rare earths industry in Europe.

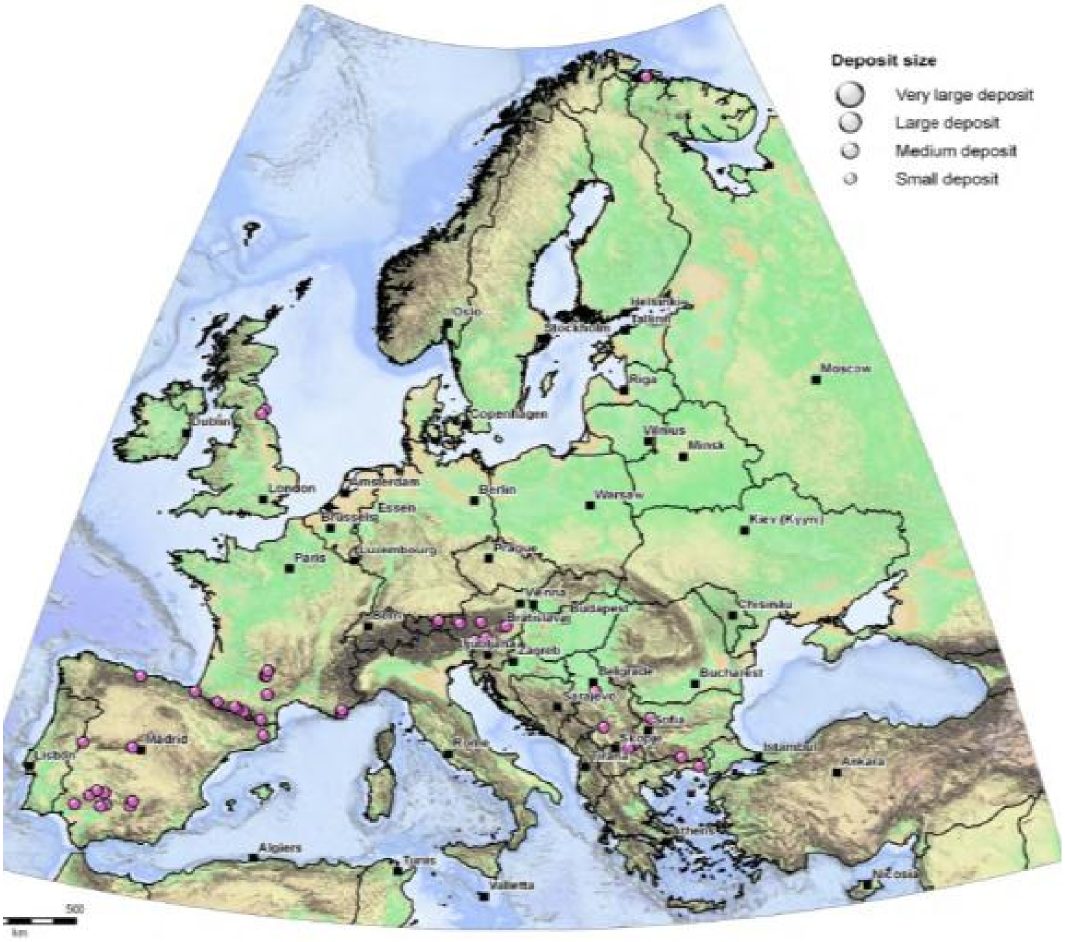
European policy-makers and member country authorities should explore ways to support companies in fast-tracking exploration activities and regulatory procedures. An alternative mitigation option, especially in the short term, would be to process rare earth concentrates from tailings, by-product sources or mines opened outside Europe. This could help to stimulate European rare earths knowledge, expertise and production capacity.

### 6.2.2 Gallium and tellurium

Increasing the supply of gallium and tellurium poses a very different type of challenge from increasing rare earths production, because they are by-products. Possibilities to expand the European output for all three metals are discussed here, because the main issues involved are very similar. However there is considerably more information available on tellurium, due to a detailed market study having been conducted (International Study Group for Nickel et al., 2012).

The key issue here is not to open new mines, but to increase by-product recovery from base metal refining, most notably from copper (for tellurium) and aluminium (for gallium) refining. Geological mapping work by PROMINE (Figure 30 and Figure 31) identified only relatively small deposits (under 20 tonnes) in Europe. However, further analysis may be necessary as geological mapping techniques have not historically looked for these metals, which have only recently seen a growing number of new and important applications. Despite the results of the geological mapping, significant reserves for both gallium and tellurium do exist within Europe. The first JRC study, for example, estimated European gallium reserves within bauxite of 21,400 tonnes and tellurium reserves (in copper) of 1,900 tonnes (Moss et al., 2011).

*Figure 30: Gallium geological mineral resource potential modelling across Europe*



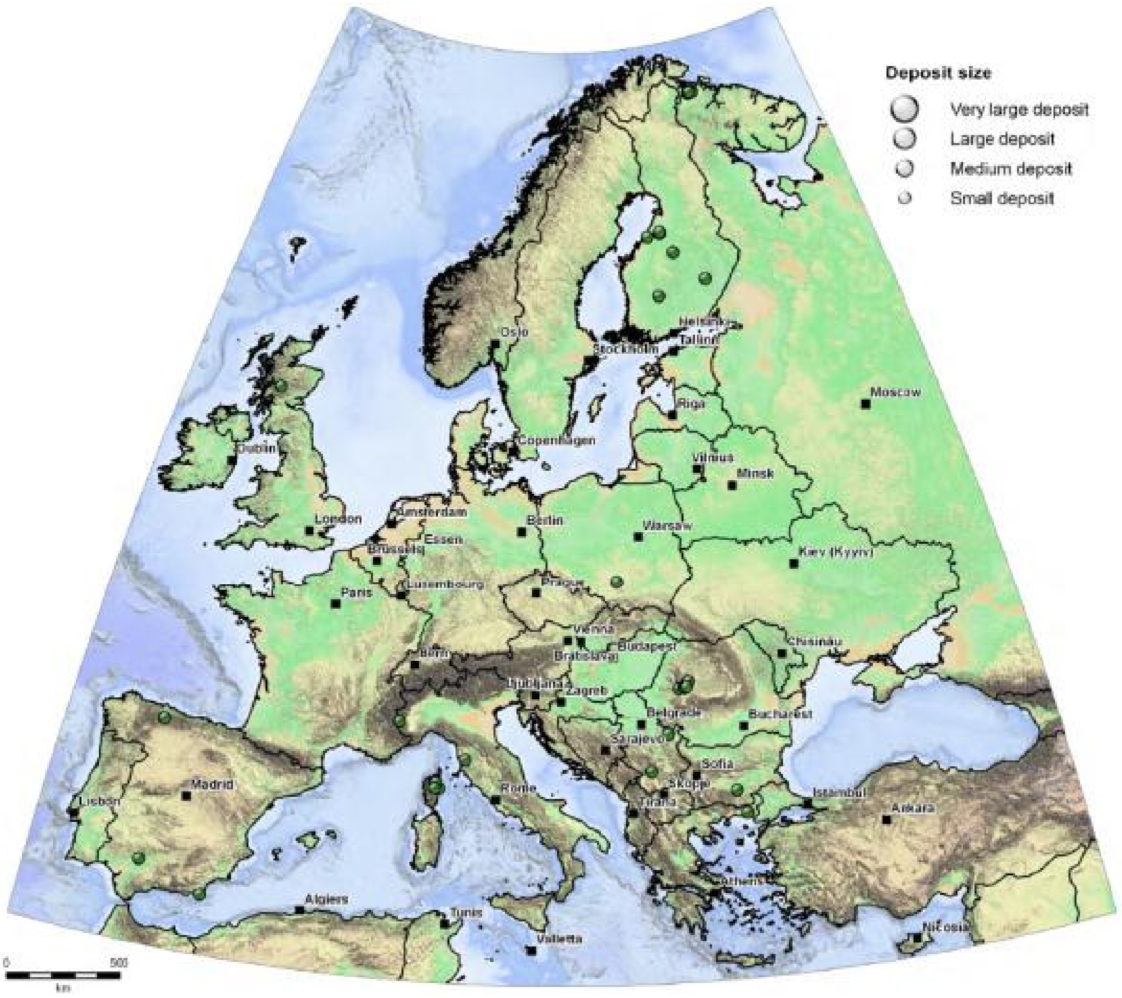
*Source: PROMINE Database*

| Legend | Very Large | Large | Medium | Small |
|---|---|---|---|---|
| Gallium | >100t | >50t | >10t | >1t |

A sizable refining industry already exists in Europe for both of these host metals and several large European refiners already have by-product extraction equipment in use at their facilities.

- For tellurium, the ICSG estimated that Europe produces approximately 30% of world tellurium supply (120-125 tonnes, International Study Group for Nickel et al., 2012). This previously unknown data considerably closes the evidence gaps existing for tellurium, and suggests that Europe has the potential to be relatively self-sufficient with respect to its estimated needs for the EU (150 tonnes in 2020, 126 tonnes in 2030).
- For gallium, the data for current and future production is not as complete. However, Europe's share of primary gallium production capacity is estimated at 17% of world capacity (USGS, 2010a), with production at around 30 tonnes per year (Moss et al., 2011). Nonetheless, these compare favourably to the EU estimates (18 tonnes in 2020 and 37 tonnes in 2030).

*Figure 31: Tellurium geological mineral resource potential modelling across Europe*



*Source: PROMINE Database*

| Legend | Very Large | Large | Medium | Small |
|---|---|---|---|---|
| Tellurium | >500t | >100t | >20t | >5t |

Significant opportunities remain for expanding and optimising existing by-product recovery in the European refining industry. In principle, this challenge can be conceptualized to consist of four parts (Moss et al., 2011):

1. The presence in the ores that refiners process. Depending on the origin of the ore, the concentrations of the by-product can vary considerably. The choice of ores depends not only on by-product content, but also on the ease of purification, long-term supply contracts and supply security considerations as well as transport costs. Most bauxite and copper ores do contain gallium or tellurium, but are not necessarily capable of economic extraction.
2. The technical capability of refiners to extract the by-product. Depending on the technology used, recovery rates can differ considerably. In the case of tellurium, state of the art extraction equipment allows for recovery rates that approach 90%, but many European copper refineries use technologies and processes recovering only 30-40% of the tellurium content. Downstream industries with vested interest in reliable and affordable supply have invested in the development of proprietary technologies for optimal extraction, and market these actively to base metal refiners. Some of these companies are even willing to assist in the installation or upgrading of the extraction equipment and guarantee off-take in order to increase the incentives to invest in

by-product extraction.

3. Financing. Industry experts estimate the costs for installing a gallium extraction unit at roughly €20 million, and tellurium extraction equipment can already be installed for as little as less than €1 million. The production capacity of such installations depends on the amount of host metal that is being refined and the concentrations of the by-product and recovery rates.
4. Willingness of refiners to get involved in production. Many refiners regard the small by-product markets as a distraction from their core business and are reluctant to invest time, money and effort to get involved in volatile niche markets that lack scale and transparency, even if price levels are currently attractive. In many cases, companies are also concerned that switching to by-product recovery will adversely affect the delicate and carefully calibrated processes for the refining of the main-product. The training and turnover of staff may also be an issue for some refiners.

Taken together, these various obstacles lead to suboptimal by-product extraction. The first JRC study documented refineries recovering by-products; however, not all the companies were willing to publicly disclose their recovery capacities. Table 158 attempts to provide a non-exhaustive overview of major European refining and by-product recovery, compiled through a series of enquiries with companies and industry experts. It is indicative of the current extent of tellurium and gallium recovery in European refining industries. It demonstrates that while there is some by-product recovery taking place in Europe, it is a relatively limited activity in the European refining industry for copper and aluminium.

In terms of the obstacles to by-product recovery, discussed above, the reasons for this limited recovery differ for tellurium and gallium. For tellurium, there is scope for additional extraction as well as significant increases in recovery rates. As well as variations in by-product concentration, a lack of interest by major refiners plays a significant role. The same holds true for gallium, for which there is probably the largest potential to increase European output by installing additional extraction units, as most bauxite ores contain economically extractable concentrations of gallium. Estimates suggest that only around 30-40% of the world's mined tellurium is actually being refined into tellurium (International Study Group for Nickel et al., 2012), with only 10% of the world's alumina producers extracting gallium (Indium Corporation, 2010).

As an illustration of their estimated revenues, the following examples are helpful:

- For tellurium: Boliden operates two copper smelters, where tellurium might be recovered. Revenues are estimated to account for only 0.2% of Boliden's total copper smelter revenues (circa $20 million, International Study Group for Nickel et al., 2012) which therefore represents a very minor by-product. For KGHM in Poland and Norilsk in Russia the tellurium revenues are much smaller, at only $2 million per year.
- For gallium: AOS Ingal's Stade plant in Germany may make around $15 million from gallium sales, around 4% of total revenues from the alumina refinery. For MAL Magyar in Hungary the contribution to revenues is much smaller at approximately 2% of total sales.

For gallium, such revenues appear to have become attractive to some alumina refineries. For example 5N Plus announced in October 2011 that it had begun discussions with Rio Tinto Alcan regarding the development a new primary gallium source in Quebec, Canada (5N Plus, 2011). A memorandum of understanding has been signed, allowing the two companies to pursue further discussions. It seems that the process might involve 5N Plus operating a gallium recovery facility adjacent to the Vaudreuil alumina facility. Different opportunities exist for tellurium where it is possible to transport the copper anode slimes to an operator at another location. However, given that the anode slimes also contain the majority of the precious metals (gold, silver, PGMs), many refiners prefer to keep this in-house.

Favourable prices for tellurium and gallium may also result in increasing recovery from sources other than copper and aluminium refining. For example, fly ash and urban coal ash, in which gallium has been found at a concentration of 200 times that of primary refinery production, might also develop into viable economic sources for gallium (Moskalyk, 2004).

*Table 158: European alumina and copper refineries and their by-product extraction (2010)*

| Type | Facility | Estimated annual capacity (kt) | Country | Company | Extraction by-product |
|---|---|---|---|---|---|
| Alumina refineries | Gardanne | 700 | France | Rio Tinto Alcan | |
| | Aughinish | 1,900 | Ireland | Rusal | |
| | San Ciprian | 1,600 | Spain | Alcoa | |
| | Distomon | 800 | Greece | Mytilineos | |
| | Ajka | 300 | Hungary | MAL Magyar Aluminum | ca. 4t Ga p.a. |
| | Stade | 900 | Germany | AOS (Ingal) | ca. 25-30t Ga p.a. |
| | Tulcea | 400 | Romania | Vimetco | |
| | **Total** | **6,600** | | | **ca. 29-34t Ga p.a.** |
| Copper refineries | Huelva | 320 | Spain | Atlantic Copper S.A. | ca. 2t Te p.a. |
| | Olen | 345 | Belgium | Aurubis | Aurubis is estimated to produce ca. 20t Te p.a. |
| | Pirdop | 180 | Bulgaria | Aurubis | |
| | Hamburg | 395 | Germany | Aurubis | |
| | Lunen | 220 | Germany | Aurubis | |
| | Harjavalta (Pori) | 153 | Finland | Boliden | Boliden is estimated to produce ca.15-20t Te p.a. |
| | Ronnskar | 250 | Sweden | Boliden | |
| | Baia Mare | 40 | Romania | Cuprom | |
| | Las Cruces | 72 | Spain | Inmet | |
| | Glogow | 480 | Poland | KGHM | KGHM is estimated to produce ca. 5t Te p.a. |
| | Legnica | 100 | Poland | KGHM | |
| | Osnabruck | 160 | Germany | KME | |
| | Barcelona | 80 | Spain | La Farga | |
| | Bersee | 35 | Belgium | La Metallo Chimique | |
| | Brixlegg | 110 | Austria | Montanwerke Brixlegg | |
| | Hoboken | 28 | Belgium | Umicore | ca. 20t Te p.a. |
| | Nikkelverk | 40 | Norway | Xstrata plc | |
| | **Total** | **3,008** | | | **ca. 62-67t Te p.a.** |

*Sources: Moss et al., 2011*

Owing to growing concerns over tellurium supply, some companies are also investigating the possibility to recover tellurium from other ore types such as gold-telluride and lead-zinc (USGS, 2012). These include Boliden, which is planning to extract tellurium from a new gold-telluride mine from 2012 onwards. At their gold-telluride Kankberg mine in Northern Sweden, Boliden anticipates average annual production of tellurium concentrate of 41 tonnes for the life of the mine (2012-2020) (Boliden, 2011). However, gold-telluride projects might be viable as gold mines, given the high price of gold, but a higher tellurium price is required to support tellurium recovery (International Study Group for Nickel et al., 2012).

With respect to tellurium, however, there has been considerable recent comment on the shift of copper refining towards new processes that are more suitable for extracting copper from lower grade ores: the hydro-metallurgic process Solvent Extraction Electro-Winning (SX-EW) makes the recovery of tellurium much more difficult, for example. There is concern that this could affect future tellurium supply as the higher grades of copper ore are exhausted (Lifton, 2009). Meanwhile the USGS comment that increased use of SX-EW has limited implications for future supply of tellurium supply, and fears may have been somewhat exaggerated. This is because the copper sulphide ores that generally contain the higher tellurium content cannot actually be refined using the SX-EW process because of the sulphur content. Therefore the actual tellurium being lost to the market as a result of SX-EW is probably quite low (International Study Group for Nickel et al., 2012).

In summary, there is considerable potential to increase the scope and effectiveness of by-product recovery in Europe, although data on current production highlights a reasonable degree of self-sufficiency already having been achieved. To decrease risks for supply chain bottlenecks for these metals, an active dialogue with refiners - as well as possible incentive schemes to promote optimal by-product recovery in the European refining industries – should be investigated. New sources for gallium and tellurium should also be explored. EU-funded research, as well as measures such as support for the financing of pilot plants, could help accelerate the access to such new sources of supply.

## 6.3 Reuse, recycling and waste reduction

### 6.3.1 Introduction

Policy measures to increase the reuse, recycling and waste reduction of the critical metals are important in alleviating future risks of supply. In essence, increased reuse and recycling expands the supply of these metals, albeit not from primary sources. Waste reduction is a demand side measure. If less material is wasted, then the same level of manufacturing demand can be achieved using less material, resulting in less pressure on limited supplies.

This section starts, however, by giving some definitions that are commonly used for recycling, as well as discussing the role and limitations of recycling. Recycling is the reprocessing of waste materials to produce materials with the same or similar properties which can then be used in products. Recycling is a cornerstone in ensuring resource efficiency and moving towards a circular economy by recovering valuable resources. Recycling reduces the demand for raw materials, and can also help reduce waste sent to landfill, lower energy demands for processing, and decrease pollution. Typically, recycling is associated with an end-of-life treatment (i.e. post-consumer), and can be viewed as reclaiming useful materials from end-of-life waste. Metals may also be recovered during processing and manufacturing, as waste may be produced at these stages. This recovery is clearly important, but it can be viewed as a different process to end-of-life recycling, as it is commonly incorporated within manufacturing processes for efficiency purposes, particularly when the materials used are expensive.

The distinction between these two forms of recycling is noted within the report. In this section the opportunities for recovery of both pre- and post-consumer waste are explored. In general, material in pre-consumer waste is easier to exploit as it is typically much less dispersed and contaminated and therefore much easier to collect and process. Additionally the long lifetimes of many of the products in which the bottleneck metals are contained, many of which have only recently been launched, mean that post-consumer recycling will only be possible in the medium to long term. Where recycling rates are discussed in this report the terms refer to the end-of-life recycling rate or the recycled content:

$$\text{EOL Recycling Rate} = \frac{\text{Metal Recycled (from EOL scrap)}}{\text{Metal Available for Recycling (EOL scrap)}}$$

$$\text{Recycled Content} = \frac{\text{Metal Recycled}}{\text{Metal Produced}}$$

Note also that some processes which are considered to be ‘recycling’ recover materials but do not retain their primary properties. In these circumstances, recycling does not displace virgin production as the function of the materials is not retained. An example is the use of furnace slags in concrete.

The recent UNEP report summarised the current status of metals recycling across the world for 60 metals. The end-of-life or post-consumer recycling rates for rare earths, gallium and tellurium have all been estimated to be less than 1% (Figure 32). These compare to rates above 50% for many base and precious metals. However, these recycling rates are often application specific with high recycling rates for precious metals in jewellery and medical applications offset by lower recycling rates from WEEE.

For rare earths and gallium, the recycled content rates - which include post-industrial recycling - are significantly higher than they are for end-of-life recycling (Figure 33). Neodymium, praseodymium and dysprosium (used for rare earth magnets) have a recycled content of between 1% and 10%; gallium has a global recycled content of 10-25%. However, recycled content rates for yttrium, europium and terbium (used for lighting phosphors) are all less than 1%.

The following sections explore possibilities to expand recycling and reuse and to minimise waste for the rare earths generally, as well as for tellurium and gallium individually.

### 6.3.2 Rare earths

Since 2011 rare earth recycling has received considerable attention due to high prices of raw materials and materials shortages experienced by a number of end-user manufacturers. Several high profile announcements and projects have been launched in this area, as well as improved data on its feasibility having become available. A recent study on the feasibility of recovering the EU's critical raw materials identified rare earths as target metals for which greater recovery would be feasible (EPOW, 2011).

In general the following aspects are recognised to be important for the implementation of a successful end-of-life (rare earths) recycling system (Umicore, 2012):

- Database of product sales, inventories and expected waste.
- Product information of components.
- Collection and sorting logistics.
- Material flow tracking.
- Pre-processing technologies.
- Design: for disassembly, reuse and recycling.
- Pilot plants and scale-up of recycling technologies.

***Data availability***

On the first two points, above, the data available is improving. For NdFeB permanent magnets, Du & Graedel (2011) estimated global in-use stocks at 97,000 tonnes for 2007 (Table 159). Computers, audio systems, wind turbines and automobiles account for 90% of the global in-use stocks. As for stocks of rare earths within other products, these total a further 350,000 tonnes, although much of this is lanthanum and cerium (Table 160). It is worth remembering however that these are stocks in society rather than end-of-life flows. Du & Graedel (2011) estimate globally that in 2007 between 1,000 and 3,000 tonnes of praseodymium, neodymium and yttrium went to landfill.

*Table 159: Global rare earth in-use stocks in NdFeB Permanent magnets, 2007 (000's tonnes)*

| **Application** | **Nd** | **Pr** | **Dy** | **Tb** | **Total** |
|---|---|---|---|---|---|
| Computers | 21.2 | 5.3 | 5.3 | 1.1 | 32.8 |
| Audio systems | 13.1 | 3.8 | 3.8 | 0.8 | 23.4 |
| Wind turbines | 10.1 | 2.5 | 2.5 | 0.5 | 15.7 |
| Automobiles | 9.8 | 2.5 | 2.5 | 0.5 | 15.2 |
| Household appliances | 3.3 | 0.8 | 0.8 | 0.2 | 5.1 |
| MRI | 3.0 | 0.8 | 0.8 | 0.2 | 4.7 |
| **Total** | **62.6** | **15.7** | **15.7** | **3.1** | **97.0** |

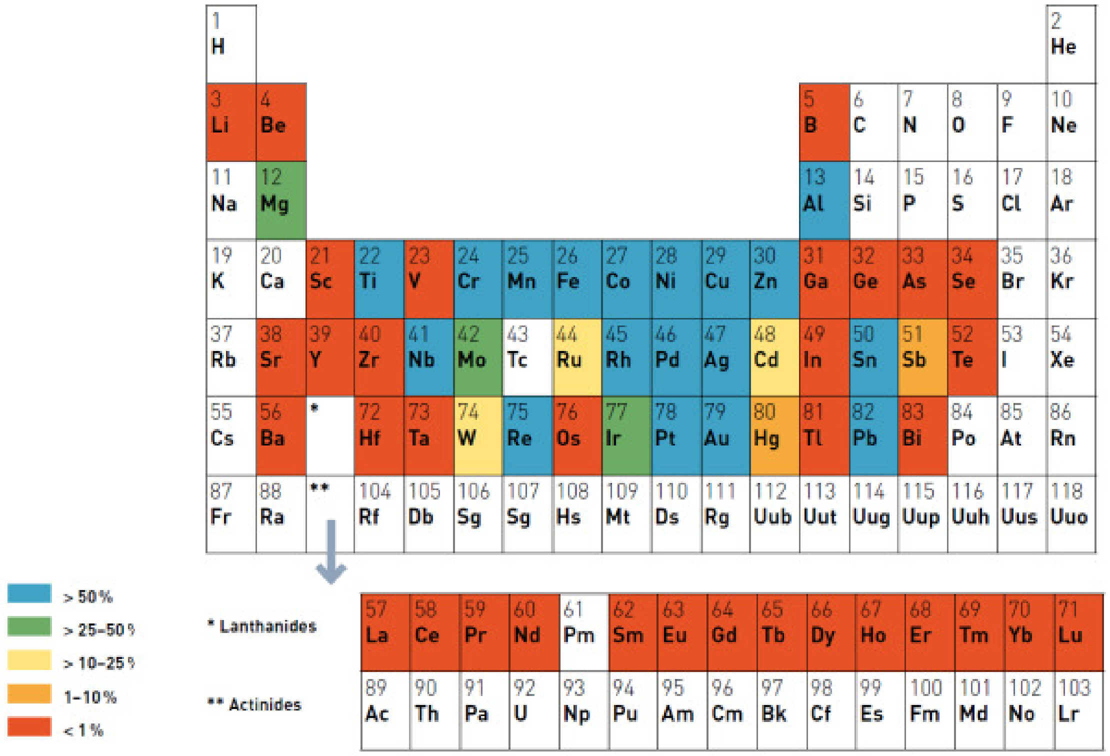
*Source: Du & Graedel, 2011*

Table 160: Global rare earth in-use stocks excluding NdFeB Permanent magnets, 2007 (000's tonnes)

| Rare Earth | La | Ce | Nd | Pr | Sm | Eu | Y | Total |
|---|---|---|---|---|---|---|---|---|
| Stock | 86.0 | 143.6 | 73.4 | 34.3 | 3.3 | 0.4 | 6.9 | 347.9 |

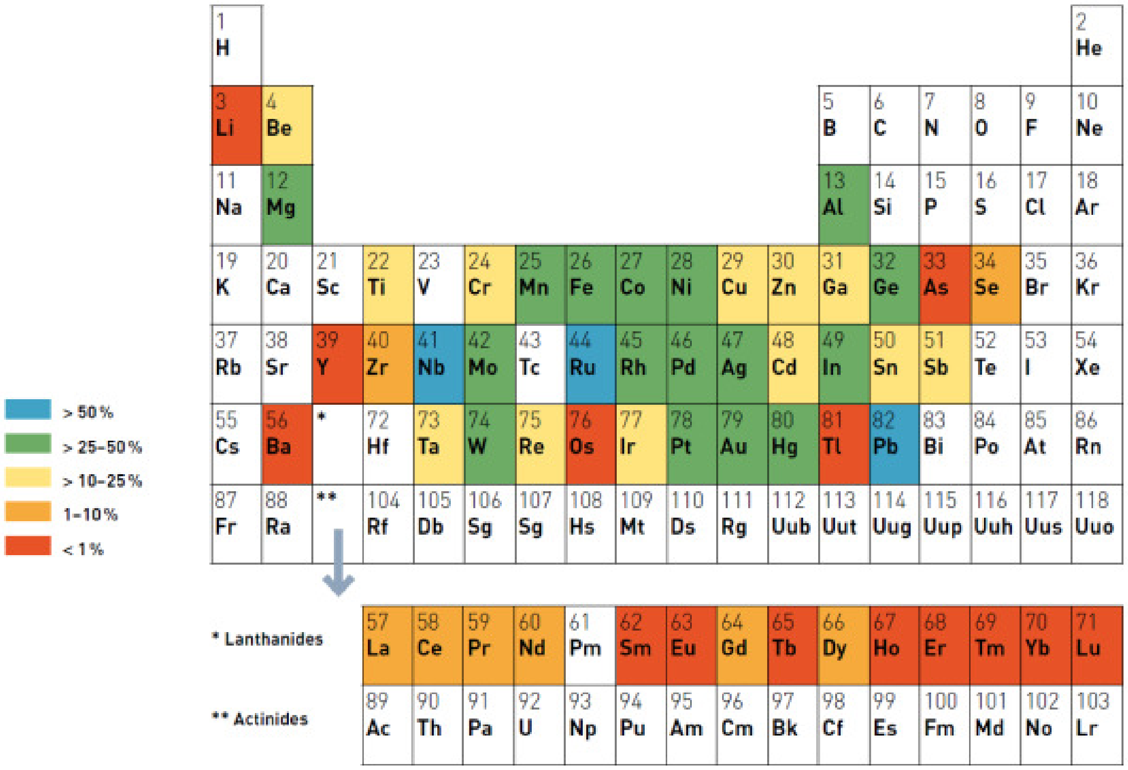
Source: Du & Graedel, 2011

Figure 32: End-of-life recycling rates for 60 metals



Source: UNEP, 2011

*Figure 33: Recycled content for 60 metals*

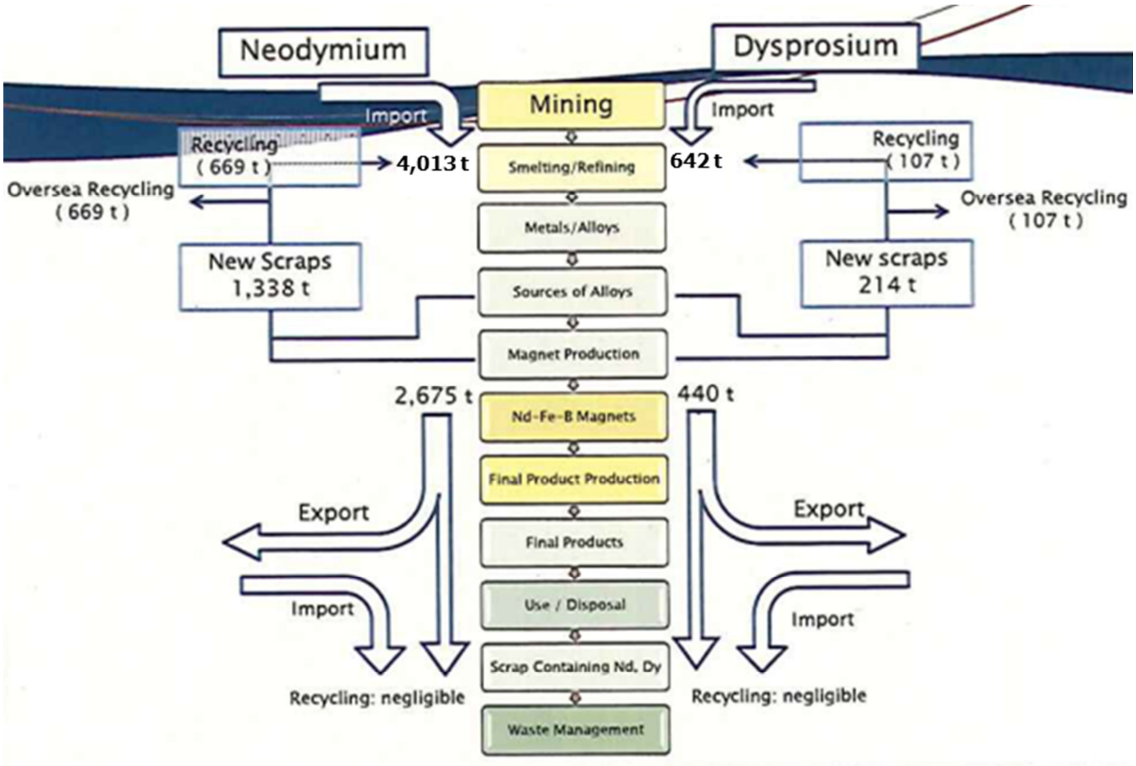


*Source: UNEP, 2011*

More detailed information is available for selective countries that have conducted materials flow analyses. For example Japan, a major manufacturer of NdFeB permanent magnets, has completed a detailed materials flow for both neodymium and dysprosium (Figure 34). The results show that Japan imported

4,655 tonnes of these rare earths in 2007 to make permanent magnets. Approximately one third of these rare earths went into new scraps, i.e. post-industrial waste streams. The study estimated that half of the magnet scrap was recycled domestically with the other 50% recycled overseas. Pre-consumer waste is an issue for NdFeB magnets as they are brittle and fracture easily, leading to breakages as well as waste cuttings. The scrap rate reported here is higher than the 20-30% estimated by Akai (Akai, 2008). However, this new evidence shows significant progress on recycling where previously the scrap materials ended up in generic scrap metal waste streams, as it was cheaper to buy newly manufactured magnets than to reprocess the scrap material.

*Figure 34: Material flows of Nd and Dy for magnets in Japan, 2007 (tonnes)*



*Source: University of Tokyo, 2012*

As for other countries, a detailed German study has been completed which estimated that the rare earth content of sales of selected electronics products amounted to 22 tonnes for 2010 (Table 161). Most of this is rare earth magnets within notebooks, which contained an estimated 15 tonnes of neodymium, 2 tonnes of praseodymium and 0.4 tonnes of dysprosium. The report indicated that no rare earths from these products were currently being recovered in Germany. Similar studies are underway in the UK and at an EU level.

### *Collection and pre-processing*

A key aspect for a post-consumer rare earths recycling system is the collection and pre-processing of rare earths containing waste streams at the end of their functional life. Many of the products that contain permanent magnets have long lifetimes and are not expected to reach end of life in the near future. For example, the low number of end-of-life hybrid and electric vehicles mean that it is not yet viable or cost-effective to implement systems for the recovery and recycling of rare earth magnets, although it may become attractive in the second half of this decade (EPOW, 2011). Similar dynamics apply to the magnets used in wind turbines, though on a longer time scale, as permanent magnet wind installations have only begun and a lifespan of at least 20 years is likely.

*Table 161: Rare earth content of sales for selected electronic products in Germany, 2010 (kg)*

| Rare Earth | Flat screens | Note-books | Smart-phones | LED lighting* | Total |
|---|---|---|---|---|---|
| Cerium | 30 | 1 | | 120 | 151 |
| Dysprosium | | 430 | | | 430 |
| Europium | 50 | <1 | | 40 | 90 |
| Gadolinium | 10 | 5 | | 910 | 925 |
| Lanthanum | 40 | <1 | | | 40 |
| Neodymium | | 15,160 | 385 | | 15,545 |
| Praseodymium | <1 | 1,950 | 80 | | 2,030 |
| Terbium | 14 | <1 | | | 14 |
| Yttrium | 680 | 12 | | 1,950 | 2,642 |
| **Total** | **824** | **17,558** | **465** | **3,020** | **21,867** |

** Assumes 70% replacement of light bulbs with LED lighting*

*Source: Oeko Institute, 2012*

The permanent magnets used in small electrical items, however, are already reaching waste streams. These applications have a relatively high turnover rate, but are dispersed into the waste stream at end of life. Recovery of these magnets is a challenge 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. TNO estimates that there are approximately 2 million tonnes of WEEE containing permanent magnets (out of 12 million tonnes arising), with a rare earth content <0.1% (TNO, 2012). Smelting could provide another avenue for recycling except that the rare earth metals oxidise easily and they are dispersed amongst the low grade slag, which makes further recovery impossible (Hagelüken & Meskers, 2009a).

There is therefore a need for greater disassembly and pre-processing of post-consumer WEEE at around 100-1000 sites across Europe to allow the recovery of rare earths for the relevant product categories. Encouragingly, awareness of rare earths at WEEE treatment centres appears to be rising. For example, a UK survey found that 56% of the respondents had heard of rare earths and some were considering whether it might be possible to recover them (WRAP, 2012). However, it is noted that the survey response rate was quite poor at just 7% of the industry. Nonetheless awareness of rare earths in the study compares favourably to that of other critical raw materials, about which less than 50% of the respondents had heard. A considerable amount of manual disassembly already occurs within the industry, with 80% of the treatment centres already carrying out manual disassembly processes on one or more different component streams, such as printed circuit boards.

On the costs of implementing an EU collection and treatment for the recovery of NdFeB, TNO estimates the total cost of such a system might be of the order €1 billion (Table 162). This estimate includes the collection, transport, pre-processing and recovery of the rare earths. Approximately 50% of these costs are additional to a conventional WEEE treatment operation.

For the metal recycling step, this might be carried out at a few dedicated facilities for rare earths, or as part of an integrated secondary smelter recovering a number of metals. In both cases the rare earths are likely to be recovered in mixed form, with further separation to individual elements required.  The yield, in terms of rare earths recovered, might be just under 2 tonnes of rare earths (1.4 tonnes Nd and 0.4 tonnes Dy). Their analysis of the rare earth prices necessary to justifies their recovery shows that, unless the collection and pre-treatment occurs for other reasons, continued high prices are necessary (of the order $45/t Nd and $2,500/t Dy).

However, permanent magnets contained within hard disc drives represent a notable exception to this. The potential risk of sensitive data loss for companies has led to targeted services for data destruction from old hard disc 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 disc drives result in the drive being shredded; this serves the dual purpose of enabling extraction of materials for sale and ensuring that sensitive data is destroyed, suggesting that access to these magnets should be relatively easy. There is no evidence that the magnets are recovered for recycling.

*Table 162: Potential EU collection and treatment costs for recovery of NdFeB magnets from WEEE*

| Step | Cost (€m) | % |
|---|---|---|
| Collection and transport | 250-300 | 28 |
| Additional pre-processing | 150 | 17 |
| Basic treatment | 200 | 20 |
| Additional recovery treatment | 300-400 | 34 |
| **Total cost** | **≈1,000** | |

*Source: TNO, 2012*

There is evidence that novel research is on-going, such as that by Hitachi in Japan (Baba et al., 2010). Manual trials by Hitachi found it takes a worker 5 minutes to get a magnet out of the hard drive, i.e. 12 units per hour. In 2010 Hitachi announced that it has developed a machine for the dismantling of neodymium magnets from hard discs and compressors. The machine has a capacity of 100 magnets per hour, about eight times faster than manual labour. The developed dismantling process will commence operation in 2013. The separation of the magnets is done using a drum type unit that shakes the HDDs until they disintegrate at which points the magnets can be manually removed. Birmingham University's Magnetic Materials Group has developed a similar process for removing permanent magnets from HDDs (Williams, 2010). Reuse is another potential option, as these magnets do not lose much strength over their lifetime. However, as the specification of the magnets is often tailored to the original purpose, and the processes to change the properties of the magnets are complex and expensive, reuse does not occur.

As for rare earth phosphors, good collection and processing systems are already in place, because of the hazardous waste (mercury) content. Estimates suggest that 1,000-1,500 tonnes of phosphor powder are available for recycling each year in Europe, of which 100-300 tonnes might contain rare earths (REconserve, 2012a). In addition, unknown but significant quantities have been stored awaiting further processing. REConserve claims that its recovery process would be highly profitable, with payback of less than one year for a €7 million investment at current rare earth prices. An internal rate of return (IRR) of around 35% is expected should europium and yttrium prices fall to €60/kg.

An alternative business model for phosphors recycling has been proposed by the HydroWEEE FP7 consortium. To get around the issue of low volumes of rare earths that are widely dispersed, HydroWEEE has developed a mobile hydrometallurgical plant that can be transported site-to-site inside a lorry container to treat batches of waste that have been built up over a period of time at WEEE treatment centres. The effect is to reduce the minimum quantities for economic operation by sharing the mobile plant: several SMEs can benefit from the same plant. Table 163 shows the input streams that the HydroWEEE process would take for recovery.

*Table 163: Input streams and target metals for the HydroWEEE process*

| Input stream | Target metals for recovery |
|---|---|
| Fluorescent powders from lamps | Y |
| Fluorescent powders from CRTs | Y, Zn |
| Liquid Crystal Displays | In |
| Lithium ion batteries | Li, Co |
| Circuit boards | Ag, Au, Fe, Ni, Zn (Pb, Sn, Pd with further processing) |

*Source: Kopacek, n.d.*

Of particular interest here is the recovery of yttrium from lamps and CRTs; however the processing of the other waste streams will presumably be very important for making the collection and recovery economics more viable for each visit.

***Recycling technologies***

Several rare earths recycling technologies have been proposed or announced, with varying levels of technical information available for them.

For rare earth magnet recycling the key aspect to ensure is that the quality of magnets made from recycled rare earths match those made from virgin materials, as the magnetic powder can be susceptible to corrosion and degradation of its magnetic properties. The two m ain strategies for this are to blend recycled powders with virgin in the production of sintered magnets, or to manufacture lower strength bonded magnets. Several technologies for recycling REE magnets have been described in the literature (Oakdene Hollins, 2010; Schuler et al., 2011). The material may be recycled as an alloy to form new magnets, or may be returned to its constituent metals for processing into new magnets. The technologies include hydrogenation disproportionation desorption recombination (HDDR) (Williams, 2010), dissolution in molten magnesium (Takeda et al., 2005) and acid leaching (Saito et al., 2006). Materials from these can be used in new magnets, but often with a loss of performance. Various Chinese studies indicated that recovery yields from recycling exceed 80% of the contained rare earth, and can be greater than 95% (Schuler et al., 2011).

The Birmingham University process is based on hydrogen decrepitation, in which the magnetic material is broken down into a hydrided powder losing its permanent magnetic properties and enabling the material to be removed from the metallic shell of the motor by a simple sieving process (Zakotnik et al., 2009). Where the magnet is nickel coated, hydrogen decrepitation is done at elevated pressure and heat (170°C and 0.7 MPa) so that the hydrogen passes through the coating and the magnet disintegrates. The nickel can be removed as flakes during the sieving process. The rare earths can subsequently be removed from the NdFeB alloy by using solvent extraction techniques. A pilot plant has been built capable of extracting 10-40kg of NdFeB per run, and the next stage is the use of pre-processed HDDs as feedstock (Walton & Williams, 2011).

Hitachi uses a dry, rather than wet, process to recover the rare earths from magnets. Heat is applied to the magnets to distil the excess extraction material and a rare earth alloy remains (Waste Management World, n.d.). Toyota (2012) and Rhodia (2012a) both report that they are developing or opening recycling facilities for rare magnets. Rhodia reports that in May 2012 they restarted three of their 18 SX batteries for separating the individual rare earths from magnets. Both companies, as well as Umicore, have interests recycling rare earths from NiMH batteries (Rhodia, 2011).

Three companies report that they have developed a process for recycling rare earth phosphors. In May 2012, Rhodia reopened 4 SX batteries for separating the individual rare earths from recycled phosphors (REconserve, 2012b). The recycling process takes places at two sites: “phosphor attack” at their site in Lyon where phosphor powders are removed from lamps, and rare earth separating and finishing at La Rochelle. REConserve’s process has been tested at a pilot scale (kg scale) and separates yttrium and europium oxides, as well as glass and halophosphate streams (REconserve, 2012b). The HydroWEEE pilot process in Romania focuses on yttrium recovery. Yields of 80-90% recovery at the leaching stage and over 90% during precipitation have been achieved in its initial results (Kopacek, n.d.).

### 6.3.3 Gallium

The major use of gallium is in semiconductors, which require that the refined material has a very low concentration of impurities. Sophisticated processing routes are required to ensure that this purity is produced. Only 15% of a GaAs ingot is actually used during electronics manufacture, and the remaining 85% can be recycled (Kopacek, n.d.). This yield may improve over time, however, as the industry matures. For example, larger substrates are increasingly being used, so that there are fewer edge exclusions and therefore higher semiconductor yields. World gallium recycling capacity in 2011 was estimated at 198 tonnes (compared to 270 tonnes of refining capacity), with recycling plants for new scrap located in Canada, Germany, Japan, the UK and USA (USGS, 2012).

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 (Compound Semiconductor Magazine, 2003). It is thought that the recycling of this internal scrap has been largely optimised, at over 90% recovery due to the prices and maturity of the technology; in addition, the processing for LEDs has become much more efficient due to changes in processing techniques resulting in less waste (Moss et al., 2011). A number of other companies and manufacturers have plants to recycle new gallium scrap in Japan such as Dowa Mining and Asahi Holdings. Lower quality LEDs can be also reused rather than discarded, e.g. as Christmas tree lights.[18]

The processes involved in the recycling of gallium arsenide are shown in Figure 35. Processed residues from the production and processing of compound semiconductor, including lumpy scrap and slurry waste, are collected from the manufacturing process. As a minimum limit for recycling, gallium content of 4-5% is required (PPM PureMetals, 2012). The recovery of gallium begins with the crushing of the scrap, release of the crushed products and sludge by means of nitric acid ($HNO_3$) and sodium hydroxide (NaOH). From the resulting solution and the addition of lime, arsenic is precipitated. Metallic gallium is obtained by electrolysis at a purity of approximately 4N (99.99%), so further purification is then required.

*Figure 35: Simplified process flow for gallium arsenide recycling*

*Source: PPM PureMetals, 2012*

However no recovery of gallium from post-consumer scrap is known to take place (Buchert et al., 2009). This is because the gallium contained within the semiconductors is highly dispersed due to their use in printed circuit boards (PCBs). The recovery of metals from circuit boards tends to take place at one of the main European integrated metal smelters or outside the EU. Various material separation technologies are used to concentrate saleable quantities of material into the manufacturing supply chain. For example, Umicore (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 re-use (Umicore, 2007). Other elements contained within the circuit board, including gallium, are generally disposed of as slag.

Research is on-going for new technologies to extract further value from the scrap; however, there is doubt that the current smelting methods of recycling could effectively recycle gallium. The relative concentration is very low, making extraction of commercially significant quantities difficult and this situation may get worse because of the drive to use less material within each component with the effect of further reducing the concentration of valuable materials within electronics.

An exception to this trend may be the nascent growth in the use of LEDs in consumer lighting, which could lead to more attractive concentrations of gallium and indium within the waste stream (EPOW, 2011). A recently launched FP7 project, CycLED (January 2012-June 2015) specifically focused on optimising the resource flows for LED products, including the recycling of scarce key metals in LED production, optimising the reliability and lifetime of LED products and opportunities for reduced resource losses in production, use and recycling. Its expected results include (cycLED, n.d.):

- reduction of environmental impacts
- increase of the resource efficiency
- reduction of production costs

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[18] Michael Heuken, Aixtron, personal communication, July 2012

- closed-loop resource management
- separate collection of LEDs and LED products
- overcoming legal, trade and geopolitical barriers for eco-innovative LED products
- Increased competitiveness and capacity building.

Recycling of pre-consumer production waste of CIGS already occurs at Umicore in Belgium, which recovers metals from high grade solar 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 because the waste feed is concentrated. For post-consumer waste, arisings are almost non-existent, although it is noted that, at present, the indium and gallium concentrations in general PV waste are too low to make the Umicore's process for PV manufacturing residues sufficiently economic on a large scale, even with complete separation (Hagelüken & Meskers, 2009b). 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.

Collection routes for end-of-life solar PV have been established through a voluntary take-back scheme, established by the PV industry in 2007 (PV CYCLE). In addition end-of-life PV is included within the revised WEEE directive, meaning that manufacturers will have to ensure the collection and recovery of their products. However, the volumes collected were very low at 80 tonnes of end-of-life PVs in Europe in 2010 (despite estimating 6,000 tonnes) with the share of CIGS being almost non-existent owing to its recent introduction (Moss et al., 2011). In addition to the PV CYCLE scheme, initiatives by the German companies Saperatec and Loserchemie are expected to have begun recovering end of life PVs from 2011. An alternative approach to recycling would be to remanufacture post-consumer PV. This would avoid the complexities of developing a recycling process, whilst still reducing a reliance on virgin raw material.

### 6.3.4 Tellurium

Each of the major applications has its own practices regarding recycling tellurium. However, since the first JRC report, relatively little progress appears to have been made, although some quantitative estimates are now available on the volume of tellurium that is being recycled from manufacturing scrap from PV solar and thermoelectric modules. These recycled sources are estimated to provide 65 tonnes of supply, which is expected to rise to 111 tonnes by 2020 (First Solar, 2012).

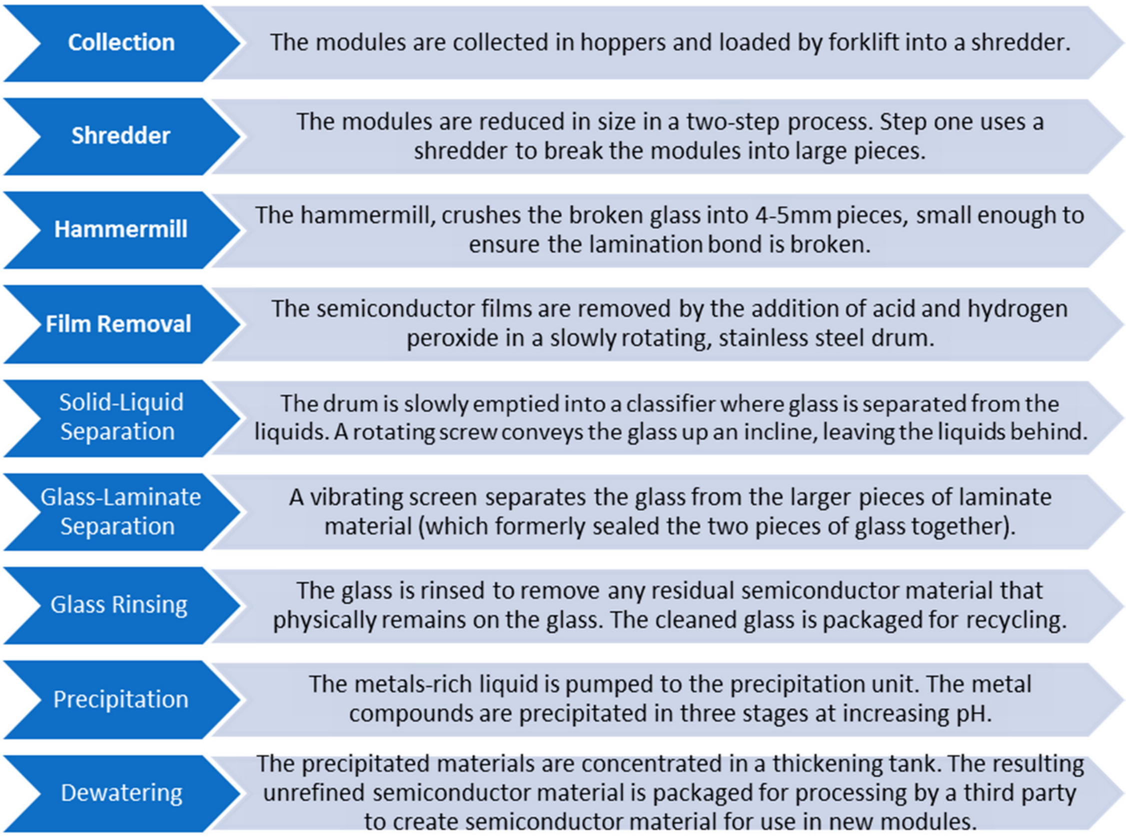
For metallurgy, additions of 0.04% tellurium are made to improve its machinability, i.e. to make the metal easier to work with in terms of bending, cutting, shaping, finishing etc. (Chemistry Explained, n.d.). The dispersed nature of this application means that the tellurium will be diluted amongst a very much larger pool of ferrous scrap, so that although the tellurium will be 'recycled' it will not be available to replace virgin raw material. Tellurium in copier drums has largely been substituted by other materials, which has led to a fall in the amount of tellurium available for recovery from scrap tellurium-based copier drums (USGS, 2008).

Some recycling opportunities do exist for the recovery of tellurium from electronic scrap where the scrap is processed at appropriate smelting plants. For example, there are recycling capacities for tellurium from electronic scrap at Dowa in Japan and at Umicore (Belgium) where tellurium is one of 17 metals that can be refined and is separated within its special metals refinery (UNEP, 2009). These facilities are available for use to recover any tellurium contained, such as within flash memory (Buchert et al., 2009), although actual production levels from recycling feed are currently low and improvements in collection rates are needed.

The use of tellurium in CdTe solar cells would appear to offer the most potential for tellurium recycling in the future, due to the rapid growth predicted. Recycling of industrial waste already occurs where solar panels are fabricated on a large scale, to increase the efficiency of the manufacturing process. Estimates of the material use rates range from 35% to 90%. The material losses are collected by filter systems with the recycling of the filter residues both feasible and economic for large scale production (Fthenakis, 2004). To that end, the world’s largest producer of CdTe solar PV, First Solar, has implemented its own recycling scheme for both pre-consumer scrap and of complete solar cells collected free-of-charge from consumers (First Solar, n.d.a).

The process operates in the US and Germany and involves shredding, removing the films using acid and hydrogen peroxide and separated the metal rich liquid for further processing (Figure 36) (First Solar, n.d.b). Although it is a lengthy process, it is highly efficient and can recover 95% of the semiconductor materials for use in new solar modules, as well as 90% of the glass (Larsen, 2009). The recycling of CdTe solar cells is therefore able to produce very high purity tellurium available for use within the production of new solar cells. However it is worth remembering that an end-of-life panel will be at least 25-30 years old before it is available for recycling.

*Figure 36: First Solar CdTe Recycling Process*



| | |
|---|---|
| **Collection** | The modules are collected in hoppers and loaded by forklift into a shredder. |
| **Shredder** | The modules are reduced in size in a two-step process. Step one uses a shredder to break the modules into large pieces. |
| **Hammermill** | The hammermill, crushes the broken glass into 4-5mm pieces, small enough to ensure the lamination bond is broken. |
| **Film Removal** | The semiconductor films are removed by the addition of acid and hydrogen peroxide in a slowly rotating, stainless steel drum. |
| Solid-Liquid Separation | The drum is slowly emptied into a classifier where glass is separated from the liquids. A rotating screw conveys the glass up an incline, leaving the liquids behind. |
| Glass-Laminate Separation | A vibrating screen separates the glass from the larger pieces of laminate material (which formerly sealed the two pieces of glass together). |
| Glass Rinsing | The glass is rinsed to remove any residual semiconductor material that physically remains on the glass. The cleaned glass is packaged for recycling. |
| Precipitation | The metals-rich liquid is pumped to the precipitation unit. The metal compounds are precipitated in three stages at increasing pH. |
| Dewatering | The precipitated materials are concentrated in a thickening tank. The resulting unrefined semiconductor material is packaged for processing by a third party to create semiconductor material for use in new modules. |

*Source: First Solar, n.d.b*

## 6.4 Substitution

The substitution of a higher risk material with a lower risk material has the potential to significantly reduce materials requirements for certain materials, and possibly within a shorter time frame than recovering materials from end-of-life products. Some existing EU legislation such as REACH and the ELV directive, already mandate the substitution of certain materials, although largely due to environmental rather than raw materials risks.

Substitution needs to be considered on a case-by-case basis: For some materials it may be possible to reduce the use of a particular metal or replace it completely. However, the use of a particular critical material can confer exceptional performance that may justify the associated supply risks and additional cost incurred. System substitution is also possible, such as by replacing permanent magnet-based motors with superconductor motors, geared systems or alternative magnetic materials.

### 6.4.1 Electric drive motors for EVs

Rare-earth based permanent magnets are the most commonly used technology for electric vehicle motors. They offer several benefits such as allowing for the smallest size and weight for equivalent performance. However, the need for a replacement to these technologies is becoming increasingly important as rare earths are expensive and in limited supply. The motor industry has responded to this problem by acting to secure supplies of rare earth metals and by investing heavily in research towards alternative motor technologies.

Substitution and reduction of the bottleneck metals, in this case neodymium and dysprosium, are effective solutions to mitigating the risk from future bottlenecks in the metal supply-chain of electric vehicles. Substitution can be either by using rare earth-free permanent magnet motors or by employing different motor technologies such as induction motors. There is also the potential to reduce the usage of rare earth in the existing drive motors by using new manufacturing techniques. The following section discusses the potential for each of these strategies, categorised by the different motor technologies.

***Permanent magnet motors***

***Reduction of neodymium and dysprosium usage in existing permanent magnet motors***

To date, NdFeB-based materials remain the strongest permanent magnets discovered, by a large margin. A vast amount of research has been targeted at improving the magnetic strength of this material and tuning its performance for different applications. For instance, neodymium is commonly substituted with dysprosium or terbium, in order to withstand high thermal loads. Temperature performance is improved by increasing the level of doping; however, the baseline magnetic strength decreases. Consequently, many different grades of magnet materials with different substitution levels are available. The main advantages of NdFeB permanent magnet motors compared to other motor types is that they have high power density coupled with low volume and weight - as well as being relatively robust.

For electric vehicle motors, neodymium is typically substituted with dysprosium (not terbium) due to price considerations. The amount of substitution will vary depending on the exact application for the motor; for instance, hybrid electric vehicles have higher doping levels of dysprosium due to the increased temperatures they experience from the ICE motor, compared to fully electric vehicles.

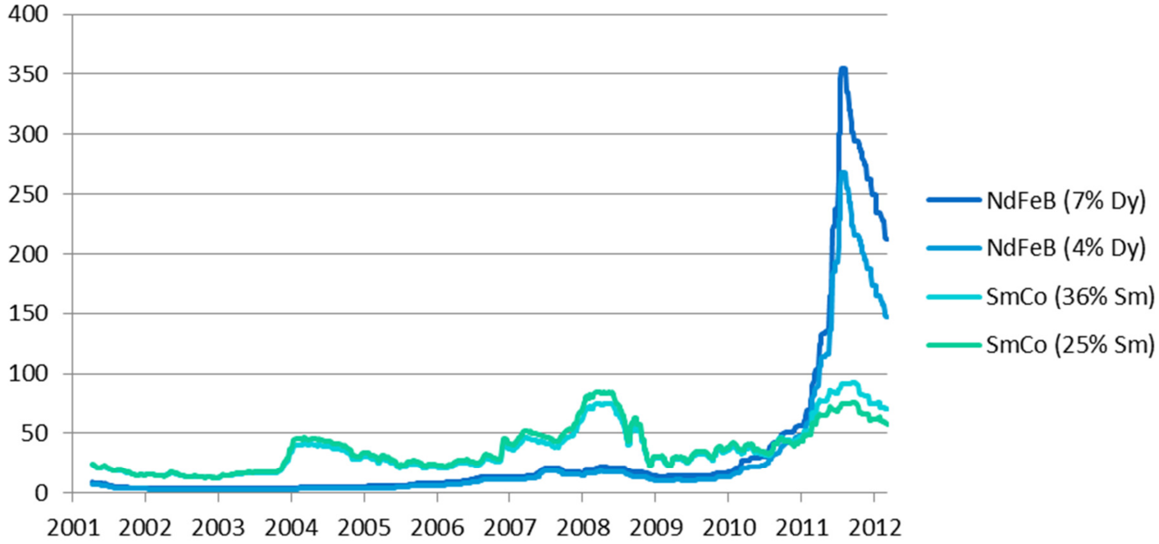
In China, TDK have developed the High-Anistropy Field Layer (HAL) production process which reduces the dysprosium requirements by 20-50% without sacrificing magnetic properties. This is achieved by dispersing the dysprosium on the surface of the magnet instead of using it as a neodymium alloy (TDK, n.d.). During the process dysprosium uniformly gathers at the periphery of the crystallizing particles; this minimises the amount of dysprosium diffusion, which is commonly encountered during conventional processes and leads to a reduction in flux density. New production techniques are also being developed to minimise the amount of neodymium required whilst providing equivalent levels of temperature resistance. Techniques such as grain boundary diffusion alloying, focus on using dysprosium more effectively within the materials chemical structure. Currently, Japanese companies and research bodies appear to be at the forefront of this research and have heavily invested in it.

***Alternative magnet materials***

The closest magnetic materials to neodymium in terms of performance are samarium-cobalt magnets. SmCo magnets are the first generation in the family of rare earth magnets and were used for high-performance applications before the development of NdFeB magnet motors. NdFeB magnets were in fact developed to alleviate supply issues associated with cobalt for SmCo magnets. SmCo magnets have superior resistance to high temperatures; unfortunately they have about half the magnetic strength of neodymium-based magnets (Hatch, 2010). As a consequence, for EV applications a far heavier magnet would be required to achieve the same power.

The high cost of SmCo has restricted the number of applications they are used in, however with increasing neodymium and dysprosium prices they might become competitive (Figure 37), particularly for higher temperature applications such as hybrid vehicles. However SmCo magnets are typically more brittle than NdFeB magnets, which can make them more difficult to work with. Figure 38 shows the relative volumes of NdFeB, SmCo, ceramic and aluminium-nickel-cobalt (AlNiCo) magnets required to achieve the same strength, thus further emphasizing the relative strength of NdFeB magnets.

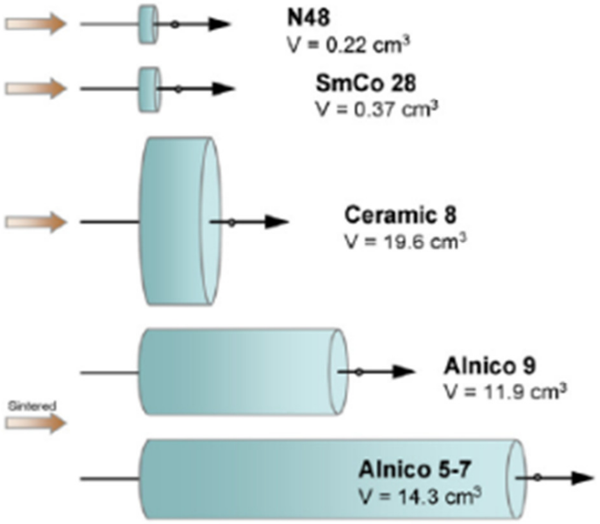
*Figure 37: Relative cost of NdFeB and SmCo magnets ($/kg)*



*Source: Calculated using Metal Pages, n.d.*

Other known permanent magnet materials, such as ferrite-based or AlNiCo magnets, are simply not powerful enough to be used as drive motors in electric vehicles. In the short term, the replacement of neodymium based magnets with 'yet-to-be-discovered' magnetic materials should not be relied on. Ongoing research in Japan has identified new ferrite materials for potential use in electric vehicle motor; however, the likelihood and timescales involved are unclear.

*Figure 38: Volume of different magnets needed to generate 1000 gauss at 5mm from pole face of magnet*



Source: Arnold Magnetic Technologies, 2011

***Alternative motor technologies***

As mentioned previously, technology choice can be another way of mitigating possible metals bottlenecks. Permanent magnet motors are a relatively new technology and there are many other types of motor, which do not require permanent magnets and therefore rare earths. Deployment of these alternative technologies will reduce the demand for neodymium and dysprosium. Different motor designs and their suitability for electric vehicles are discussed below. These range from mature established technologies to novel technologies, which are still under development:

> ***Induction motors (asynchronous)***
>
> Induction motors are a mature and well established technology and are widely used in industrial appliances of all types. Several electric vehicle manufacturers, including Tesla Motors, use induction motors in their fully electric BEVs and they are currently the most viable alternative to rare earth motors for EVs. Induction motors do not require permanent magnets; instead a magnetic field is produced from copper coils. They have good efficiency at nominal load, but have low efficiency at some operations (Schuler et al., 2011).In comparison to NdFeB motors, induction motors are relatively cheap to manufacture due to the high volumes which are produced. The amount of copper required depends on the size of the motor, which for an EV typically varies from 1.5 to 9kg (General Motors, 2011). A disadvantage is their relative size; for instance, the induction motors used by Audi are 20-30% larger and heavier than an NdFeB magnet motor of the same power (Fraunhofer, 2010).
>
> ***Switch reluctance***
>
> The advantages of reluctance motors are that they have a simple and robust construction and are relatively cheap. However, the major disadvantage is that this type of motor is particularly noisy. This has been a deterrent for their use in electric vehicles. Despite this, research effort has been directed at designing switch reluctance motors suitable for use in electric vehicles (Andrada et al., 2003; Takau and Round, 2003).
>
> ***Wound rotor synchronous motors***
>
> Wound rotor synchronous motors are used in the Renault Fluence Z.E. They do not require rare earths but have a high copper demand for their copper coils. In comparison to neodymium-based magnet motors they are large and heavy and require additional electronics (ExpertVE, n.d.).
>
> ***Hybrid motors***
>
> These are a combination of permanent magnet and reluctance motors; they are currently under development but have high potential for the future (General Motors, 2011). An advantage of hybrid motors is that they use fewer rare earth metals compared to NdFeB magnet motors.

### 6.4.2 Lighting

Trends towards larger display technologies and energy efficient lighting have increased demand for phosphors. Subsequently, demand for rare earth elements - in particular terbium, yttrium and europium - are also on the increase. Substitution and reduction of rare earth elements can offer effective solutions to mitigating the risk from future supply-chain bottlenecks. Light emitting diodes (LEDs) are expected to gain increased market share; compared to fluorescent lighting, LEDs are more efficient and have lower rare earth content.

Rare earth elements have been selected for use in lighting applications because of their optical properties, which arise due to localised electrons in the f-orbitals. It seems unlikely that the performance in terms of colour quality and energy efficiency will be achieved without the use of rare earth elements. Consequently, research has been focused on reducing the use of rare earth elements in phosphor as supposed to substitution. Strategies for both reduction and substitution of rare earth elements in phosphor, as well as alternative lighting technologies are discussed below.

***Rare earth reduction and substitution in solid-state lighting***

The phosphor powder found in fluorescent lights has a rare earth oxide content of 18%, or 0.54% of the total weight of the lamp. The rare earth compositions vary, as discussed in section 3.10.3, but typically contain lanthanum, cerium, europium, terbium, yttrium and gadolinium. Shortages in global supplies of rare earth elements have already affected the price of fluorescent lighting, for instance Philips have reported a price increase of 300% as of July 2011 (Phillips Lighting North America, 2011).

White light LEDs contain a range of different metals, such as nickel, gallium, arsenic, indium, antimony, cerium, europium and yttrium. The amount of rare earth metals found will depend on the method employed to produce white light, either by using a blue or near UV LED chip and a phosphor coating or by mixing light from red, green and blue LED chips.

### *Strategies for rare earth reduction in phosphor powder*

There are several different approaches currently under investigation for reducing the amount of rare earth elements - in particular terbium and europium - required in phosphor powders. One is the use of new phosphor compositions which require less europium and terbium, such as cerium-based phosphors (Tomoko Akai National Institute of Advanced Industrial Science and Technology, 2012). In classical phosphors, a dramatic loss of brightness is experienced when the terbium or europium content is reduced. Therefore new phosphor designs are required in order to reduce the rare earth content without loss of efficiency. Rhodia's research in this area has shown that significant REE savings can be achieved by redesigning phosphors. They have developed a new design for green phosphor (LAP) which uses 30% less terbium than previous designs, without sacrificing performance (Rollat, 2012).

Another is the use of alternative methods for producing phosphors which consume reduced amounts of rare earth elements. One method under investigation is a new synthesis route which aims to increase doping efficiency, and thereby reduce the use of rare earth elements, by precise control of the placement of REE dopants in the host material. Reducing the amount of phosphors required in lights by increasing the efficiency of lamps may also provide a method for reducing the amount of rare earth elements required. One method under investigation employs luminescent silica materials and UV light in the lamp. Another strategy is to increase the extraction efficiency of the light by patterning of nanostructures on the glass surface.

### *Strategies for rare earth substitution in phosphor powder*

Manganese-based phosphors, such as $Zn_2SiO_4$:Mn and $MgGa_2O_4$:Mn, are currently being explored as alternatives to rare earth-based phosphors. A project sponsored by the US Department of Energy Office of Science is exploring the use of manganese in its various oxidation states as a replacement for rare earth element activators in phosphor (IMCOA in US DOE, 2011). However, these technologies are still in the early stages of development and, so far, stability issues have been reported to be a major issue.

### *Organic light emitting diodes (OLEDs)*

OLEDs were developed in the 1980s as an alternative technology to the more commonly used LEDs, and they have the potential to become a viable rare earth-free alternative to other low energy lighting technologies such as LEDs and fluorescents. In OLEDs the electroluminescent layer is a film of organic compound - either small molecules or polymers - instead of the inorganic semiconductors. OLEDs are comprised of a series of thin organic layers, each around 100-200nm thick, placed between an anode and a cathode. The organic materials are selected for their conductive properties and are considered organic semiconductors. The most commonly used anode material for OLEDs is indium tin oxide (ITO) and the cathode is typically made from barium or calcium with a capping layer or aluminium.

The high cost of manufacture has prevented OLEDs from being commercially widespread. Despite this they are beginning to appear in a range of consumer electronics. Successful commercial applications of OLEDs include displays for mobile phones and digital cameras and televisions. Due to their high manufacturing cost, OLEDs are more commonly found in consumer electronics than in lighting applications. Many challenges still remain before the technology can be successfully used in lighting applications. OLED lighting panels are currently available as prototypes for niche applications at very high prices.

In contrast to LEDs and incandescent light bulbs, OLED lighting is produced as light panes and not as light points. The major difference between OLEDs and LEDs is that OLEDs produce light at low intensity spread over large areas whereas LEDs are more compact sources. An advantage of OLEDs over other light sources is that there is no glare emitted and as a result they do not require reflectors. The efficiency of OLED lighting is yet to match that of LED lighting. However, research has shown that the efficiencies of OLEDs can be significantly increased through doping with transition metal complexes such as rhenium, osmium or iridium based phosphorescent dyes (Thorseth, 2007). Rare earth metals can also be used as dopants in OLED applications.

The lifespans of OLED systems are currently lower than that of LEDs; current state of the art is around 5000 operating hours. However, due to increased research in this field the lifespan is constantly increasing and it is expected that they will be similar to those of LEDs in the near future. While there is great potential for OLEDs in architectural and niche decorative applications, it remains to be seen whether or not the technology can contribute to energy savings in general lighting applications.

***Quantum dots***

Quantum dots are a promising technology for lighting applications, as well as in electronic displays and automotive markets. The first commercial lighting applications of quantum dots used them as a coating on blue LEDs to help create a warmer white light; this is known as quantum dot LEDs (QD-LED). The advantage of this approach is that blue LEDs are the most efficient; in addition fewer LED chips are required when a quantum dot coating is required, thus leading to further increases in efficiency.

The first commercially available light bulb with this technology was delivered in 2010 (Nexxus Lighting, 2010). The Nexxus Array Quantum LED™ R30 is reported to use up to 80% less energy and last up to 25 times longer than an equivalent incandescent light bulb. The technology for quantum dot LEDs is still in its infancy; however, it is a viable alternative to traditional white LED lights with a lower demand for rare earth elements such as europium.

To obtain white light in fluorescent lights, red, green and blue phosphors are blended. Semiconductor nanocrystals, or quantum dots are being investigated as an alternative to phosphors for the generation of white light (SAND, 2004).By using quantum dots it is possible to create white light directly, thus eliminating the need for a range of phosphors. The range of visible photoluminescence emitted by quantum dots can be tuned by altering their size and surface chemistry. Zinc sulphide quantum dots have shown potential as an alternative to rare earth phosphors for both white LED and fluorescent lighting applications (The Economist, 2010).

### 6.4.3 Tellurium

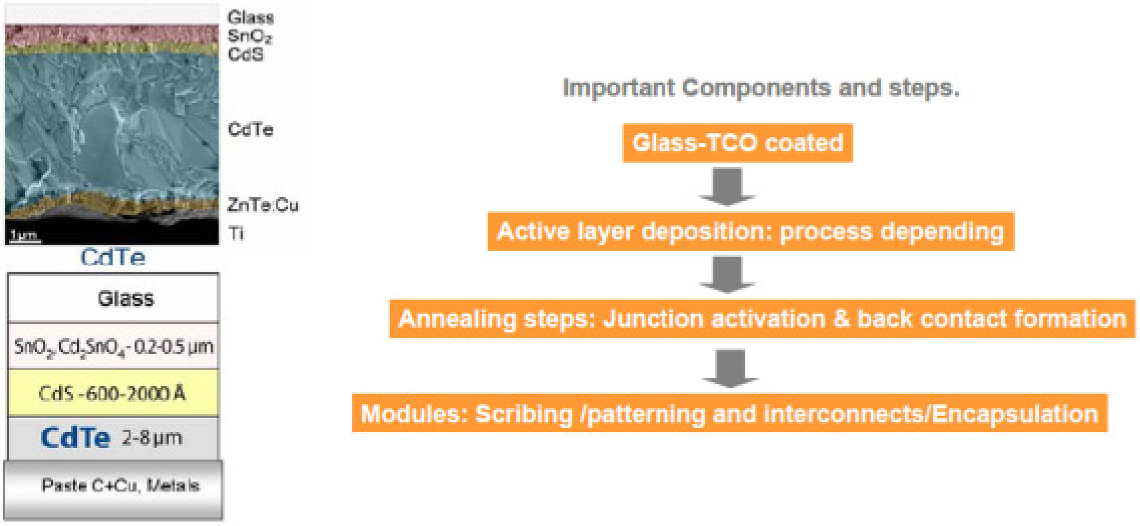
There has been noticeable activity in the past year with regards to the minimisation of the thickness of CdTe thin films, and substitution away from traditional applications.

***Thin film solar***

Historically, the thickness of CdTe thin films is commonly quoted as being 2-8 microns, with a mid-value of 5 microns (Figure 39). Research undertaken for the first JRC study highlighted the developmental nature of the technology in terms of uptake, technology mix and material composition. In that study, based upon interviews conducted with leading manufacturers and review of additional data, a thickness of CdTe films of 2.5-3 microns was modelled. Furthermore indium tin oxide was declared as not being the TCO of choice for First Solar, the dominant player in CdTe with a market share of near 90% for this technology. However some of the smaller CdTe manufacturers are known to use indium-based TCOs.

In its recent materials roadmap for photovoltaic technology, the EC JRC has set targets for the thickness of CdTe thin films, as well as various other parameters for efficiency and material usage (Table 164). For 2012 the KPI is for a CdTe layer thickness of 1.8 microns. If this is achieved, this will reduce the tellurium usage by a third compared to the estimates contained in this study. The long-term KPI is for a thickness of 1 micron from 2020 using graded absorbers and the minimisation of cadmium and mercury. This indicates the effect that resource efficiency and material substitution can have upon metal demand.

*Figure 39: CdTe cell configuration and manufacturing value chain*



*Source: EC, 2011f*

*Table 164: Key Performance Indicators (KPIs) for the EU CdTe Material Usage*

| KPI | Unit | 2012 | 2015 | 2020 | 2030-2050 |
|---|---|---|---|---|---|
| Industrial manufactured module efficiency | % | | 13 | 15 | 18 |
| Industrial manufacturing cost | €/Wp | | <1 | 0.5 | 0.3 |
| CdTe layer thickness | µm | 1.8 | 1.5 | 1.0 graded absorbers and minimisation of Cd / Hg | |
| CdS layer thickness | µm | 0.1 | 0.1 | 0.1 | 0.1 |
| Al layer thickness | µm | 0.3 | Alternative back contact | | |
| Deposition temperatures | °C | 450 | 400 | =/< 350 Non vacuum printable deposition processes | |

*Source: EC, 2011f*

***Other applications***

Traditional applications for tellurium include: metallurgy, in which tellurium is included as an alloying additive to improve machining characteristics; as a vulcanising accelerator in the rubber industry; and some other uses in the chemicals and pharmaceutical industries. Substitution is possible in these uses; indeed Jaffe (2010) suggests that it is likely to be more economic than mining primary tellurium ores or recovery from zinc or lead sulphide ores. However, increasing tellurium recovery from electrolytic copper refining remains the priority in his opinion. Policy measures to encourage substitution of tellurium in these lower value applications may involve raising the profile and awareness of these alternative materials within the relevant industries.

Selenium can replace tellurium in free-machining low-carbon steels, as can bismuth, calcium, lead, phosphorus and sulphur (USGS, 2008). Tellurium can be replaced by selenium and sulphur in rubber compound applications and selenium, germanium and organic compounds in electronic applications. Selenium can also replace tellurium in chromium-tellurium magnetic alloys. However, the replacement of tellurium with selenium can have problems, as selenium is considerably more toxic than tellurium so additional precautions need to be taken in the work place. Indeed the USGS expects consumption of tellurium within these low-value products to decrease as the cost of tellurium rises due to demand from solar PV (USGS, 2008).

It is noticeable that in earlier sources metallurgy is commonly quoted as the most significant application for tellurium (42% of usage), followed by solar PV (26%) and chemicals and pharmaceuticals (21%) (EC, 2010a). This situation seems to have now been reversed with solar now accounting for 40% of tellurium usage, compared to 15% for metallurgy (see Appendix 6, Figure A6.15). This is expected to continue - although is more for the long term, as it requires formulation changes in steel (International Study Group for Nickel et al., 2012). As for other tellurium applications, substitution has already been largely completed within the photoreceptors of copiers and printers. The STDA comments that use of tellurium in the rubber industry is price-sensitive, and that much of tellurium use in thermoelectric modules is also price-sensitive. However, at the high end (for example mobile devices, laptops and phase change memory) price sensitivity is lower.

## 6.5 Summary

The evidence reviewed in this chapter has identified numerous initiatives that are underway to mitigate raw materials risks associated with rare earths, gallium and tellurium. These are largely driven by the costs of these materials, but also to some extent by concerns regarding their availability.

In terms of increasing primary supply, possibilities exist for a rare earths mine within Europe, although development is still in the early stages. The Norra Kärr deposit in Sweden is relatively attractive given its high proportion of heavy rare earths. An alternative mitigation option, particularly in the short term, is to process rare earth concentrates from tailings, by-product sources or open another mine outside Europe. This could help to stimulate European rare earths knowledge, expertise and production capacity and use the processing and separation facilities that already exist in Europe. The data indicate that Europe already has a degree of self-sufficiency for gallium and tellurium; however, opportunities may exist to create further refineries to boost recovery of these materials.

For reuse, recycling and waste reduction, the data indicate that significant improvements have already been made in recent years regarding the recycling of post-industrial waste streams. The evidence shows that wastes from magnet, semi-conductor and photovoltaic manufacture are now commonly being recycled. The recycling of post-consumer waste streams is more of a problem owing to the issues associated with collecting, sorting and pre-processing the relevant waste streams. The long lifetimes of certain product groups - notably hybrid and electric vehicles, wind turbines and photovoltaic cells – are a further limitation due to the low volumes available for recycling. Nevertheless, near term opportunities and initiatives do exist for the recovery of rare earth magnets from hard disc drives and rare earth phosphors from lighting.

For substitution, the cost implication of these materials has already resulted in significant reduction in materials intensity for some applications. This includes the reduction of dysprosium and neodymium in rare earth magnets, of terbium and europium within rare earth phosphors and the minimisation of the thickness of tellurium within thin film photovoltaic solar. Systemic approaches to materials substitution are also being widely considered including alternative motors technologies e.g. asynchronous or switch reluctance; and alternative lighting technologies e.g. LEDs, OLEDs and quantum dots. Opportunities also exist to substitute current use of the critical materials from traditional applications where other materials are suitable e.g. eliminate tellurium from steel alloys.

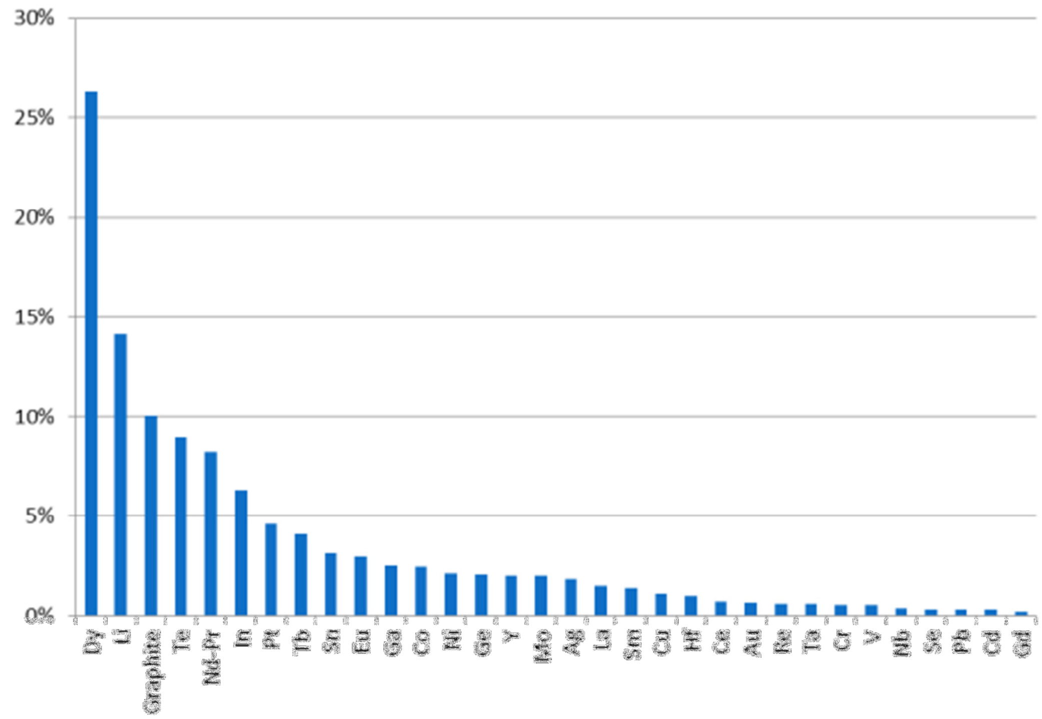
# 7 Conclusions and Recommendations

## 7.1 Summary

The last two years have seen much debate on how to categorise the resources of ‘critical’ importance to a particular business or country. However, in a world of diverse interests and timescale considerations, a broad consensus seems to have emerged on which resources are critical, including rare earth elements from China and various other ‘minor’ metals. This study contributes to this policy debate by identifying important materials for particular low-carbon technologies, and assessing the market and geopolitical risks associated.

This study has built on the existing research conducted in the first JRC study (Moss et al, 2011) and by modelling the uptake and material intensity of key low-carbon technologies within the EU, mostly using scenarios from the EU Energy Roadmap 2050 (EC, 2011b). The top 32 metals identified within the current study in terms of the estimated requirements within the EU versus projected supply are shown in Figure 40.

*Figure 40: Annual EU metals demand from decarbonisation technologies, % of expected supply 2020-2030*



The results identified dysprosium as having the most significant demand compared to projected supply, with the EU requiring over 25% of expected world supply to meet EU demand for hybrid and electric vehicles and wind turbines. Other materials of significance include: lithium, graphite, neodymium and praseodymium (for hybrid and electric vehicles, and wind); tellurium, indium and tin (for solar energy); platinum (for fuel cells); and terbium, europium, yttrium, germanium and gallium (for lighting). The full list of the 32 metals with their associated technology(ies), shown in brackets, is given in Table 165.

*Table 165: Reduced list of 32 materials with the associated key decarbonisation technology*

1. Dysprosium (vehicles, wind)
2. Lithium (vehicles)
3. Graphite (vehicles)
4. Tellurium (solar)
5. Neodymium-Praseodymium (vehicles, wind)
6. Indium (solar, lighting, nuclear)
7. Platinum (fuel cells)
8. Terbium (lighting)
9. Tin (solar)
10. Europium (lighting)
11. Gallium (lighting, solar)
12. Cobalt (vehicles, fossil fuels)
13. Nickel (desalination, vehicles, geothermal)
14. Germanium (lighting)
15. Yttrium (lighting)
16. Molybdenum (desalination, wind)
17. Silver (solar, lighting)
18. Lanthanum (vehicles)
19. Samarium (vehicles)
20. Copper (CHP, solar, vehicles, grids)
21. Hafnium (nuclear)
22. Cerium (vehicles)
23. Gold (lighting)
24. Rhenium (fossil fuels)
25. Tantalum (geothermal, fossil fuels)
26. Chromium (desalination)
27. Vanadium (CCS)
28. Niobium (CCS)
29. Selenium (solar)
30. Lead (grids, storage)
31. Cadmium (solar)
32. Gadolinium (lighting)

These 32 metals were further analysed according to market and geopolitical factors to assess their criticality. Based on the combination of supply chain risks, a reduced list of metals was derived (see Table 166):

- Eight metals were given a high criticality rating and are therefore classified as 'critical'. These are the six rare earth elements: dysprosium, europium, terbium, yttrium, praseodymium and neodymium; and the two elements gallium and tellurium.

- Six metals were given a medium-to-high rating and are classified as 'near critical'. It is suggested that the market conditions for graphite, rhenium, hafnium, germanium, platinum and indium are monitored in case these metals markets deteriorate with the effect of posing supply chain bottleneck risks.

*Table 166: Criticality ratings of shortlisted raw materials with their associated technology*

| Element | Rating | Associated Technology |
|---|---|---|
| Rare Earths: Dy, Pr, Nd | High | vehicles, wind |
| Rare Earths: Eu, Tb, Y | High | lighting |
| Gallium | High | lighting, solar |
| Tellurium | High | solar |
| Graphite | Medium-High | vehicles |
| Rhenium | Medium-High | fossil fuels |
| Hafnium | Medium-High | nuclear |
| Germanium | Medium-High | lighting |
| Platinum | Medium-High | fuel cells |
| Indium | Medium-High | solar, lighting, nuclear |

## 7.2 Mitigation strategies for the high-critical group of metals

Numerous initiatives are underway to mitigate raw materials risks associated with rare earths, gallium and tellurium. These are largely driven by the costs of these materials, but also to some extent by concerns regarding their availability. A more detailed review of the mitigation possibilities for these metals was presented in Chapter 5. To summarise:

- In terms of increasing primary supply, possibilities exist for a rare earths mine within Europe, although development is still in the early stages. The Norra Kärr deposit in Sweden is relatively attractive given its high proportion of heavy rare earths. An alternative mitigation option, particularly in the short term, is to process rare earth concentrates from tailings, by-product sources or open another mine outside Europe. This could help to stimulate European rare earths knowledge, expertise and production capacity and use the processing and separation facilities that already exist in Europe. The data indicate that Europe already has a degree of self-sufficiency for gallium and tellurium; however, opportunities may exist to create further refineries to boost recovery of these materials.

- For reuse, recycling and waste reduction, the data indicate that significant improvements have already been made in recent years regarding the recycling of post-industrial waste streams. The evidence shows that wastes from magnet, semi-conductor and photovoltaic manufacture are now commonly being recycled. The recycling of post-consumer waste streams is more of a problem owing to the issues associated with collecting, sorting and pre-processing the relevant waste streams. The long lifetimes of certain product groups - notably hybrid and electric vehicles, wind turbines and photovoltaic cells – are a further limitation due to the low volumes available for recycling. Nevertheless, near term opportunities and initiatives do exist for the recovery of rare earth magnets from hard disc drives and rare earth phosphors from lighting.

- For substitution, the cost implication of these materials has already resulted in significant reduction in materials intensity for some applications. This includes the reduction of dysprosium and neodymium in rare earth magnets, of terbium and europium within rare earth phosphors and the minimisation of the thickness of tellurium within thin film photovoltaic solar. Systemic approaches to materials substitution are also being widely considered including alternative motors technologies e.g. asynchronous or switch reluctance; and alternative lighting technologies e.g. LEDs, OLEDs and quantum dots. Opportunities also exist to substitute current use of the critical materials from traditional applications where other materials are suitable e.g. eliminate tellurium from steel alloys.

It should be noted that considerable uncertainty affects the results of this study in at least the following areas:

- the uptake of particular low-carbon technologies
- the technology mix between competing sub-technologies
- the materials composition and associated quantities of some components
- the substitutability of key materials in certain technologies
- the projected supply of various metals to 2020 and 2030.

## 7.3 What can be done in response to supply risks for critical raw materials?

Many governments and companies are pursuing policies to mitigate their materials risks. Six main areas are important, aimed at addressing different concerns:

1. Data collection and dissemination.
2. Primary production.

3. Resource efficiency strategies (includes recycling).
4. Design and innovation (includes substitution).
5. Trade and international co-operation.
6. Procurement and stockpiling.

Numerous mitigation options available to reduce the supply-chain risks for the critical metals have been considered. Numerous initiatives were reviewed that are underway, largely driven by the costs of these materials, but also to some extent by concerns regarding their availability. These included increasing primary supply; encouraging reuse, recycling and waste reduction, and considering materials substitution opportunities.

### 7.3.1 Data collection and dissemination

For some metals there are surprisingly large evidence gaps regarding production, trade, use and even pricing. Without accurate and reliable information, it is almost impossible for governments and businesses to make appropriate decisions:

- For example with tellurium, an important material for thin film solar PV, official data only identifies the origin of around a quarter of world production. To fill this data gap, a recent study conducted on behalf of the International Copper Study Group undertook a survey of copper refineries to assess their tellurium production.
- Other materials remain unquantified and regular supply-demand studies are useful. The formation of International forums, organisations akin to the International Metals Study Groups might be encouraged for this purpose, or existing organisations such as the European Aluminium Association or Eurometaux should be requested to undertake similar studies, such as for gallium.
- The research also identified a relative lack of reliable or historic estimates of the contribution to world production from recycled sources. Further research in this area may be considered to be desirable in the near future.
- To support decision-making on recycling, data is required on the volumes of critical raw materials available for recycling. Some of this data has been, or is in the process of being, collected – such as for the flows of critical raw materials within electronics products in the German and UK economies. Other product categories should be considered for research e.g. aerospace, defence and automotive.
- Small- and medium-sized enterprises in particular may be unaware of materials risks or of possible actions to mitigate them. Action is needed to target SMEs and point them to useful information.

### 7.3.2 Primary production

Investors have been quick to spot the need for and potential profit of new mines, with numerous exploration and development projects underway. There is a growing demand for base metals - for infrastructure in emerging markets and minor metals in electronics and clean technologies - but longevity of products means that these metals will not be available for recycling until far in the future. Thus new demand is likely to continue to drive commodities markets for many years.

Some stakeholders view new primary production to be an “elephant in the room”, because of potential environmental and land-use impacts. There is a recognised need to ensure that the highest environmental and social standards are upheld in order to minimise the consequences of mining and refining. China has started closing down many of its small, illegal and highly polluting mines; however the environmental impact of mining is an issue throughout the whole world. Further research, development, demonstration and implementation are necessary for suitable technologies that can alleviate stakeholder concerns with respect to new and existing facilities. Greater transparency and traceability of raw materials should also be encouraged as a means to this end.

However opportunities are not limited purely to new mining projects. Existing reserves, mines, facilities, urban mines and spoils offer significant potential. For example, our research has shown that, across the world, there are major base metal smelting and refining operations ignoring the potential to recover valuable by-product metals such as gallium, germanium and indium. More speculative opportunities include revisiting old mines and refining sites, which might now be considered to be high grade deposits by conventional standards, or contain valuable by-products.

Contrary to popular belief, the world is not running out of critical materials, however better geological mapping appears necessary for some of these metals, which have only recently seen a growing number of new and important applications. However, a word of caution should be noted about attempts that may specifically allocate EU funding to projects on the basis of raw materials criticality.

### 7.3.3 Resource efficiency strategies

Resource efficiency has been widely touted as a solution to Europe's combined challenges of resource security, environmental protection and business competitiveness. These are legitimate and lofty aims, but lack specific focus on practical actions that avoid blind alleys:

- Quick-wins often lie in post-industrial waste streams such as scrap from photovoltaic solar panel manufacture or superalloy turnings from aircraft engine production. Companies such as Rolls Royce can attest to the role that better resource management control has made to conservation of scarce materials such as rhenium (Benton and Hazell, 2012).
- For products such as electronics, appropriate solutions are still needed. The very low recycling rate of metals such as beryllium, tantalum and rare earths continue to pose a challenge. New innovative technologies for electronics dismantling, separation and recycling need to be developed.
- The benefits of reuse, remanufacture and repair should be promoted as they offer the potential to considerably extend the lifetimes of products and conserve raw materials that are often currently difficult to recover. Standards, such as PAS141, can underwrite and reward legitimate operators. Reuse, remanufacturing and repair are poorly understood at a policy level.

The appropriate policy mechanisms and scale of critical metals recycling is an important issue to be addressed by the EU in the near future. This concerns the collection and recovering of raw materials from end-of-life products and the current practice of exporting significant quantities of waste overseas. There are two main sides to this policy debate. The first is the preference by some actors to let market forces be the determining factor. The second relates to the wish to recover critical raw materials within the EU for strategic reasons.

A debate is necessary about which is desirable. However, this issue is only addressed to a relatively limited extent within this study. This is because the focus is on which and how much raw materials are required, and not the stage of the value chain at which they are incorporated within the decarbonisation technologies. For some technologies the decarbonisation technologies may be manufactured overseas, and then imported into Europe, already containing the critical raw materials.

### 7.3.4 Design and innovation

Design and innovation, whether by eco-design to better enable disassembly, recycling and remanufacture, or the substitution of one insecure material with another material or compound, offer significant scope to mitigate resource risks to business. Reductions in the quantities of key materials used in energy technologies, such as through nanotechnology could have significant implications to the estimates presented in this report.

Innovation is an important lever in the mid-to-long term in order to ease that balance particularly where genuine supply limitations have been identified, such as heavy rare earth elements for automotive or rhenium for the aerospace industry. For rare earth elements, considerable activity is underway in the automotive industry to replace permanent magnet-based motors within hybrid and electric vehicles. This motivation is based on both a combination of security of supply and cost. The relative cost compared to vehicles with internal combustion engines, is key for their successful uptake on the mass-market.

Substitution needs to be considered on a case-by-case basis: for some materials it may be possible to reduce the use of a particular metal or replace it completely. However, the use of a particular critical material can confer exceptional performance that may justify the associated supply risks and additional cost incurred. System substitution is also possible, such as by replacing permanent magnet-based motors with superconductor motors, geared systems or alternative magnetic materials. Continued, but targeted, investment in basic and applied sciences, and support for the development to market is needed to meet these challenges.

### 7.3.5 Trade and international co-operation

With resource nationalism on the rise, strategic alliances are now on the agenda of many foreign ministries. The role of international partnerships has been exemplified by transatlantic and trilateral conferences on raw materials involving the governments and companies of the European Union, United States and Japan. This has helped facilitate collaborative discussion and exchange of knowledge on the subject of raw materials. The role of International Metals Study Groups has already facilitated considerable international dialogue on the topic of by-product metals.

However, following the lodging of raw materials disputes at the World Trade Organisation, the opposite approach seems to have been taken against China. It remains to be seen if these appeals will be successful and what impact they might have on international relations.

### 7.3.6 Procurement and stockpiling

Western governments have not pursued stockpiling as a resource policy, the notable exception being the small US Defense Strategic Stockpile. Good reasons for this include the prominence of free market economic ideologies, but also the difficulty of timing sales and purchases without distorting world markets.

On the other hand, Japan has long been a proponent of materials stockpiling for specific metals, but it is worth noting that the onus does not all fall on the Japanese government. Private stockpiling by major companies constitutes 18 days’ worth of domestic demand of the total 60 day stockpiling target, illustrating that a mixed approach may offer benefits.

Action on raw materials risks has traditionally taken a back seat to short-term cost savings. Like governments, private businesses can stockpile, but an alternative is to secure their supply chain through off-take agreements and joint ventures with junior mining projects. These strategies have been successfully pursued by Toyota and Sumitomo amongst others.

### 7.3.7 Possible further research

A number of topics were identified as possibly meriting further research, but could not be considered within the immediate scope of this study. Some have been discussed above, but the full list includes:

- A meta-study of the raw materials requirements for hybrid and electric vehicles considering a wider range of technology uptake and penetration scenarios than considered within this project.
- The implications on raw materials of missing or exceeding targets for the uptake of certain decarbonisation technologies.
- Research into the implications for raw materials of continued improvements of internal combustion engines, including advanced lead acid batteries and catalytic convertors.
- Development of new and more detailed scenarios for the uptake and technology mix of options for stationary energy storage in particular.
- Similar studies could be undertaken for other sectors such as defence and aerospace.

- An investigation on the location of production of the decarbonisation technologies and the stage of the value chain conducted within Europe.
- Improving statistics on the contribution of recycling to world production for a number of metals.
- An assessment of the appropriate scale and location of recycling technologies.
- The purity of the raw materials required for different decarbonisation technologies.
- Contribution of greater traceability and transparency to reducing raw materials supply risk.

### 7.3.8 Recommended actions

To conclude, there are numerous risk mitigation strategies available, but ultimately a combination of actions is required by both governments and businesses. Table 167 summarises a list of possible policy actions to mitigate raw materials risk. It is noted that some of these are already underway.

However, it is important not to overstate the risks of raw materials bottlenecks for key decarbonisation technologies. This is because there are still many years before the large uptake of some technologies and there are numerous options available to mitigate the risks identified.

Table 167: Possible policy actions to mitigate raw materials risks for the EU path to decarbonisation

| Type | Recommended action |
|---|---|
| Data collection & dissemination | • Collect better data on the production, use, trade and prices of minor metals including gallium and other by-product metals<br>• Conduct research on product, material flows in the economy, and supply chains such as for the aerospace and defence sectors |
| | • Publish regular studies on supply, demand, prices and outlook for critical metals for materials designated as being critical or near critical for EU decarbonisation<br>• Conduct further research on the contribution of recycling to world metal production |
| | • Improve the traceability and transparency of raw materials supply chains<br>• Disseminate information on material risks and mitigation solutions to SMEs |
| Primary production | • Encourage the development of new mines and refineries in Europe, in particular for heavy rare earth elements, tellurium and gallium<br>• Build greater public acceptance of mining and refining, including the enforcement of appropriate environmental and social standards |
| | • Support RD&D to lower the environmental impact of mining and refining<br>• Raise awareness of valuable by-product metals in mining/refining waste streams, among major mining companies in particular |
| | • Improve geological mapping for critical metals, including revisiting the geological potential of old mines and refineries, urban mines and spoils |
| Resource efficiency | • Investigate recycling potentials for post-industrial waste streams, including improving resource management control procedures within companies<br>• Improve collection rates of WEEE and other end-of-life products in order to indirectly increase the availability of scrap in supply chains |
| | • Develop new mechanical pre-processing techniques for WEEE to effectively dismantle end-of-life products and to minimise/capture fines for recycling<br>• Promote the benefits of reuse and remanufacturing at a EU policy and company level such as by supporting the uptake and certification of reuse standards |
| | • Increase the product lifetimes of key products and components including wind turbines, engineering components and photovoltaic solar |
| Design & innovation | • Promote eco-design practices to better allow disassembly, recycling and reuse<br>• Support RD&D for the development of recycling technologies for CRMs in WEEE, including pre-processing and metallurgical recover techniques |
| | • Continue RD&D for substitution of supply constrained materials such as for heavy rare earths within magnets and lighting phosphors or tellurium within steel alloys<br>• Support research in technologies such as nanotechnologies, with the potential to reduce materials requirements of key technologies such as photovoltaic solar |
| International co-operation | • Continue to collaborate internationally to exchange knowledge<br>• Consider the formation of additional International Metals Study Groups |
| Stockpiling & procurement | • Consider long-term incentives and risk in procurement decisions<br>• Explore possibilities to secure materials supply chain |

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# Appendix 1: Technology Descriptions

The technology descriptions considered in this report are taken primarily (apart from road transport efficiency and desalination) from the JRC's 2011 Technology Map (EC, 2011c), which provides a concise and authoritative assessment of the state of the art of each technology, their current and estimated future market penetration and the barriers to their large-scale deployment, as well as the on-going and planned R&D and demonstration efforts to overcome technological barriers. Other sources (with references) have been used to supplement the descriptions. The following sections provide an overview of the salient features of each the technology, as used to develop the assessments for material needs and consequent demand-to-supply figures.

## A1.1 Hydropower

### A1.1.1 Background

Hydropower plants exploit the kinetic energy in flowing water or potential energy in stored water to generate electricity. Turbines are placed within the flow of the water to extract the energy and convert it to electrical energy by use of a generator. There are several different types of hydropower plants, including those with storage reservoirs which can generate electricity as and when needed, thus providing a reliable form of large-scale energy storage. Compared to other renewable energy technologies, hydropower is a mature technology and is currently the most widely used form of renewable energy for electricity production, accounting for almost 12% of gross electricity generation in Europe (EC, 2011c).

However, reliance on geographical location and the high capital costs arising from the construction of dams present limitations for hydropower in Europe. Currently 64% of economically viable hydropower potential is being exploited in Europe; this suggests that Europe's potential for hydropower is not yet exhausted (Deutsche Bank Research, 2010). Areas such as Scandinavia and the Alps, where hydropower has long been part of the energy mix, have potential for new hydropower plants; in particular pumped-storage generating plants as they can be used to match supply from variable renewable sources. There is also scope to improve the energy efficiency of older hydropower plants by retrofitting them with new turbines and generators.

### A1.1.2 Sub-technologies

Hydropower technology can be split into three main systems. These are:

- reservoir-based hydropower
- run-of-the-river (ROR) hydropower
- pumped hydro energy storage (PHES).

Another commonly used categorisation is to define hydroelectric power plants by their generating capacity. Although there is no internationally accepted standard for size categories (Egré and Milewski, 2002) the classification system suggested by the JRC (EC, 2011c) offers some general guidelines: large (> 10 MW), medium (1 - 10 MW), small (100 kW – 1 MW), micro (5 – 100 kW) and pico (< 5 kW).

***Reservoir-based hydropower***

The most commonly used form of hydropower uses dams to create storage reservoirs. These reservoirs enable electricity generation with rapid response to load changes. Small dams allow for short term storage, while larger dams enable a consistency of energy supply over seasonal changes. Water from the reservoir is delivered to the turbines via a large pipe called a penstock. The three largest hydroelectric plants in the world also have the largest generating capacity of any type of power station. These are the Three Gorges Dam in China (22.5 GW), Itaipu on the Brazil-Paraguay border (14 GW) and Guri Dam in Venezuela (10.2 GW).

***Run-of-the-river (ROR)***

ROR systems have either no reservoir or only a small reservoir, leaving such systems vulnerable to seasonal water flow. ROR hydropower is therefore most appropriate for streams or rivers with little seasonal change, or those that have a reservoir further upstream regulating water flow. A small dam may be used to ensure that there is enough water channelled into the penstock to deliver to the turbines further downstream. These small dams do not result in large flooded areas of land characteristic of the reservoirs used in conventional systems and do not significantly alter the normal course of the river.

***Pumped hydro energy storage (PHES)***

PHES systems provide a means of storing energy and are used to assist power plants in balancing the load across periods of low and high demand. PHES systems consist of two or more reservoirs sited at different elevations and connected to each other by a penstock, pump and turbine equipment. The energy to pump water to the upper reservoir must come from the grid, and therefore pumping usually takes place during periods of low energy demand when there is excess generating capacity and the cost of supply is low. The water in the upper reservoir is then released during periods of high demand. Both pumping and electricity generation are carried out by reversible Francis turbines or by separate pumps and turbines. Systems that consist entirely of artificial reservoirs and which do not include any natural waterways are usually referred to as ‘closed loop’.

PHES is currently the best available method for large scale energy storage and can be used to regulate the supply of electricity when used in conjunction with renewable sources of energy, especially where the supply is variable – such as occurs with wind power. Reservoir-based hydropower systems may be also outfitted to pump water from a lower to a higher level (essentially reversing its normal function) in order to store energy in times of excess power generation, such as during off-peak periods. The water can then be allowed to flow down again to recover the energy.

## A1.2 Geothermal energy

### A1.2.1 Background

Geothermal energy sources consist of thermal energy from beneath the earth’s crust, stored in liquid water, and trapped steam and rock. The utilisation of geothermal energy sources can be grouped into the following applications: electrical power generation, direct use (for heating applications), indirect use (e.g. heat pumps) and co-generation applications (combined heat and power, CHP). The temperature and enthalpy of the geothermal source is characterised by the geological environment. For instance, high-temperature geothermal sources (above 180°C) are often associated with recent volcanic activity and are found near tectonic plate boundaries. In these locations the crust is often highly fractured owing to seismic activity, and is thus permeable to vapour and fluids.

Geothermal power plants often require high capital expenditure arising from the need to drill deep wells to reach high-temperature geothermal sources. It has been reported that the European geothermal potential is 3.5 GW for hydrothermal electricity and approximately 70 GW from enhanced geothermal systems (EC, 2011b). The piping used in geothermal systems may employ corrosion resistant alloys that contain metals such as titanium and molybdenum, which are of interest to this study. There are several different methods used to obtain energy from geothermal sources. The choice of technological approach is determined by the temperature and pressure of the geothermal fluid.

### A1.2.2 Sub-technologies

The technologies which will be explored for geothermal energy are:

- flash steam plants
- dry steam plants
- binary cycle plants
- combined cycle plants

- co-generation plants
- enhanced geothermal systems (EGS).

***Flash steam plants***
Flash steam is the most common system in use today and is chosen when the geothermal fluid is at a temperature greater than 180°C. Hot high pressure fluid from an underground reservoir is pumped to the surface through a production well and is injected into a tank held at a much lower pressure. The resulting mix of brine and steam are then separated and the steam is expanded in a turbine (EC, 2011c). The remaining unvaporised fluid can be flashed twice or three times more at progressively lower pressures and temperatures. The waste hot water is then pumped back into the underground reservoir.

***Dry steam plants***
Dry steam plants use high-temperature geothermal steam and were the earliest power plants for generating electricity from geothermal resources and have the lowest power plant costs (Bloomquist, 2009). The steam is piped from underground wells to the surface where it is used to drive a turbine. However, the expansion of this type of system is limited by the rare natural occurrence of geothermal steam.

***Binary cycle plants***
In binary cycle geothermal power plants the geothermal fluid never comes into contact with the turbines. Water or brine from geothermal sources is pumped to the surface where it passes through a heat exchanger containing an organic fluid such as butane or pentane. These secondary fluids have a much lower boiling point than water and so the heat transferred from the water causes the secondary fluid to vaporise. This vapour is then used to drive a turbine.

***Combined cycle plants***
A combined cycle plant is composed of a flash steam plant and a binary cycle plant. First flash steam is used to power a turbine and then the remaining geothermal fluid is used to heat a secondary fluid with a lower boiling point, which in turn is vaporised and used to power a turbine.

***Co-generation plants***
Co-generation plants combine electricity generation with direct use of the waste heat released from the generating units or excess heat from the geothermal source. This heat may be directed towards a variety of uses, such as district heating systems, heating greenhouses for agriculture or providing warm water for swimming pools.

***Enhanced geothermal systems***
A long-researched development in geothermal power involves drilling an injection well and pumping water under high pressure to fracture hot rocks several kilometres below the Earth's surface, increasing their permeability to water. Water injected under pressure into these rocks is heated and returns to the surface via another borehole called a production well. When the hot fluid reaches the surface it is used to generate electricity using one of the previously described techniques such as flash steam or binary cycle.

The method, termed enhanced geothermal systems (EGS), allows the extraction of heat from deep sources that lack adequate water and/or where the rocks are insufficiently permeable. Such systems would allow geothermal energy to be extracted from many more locations than are possible using conventional systems. Currently the EGS research facility at Soultz-sous-Forêt is at the most advanced stage of development and has commissioned the first working power plant, which will provide 1.5 MWe of power. By 2011, 20 EGS projects were under development in Europe (IEA, 2011d).

## A1.3 Marine energy

### A1.3.1 Background

Although different estimates exist regarding the global potential for electric power generation from ocean energy, there is significant potential from this source that has not been developed as yet. Compared to wind and solar, ocean energy has the advantage of being more predictable and having a reduced visual impact. However, unlike wind and solar, most concepts for the generation of electric power from ocean energy have yet to demonstrate both their operational performance and their robustness in the marine environment to move from pilot scale to larger-scale pre-commercial installations (Frost & Sullivan, 2008; European Ocean Energy Association (EOEA), 2010).

### A1.3.2 Sub-technologies

According to the IEA, the topic 'Ocean energy' can be divided into the following sub-technologies (IEA, 2012):

- tidal barrage and tidal current energy
- wave energy (largest potential both in Europe and worldwide)
- salinity gradient (osmotic) energy and
- temperature gradient (thermal) energy.

***Tidal barrage and tidal current energy***

Tides are a result of the gravitational pull of both sun and moon on the world's oceans. Depending on the relative positions of the sun, the moon and the earth, the sea level rises and falls twice a day, leading to both horizontal and vertical movements of the seawater, containing a large amount of kinetic and potential energy. Different approaches for the generation of electricity are possible based on these two forms of energy (Frost & Sullivan, 2008).

To use the potential energy of the tidal range (difference in sea level between high and low tide), barrages can be built in estuaries or other suitable coastal sections with a large tidal range. With this method, a difference is created in the water level either side of the barrage. The water comes in through sluices with the high tide and is released back to the ocean in times of low tide (Department of Energy and Climate Change (DECC), 2010). As with conventional hydropower, the water drives a turbine to generate electricity (EOEA, 2010). One of the most famous examples for this kind of power generation is the La Rance barrage near Saint-Malo in northern France, which has been in operation since 1964. With a capacity of 240 MW it was the biggest tidal power plant until 2011, when the 254 MW Sihwa plant in South Korea was completed. There are smaller barrages (with capacities of less than 20 MW) in Canada, China and Russia (Daewoo E&C, 2009)

Compared to the construction of tidal barrages, using the kinetic energy of maritime currents is a newer form of power production (Blunden and Bahaj, 2006). The technology is comparable to wind power even though the construction has to be adapted to underwater conditions and the turbines are driven by water instead of air (DECC, 2010). According to Frost & Sullivan (2008), the most promising designs are reciprocating tidal stream devices, Venturi-effect devices and open hydro devices. The first commercial tidal current plant is named SeaGen and started electricity production in 2008 at Strangford Lough in Northern Ireland. It has a capacity of 1.2 MW and is able to supply electricity to 1,500 households (Sauter, 2011).

In general, using maritime currents is a very efficient way to generate electricity because of the specific properties of seawater: its density is more than 830 times higher than that of air, so that the energy of a 5 knot current is sufficient to deliver the same amount of energy as wind blowing with 350 km/h (Frost & Sullivan, 2010b). Moreover, unlike other renewable energy sources, tidal energy is very reliable and predictable far into the future, which has positive implications for the installation and maintenance of facilities. Due to its predictability, there are also fewer problems to integrating tidal-based energy production into an existing power grid (Denny, 2009; Frost & Sullivan, 2010b). Barriers to the implementation of tidal power plants are the high installation costs and their potential environmental impact: Several billions of dollars are required for the construction of a barrage, and further research is needed into the effect of barrages on the habitats of fish and bird populations (DECC, 2010; The Australian Institute of Energy, 1999).

### *Wave energy*

Waves are created as wind blows over the surface of the oceans due to differential heating of the earth by solar radiation (Thorpe, 1999). The energy content of the waves, which can reach 100 kW per metre of wave front, depends largely on the wind speed and the distance covered (Frost & Sullivan, 2010b).

Existing systems to produce energy from waves can be divided into the three categories (Frost & Sullivan, 2012b):

- Onshore devices. For onshore power generation, overtopping devices can be used, which are 'awashed' by waves and hold back the water. When the water is released back to the sea, it turns the blades of a turbine (Frost & Sullivan, 2012b). A further approach to extract wave energy onshore is the use of oscillating water column (OWC) devices. Seawater flows into a chamber through a sub-surface opening. The vertical movement of the water column caused by the waves, forces trapped air to stream through an opening where it drives a turbine (Thorpe, 1999).
- Near-shore devices. These devices are deployed in water depths of 20-25 metres, up to 500 metres away from the shore (EC, 2012c). Point absorbers consist of two connected floating elements moved relative to each other by the waves. The kinetic energy of the relative movement is then converted to electricity (Frost & Sullivan, 2008).
- Offshore devices. These are positioned in depths greater than 25 metres with the advantage that more powerful waves can be used than by onshore or near shore devices (EC, 2012c). Examples for offshore devices are attenuators: long structures consisting of several connected floating elements which are arranged parallel to the direction of the waves. The relative movement between the attenuators' different sections is then transformed into electrical power (Minerals Management Service, 2012; The European Marine Energy Centre Ltd, 2012).

Compared to tidal energy the installed capacity of wave power is still at a low level. In 2000 a 500 kW wave power station commenced working on the Scottish island of Islay. Other wave power plants are located in Spain and Israel with capacities of 300 kW and 40 kW respectively (SDE, 2012; Voith, 2012).

### *Salinity gradient (osmotic) energy*

Osmosis is the natural phenomenon of water molecules moving between two solutions with differing salt concentrations through a semi-permeable membrane due to a difference in chemical potential (Post et al., 2007). While water is able to pass the membrane, the salt ions are held back. With water flowing from the solution of low salt concentration to the one with the higher salt concentration, the volume of the latter increases, leading to a corresponding pressure increase if the volume is constrained.[19] In an osmotic power plant, freshwater and seawater are brought into contact through a semi-permeable membrane. The freshwater migrates through the membrane into the seawater where the pressure rises up to 27 bar (2.7 MPa). This pressurized water can be used for power production in a turbine (Aaberg, 2003; Skilhagen et al., 2007).

Suitable locations for osmotic energy are places that can provide a sufficient reservoir of seawater and freshwater, e.g. near estuaries (Post et al., 2007). The first (experimental) osmotic power plant was started in Norway in 2009 (Statkraft, 2012).

### *Temperature gradient (thermal) energy*

Using the ocean's natural thermal gradient for the production of electrical energy is commonly known as ocean thermal energy conversion (OTEC). The thermal gradient in this case is the temperature difference between the warm surface of the ocean and the cold sub-surface water (Frost & Sullivan, 2008).

In a closed-cycle OTEC, a low boiling working fluid, such as ammonia, is evaporated by the warm surface water in a heat exchanger. The ammonia vapour drives a turbine and electricity is generated. The vapour is re-condensed using cold water which is pumped up from the deep in intake pipes (Fujita et al., 2012).

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[19] The reverse process (reverse osmosis) is used for seawater desalination by applying pressure to the high-salt side of the semi-permeable membrane and driving the water to the low-salt side of the membrane against the osmotic pressure.

An open-cycle OTEC uses the surface water itself as a working fluid. The warm water is evaporated in a vacuum and the steam drives a turbine before it is condensed back to liquid in a heat exchanger by cold deep-ocean water (DiChristina, 1995).

The highest efficiencies of OTECs are reached when the thermal difference between the warm and the cold waters is at least 20°C, which limits their deployment to tropical areas. Moreover, high installation costs - due to the large pipes required – make OTEC technology uncompetitive compared to other renewable forms of energy production (Frost & Sullivan, 2008).

## A1.4 Co-generation or combined heat and power

### A1.4.1 Background

Modern fossil-fuel power plants have a maximum efficiency of around 50%, with the remainder of the energy being converted to 'waste' heat and lost through cooling circuits. Co-generation plants generate electricity and use the residual heat generated in the process for applications requiring steam or hot water, such as district heating. Consequently, the use of co-generation leads to a significant reduction in total fuel consumption. Co-generation of heat and power is a mature technology and various fuels and power generation methods can be used. Fossil, nuclear, waste and renewable fuels such as biomass can all be used to power CHP plants. In Europe, co-generation currently prevents the emission of around 200 million tonnes of $CO_2$ per year and there is potential for at least 25% of total electricity production to come from CHP (COGEN Europe website, knowledge centre, 2012). Cogeneration systems are at their most efficient when there is a need for hot water close to the power station. Efficiency is reduced when the waste heat must be transported over long distances.

### A1.4.2 Sub-technologies

Combined heat and power (CHP) generation is often used as an addition to existing power generation methods. The piping used to deliver the hot water to its destination does not require unusual alloys. However, smaller CHP systems may use other technologies such as fuel cells (dealt with in separate section), which include rare earth metals in their design.

The co-generation technologies which will be considered in this report are (EC, 2011c):
- combined heat and power plants
- combined cycle gas/steam turbine
- micro-combined heat and power.

***Combined heat and power plants***
Co-generation can be combined with a number of different existing power plants to increase their efficiency. Conventional power plants are typically only around 35-45% efficient, but using the waste heat for other applications, such as district heating systems, has the potential to increase efficiency to values of around 85% .

***Combined cycle gas/steam turbine***
Combined cycle power stations employ several power generating engines that work in tandem to produce electricity. The waste exhaust from one engine is used as the power source for the next engine, thus resulting in efficiencies of up to 60% (EC, 2011c). When these power stations are used for CHP, further efficiencies can be realised by using the final waste heat for district heating systems or other applications requiring heating such as greenhouses or swimming pools.

***Micro-combined heat and power***
Micro-CHP systems can be used for single family homes or small offices and are essentially small power plants that are used to provide both electricity and heating. Again, these systems are used to extract more energy from fuel than would be possible from the generation of electricity alone. A micro-CHP unit typically produces around 1 kW of electricity and may be powered using a gas engine or a Stirling engine.

Micro-CHP systems using fuel cells have also undergone trials and are considered to be close to commercialisation. Of these approaches, fuel cells have the potential to offer the greatest efficiencies, with an electrical efficiency of around 60% (EC, 2011c). In comparison, the electrical efficiency of Stirling engines is only around 10%. Micro-CHP also has the advantage to the user that surplus electricity may be sold to an electrical utility company.

## A1.5 Advanced fossil fuel power generation

### A1.5.1 Background

Europe relies on fossil fuels for the majority of its electricity generating capacity (53% in 2010), and fossil fuels will remain a major source of energy for the foreseeable future (EC, 2011c). As a consequence, it is essential to reduce $CO_2$ emissions from fossil fuel power plants: the two main ways of doing this are by using carbon capture and storage (CCS) and by increasing the efficiency of the power plant.

The majority of Europe's fossil fuel power plants are now over 20 years old and are not benefitting from the emission reductions through increased efficiency which the current best available technologies offer (RWE, 2008). However, retrofitting older power plants with new technologies, such as advanced boilers and turbines, allows increased efficiency and fuel flexibility as well as lowered emissions. It has been estimated that, for the same amount of power produced, 23.6% of $CO_2$ emissions could be saved by retrofitting sub-critical power plants with supercritical steam cycles or retiring old power plants and replacing them with new ones (EC, 2011c).

Technologies for electricity generation from fossil fuels can be categorised by the type of fuel used, the technology used for the conversion of the fuel's chemical energy to thermal energy, and the type of turbine used and the generated steam conditions. Pulverised coal combustion (PCC) is the main fossil fuel electricity generation technology, both worldwide and in the EU. However, the use of natural gas has become increasingly popular and in 2008 represented a 23% share of fuel used in power stations. The primary motive for switching to gas has been economic, and was a result of the low gas prices for much of the 1990s compared with coal.

### A1.5.2 Sub-technologies

The technologies which will be explored for advanced fossil fuel generation are listed below:

- ultra-supercritical and advanced ultra-supercritical PCC (USC and A-USC)
- combined cycle gas turbines (CCGT)
- integrated gasification combined cycle (IGCC)
- circulating fluidised bed combustion (CFB).

The current status of the technologies is summarised in Table A1.1.

***Ultra-supercritical and advanced ultra-supercritical PCC power plants***

From 2015 the output from subcritical pulverised coal combustion power plants will begin to subside, and consequently the role of supercritical and ultra-supercritical coal power plants will become significant (IEA, 2010b). Supercritical plants have been in commercial operation for decades and typically have steam conditions of 540°C and 25 MPa. More recently ultra-supercritical plants have been introduced; these operate at steam conditions of 600°C and 30 MPa. Currently, the most efficient pulverised coal power plant is NordJyllandsvæket in Denmark, which achieves efficiencies of up to 47%. However, the global share of power generation for ultra-supercritical steam plants is currently under 1% (IEA, 2011e).

The coming years will see the introduction of 700°C ultra-supercritical power plants, with efficiencies of over 50%. In order to achieve these efficiencies the use of stronger and more corrosion resistant steels will be required. To date there has been a range of demonstration projects with the aim of testing and developing Ni-based superalloys for use at the high temperatures, which these power plants will require.

*Table A1.1: Current status of technologies for advanced fossil fuel power generation*

| Technology | Status | Efficiency | Issues | Current installed capacity |
|---|---|---|---|---|
| Ultra-supercritical (USC) | Commercial | 43-47% | Requires major retrofit of existing power plants | >15 GWe (Europe) |
| Advanced ultra-supercritical (A-USC) | R&D – first test plant 2014 | Over 50% | Requires Ni-based superalloys | 0 |
| Combined cycle gas turbines (CCGT) | Commercial, well established technology | 55-61% | High capital costs | 160 GWe (Europe), (IEA, 2010c) |
| Integrated gasification combined cycle (IGCC) | Commercial demonstrations | 43-46% | High Capital costs, complex (Oliver, 2008) | 1 GWe (coal, Europe), (NEEDS, 2008) |
| Circulating fluidised bed (CFB) | Commercial | 41-43% | Flue gas carries a high dust load | 20 GW (Global) |

***Combined cycle gas power plants***

Combined cycle power plants have been the dominant technology for power generation from gas since the early 1990s. Currently, efficiencies of 52-60% can be achieved, however by 2020 it is expected to increase to around 64% with further improvements in turbine technology (IEA, 2010b). CCGT plants contain two turbines which both generate electricity. The first turbine is driven by combusting gas; the exhaust gases are used to produce steam which then rotates a second turbine to drive an electrical generator (IEA, 2010c). This process allows more useful energy to be extracted from heat which increases the overall efficiency and reduces fuel consumption.

***Integrated gasification combined cycle***

Integrated gasification combined cycle power plants operate on the same principles as CCGT plants but have added functionalities. As well as generating energy, the gasification process can also produce chemical products such as hydrogen and synthetic oil. An IGCC process can be divided into four steps: gasification, gas cleaning, power generation and air separation. IGCC plants use gasification to achieve efficiency improvements; the fossil fuel is combined with oxygen and steam to produce syngas. The syngas then passes through a gas cleaning process where air pollutants and particles are removed. The cleaned syngas passes through a combined power cycle and is converted into electricity. The gas then passes through an air separation unit and is re-used in the gasification process.

IGCC plants are not limited to gas; coal can also be used, provided that a gasification process is included. However, there are only six IGCC plants globally which are coal-based, of which two are in Europe (NEEDS, 2008). There are several barriers which need to be addressed before IGCC plants can be more widely deployed, most of which are economic. There is little certainty over operation and maintenance costs, and the capital costs are currently higher that other types of fossil fuel fired power stations.

***Circulating fluidised bed***

Fluidised bed combustion was developed in the 1980s as a method for controlling and reducing emissions from fossil fuel power stations. Fluidised bed combustion can be divided into atmospheric systems, pressurised systems, bubbling and circulating fluidised bed (CFB). Fluidised bed firing is best suited for biomass fuels and plants which require fuel flexibility. CFB technology provides a unique ability to burn in a given boiler a large range of fuels, including difficult fuels such as biomass. During the combustion process solid fuels are suspended in upward air jets, allowing for lower combustion temperatures and consequently lower $NO_X$ emissions and more effective heat transfer. Total global CFB capacity is currently at around 20 GW; however, this has been steadily growing over the past decade (IEA, 2011e).

## A1.6 Fuel cells and hydrogen

### A1.6.1 Background

Fuel cells are devices which use electrochemical processes to generate electricity from various feedstocks, typically with water and heat as the only by-products. The most commonly used feedstock for fuel cells is hydrogen gas. Fuel cells operating on hydrogen emit zero emissions at source and are very efficient. Hydrogen is a non-toxic gas, which can be produced from a range of feedstocks including natural gas, coal, water and biogas. In the transport and energy sectors it can be used as a fuel, as energy storage and in conjunction with fuel cells. Fuel cell technologies are beginning to progress from R&D programmes to commercial activity. For example, the HyFLEET:CUTE project has already demonstrated the feasibility of fuel cell buses in nine European cities (HyFLEET:CUTE, 2009). The fuel cell and hydrogen applications under consideration are: transport including re-fuelling infrastructure, hydrogen storage and production, and stationary fuel cells.

A generic fuel cell consists of a layered structure composed of a cathode and an anode between which are sandwiched a cathode catalyst layer, an electrolyte layer and an anode catalyst layer. The reactants are transported by diffusion and/or convection along channels in the cathode and anode to the catalyst layer. Here electrochemical reactions take place, which - in the case of hydrogen as fuel - separate the hydrogen nucleus from its electron, leaving a proton and an electron. The positively charged protons are then drawn across the electrolyte from the anode layer to the cathode layer where they combine with oxygen to form water. The free electrons, however, are drawn from the anode to the cathode through an external circuit, resulting in direct current (DC) electricity.

Since each individual fuel cell generates less than 1 V it is necessary to arrange fuel cells in stacks to produce higher voltages. To achieve the voltages necessary for automotive purposes, as many as 200 fuel cells may be arranged into a single stack. Fuel cells are generally classified by the kind of electrolyte they employ, but they can also be divided into those that operate at high temperatures and those that operate at low temperatures. In low temperature fuel cells, to increase chemical reaction rates, noble metal catalysts are employed; principally platinum, which is one of the metals of interest to this study.

### A1.6.2 Sub-technologies

The sub-technologies which will be explored for this area include different types of fuel cells spanning transport and stationary applications, as well as hydrogen production and storage (EC, 2011c):

- solid oxide fuel cells (SOFC)
- polymer electrolyte membrane fuel cells (PEMFC)
- molten carbonate fuel cells (MCFC)
- direct methanol fuel cells (DMFC)
- alkaline fuel cells (AFC)
- phosphoric acid fuel cells (PAFC)
- hydrogen production
- hydrogen storage
- refuelling infrastructure

***Solid oxide fuel cells***

In solid oxide fuel cells (SOFC) the term solid oxide refers to the electrolyte material used, which is typically made of zirconium oxide stabilised with yttria. The fuel cells belong to the group that operates at high temperatures, in this instance between 500˚C and 1,000˚C (EC, 2011c). The high temperatures used in SOFCs promote increased reaction rates, which negate the need for noble metal catalysts such as platinum. SOFCs can use natural gas, propane or liquid petroleum gas as their fuel, increasing the flexibility of their use. They have a range of possible applications in power units for automotive vehicles, stationary power generators and combined heat and power units.

### *Polymer electrolyte membrane fuel cells*

PEMFCs, also known as proton exchange membrane fuel cells, have the distinguishing characteristic of an electrolyte layer made of a polymer membrane, most commonly Nafion, which is made by DuPont. They operate at temperatures below 100˚C and consequently require noble metal catalysts to accelerate electrochemical reactions. Platinum is most commonly used, and is required for both the anode and cathode catalysts.

### *Molten carbonate fuel cells*

As their name implies, molten carbonate fuel cells (MCFC) operate at high temperatures; between 600˚C and 700˚C. They can be fuelled with coal-derived fuel gas, methane or natural gas. The molten carbonate is generally either a combination of lithium carbonate with potassium carbonate, or lithium carbonate with sodium carbonate. When molten, these carbonates are highly corrosive and so MCFCs face technical difficulties providing a working lifetime of 40,000 hours (EC, 2011c). The anode is typically made of a low surface area porous nickel doped with chromium; the cathode may be made of lithiated nickel oxide. Since these fuel cells operate at high temperature, there is no requirement for noble metal catalysts.

### Direct methanol fuel cells

The design of a direct methanol fuel cell (DMFC) is similar to that of a PEMFC except that the fuel is a liquid solution of methanol and water, rather than hydrogen gas. DMFCs operate at low temperature and so have catalysts made of platinum. The anode catalyst often also includes ruthenium, which belongs to the platinum group metals and is of interest to this study.

### *Alkaline fuel cells*

Alkaline fuel cells (AFCs) have been in use since the 1960s when they served as auxiliary power units on the Apollo missions and later on the space shuttle. These fuel cells use an alkaline electrolyte such as potassium hydroxide (KOH) in water. Hydrogen oxidation in these fuel cells occurs at the anode, rather than at the cathode as occurs in PEFC fuel cells.

### *Phosphoric acid fuel cells*

As its name suggests, the electrolyte used in PAFCs is phosphoric acid. They are used for stationary and residential power applications and have also been used in buses, but their automotive application has largely been superseded by lighter PEMFCs. A PAFC - the PC25 developed by ONSI - was the first commercially available fuel cell for stationary applications and was introduced in 1992. Such fuel cells' power units are more expensive per kW than other sources of power generation, but they have applications where low noise level operation is essential. PAFCs operate at temperatures between 160˚C and 210˚C but still require the use of platinum as their catalysts, and may also employ chromium, vanadium or cobalt (EC, 2011c).

### *Hydrogen storage*

Hydrogen storage covers many different technological approaches appropriate to different applications. For light duty vehicles using hydrogen fuel cells, between 5 kg and 13 kg of hydrogen are needed to achieve a driving range of around 480 km. To fulfil this requirement, hydrogen can be stored either in cryogenic liquid hydrogen tanks or in compressed gas tanks, both of which require energy to achieve these states from the gaseous state. Liquid hydrogen tanks can store more hydrogen than compression tanks for the same volume. However, large amounts of energy - approximately 30% of the heating value of hydrogen - are required for hydrogen liquefaction (EC, 2011c). Additionally, hydrogen may be lost as a consequence of boil off, so storage methods must employ efficient insulation to minimise this effect.

Compression tanks have been certified that contain hydrogen at pressures 350 (35) and 700 (70) bar (MPa), which requires materials and design that can safely hold hydrogen at these pressures (EC, 2011c). Currently under development are hydrogen tanks that use carbon-fibre as a reinforcement. Such tanks have an inner liner made of a high molecular weight polymer, a second layer made of a carbon fibre / epoxy resin composite shell, and an outer shell to protect against impact.

Hydrogen may also be stored in a number of chemical forms including as metal hydrides or carbohydrates, in ammonia and in methanol. Portable fuel cells that use metal hydride refillable storage cartridges are already commercially available. For non-mobile purposes, hydrogen can be stored in caverns, depleted oil and gas fields, or in salt domes - in either liquid or gaseous form. Hydrogen can also be transported along networks of pipelines.

***Hydrogen production and refuelling infrastructure***

The production of hydrogen and the infrastructure necessary for a hydrogen economy were examined but detailed information on scenarios, technology requirements and material requirements was not found. However, in the case of an infrastructure using pipelines available data suggests that such pipelines are unlikely to operate under high pressure and so will not require unusual alloys.

## A1.7 Electricity storage in the power sector

### A1.7.1 Background

Balancing supply and demand of electricity at all times is a key goal of electricity systems. With conventional (largely fossil fuel-based) energy generation, this is generally done by adjusting the energy supply (i.e. increasing or reducing the power delivered by one or more power plants). This balancing act becomes more difficult with a more extensive uptake of renewable energy sources, leading to an increased need for the extensive deployment of reliable energy storage technologies to help achieve this balance[20].

There is a variety of energy storage technologies currently available which, in principle, allows the foreseeable needs for energy storage to be satisfied. However, there is no single universal solution to energy storage. Furthermore, the storage of energy is generally done indirectly and is thus tied to a transformative energy loss (e.g. from electrical to thermal and chemical energy) which reduces the overall efficiency in the supply of electrical energy (Oertel, 2008; Wietschel et al., 2010; EC, 2011c).

### A1.7.2 Sub-technologies

The different stationary energy storage sub-technologies may be grouped into four types according to their function (Oertel, 2008):

- mechanical storage – in the form of kinetic or potential energy; this includes compressed air energy storage, hydro-pump storage, flywheels
- chemical storage – including hydrogen storage and batteries in all their forms (conventional, advanced, and flow batteries)
- electrical or electromagnetic storage – including super-capacitors and superconducting coils
- thermal storage – used mostly for storing heat but with certain applications for the electricity sector, e.g. in solar thermal power plant (molten salt).

In addition, there is the possibility of virtual energy storage: in this case it is the energy demand which is controlled rather than the supply. Virtual energy storage will not be considered in this work.

Currently only pumped hydro is able to provide grid storage at competitive costs, although compressed air storage has also been demonstrated for this purpose. None of the other storage technologies are widely applied for grid scale storage apart from some demonstrators but rather to ensure power quality or stabilise distribution grids. Also, it is not yet clear what needs for storage will actually emerge from renewables deployment as storage is just one of several options to integrate renewable energy systems.

Of the technology groups listed above, the raw material content of individual technologies will be considered in as much as they (a) have direct relevance to the power sector, and (b) have a credible potential for extensive deployment in the short to medium term.

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[20] Other possible measures are demand side management, enhanced interconnection, flexible generation and curtailment of regenerative energy production.

## Mechanical storage

### *Pumped storage hydropower station*

Pumped storage hydropower stations are hydropower stations equipped to pump water from the low level into the high level reservoir (potential energy) using surplus energy. The overall efficiency of pumped storage hydropower station is around 70-80% (Oertel, 2008). A more complete description of PHES is given in Section A1.1.

### *Compressed air energy storage (CAES)*

In CAES systems, electricity is used to compress air and store it under pressure. The energy is recovered when the air is allowed to expand again, thereby driving a turbine. As compression of the air leads to a temperature increase, the air must be cooled during this step to prevent damage to the reservoir. The reverse process, expansion of compressed air, leads to a temperature drop which is compensated by burning natural gas with the compressed air to prevent icing of the turbine blades. The efficiency of CAES is, therefore, comparatively low at around 50-55% (Oertel, 2008).

The type of facility used to store the compressed air depends on the desired amount of energy stored. Underground storage is preferred for power plants with storage capacities above 100 MWh or five hours of storage. Therefore, such CAES facilities can only be built at sites exhibiting the required geological formations or which can be suitably prepared (e.g. salt caverns created by solution or dry mining, abandoned hard-rock mines, purpose-built hard-rock caverns, and naturally occurring porous rock formations from porous rock aquifers or depleted gas or oilfields).[21] Storage above ground in gas pipes or pressure vessels is generally practical and economical for storage capacities below five hours (EPRI, US Department of Energy (DOE), 2003).

Currently, there are two CAES facilities operating, one in Germany (290 MWe) and one in the USA (110 MWe). Efficiency improvements are expected by storing heat from the compression step and using this - instead of burning natural gas - in the expansion step. This process, termed advanced adiabatic CAES (AA-CAES) is expected to reach an efficiency of around 70%. A demonstration plant is planned in Germany but will not be ready before 2016 at the earliest (RWE Power, 2010).

CAES has several notable advantages (EPRI, US DOE, 2003):

- it is a proven technology (e.g. the CAES plants in Germany and USA)
- it can provide significant energy storage, flexibility and load management at relatively low cost
- it is capable of ‘black start’
- CAES facilities come on-line very fast (normally 10-12 min; 5 min in emergencies)
- CAES facilities are more efficient at part load than oil, gas and coal power plants.

Despite these advantages and immense potential, there are only two commercial-scale facilities operating today, although these have now been operating for a number of years now. Given that these two installations are still successfully working is a strong sign that this technology may be seen as proven though not widely implemented. Relevant new information will only come from new installations possibly working under different conditions which may lead to a more differentiated experience. Some planned facilities have been delayed or abandoned (FirstEnergy, 2011; The Iowa Stored Energy Park, 2011).

### *Flywheels*

Flywheels store energy in the form of kinetic (rotational) energy. Electricity is used to drive an electric motor/generator which accelerates a mass (rotor). To retrieve the energy, the motor/generator is driven by the rotor to produce electricity, decelerating the rotor (Frost & Sullivan, 2011b). Therefore it is necessary to match the decreasing speed of the flywheel during discharge and the acceleration when recharged with a fixed frequency electrical system (EPRI, US DOE, 2003). Over short time frames, storing

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[21] Suitable sites are dependent on the local geology but not necessarily scarce. For example, 80% of the US territory has suitable CAES sites (EPRI, US Department of Energy, 2003).

and recovering energy in flywheels can reach an efficiency of 90-95%; however, the stand-by losses are large and amount to up to 20% per hour. To reduce frictional losses, mechanical or magnetic bearings are used and the rotating mass is placed within an evacuated enclosure. The enclosure also serves a safety purpose, namely to contain the rotor in case of an accident (Oertel, 2008; Wietschel et al., 2010; Flint, 2011).

The amount of energy stored in a rotating body depends on both the mass of the body and on the speed at which it is rotating. Therefore, two possibilities exist for constructing flywheels with large storage capacities: using heavier rotors or having the rotors rotate at a higher velocity. The first strategy leads to systems generally rotating at 1,000-7,000 rpm (low-speed flywheels). Low-speed flywheel systems are usually designed for high-power output. The second strategy leads to high-speed flywheels: systems with lighter rotors spinning with velocities typically between 25,000 rpm and 36,000 rpm, in which either power output or energy storage can be maximized (EPRI, US DOE, 2003; Frost & Sullivan, 2008). Intermediate rotational speeds are also possible (e.g. 8,000-16,000 rpm; Beacon Power, 2012).

Due to the underlying physics, increasing rotational speed is a more effective way to increasing storage capacity. In practice, this is limited by the maximum rotational stress that the rotor material can withstand (EPRI, US DOE, 2003).

A key role of flywheels in the power sector is expected to be the rapid reaction to grid imbalances (frequency regulation), thus increasing grid reliability and electric energy quality (Wietschel et al., 2010; Frost & Sullivan, 2011b). Flywheels are compact, have a very low environmental impact, their energy storage capacity does not degrade over time, can operate in a wide temperature range, exhibit very fast response times both for charging and discharging, and have a high cycle and calendar life (EPRI, US DOE, 2003; Frost & Sullivan, 2009a). The first grid scale flywheel storage facility with 20 MW / 5 MWh capacity and around 85% round-trip efficiency was commissioned in 2011 (Lazarewicz and Judson, 2011).

### Chemical and electrochemical storage

#### *Hydrogen*

Energy storage in chemical bonds is a key component of life in our planet: Through photosynthesis, plants capture energy in the form of light and store it in chemical bonds by reducing $CO_2$. The same idea may be used to store excess electrical energy in the form of hydrogen (produced through the electrolysis of water) to be used later to generate electricity again (see Section A1.6). However, the efficiency of this process is low, at around 30-40% for a round trip (Friedrich, 2012; Scholz and Heide, 2012).

There is substantial experience in the operation of hydrogen storage caves: the facility in Teeside (UK) with a capacity of 25 GWh (4.5 MPa) has been in operation for around 30 years, and the facilities in Lake Jackson (Texas, USA; 7.0-13.5 MPa; operating since 1986) and Liberty County (Texas, USA; 7.6-13.4 MPa; operating since 2007) hold a combined 192 GWh. In addition to in caves, $H_2$ may be stored in and distributed through the natural gas distribution network (Friedrich, 2012).

#### *Lead-acid batteries*

Lead–acid batteries, invented in 1859 by the French physicist Gaston Planté, are the oldest type of rechargeable battery. In comparison with newer battery concepts such as lithium-ion batteries, lead-acid batteries have a low energy-to-weight ratio and energy-to-volume ratio. However, their ability to supply high surge currents means that the cells maintain a relatively large power-to-weight ratio. Also because of their low cost, they are optimised to be used in motor vehicles to provide the high current required by automobile starter motors (Oertel, 2008; Wietschel et al., 2010). In addition, lead-acid batteries are currently the chemistry of choice to provide reliable, robust, and cost-efficient stand-by energy storage (backup power and power quality) for applications such as uninterruptible power supply, telecommunications and broadcasting, emergency lighting, security and signalling systems, oil and gas exploration, and renewable energy integration (Frost & Sullivan, 2011c).

As indicated by the name, lead and acid are two key components in a lead-acid battery. Energy is stored by reducing Pb(II) ions to metallic lead at the negative electrode, at the same time oxidising Pb(II) ions to Pb(IV) ions at the positive electrode in an acidic electrolyte (dilute sulphuric acid). Energy is retrieved by allowing metallic lead to be oxidised to Pb(II) ions at the negative electrode while reducing Pb(IV) ions to Pb(II) ions at the positive electrode (the same process as above but in the opposite direction). The relevant equations are (Berndt and Spahrbier, 2001):

$$\mathrm{Pb(II)SO_4 + 2H^+ + 2e^- \leftrightarrow Pb(0) + H_2SO_4} \text{ (negative electrode)}$$

$$\mathrm{2Pb(II)SO_4 + 2H_2O \leftrightarrow Pb(IV)O_2 + H_2SO_4 + 2H^+ + 2e^-} \text{ (positive electrode)}$$

The reactions proceed from left to right while charging, and from right to left while discharging. Based on this chemistry, there are a large number of different designs of lead-acid batteries (materials, geometry and production of the electrodes) that have been optimised for different purposes.

***Nickel-cadmium (NiCd) batteries***

NiCd batteries have traditionally been the alternative to lead-acid batteries. NiCd batteries show good low-temperature performance, suffer only little corrosion, and can be sealed completely so that the electrolyte cannot be spilled and gases and fumes do not escape from the battery. This combination of advantages enabled NiCd batteries to gain significant importance in cordless power supply and for electric or electronic devices (Berndt and Spahrbier, 2001). However, due to operational and especially environmental issues related to cadmium, the industry is gradually moving away from NiCd batteries, particularly for portable applications.

For energy storage, one plant operates worldwide (Fairbanks, Alaska, USA) with NiCd batteries, providing 27 MW of electricity for 15 minutes (DeVries et al., 2004). The main purpose of this plant is grid stabilization (Frost & Sullivan 2011c).

***Redox-flow batteries***

Redox-flow batteries are electrochemical electricity storage devices in which the energy-containing materials are stored outside the reaction cell in two separate storage tanks. The electrochemical reactions take place within a cell - referred to as the ‘stack’ - consisting of two half-cells with graphite electrodes. The two half cells are separated by a membrane permeable to protons ($H^+$). The purpose of the membrane is to prevent the mixing of the electrolyte, although in practice this goal is not achieved completely. The positive (catolyte) and the negative electrolyte (anolyte) are pumped through the respective half-cells (on either side of the membrane) and react at the electrodes, consuming and generating electrons (Angerer et al., 2009).

Different electrolyte systems are used in redox-flow batteries, with the vanadium (V) system being the most technically mature. The chemistry of the V system is given by (Berndt and Spahrbier, 2001):

$$\mathrm{VO_2^+ + 2H^+ + e^- \leftrightarrow VO^{2+} + H_2O} \text{ (cathode)}$$

$$\mathrm{V^{2+} \leftrightarrow V^{3+} + e^-} \text{ (anode)}$$

The reactions proceed from left to right during charging and from right to left during discharging. Other systems are the vanadium bromide and the zinc bromide redox-flow battery (Angerer et al., 2009).

The performance of a redox-flow battery is determined by the size of the stack and the size (energy content) of the storage tanks for the electrolyte (Angerer et al., 2009). A key advantage of redox-flow systems is that the electrode reactions do not involve solid phase changes or precipitation mechanisms. As a consequence, a large number of cycles can be reached, and deep discharges are not critical (Berndt and Spahrbier, 2001). In addition, because the energy is stored separately, the power output and energy storage capacity are variable independently. The most striking disadvantages of these systems are the comparatively low values of specific energy (Wh/kg) and energy density (Wh/L). They are caused by the low concentration of the reacting species on account of limited solubility. The specific power (W/kg) is limited for the same reason (Berndt and Spahrbier, 2001).

Redox-flow plants are used for 'peak shaving', for the storage of excess power from wind turbines and for uninterruptible power supply. The plants are small, with systems ranging from 200 kW to 1.5 MW and capacitances from 800 kWh to 12 MWh. However, because of their modular nature, individual batteries may be combined into larger facilities (e.g. 10 MW; Prudent Energy, 2011).

### *Lithium-ion battery*

The battery system which currently best meets automotive requirements is the lithium-ion cell (Thielmann et al., 2010). Lithium-ion batteries may also be used for a range of applications in distributed energy generation (e.g. small scale integration of renewable energy, for frequency regulation and grid support; (Frost & Sullivan, 2011b). One example of this is the on-going Sol-Ion project, which provides electricity storage for decentralised on-grid, residential solar photovoltaic systems.

In lithium-ion batteries, the positive electrode (cathode) is made of a metal oxide in which lithium ions can be stored reversibly. For the negative electrode (anode) graphite is used, which can also store lithium ions. Six carbon atoms can be incorporated per lithium atom ($LiC_6$) (Angerer et al., 2009). When discharging, the graphite releases lithium ions, which then migrate through a water-free lithium-conducting organic electrolyte to the positive electrode, where they are stored reversibly in the lattice of the metal oxide. The process is reversed when the battery is charged. At each charging and discharging process, 50-90% of the lithium is exchanged, depending on the cathode (ICT, 2007; Döring, 2008).

Depending on the required capacity or current strength, different metal oxides can be used. For high capacity, cobalt cathodes in the form of $LiCoO_2$ are preferred. Manganese ($LiMn_2O_4$) and iron phosphate ($LiFePO_4$) cathodes can achieve high operating currents. R&D is ongoing with nickel oxides and mixtures of different metal oxides containing cobalt, manganese and nickel. The performance of lithium-ion systems is not yet exhausted, and research and technology development is still strong; which system will prevail is not yet foreseeable. The cobalt system has higher energy density, but cobalt cells have a large internal resistance and the charge current must be limited in order to avoid excessive heat development which would lead to cell destruction. The manganese and phosphate systems have a lower internal resistance, but a lower energy density (Angerer et al., 2009).

## Chemical and electrochemical storage

### *Double-layer capacitors*[22]

Capacitors are able to store electrical energy directly in the form of an electric field. In conventional capacitors, this is achieved across two parallel plates separated by a dielectric material. However, the low energy density of conventional capacitors makes them uneconomic for stationary power storage applications (Chen et al., 2009). Supercapacitors store energy in the form of an electric field between two opposing surfaces separated by a liquid electrolyte (instead of a dielectric material). The electrodes are made of a porous material leading to very high surface areas (e.g. up to 2,000 $m^2/g$ for activated carbon) and the electrodes can be placed very close to each other (< 1 nm) leading to very high capacitances and stored energy (around 100 times larger than conventional capacitors), (EPRI, US DOE, 2003).

Double-layer capacitors can withstand a very large number of charge/discharge cycles with high efficiency (around 95%). Though stand-by losses are lower than for flywheels, they are much higher than for batteries, reaching 15% after one week and 23% after four weeks – also depending on the charge state and quality of the capacitor. In practice, however, double-layer capacitors are mainly used for power quality applications (e.g. 1 MW, 0.0023 MWh in Cologne/Germany) with storage times ranging from seconds to minutes. Although it is possible to modularly extend the capacity of capacitor-based storage, they are generally not suitable for storing large amounts of energy (Wietschel et al., 2010).

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[22] Also called electric double-layer capacitors, supercapacitors, supercaps, ultracapacitors, ultracaps.

### *Superconducting magnetic energy storage (SMES)*

Superconducting coils make it possible to store electrical energy in the form of an indefinitely circulating current. This has the advantage that no conversion losses other than AC-DC power conversion are present and, due to the superconductive properties of the coils, essentially no stand-by losses occur. This leads to very high storage efficiencies (around 97%). In practice, superconductivity only occurs at low temperatures such that the unit requires external cooling typically using liquid helium (4.2 K). This cooling requirement is essentially a stand-by loss. This loss becomes smaller the larger the SMES unit is because of the lower surface-to-volume ratio results in reduced specific cooling requirements (EPRI, US DOE, 2003; Chen et al., 2009; Wietschel et al., 2010).

The response times of superconducting coils are of the order of a few milliseconds, and their high efficiency for short-term storage makes them suitable for power quality applications. The typical rating for superconducting coil units is in the range of 1-10 MW, with storage times of seconds. Over 100 MW of SMES units were reported to be in operation by 2009 worldwide after rapid introduction through several companies. On-going research aims to extend the specifications of SMES units to the range of 10-100 MW and storage times of minutes (Chen et al., 2009).

## Thermal storage

Thermal energy storage (TES) in the electricity sector is mainly relevant for solar thermal power plants which should be able to produce electricity even when the sun is not shining. Therefore, it is necessary to store some of the solar energy collected during the day and convert it into electricity at night (Gil et al., 2010). There are several ways to classify the diverse TES technologies, such as by temperature, duration of storage, state of aggregation or thermodynamic processes (in.RET Institut für Regenerative Energietechnik, 2009). In this report, the three thermodynamic categories ‘sensible load’, ‘latent load’ and ‘bond energy’ are used.

### *Sensible heat storage (SHS)*

SHS systems are characterised by their temperature change; for electricity generation, high temperature thermal storage (HTTS) is particularly relevant. SHS consists of a solid or liquid medium which is heated by an energy source (e.g. solar radiation). As the temperature of the medium is increased it leads to a temperature difference (ΔT) to the surroundings. This ΔT can later be used to generate electricity, for example by vaporising water in a heat exchanger to turn a turbine (Ibrahim et al., 2008). Another characteristic of SHS is that there is no phase change in the utilized medium. The amount of energy that can be stored depends on the specific thermal capacity of the material, on its mass and on the temperature difference ΔT (in.RET Institut für Regenerative Energietechnik, 2009).

Liquid media for thermal energy storage are molten salt, mineral and synthetic oils (Gil et al., 2010). Salt - consisting mostly of a mixture of sodium nitrate and potassium nitrate - is used in solar power plants as well as in the chemical and metals industry for heat transfer purposes, due to its favourable thermophysical properties. Moreover, salt has the advantageous characteristics of being non-flammable, non-toxic, inexpensive and relatively efficient (Frost & Sullivan, 2011b). To store solar energy it is heated up to temperatures of several hundred degrees Celsius and then stored in insulated tanks (Fernandes et al., 2012). As well as from liquid storage, there are several solid storage media available ranging from rocks and pebbles to concrete, ceramics and different kinds of salt (Frost & Sullivan, 2011b; Fernandes et al., 2012). The use of concrete blocks as thermal storage devices is a particular focus of further research; its advantage over molten salt storage technologies include lower costs as a carrier medium and its insensitivity towards low temperatures (Deutsches Zentrum für Luft- und Raumfahrt e.V., 2012).

The growth potential for SHS in the context of solar electricity production is expected to be high, especially in Mediterranean countries such as Spain and Italy. There, early power plants are already using molten salt-based SHS for solar energy storage (Frost & Sullivan, 2011d).

### *Latent heat storage*

The underlying principle of latent heat storage is the absorption or release of energy at nearly constant temperatures during the phase change (e.g. from solid to liquid) of a storage medium (Fernandes et al., 2012). This is familiar from hand warmers for outdoor applications, which function in the same way although on a much smaller scale (Tamme et al., 2006).

For latent heat storage processes suitable materials, called phase change materials (PCMs), are needed. According to (Sharma et al., 2009) there are different kinds of PCMs available, including paraffin compounds, salt hydrates and metallics. There are also eutectic PCMs, which consist of a mix of two or more components. Both solid/liquid and liquid/vapour transitions can be exploited to charge and discharge the phase change materials, though solid/liquid systems are the most common (Oertel, 2008; Gil et al., 2010). Compared to the more conventional SHS, latent heat storage has the advantage that large amounts of energy can be stored in a small temperature range inside relatively compact containers (Tamme et al., 2005; Frost & Sullivan, 2011b). Furthermore, the prices for phase change materials are moderate and their availability is ‘non-critical’ (Fernandes et al., 2012), so that the main problems of latent heat storage are caused by insufficient heat transfer between the working fluid and storage materials (Tamme et al., 2005).

***Thermo-chemical storage***

Thermo-chemical energy storage, in which the energy is reactively bound as internal chemical energy, has the highest theoretical energy density of all thermal storage possibilities. Its basis is the use of two different substances that interact with each other. In a first step heat is used to excite a reversible endothermic chemical reaction. Later, the energy used for this procedure can be recovered by the corresponding exothermic reaction (Gil et al., 2010). Materials of particular interest for thermal energy storage are SOx/Sn and ammonia systems as well as zeolite and silica gel (in.RET Institut für Regenerative Energietechnik, 2009; Fernandes et al., 2012).

In general, thermo-chemical processes are a very effective way to store energy in the form of heat due to the high energy densities and the long storage duration at ambient temperature. Nevertheless, this technology is still at an early stage of development (Gil et al., 2010). It seems that there is a large potential for future use, but high costs remain a barrier to commercial deployment (Fernandes et al., 2012): currently, only pilot plants for experimental research are in operation (in.RET Institut für Regenerative Energietechnik, 2009).

## A1.8 Energy-intensive industries

### A1.8.1 Background

The EU is aiming for a 20% cut in Europe's annual primary energy consumption by 2020. In 2010, 25% (292 Mtoe) of final energy consumption in the EU-27 was by industrial users (EC Eurostat, 2012). The work of the EU Technology Map to energy efficiency and $CO_2$ reduction in industry to date has focused specifically on three energy-intensive industries:

- cement
- iron and steel
- pulp and paper.

These industries accounted for almost 43% of the final energy consumption within industry for the EU-27 in 2010 (Figure A1.1). Note that cement is included within non-metallic minerals. It is these three industries that are covered within this project.

### A1.8.2 Sub-technologies

For the cement industry, the main sub-technologies identified include:

- decrease of the proportion of clinker in cement
- use of alternative fuels

- site-specific energy efficiency measures
- deployment of CCS (covered in Section A1.5)
- fluidised bed technologies.

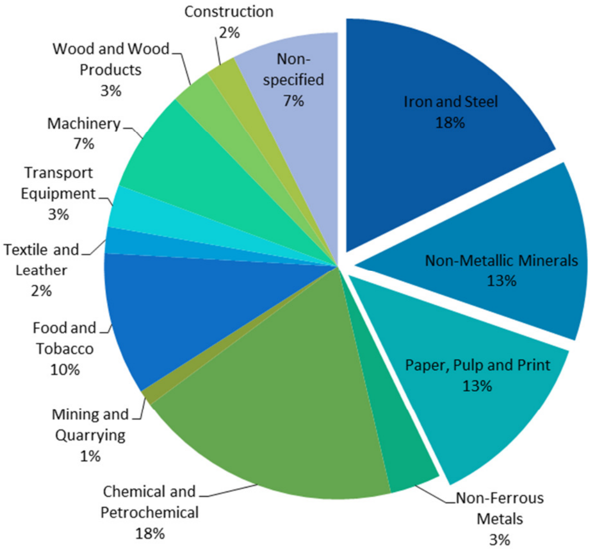
For the iron and steel industry, the main sub-technologies identified include:

- integrated production – dissemination of BAT
- electric arc furnaces
- direct-reduced iron
- smelting reduction
- ultra-low $CO_2$ steelmaking (ULCOS):
  - top gas recycling blast furnace
  - Hlsarna technology
  - ULCORED (advanced direct reduction with CCS)
  - ULCOWIN and ULCOSYS (electrolysis).

For the pulp and paper industry, the main sub-technologies identified include:

- CHP generation (covered in Section A1.4)
- use of recycled fibres in integrated paper production
- bio-route: integrated bio-refinery complexes
- innovative drying technologies
- mechanical pulping optimisation.

*Figure A1.1: Final energy consumption in the EU-27 by industry, 2010 (ktoe)*



*Source: EC Eurostat, 2012*

Scenarios for the implementation of these technologies will be developed in accordance with industry experts, the relevant trade associations (Cembureau, Eurofer and CEPI respectively) and other stakeholders as appropriate. Two comments are of note for these sub-technologies:

1. Research for several is at an early stage: e.g. fluidised bed technologies (cement), ULCOS (iron and steel) and bio-route (pulp and paper).
2. The role of critical metals may be limited; e.g. in the use of alternative materials or fuels.

## A1.9 Energy efficiency in buildings

### A1.9.1 Background

Energy consumption in buildings (residential and services) accounted for 40% of the EU-27 total final energy consumption in 2010 (Figure A1.2). Within this, approximately two thirds of energy consumption is used for space conditioning (temperature and ventilation) and one third for installations and appliances (EC, 2011c). Three main areas determine the energy performance of buildings (of which the first two are of most relevance for this project):

1. building energy needs (savings)
2. building systems energy (efficiency)
3. occupancy energy consumption (behavioural).

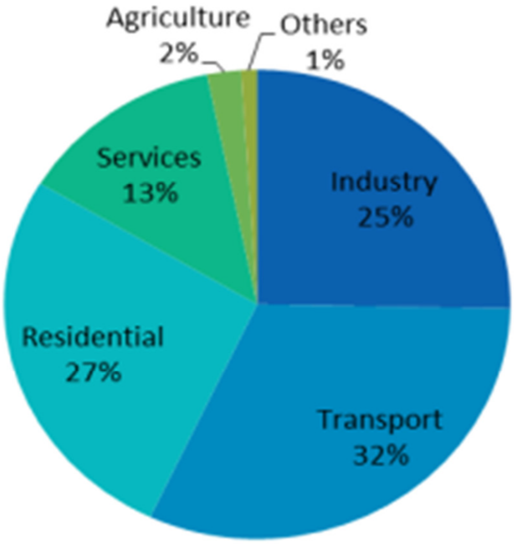
### A1.9.2 Sub-technologies

There are numerous sub-technologies that could be considered, including:

- high-efficiency boilers & efficient heat exchange ventilation
- insulation materials: walls, roof, floor, windows
- solar thermal & aero-thermal energy (geothermal energy is covered in Section 2.3)
- lighting: phosphors, LEDs, halogen etc.
- energy efficient appliances
- smart meters.

Further details on each of these are described in Section 3.10.

*Figure A1.2: Final energy consumption in the EU-27 by sector, 2010 (ktoe)*



*Source: EC Eurostat, 2012*

Scenarios for the implementation of these technologies will be developed in accordance with industry experts, the relevant trade associations and other stakeholders as appropriate. Two comments are of note for these sub-technologies:

1. The role of critical metals may be limited; e.g. in building insulation.
2. Critical metals may not be the enabling factor for the technology. For example, electrical appliances may use various metals in the electronics or circuit boards, but their use does not specifically contribute towards energy efficiency. Where this is the case, the sector study will make note of these metals.

3. Many scenarios exist which model the consumption of energy within the residential and services sectors; however, most do not give a breakdown of the contribution of the different sub-technologies for energy efficiency.

## A1.10 Road transport efficiency

### A1.10.1 Background

In Europe, road transport accounts for over 70% of transport-related emissions, and passenger cars contribute approximately 60% to this total (EC, 2011d). With both passenger transport and freight haulage set to increase significantly over the coming years, there is a need for new technologies which reduce $CO_2$ emissions (EC, 2011d). At present, internal combustion engines (ICEs) are the drive train of choice for road vehicles in Europe. The use of fuel additives and advanced catalytic converters, light-weighting of components and advanced engine designs all offer opportunities for improved efficiency of ICEs. However, their efficiency cannot match that of electric motors; this has been proved by well-to-wheel analyses over a broad range of primary energy sources (McKinsey, 2010).

A combination of electric vehicles (EVs) and more efficient ICEs will be needed to ensure that Europe meets its targets for reductions in vehicle $CO_2$ emissions. The motor industry is investing heavily in both these areas, with an ever-increasing number of EVs being launched and fuel efficiency technologies such as direct injection petrol engines and stop-start mechanisms being introduced on a wider range of models. EVs have yet to penetrate the European market, and market share remains low compared to that in Japan and the US where EVs are more prevalent. Battery electric vehicles (BEVs) are limited by the energy density of their batteries, as this determines the distance they can travel between charging. Weight, size and cost are other limitations which new battery technologies must overcome. In the medium to long term, fuel cell and hydrogen vehicles are likely to achieve a significant market share; these technologies are reviewed separately in Section 2.7, but they will be included in the passenger vehicle mix where relevant.

### A1.10.2 Sub-technologies

***Advanced combustion engines***

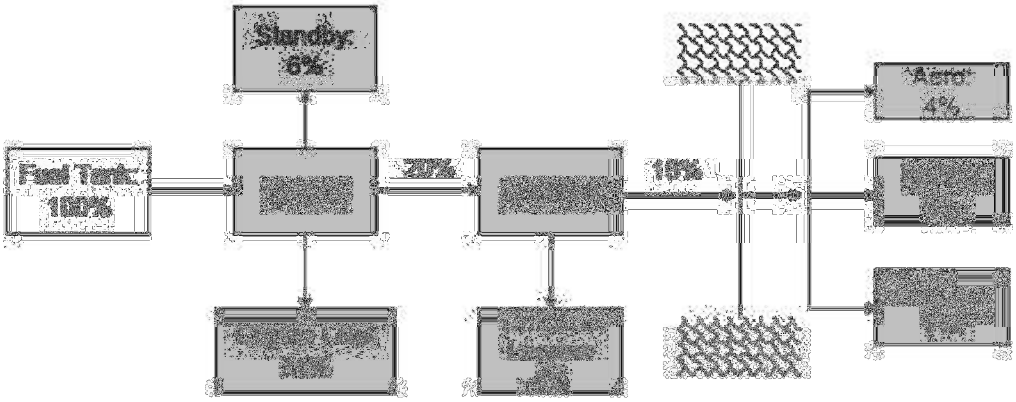
Reducing losses across propulsion and non-propulsion systems leads to a reduction in vehicle fuel consumption. From the representation of vehicle energy flows in Figure A1.3 it is clear that energy lost through engine inefficiency accounts for the majority of energy lost.

Improvements to design of combustion engines include (Massachusetts Institute of Technology (MIT), 2008):

- lean burn injection petrol engines
- friction reduction through use of advanced materials
- smart cooling systems
- cylinder deactivation
- variable compression ratio engines
- petrol direct-injection
- turbocharged engines
- higher pressure fuel injections for diesel engines
- homogenous charge compression ignition
- camless valve trains.

Materials requirements for advanced combustion engines will be assessed in the sector studies.

*Figure A1.3: Vehicle energy flows in an urban driving cycle*



*Source: MIT, 2008*

***Catalytic converters***

Catalytic converters reduce harmful emissions from engines and use platinum group metals and cerium to convert post-combustion gases such as carbon monoxide and nitrous oxides to more environmentally benign chemicals such as carbon dioxide, nitrogen and water. They are not a new technology (they were introduced in the 1970s) and are now a requirement for all new vehicles due to engine emissions regulations. The ratio of different metals used in catalytic converters varies depending on the engine type: for example, catalytic converters for petrol engines typically have a higher proportion of palladium than those for diesel engines (EPOW, 2011). Materials requirements for catalytic converters will be assessed in the sector studies.

***Light-weighting of vehicles through use of advanced materials***

Reduction in vehicle weight is an effective way of increasing fuel efficiency; every 10% of weight reduced from the average new car can cut fuel consumption by around 7% (MIT, 2008). There are three general strategies for reducing vehicle weight:

- lightweight materials substitution
- vehicle redesign to minimise weight
- down-sizing the vehicle fleet by shifting sales away from larger heavier vehicles.

Candidates for lightweight materials substitution include, but are not limited to: aluminium, high strength steels, magnesium, glass-fibre reinforced polymer composites and carbon-fibre polymer composites. These materials requirements will be further discussed in the sector studies.

***Electric vehicles***

There are five different types of electric vehicle (EV) which will be considered:

- battery electric vehicles (BEV)
- hybrid electric vehicles (HEV)
- plug-in electric vehicles (PHEV)
- mild hybrids
- fuel cell vehicles (FCV).

BEVs are purely electrical vehicles, which are powered exclusively from the electricity from on-board batteries which are charged from the grid; they currently have a range of 125-160 km. HEVs employ both an internal combustion engine and an electric motor for propulsion, and they use regenerative braking to recharge the batteries. PHEVs are similar to HEV, except that they can charge from the grid to extend the electric range. They are classified by how far they can travel on electricity; for example, a PHEV-50 can travel 50 km. PHEVs come in two varieties: parallel or series, the difference being that parallel PHEVs use the ICE to provide range extension by directly powering the wheels, whereas series PHEVs use the ICE to recharge the batteries and only the electric motor drives the wheels (CreditSuisse, 2009a). Mild hybrids are ICE vehicles which are equipped with electric motors for regenerative braking and/or start/stop systems. FCVs convert energy from a fuel (usually hydrogen) into electricity by using a fuel cell; the electricity is then used to power an electric motor and can also be stored in a battery or a capacitor (Electric Drive Transportation Association, n.d.).

## A1.11 Desalination

### A1.11.1 Background

Desalination in its many forms is a water treatment technology that can be used to produce both drinking water and high-purity water from seawater or brackish water. The raw water is separated into two streams: a fresh water stream and a remaining brine solution that needs to be disposed of. Interest in desalination emerged in arid areas of the world, such as the Middle East and the southwest States of the USA. The first major desalination plants were erected in Kuwait between 1950 and 1955, making Kuwait almost independent for its water needs (Delyannis and Belessiotis, 2010). Today, seawater desalination plants are also a vital source of fresh water for other Middle East countries such as Saudi Arabia and the United Arab Emirates. Outside of the Middle East, the largest market worldwide, (Frost & Sullivan, 2009b, 2010b) significant desalination capacities also exist in the USA and Spain (Khawaji et al., 2008).

With energy consumption being one of the key concerns in desalination R&D efforts, extensive research has been devoted to increasing the efficiency of the process itself, leading to significant cost reductions (Rachwal and Judd, 2006). In addition, concepts for the coupling of desalination for drinking water treatment to non-renewable (Angerer et al., 2009) and renewable energy (e.g. ProDes Consortium, 2010) sources have been explored and implemented.

### A1.11.2 Sub-technologies

Desalination technologies can be classified as either:

- thermal (multi-stage flash evaporation, multi-effect distillation, vapour compression), or
- membrane (mainly reverse osmosis) processes.

Currently, the three most widely used technologies for the desalination of seawater and brackish water are multi-stage flash (MSF) distillation, multi-effect distillation (MED) and reverse osmosis (RO). Typical capacities for desalination plants are up to 40,000 $m^3$/day for reverse osmosis, greater than 35,000 $m^3$/day for MED and greater than 75,000 $m^3$/day for MSF (Frost & Sullivan, 2009b). Whilst the original desalination plants all operated thermally, reverse osmosis - a membrane process - has become an important source of desalinated water in recent years. Whereas MSF and MED plants still hold the majority share of installed desalination capacity, well over 90% of newly-built desalination plants are based on RO (Khawaji et al., 2008; Frost & Sullivan, 2010a).

***Thermal processes***

Thermal desalination processes use thermal energy to obtain fresh water out of seawater and brackish water by means of evaporation. To reduce energy demand, thermal processes operate at low pressures and reuse substantial amounts of heat. The three main thermal processes are:

- MSF distillation. Flash distillation is based on the rapid evaporation of water by suddenly reducing the surrounding pressure. In MSF, pressure is reduced in multiple steps (e.g. from 0.6 bar (0.06 MPa) to 0.07 bar (0.007 MPa) in 18 steps) and heat is recovered after each step by condensing against the fresh seawater. The thermal coupling of the individual flash stages with the heating of seawater reduces external heat input to one seventh of the total process heat required (Stichlmair, 2010). External heating is generally provided by low pressure steam from a co-generation power plant. The top brine temperature in modern large MSF plants is usually in the range 90-120°C, with 19-28 flash stages. More stages increase both the capacity and efficiency of an MSF plant but imply higher capital costs (Khawaji et al., 2008). The costs of water produced via MSF distillation are higher than those for MED plants (Frost & Sullivan, 2009b). However, MSF distillation has historically been the preferred desalination technology due to its simplicity, ease of operation, very high reliability, and very low performance degradation over time

(Borsani and Rebagliati, 2005).

- In addition to the current coupling with conventional power plants, MSF distillation may be combined with other (renewable) heat sources including concentrating solar power and geothermal (ProDes Consortium, 2010).
- MED is a distillation process carried out in multiple evaporators (called effects). A fraction of the water is allowed to evaporate in each effect and heating is provided over evaporation tubes (horizontal, vertical or submerged). For the first effect, heating is provided by steam flowing inside the evaporation tubes, normally generated using heat from a co-generation power plant. The remaining liquid is then transferred to the next effect where it encounters a lower pressure, reducing the amount of heat needed for evaporation. The heat in the evaporation tubes for all effects but the first is provided by the condensation of the water vapour from the previous effect. Thus, external input of heat is only required in the first effect. MED is the oldest desalination process and is more efficient than MSF from both a thermodynamic and heat transfer (capacity) point of view, and requires little electrical power compared to MSF. Seawater treated by MED does not require any pre-treatment and, because it can operate at low temperatures (e.g. with a top brine temperature of 70 °C), corrosion, scaling are limited (Khawaji et al., 2008; Frost & Sullivan, 2010a).
- In principle, MED may be combined with other (renewable) heat sources including solar thermal collectors, concentrating solar power and geothermal energy and ocean thermal energy in addition to the current coupling with conventional power plants (ProDes Consortium, 2010).
- Vapour compression distillation (VCD) is a simple and reliable process that runs on electrical power (i.e. it does not need an external heat source). It is therefore mostly used for small-scale desalination units. In VCD, vapour is extracted from the evaporation chamber and fed to the condenser, thus generating a vacuum in the evaporation chamber, facilitating evaporation. The extracted vapour is condensed by compression inside a tube bundle, onto which seawater is sprayed and evaporated (Khawaji et al., 2008). The coupling of VCD to renewable energy occurs via the electricity mix.

***Membrane processes***

The introduction of RO into the desalination market led to a drastic decrease in desalination (Frost & Sullivan, 2009b). The process itself is fundamentally different from MSF and MED. Instead of evaporating and condensing fresh water from seawater, the separation occurs by forcing fresh water through a membrane which prevents the passage of salts. This is the opposite of osmosis - the spontaneous process in which water flows across a membrane from the side with lower salt concentration to the side with higher salt concentration until the concentrations are equal – hence the term ‘reverse osmosis’. RO is achieved by applying sufficient pressure (enough to overcome the osmotic pressure) to the side with the higher salt concentration. Therefore, unlike MSF and MED, RO plants do not have to be built close to a power plant but need only a connection to the power grid.

A salient feature of RO desalination plants is the effort invested in pre-treatment of the incoming seawater. To protect the polymer membrane from suspended solids as well as from fouling and scaling, mechanical and chemical pre-treatment of the water is necessary (Khawaji et al., 2008; Rautenbach, 2011). Despite these efforts, periodic maintenance of the RO membranes is a requirement and a major issue in the design and operation of RO plants (Frost & Sullivan, 2010a). In addition to electrical power from renewable sources, it is possible to couple RO with mechanical power obtained from the ocean. The combination photovoltaic-RO was recently identified as the most common renewable energy/ desalination coupling (ProDes Consortium, 2010).

***Other technologies***

MSF, MED and RO combined account for more than 95% of the desalination market worldwide. The remaining 5% is shared between VCD and other technologies; some proven, some still in development. These include freezing, ‘dewvaporation’, electro-dialysis, membrane distillation, ion exchange and capacitive deionization (Frost & Sullivan, 2010a).

# Appendix 2: Metal Uses

## Aim

The study focuses on resources used in technologies which are part of the EU path to the decarbonisation of the energy sector; however, it is important to realise that there are other sectors that may be competing for the same resources. As a consequence, activity in these other sectors may limit the availability of certain materials for use for low-carbon energy technologies.

For the purposes of this study, the competing sectors of particular interest are the automotive and electronics/ICT sectors:

- In 2010, 12.6 million people were employed directly or indirectly by the automotive sector in the EU, producing a total of 15.1 million vehicles or 22% of worldwide motor vehicle sales (ACEA, 2011).
- The electronics/ICT sector accounted for 8.5% of total business value added in the EU and 3% of total business sector turnover (EC, 2012b). Europe’s share of worldwide electronics and ICT turnover is estimated at around 30% (Deloitte, 2010); however, this estimate includes sales from non-EU countries such as Russia, Turkey and Ukraine. Apportioning the EU’s share of European population using 2010 UN Population statistics puts the EU share of the worldwide electronics market at 18%.

## Methodology

There are potentially 60 materials of relevance to analyse in total, so it is not practical to produce a detailed forecast for each of them nor to collect primary data on their end-use. The approach therefore needs to be relatively generic and to apply largely a common data source and methodology.

## Data

The main source of data is end-use statistics compiled by the EU Raw Materials Initiative for its assessment of critical raw materials for the EU (EC, 2010d). That study compiled data for 41 metals and minerals. For gallium, a stakeholder commented that the data provided by EU Raw Materials Initiative report was actually for gallium use in the United States, rather than for worldwide gallium use. Alternative data was therefore sourced.

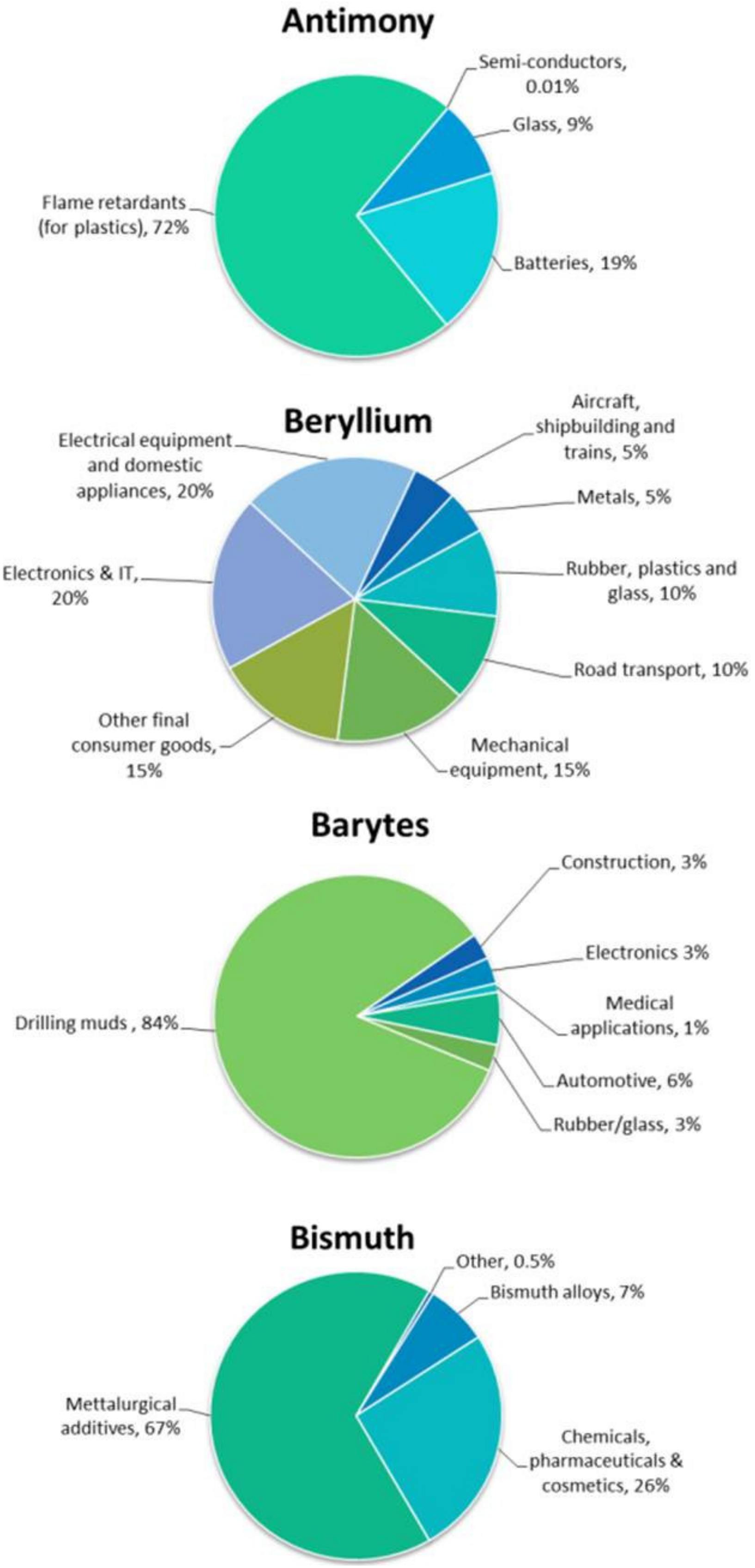
A recent report by the International Study Groups for Nickel, Lead & Zinc and Copper compiled data for 11 metals produced as by-products of these principal metals (International Study Group for Nickel et al., 2012). As this report is a recent and in-depth study on these metals, this data has been used for the relevant metals.

Detailed end-use data for individual platinum group metals and rare earth elements is courtesy of Johnson Matthey and the United States Geological Survey respectively. A few metals are not covered by these references, including cadmium, gold, hafnium, lead and zirconium. For these metals the reference for the data is clearly stated underneath the figure.

For some metals further data sources have been used to attribute a share of a particular use (e.g. batteries and steel alloys) to electronics and ICT or automotive, for example (EPOW, 2011).

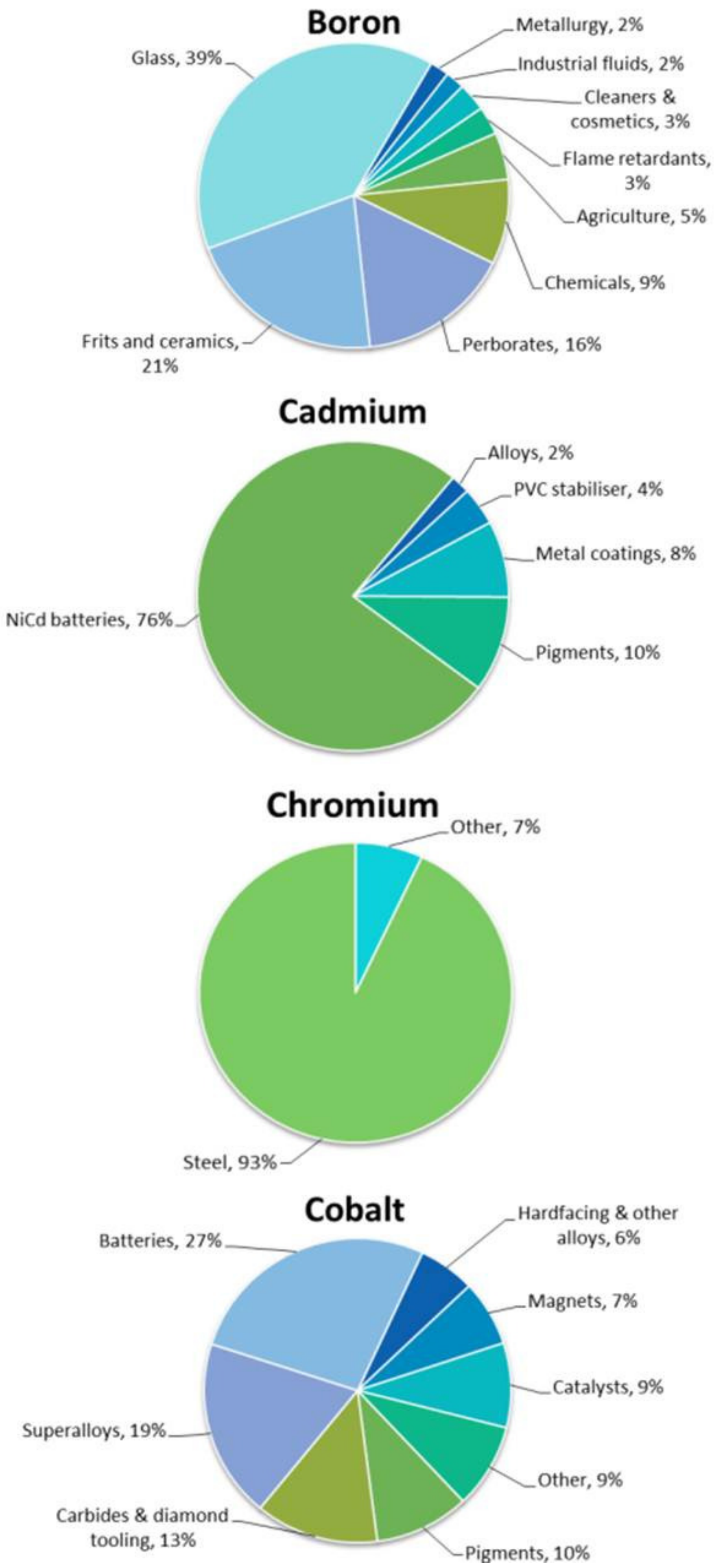
The following pages provide end-use statistics for each of the metals.

*Figure A2.1: Worldwide uses of antimony, barytes, beryllium and bismuth*



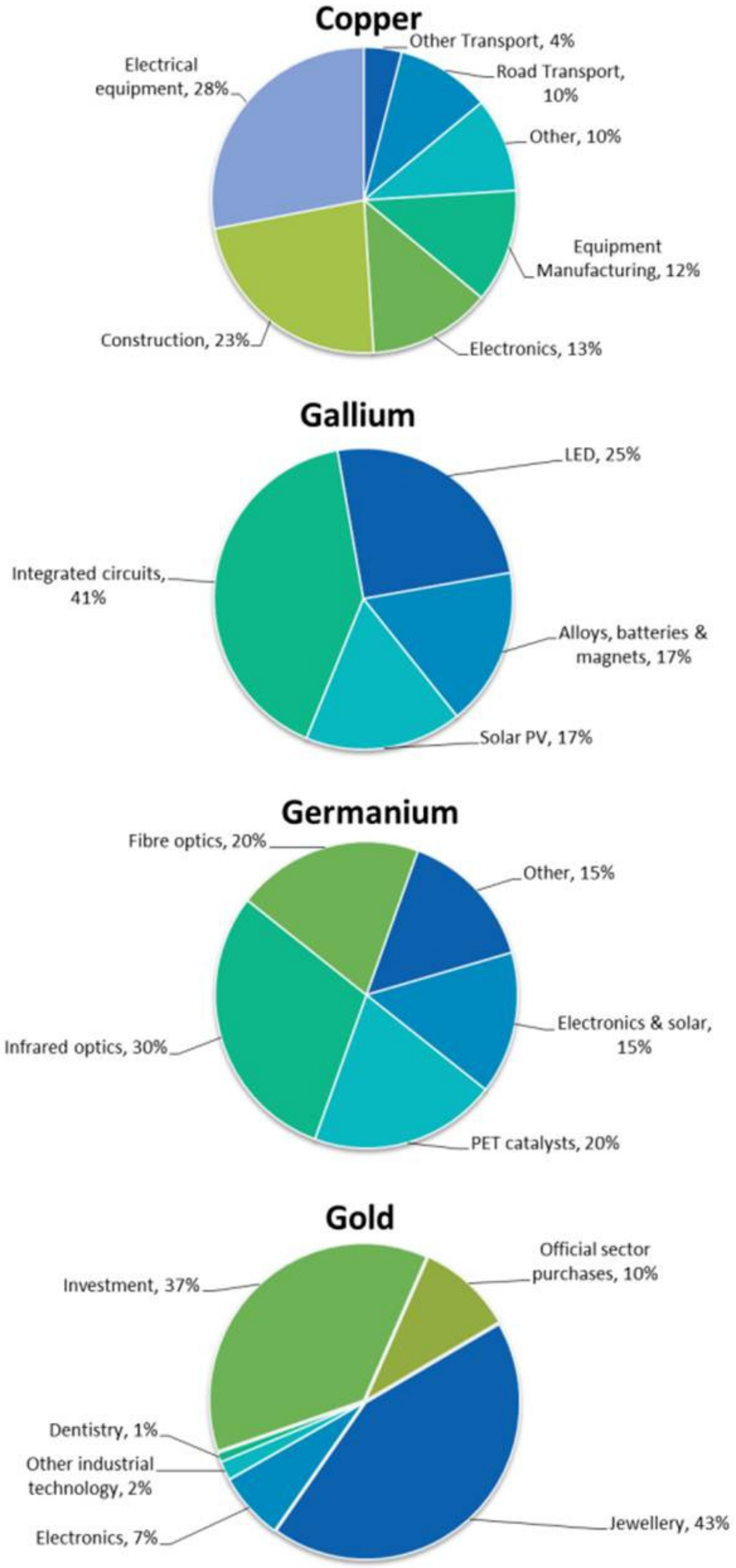
*Sources: All EC, 2010d, except Bismuth: International Study Group for Nickel et al., 2012 (USA only)*

*Figure A2.2: Worldwide uses of boron, cadmium, chromium and cobalt*



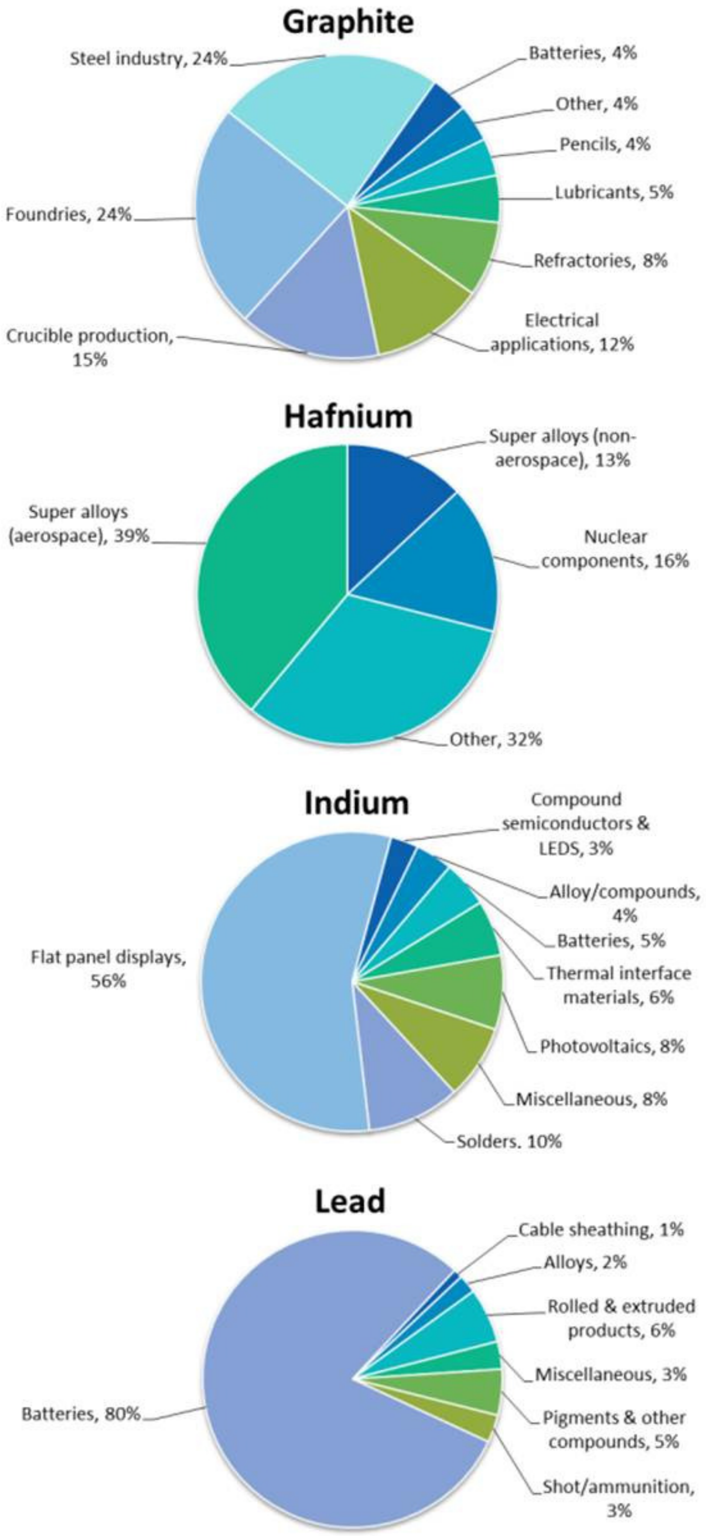
*Sources (top to bottom): EC, 2010d; Moss et al., 2011; EC 2010e; and International Study Group for Nickel et al., 2012*

*Figure A2.3: Worldwide uses of copper, gallium, germanium and gold*



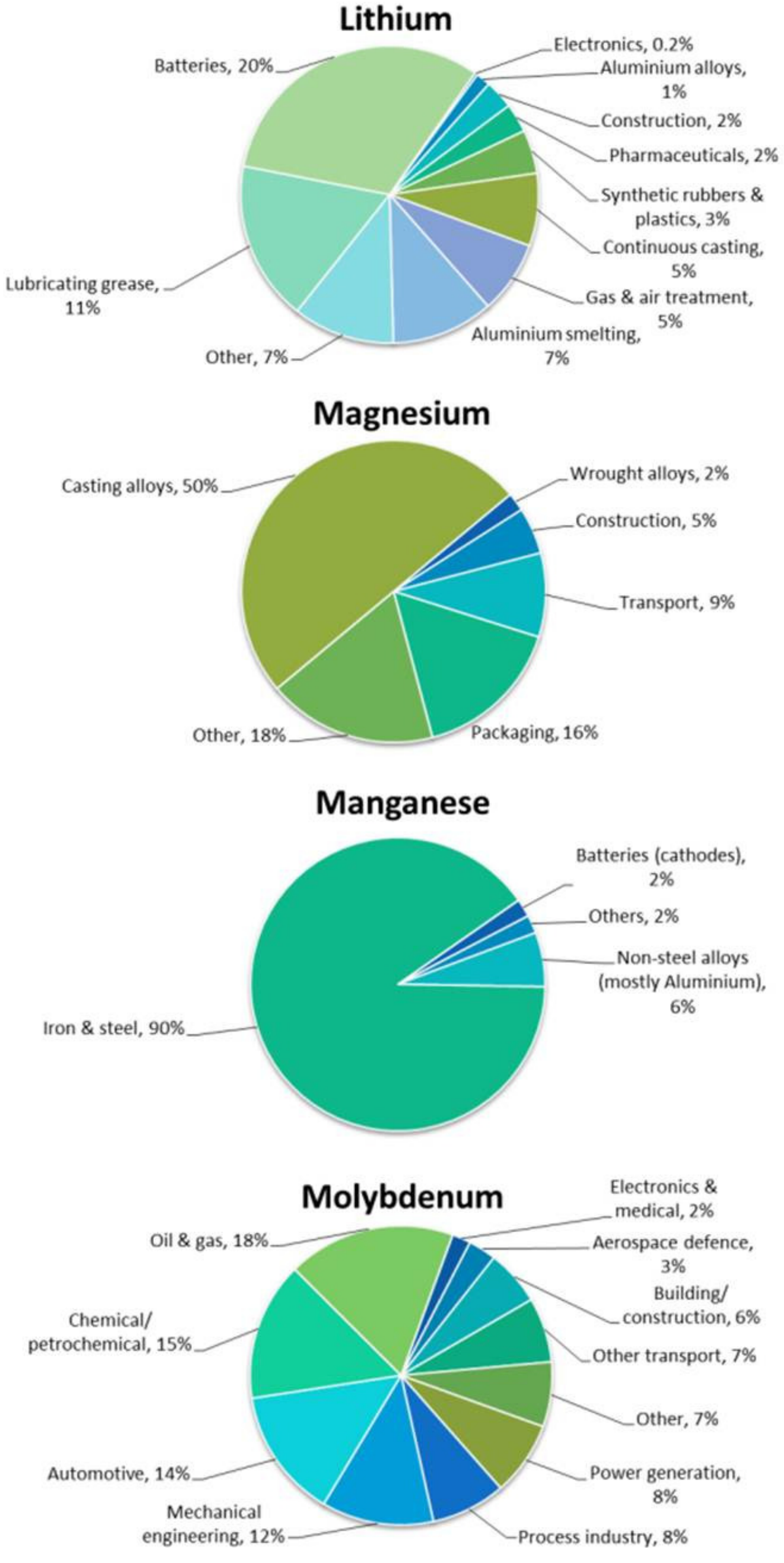
*Sources: (top to bottom) EC, 2010d; Indium Corporation, 2010;*
*International Study Group for Nickel et al., 2012; Thomson Reuters GFMS, 2012*

*Figure A2.4: Worldwide uses of graphite, hafnium, indium and lead*



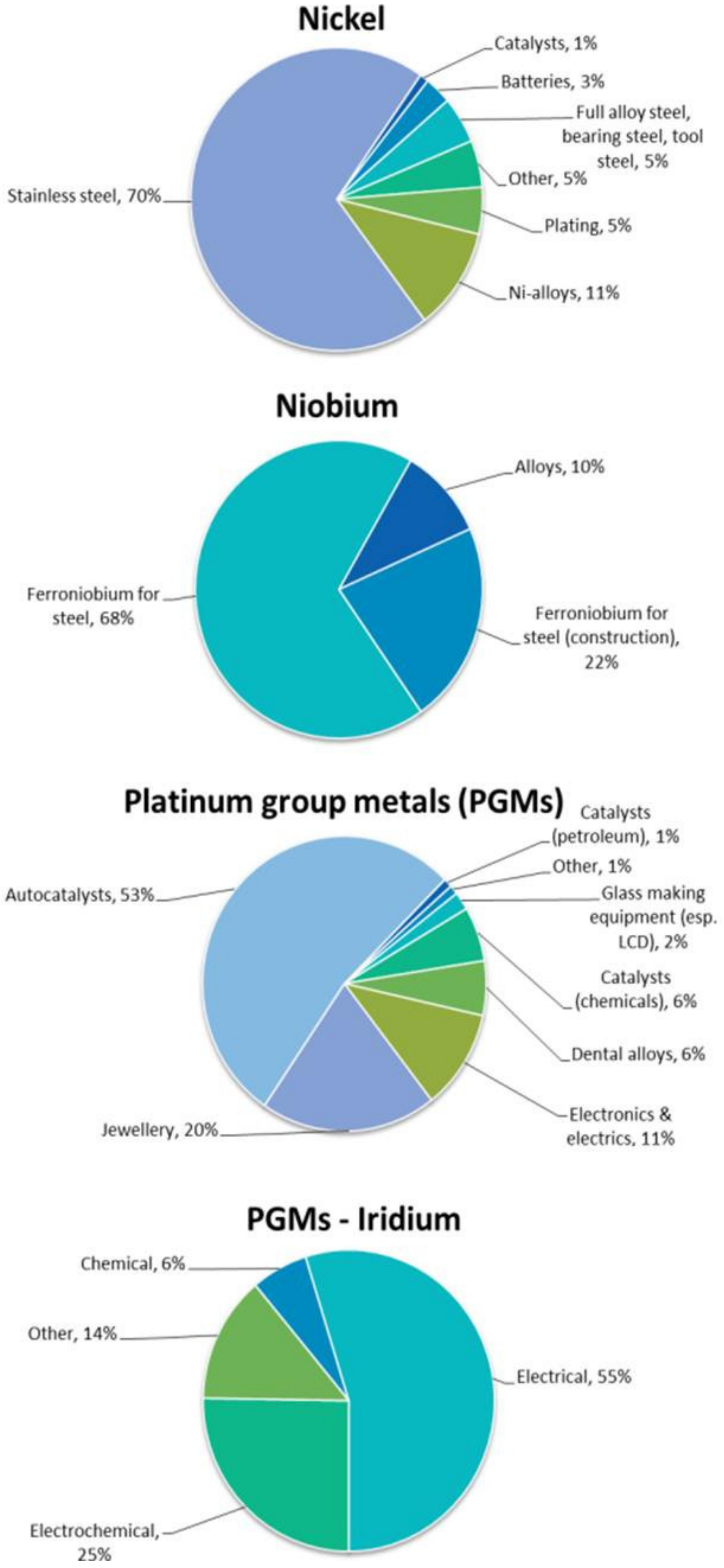
*Sources: (top to bottom) EC, 2010d;Moss et al., 2011; International Study Group for Nickel et al., 2012; ILZSG 2012c*

*Figure A2.5: Worldwide uses of lithium, magnesium, manganese and molybdenum*



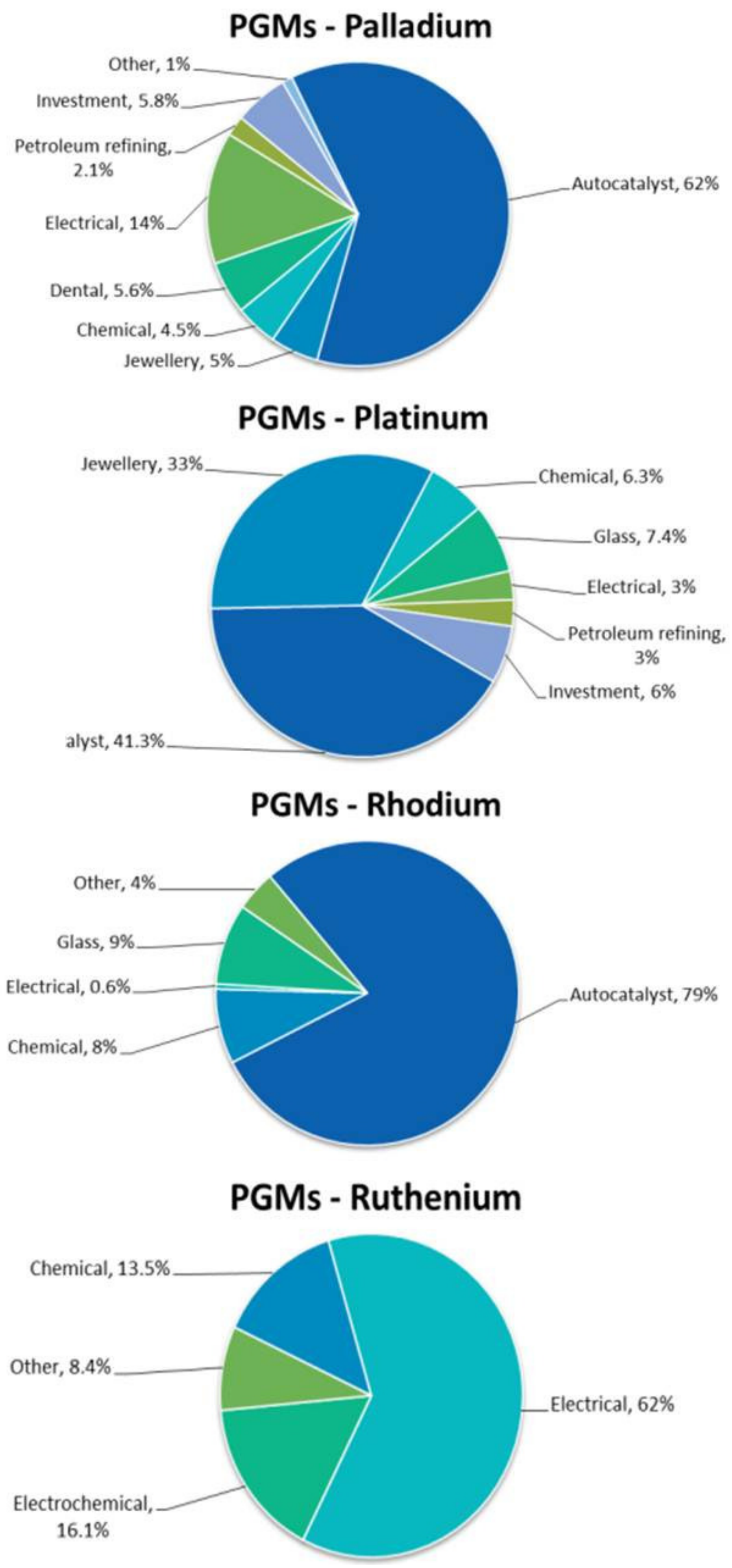
*Sources: (top to bottom) EC, 2010d; EC, 2011e; EC 2010b;*
*International Study Group for Nickel et al., 2012*

*Figure A2.6: Worldwide uses of nickel, niobium, PGMs and iridium(PGM)*



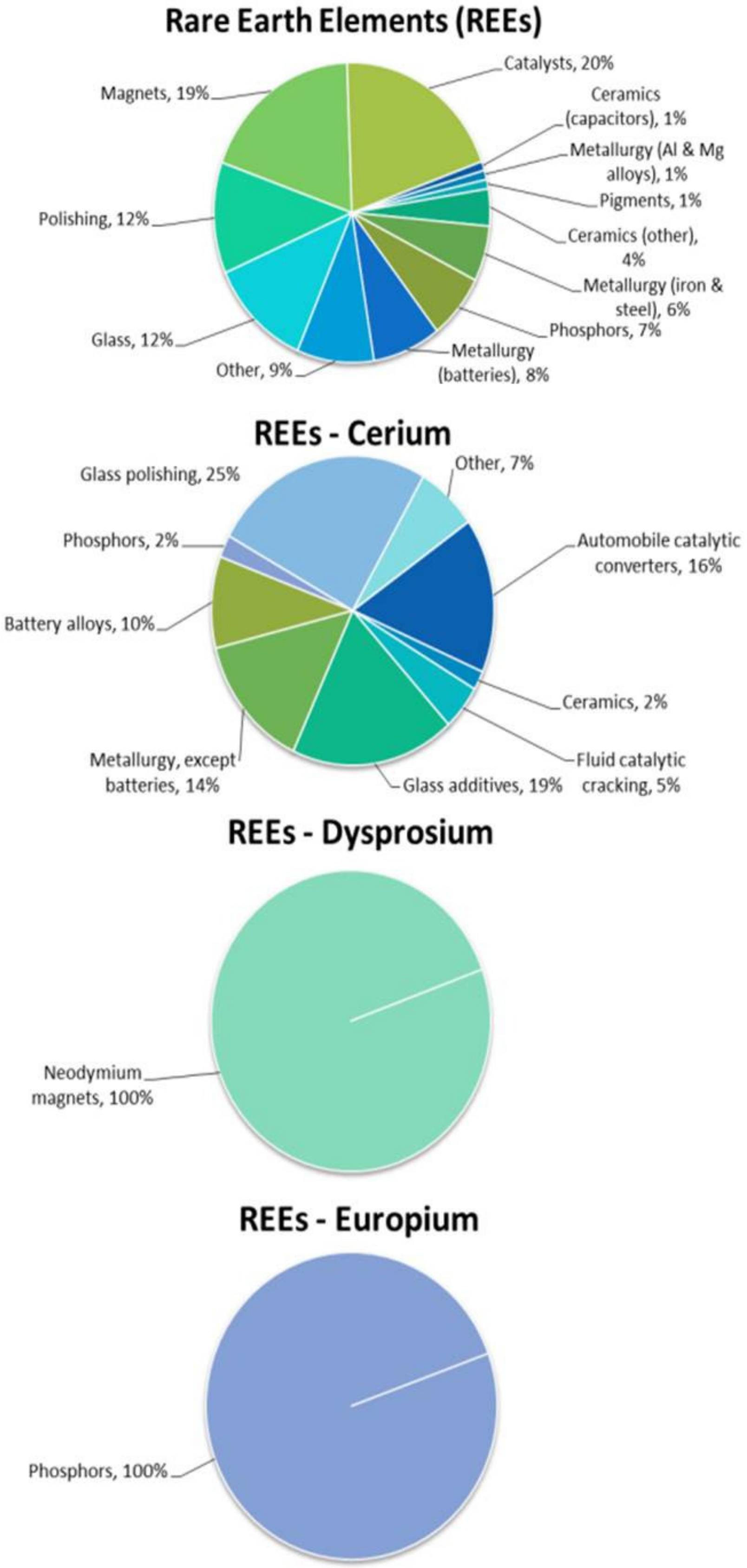
*Sources: All EC, 2010d; except Iridium: Johnson Matthey, 2012*

*Figure A2.7: Worldwide uses of PGMs: palladium, platinum, rhodium and ruthenium*



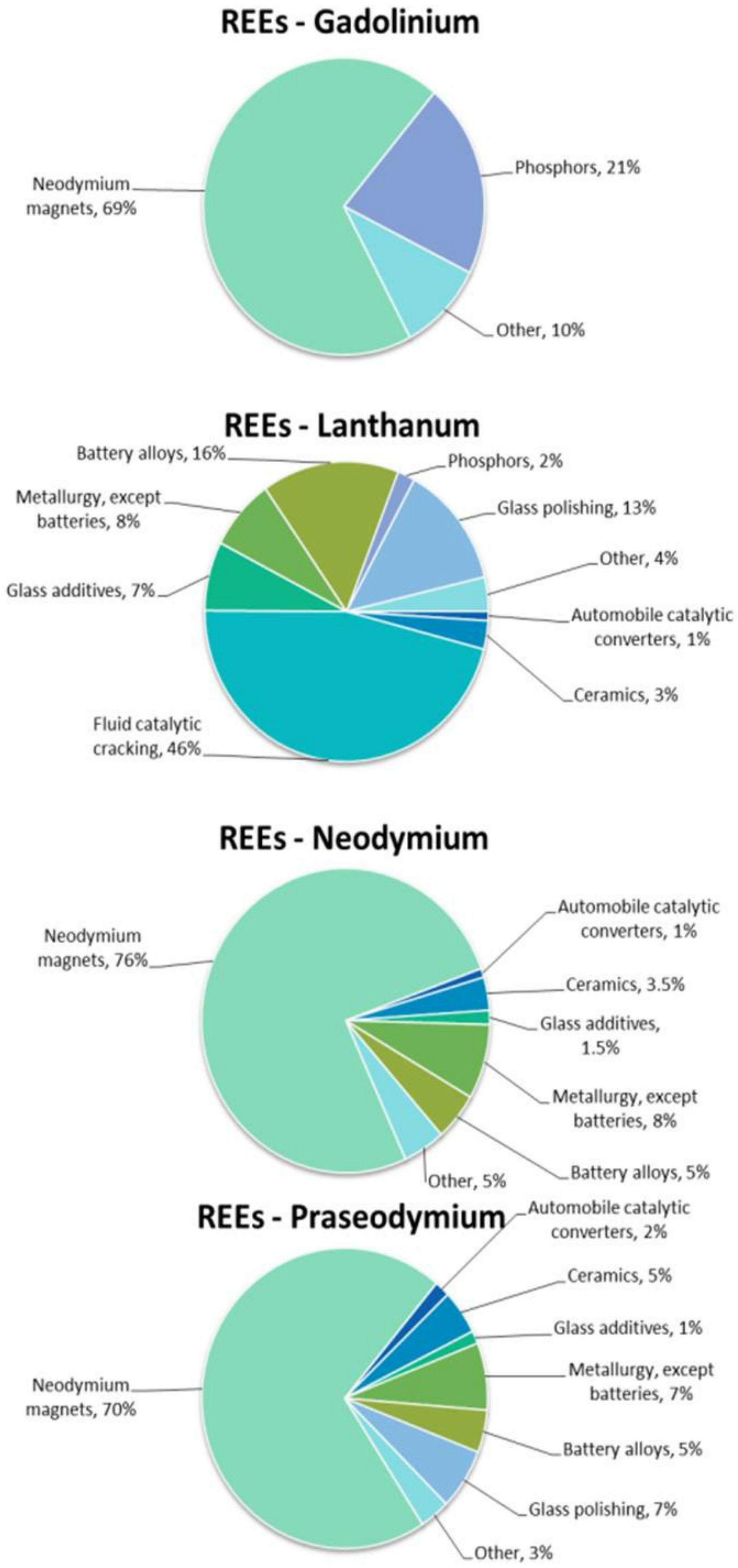
*Sources (All): Johnson Matthey, 2012*

*Figure A2.8: Worldwide uses of REOs: in general, cerium, dysprosium and europium*



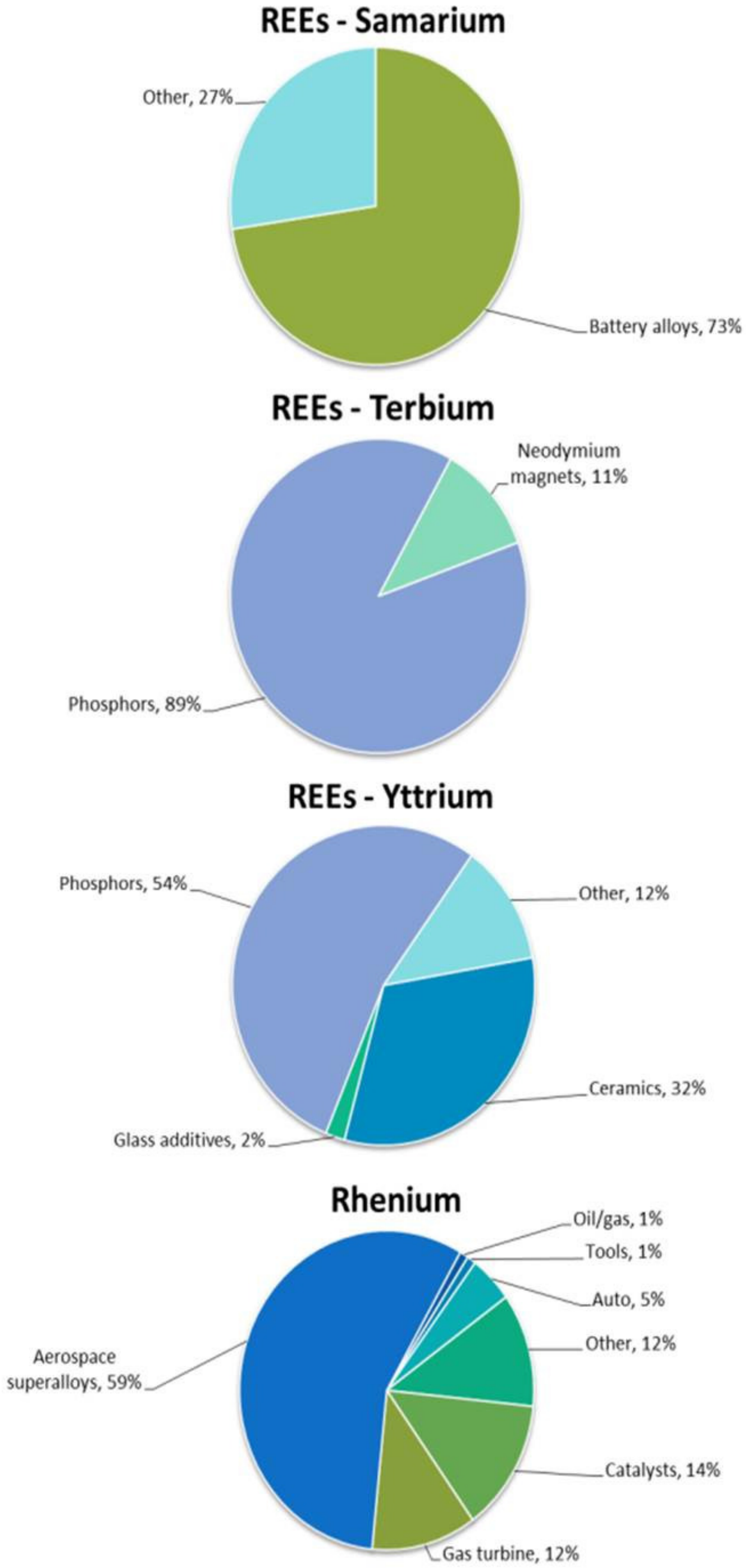
*Sources: (top) EC, 2010d; rest: USGS, 2011c*

*Figure A2.9: Worldwide uses of REOs: gadolinium, lanthanum, neodymium and praseodymium*



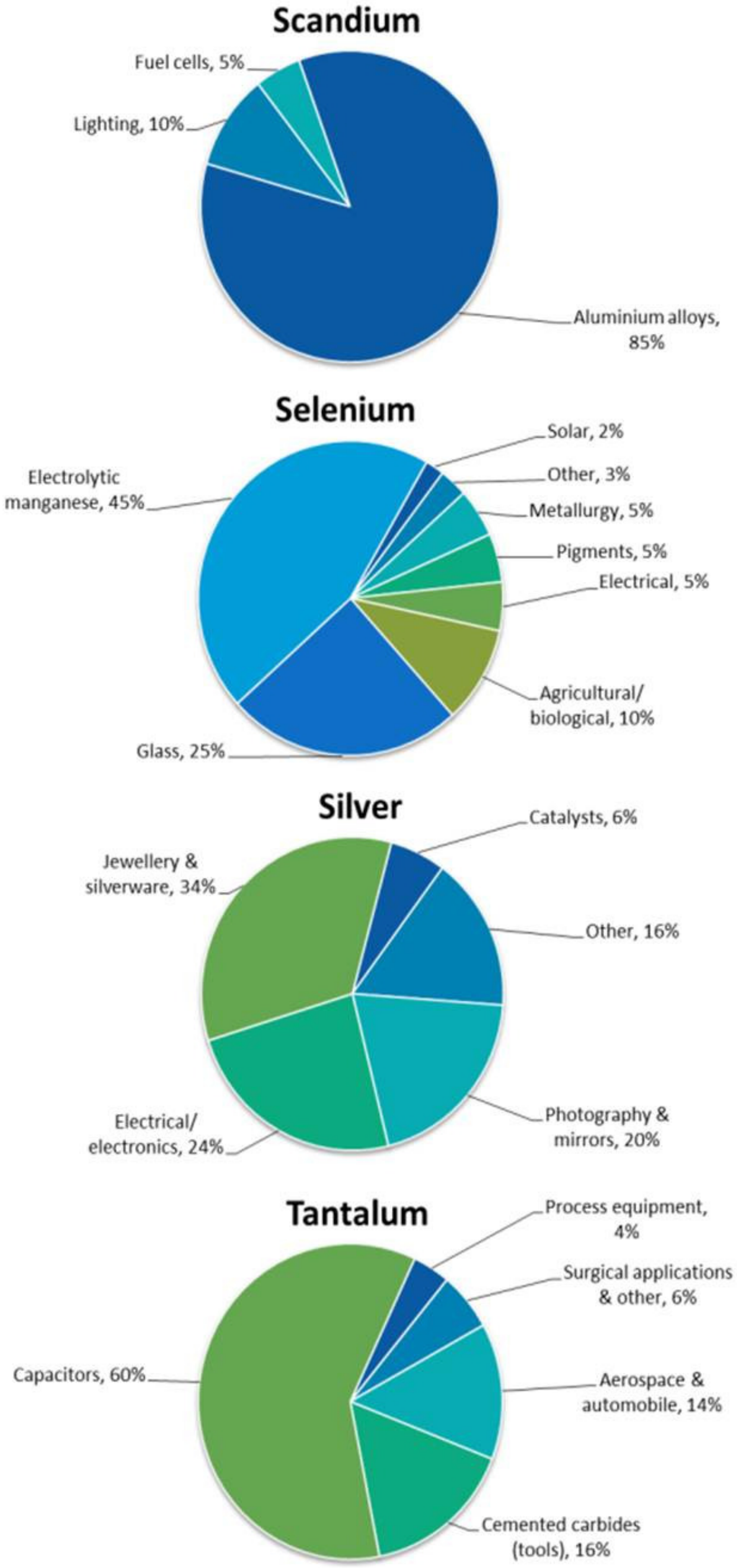
*Sources: (all) USGS, 2011c*

*Figure A2.10: Worldwide uses of the REOs (samarium, terbium, yttrium) and rhenium*



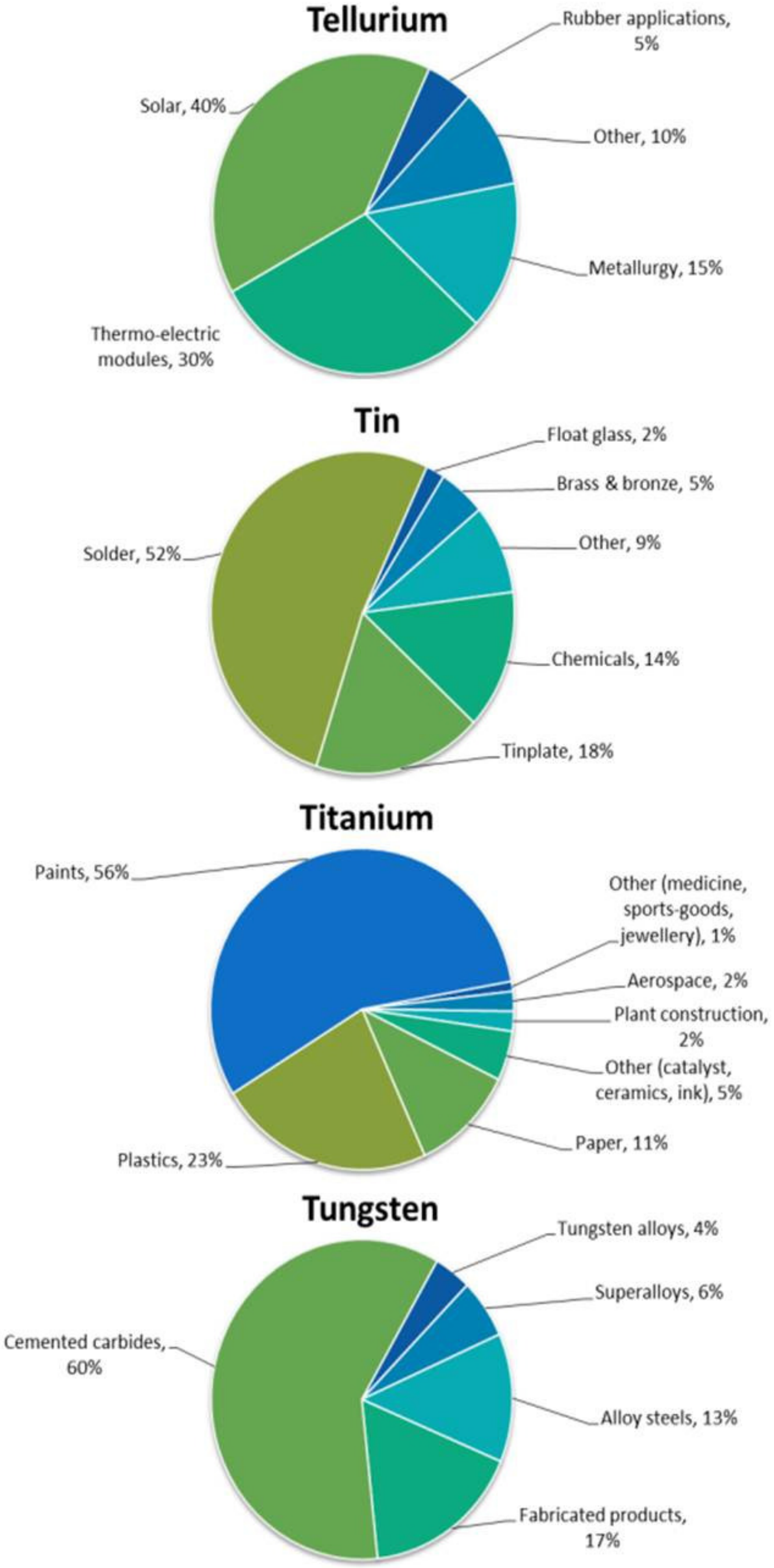
*Sources: REOs: USGS, 2011c; Rh: International Study Group for Nickel et al., 2012*

*Figure A2.11: Worldwide uses of scandium, selenium, silver and tantalum*



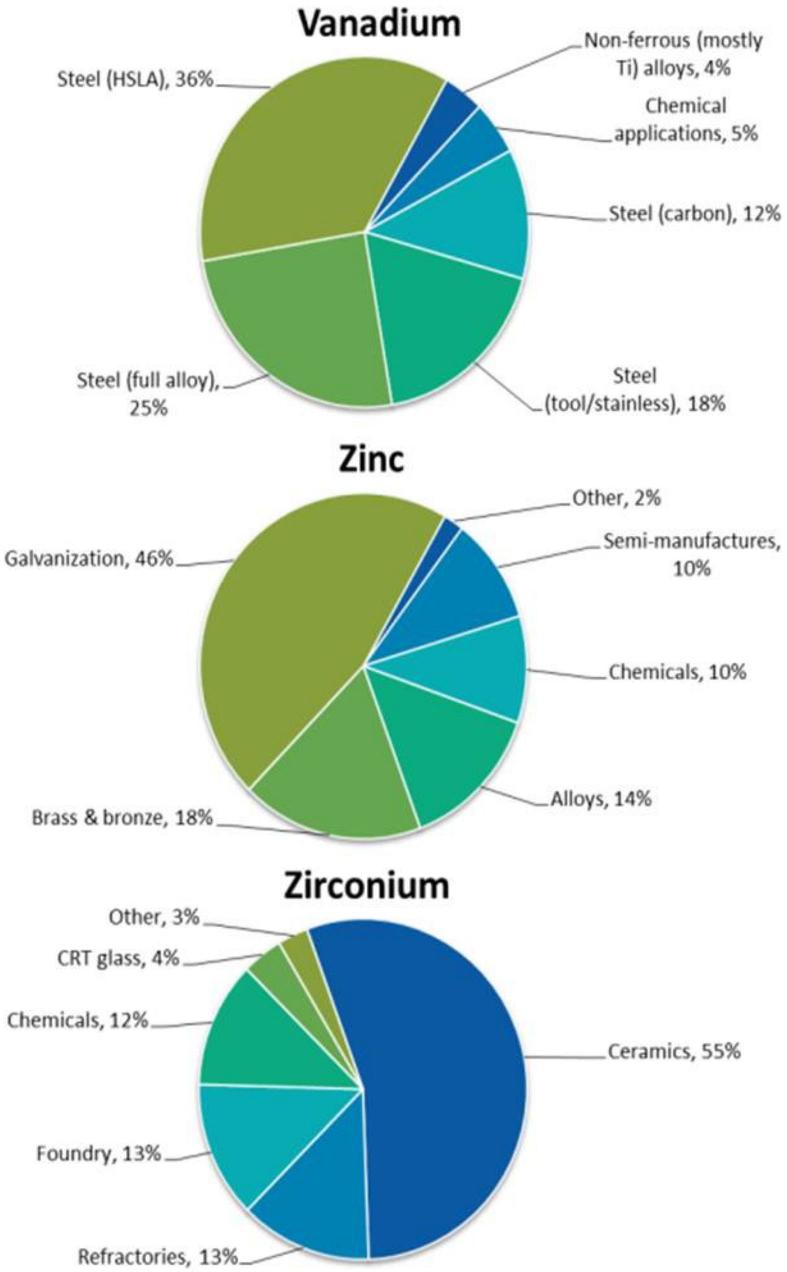
*Sources: (Sc, Se) International Study Group for Nickel et al., 2012; (Ag, Ta) EC, 2010d*

Figure A2.12: Worldwide uses of tellurium, tin, titanium and tungsten



*Sources: (Te) International Study Group for Nickel et al., 2012; (rest) EC, 2010d*

*Figure A2.13: Worldwide uses of vanadium, zinc and zirconium*



*Sources: (Va, Zn) EC, 2010d; (Zr) Roskill, 2007*

# Appendix 3: Long Term Metal Supply Projections

## *Expected supply of metals*

To get a sense of scale of the material demand estimates of the EU path to the decarbonisation of the energy sector, it is important to provide the context of metals supply estimates. The latest available data for metals supply estimates is for 2011. The EU materials demand estimates can also be compared against long term supply projections for 2020 and 2030. This provides a more dynamic measure of materials availability.

## *Scope*

There are potentially 60 materials of relevance to analyse in total (see Table 64), so it is not practical to produce a detailed forecast for each of them. The approach therefore needs to be relatively generic and apply largely a common data source and methodology. The length of the projections is around 20 years – 2011 to 2030. Due to the volatility that is inherent in many commodity markets, particularly those for many minor metals, a long term forecast cannot be considered reliable. Indeed, even for the base metals (i.e. copper, lead, nickel, steel, tin and zinc) for which the markets are much more transparent and less volatile than the minor metals, most forecasts are only for a period of around 2-5 years. It is therefore clear that the data here should not be understood to be forecasts.

## *Data*

The main source of data used for the long term supply projections is historical supply data collated by the United States Geological Survey Mineral Commodity Specialists for around 90 mineral commodities (USGS, 2011a). This data has then been augmented with 2011 production estimates (USGS, 2012). Long term supply trends have then been linearly extrapolated to form the supply projections to 2030. For some metals (cobalt, gallium, indium, lithium, nickel and tellurium) the USGS provides estimates of reclaim and projected capacity for 2015 (Bauer et al., 2010). This data has been taken into account in the supply projections.

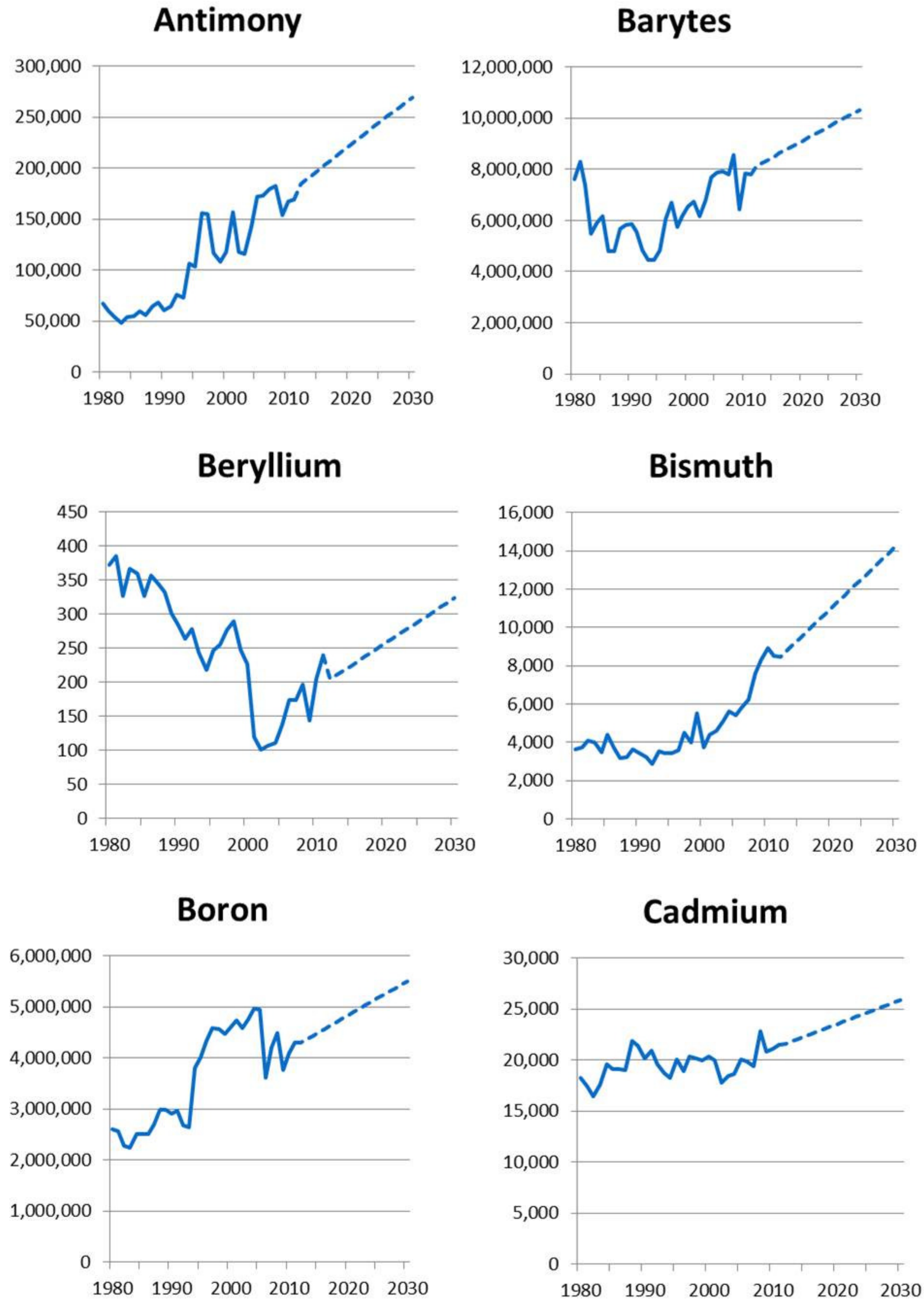
Some supplementary data has been included for particular metals where additional data was felt to be useful in providing further details or was missing from USGS data. These include:

- JRC data on hafnium supply, which the USGS does not provide recent supply data (Moss et al., 2011).
- INSG/ILZSG/ICSG supply data for 11 metals produced as by-products from these base metals. This was of particular use for selenium, tellurium and scandium (International Study Group for Nickel et al., 2012).
- BGS data of lithium and titanium dioxide content of the host ores (BGS, 2012a).
- Johnson Matthey data on the supply and demand of the minor platinum group metals (Johnson Matthey, 2012).
- Lynas and IMCOA data on the composition of rare earth supply, both current and forecast, of each of the individual rare earth elements (Lynas Corporation Ltd, 2010; IMCOA in US DOE, 2011).

## *Results*

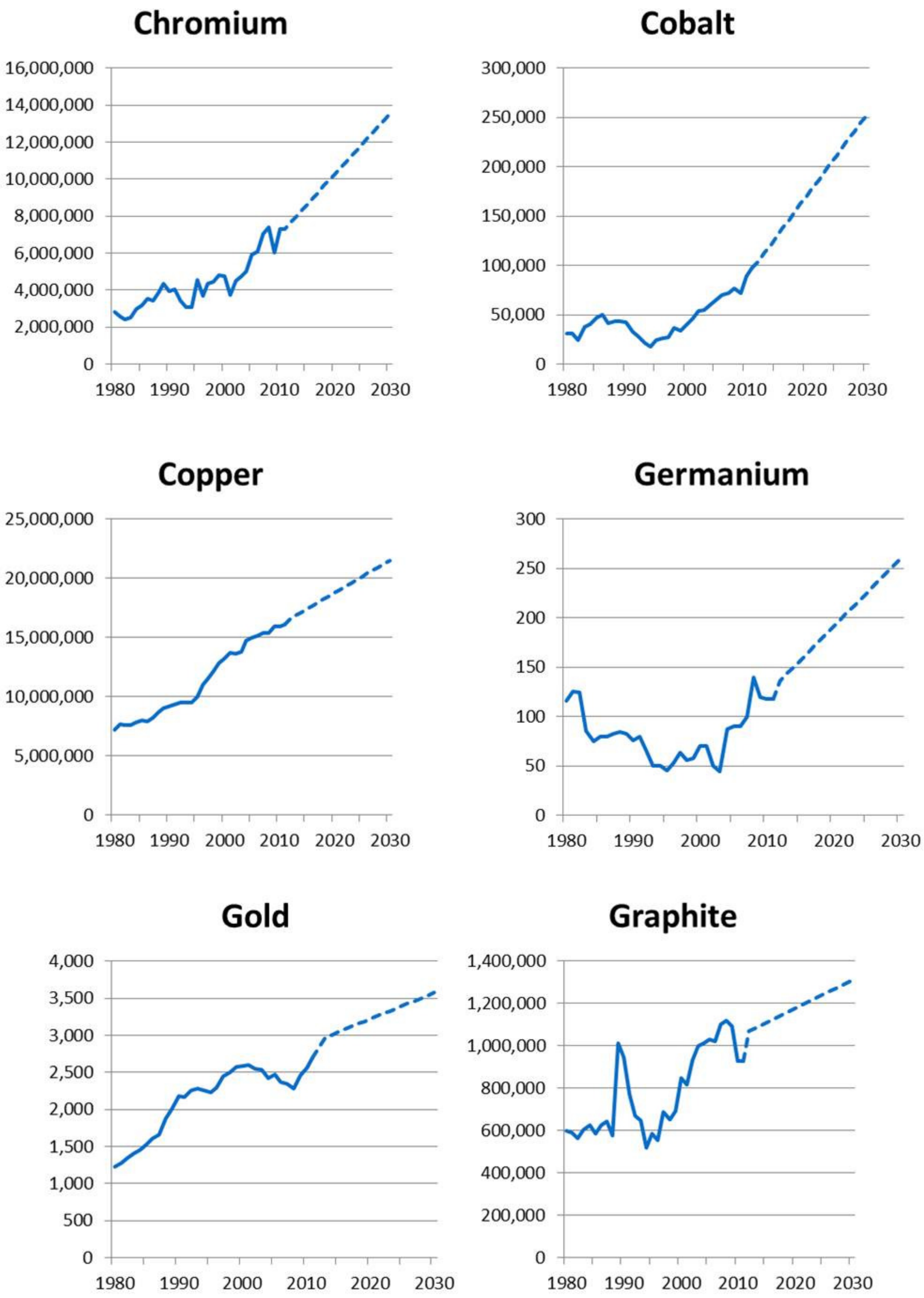
The supply projections are summarised in Table 64, providing 2011 production estimates and projections for 2020 and 2030, and the implied compound annual growth rate (CAGR) for the 20 year period. For the metals where reliable historical production data is available these are shown graphically in Figures A3.1 to A3.5, along with the supply projections. These projections should be considered as illustrative rather than definitive, as they are reliant upon the continuation of current trends. Nevertheless they do allow comparison against estimated demand within EU decarbonisation technologies and enable a comparison to be made between different metals, and thus help identify specific risks and priorities. Data for recycled production has been added to the overall supply estimates contained in Table 58. See Appendix 5 on the data sources and methodology that has been applied for this.

*Figure A3.1: Metals production trends for antimony, barytes, beryllium, bismuth, boron & cadmium (tonnes)*



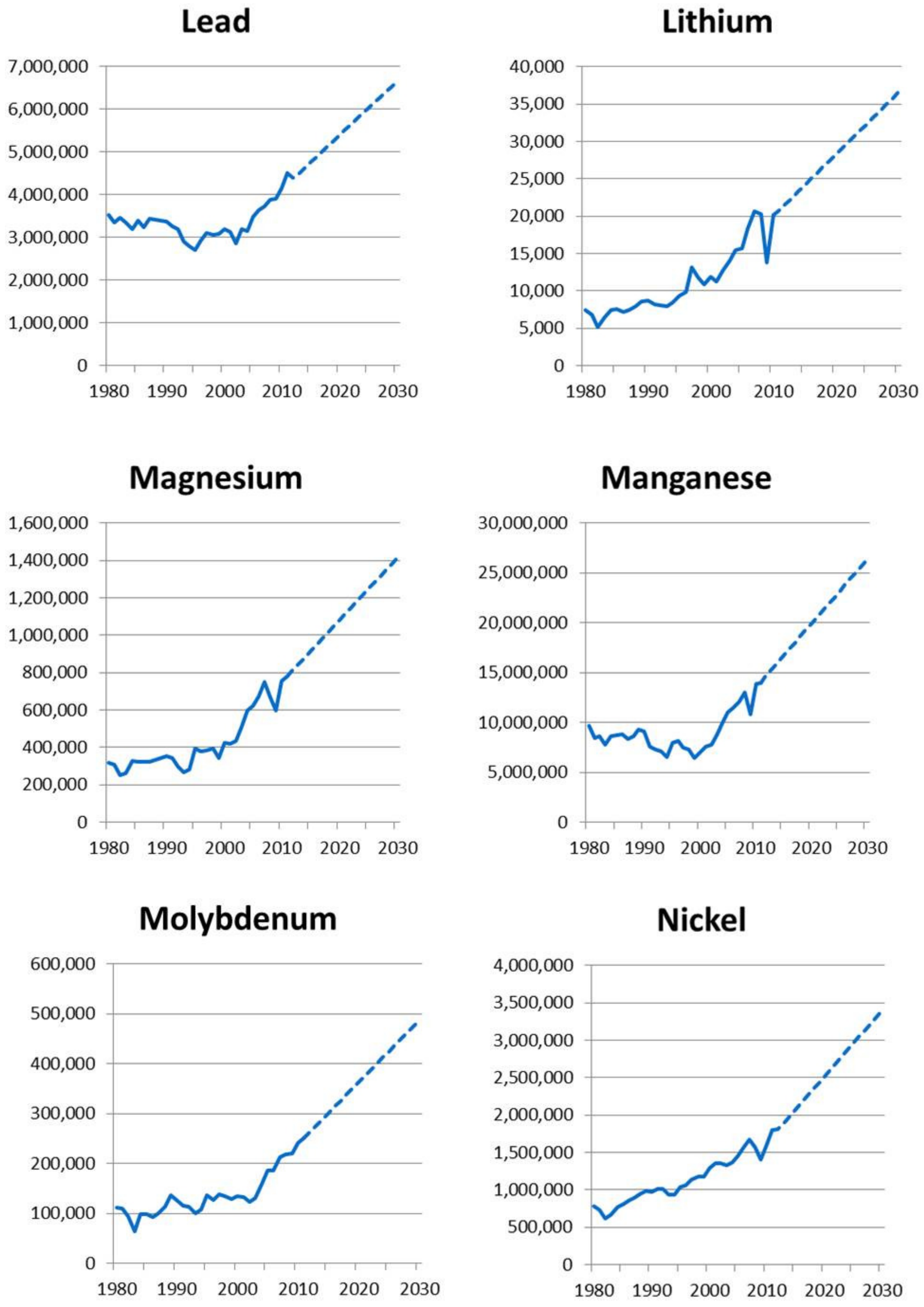
*Source: USGS, 2011a; projections thereafter.*

*Figure A3.2: Metals production trends for chromium, cobalt, copper, germanium, gold & graphite (tonnes)*



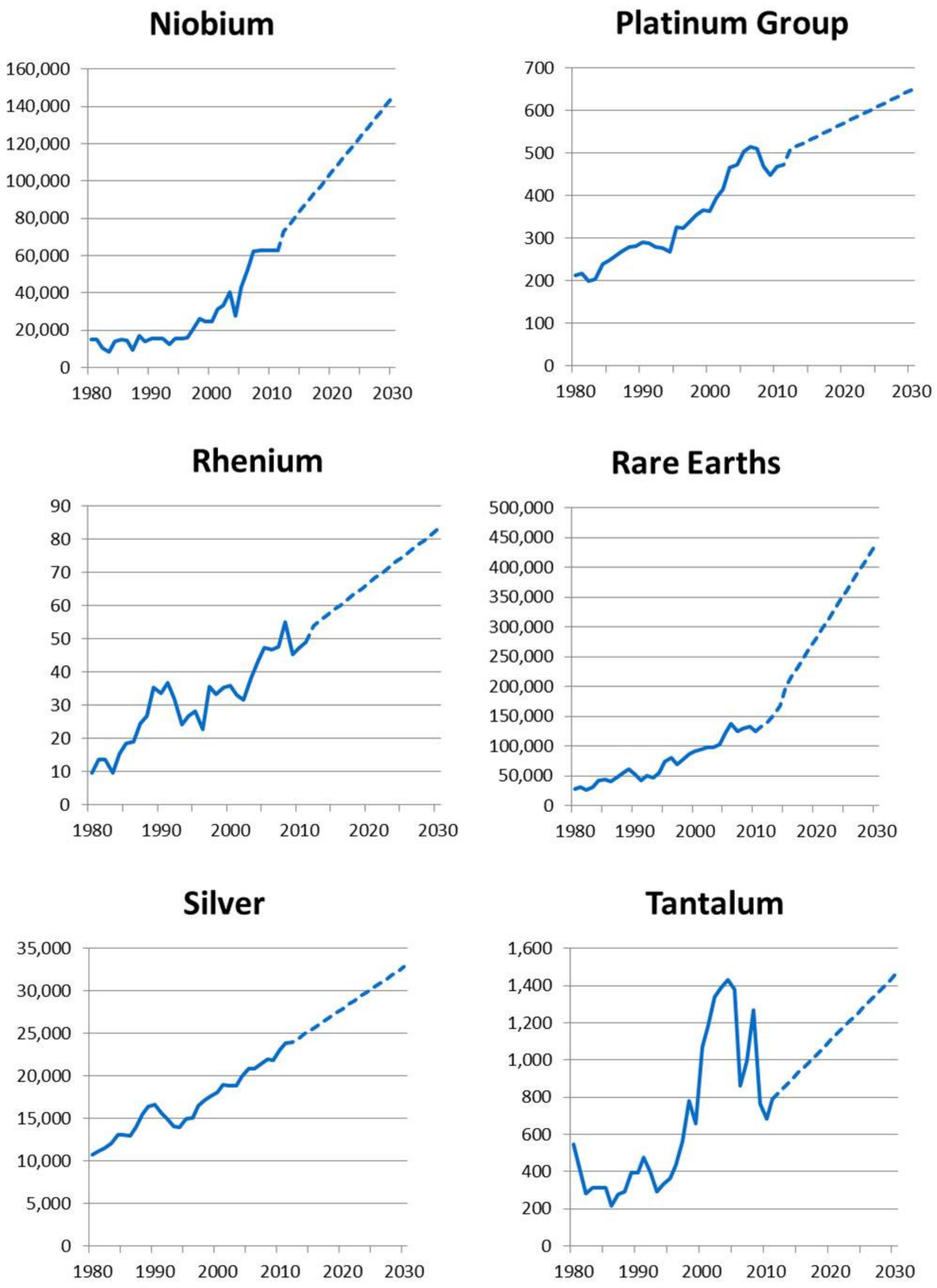
*Source: USGS, 2011a; projections thereafter.*

*Figure A3.3: Metal production trends for lead, lithium, magnesium, manganese, molybdenum & nickel (tonnes)*



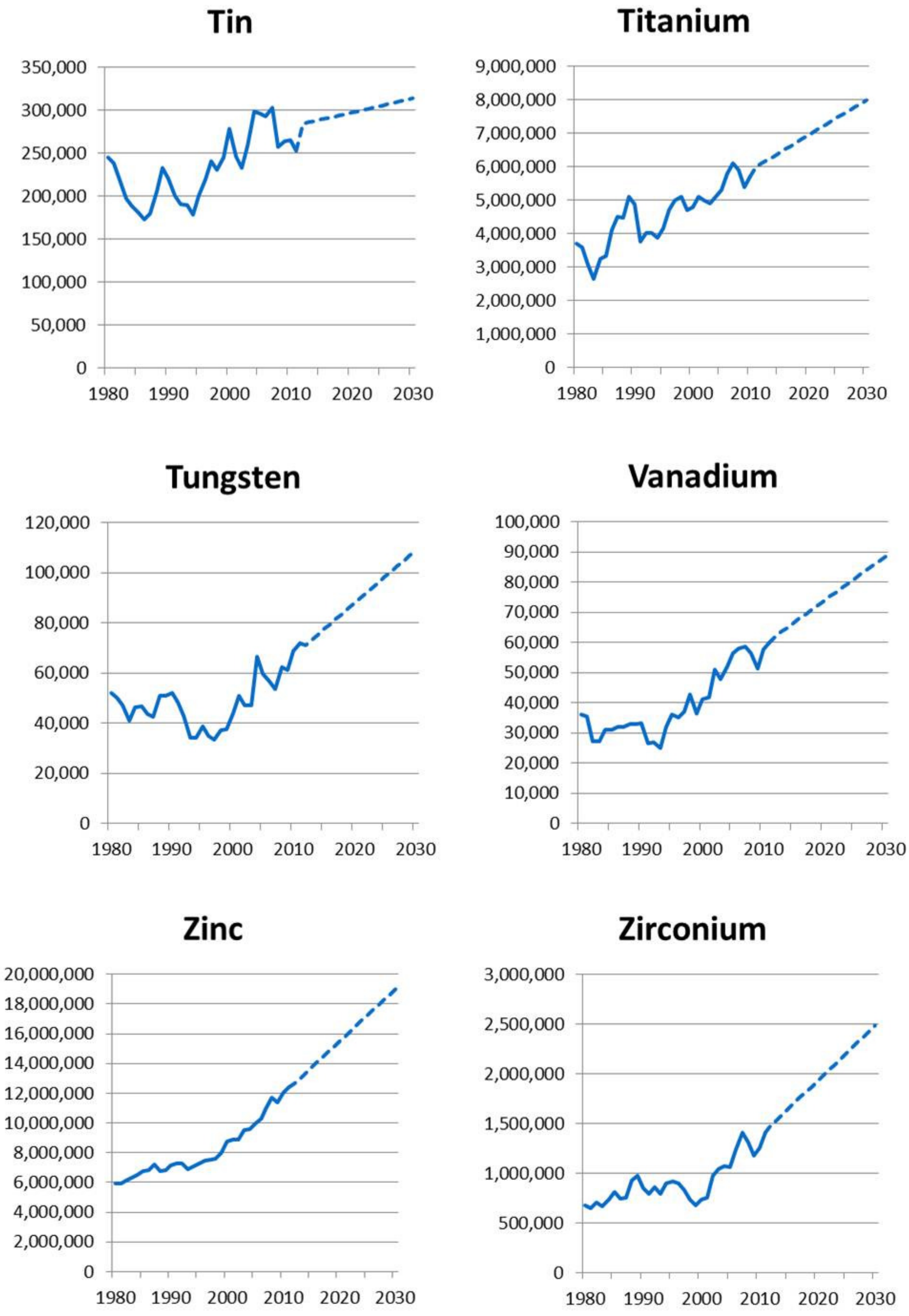
*Source: USGS, 2011a, except lithium; BGS, 2012b; projections thereafter.*

*Figure A3.4: Metals production trends for niobium, PGMs, rhenium, rare earths, silver & tantalum (tonnes)*



*Source: USGS, 2011a; projections thereafter.*

*Figure A3.5: Metals production trends for tin, titanium, tungsten, vanadium, zinc & zirconium (tonnes)*



*Source: USGS, 2011a, except titanium; BGS, 2012b; projections thereafter.*

# Appendix 4: Recycled Metals Statistics

## Purpose

In addition to the virgin or primary supply of raw materials, for some metals secondary or recycled sources represent a significant proportion of world production. It is important that the world supply estimates within the report reflect this in order to present an adequate comparison to EU demand for the decarbonisation technologies.

The recent study by the United Nations Environment Programme reviewed data on the recycling rates for metals, including old scrap ratios, recycled content and end-of-life recycling rates (UNEP, 2011). The study investigated 60 metals in total, and is the first comprehensive study of this nature. The results of the study gave indicative ranges of the recycling rates for the metals where data of sufficient quality was available. Some of the references identified differing recycling rates for the same metal, or were based upon a US or EU reference rather than a world estimate.

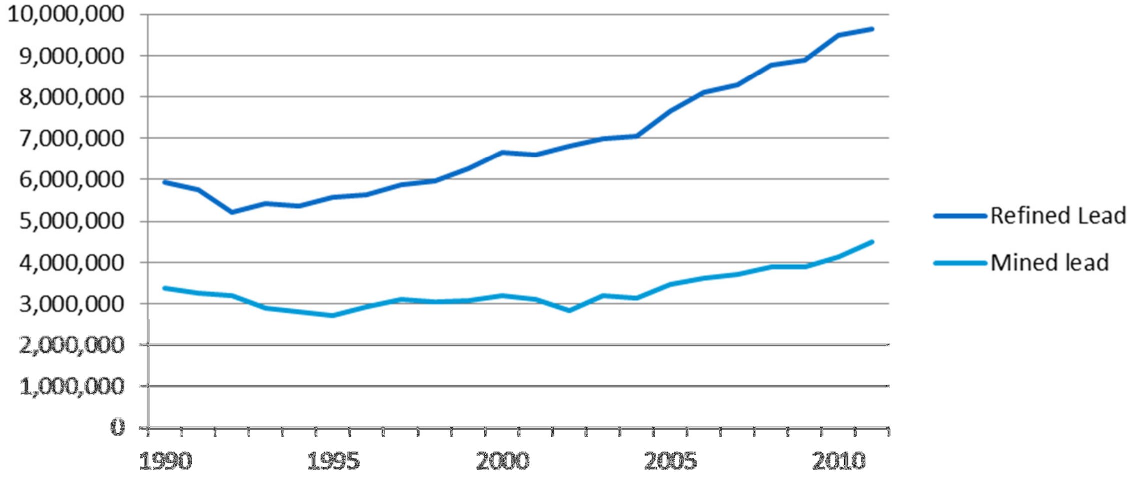
In light of these issues, it was deemed appropriate to search for additional data, rather than simply use the recycling rate percentages suggested by (UNEP, 2011), and apply these to primary production to get a world supply estimate that include production from recycled sources. Nonetheless, the study does help identify the metals with the highest recycling rates. These include: aluminium, chromium, cobalt, copper, gold, iron, lead, magnesium, manganese, molybdenum, nickel, niobium, platinum group metals, rhenium, silver, tin, titanium, tungsten and zinc. In addition, metals such as gallium, germanium and indium have high recycled content rates but not high end-of-life recycling rates (UNEP, 2011).

## Methodology and data

This study therefore searched for historical time-series data for recycled supply of these metals. This data can then be projected and added to the long-term supply projections shown in Appendix 3:

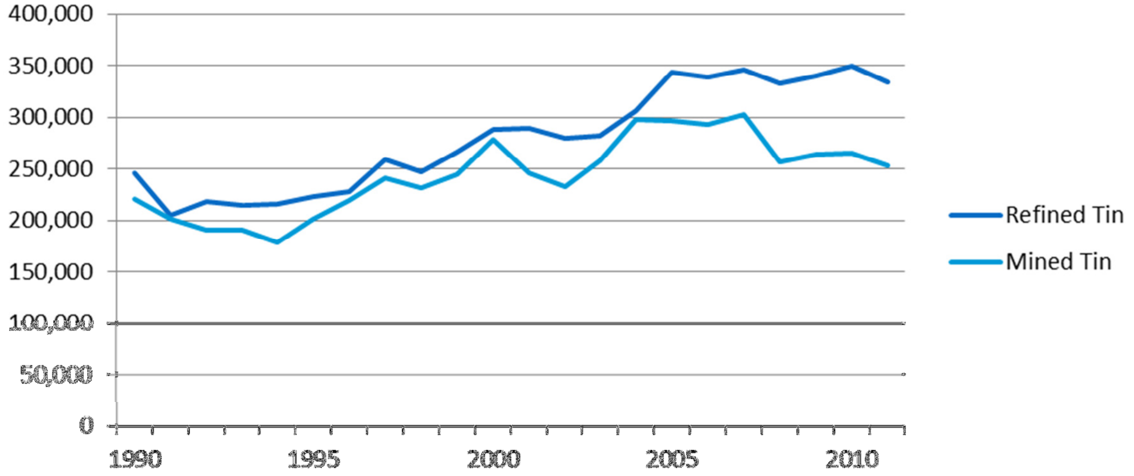
- For base metals such as cobalt, copper, lead, tin and zinc; the USGS provides statistics for refined production, as well as mine production (USGS, 2011a). In the case of lead, refined production is approximately twice that of mine production, owing to the very high recycling rate of lead acid batteries (Figure A4.1). In the cases of copper and tin, refinery production is approximately 20-30% higher than mined production (Figure A4.2 and Figure A4.3). For zinc the difference is relatively small, and refined production of cobalt is actually lower than its mined production.
- For precious metals such as gold, silver and PGMs; data is publicly available and collected by a reputable source. For gold and silver, GFMS began collecting data on recycled supply from 2002 on behalf of the World Gold Council and Silver Institute respectively. Recycled sources represent around a quarter to a third of annual production for these metals (Figure A4.4 and Figure A4.5). For the platinum group metals, data on recycled supply is collected by Johnson Matthey for platinum, palladium and rhodium of which platinum is of the greatest interest for this study (Figure A4.6). Again, recycled supply represents around a quarter to a third of annual platinum production.
- For the other metals data is much less readily available. For some metals such as gallium and indium, data published by the US Department of Energy includes estimates of reclaim or secondary production (Bauer et al., 2011). Some estimates are available for metals such as germanium, rhenium and tellurium but not typically from an independent source (International Study Group for Nickel et al., 2012). Allowance has been made for this data, given the importance of these metals in this report. For other metals no similar data was identified, other than that listed in (UNEP, 2011), so recycled content estimates have been conservatively applied where the data was deemed to be sufficiently robust (Table A4.1). This may reflect the use of these metals as alloying elements, where recovery is often of the alloy rather than the metal. Further research in this area may therefore be considered to be appropriate.

*Figure A4.1: Statistics for world mine and refinery production of lead (tonnes)*



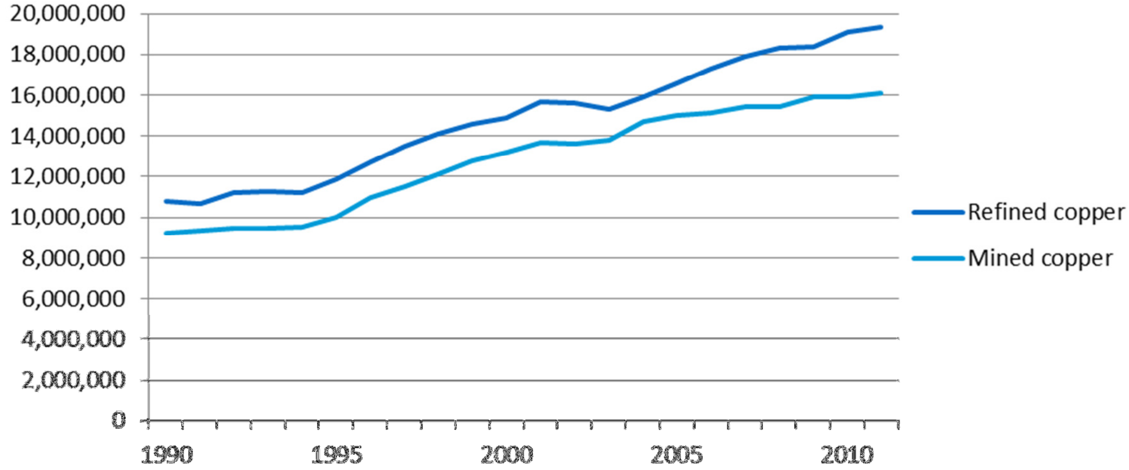
*Source: USGS, 2011a*

*Figure A4.2: Statistics for world mine and refinery production of tin (tonnes)*



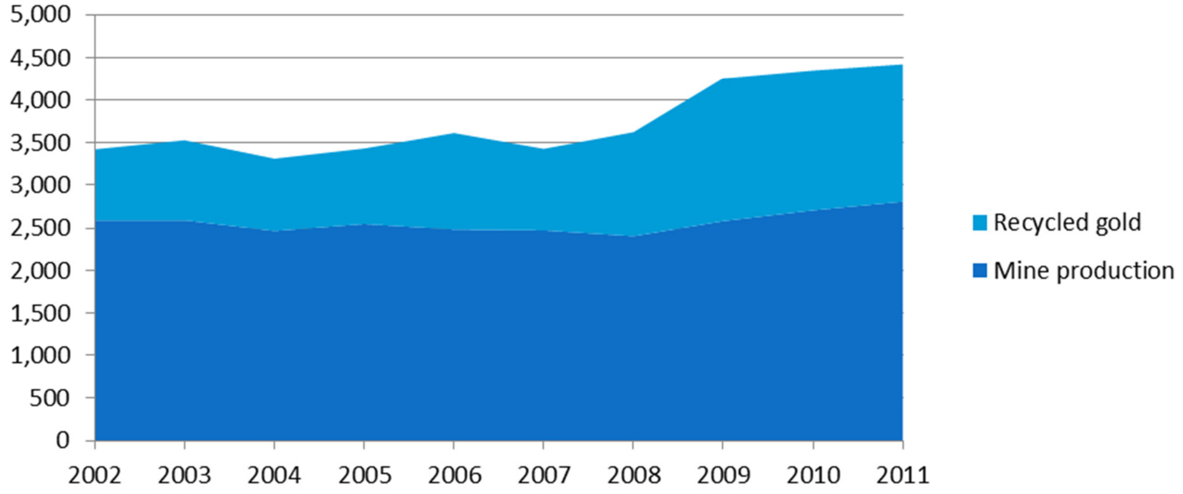
*Source: USGS, 2011a*

*Figure A4.3: Statistics for world mine and refinery production of copper (tonnes)*



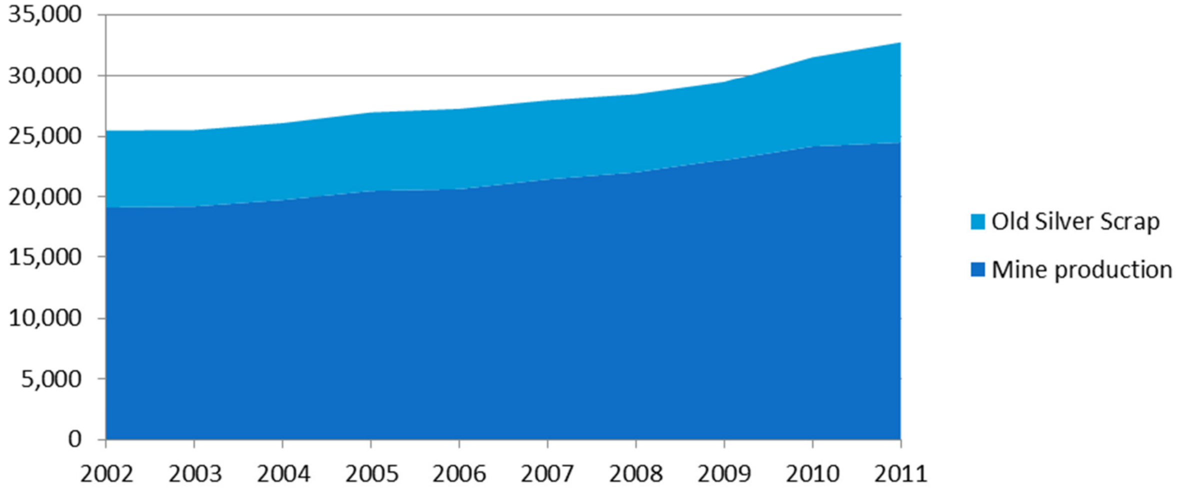
*Source: USGS, 2011a*

Figure A4.4: Statistics for world mine and recycled gold production



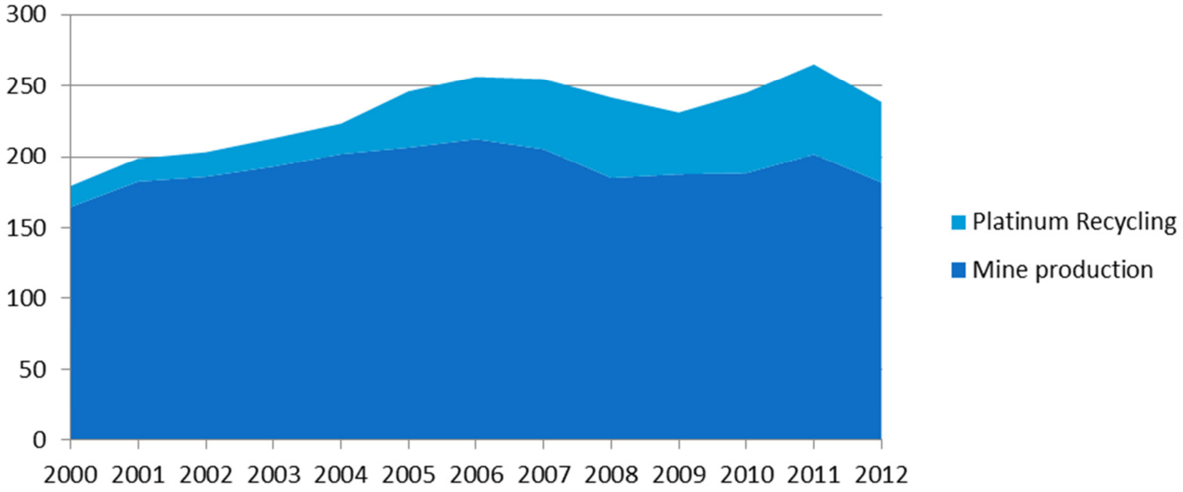
*Source: Thomson Reuters GFMS, 2012*

*Figure A4.5: Statistics for world mine and recycled silver production*



*Source: Silver Institute & GFMS, 2012*

*Figure A4.6: Statistics for world mine and recycled platinum production*



*Source: Johnson Matthey, 2012*

*Table A4.1: Metals for which recycled production has been included, 2011 production (tonnes)*

| **Metal** | | **Primary Production** | **Secondary Production** | **Total Production** | **Recycled Sources (%)** | **Key Reference** |
|---|---|---|---|---|---|---|
| Antimony | Sb | 169,000 | 29,800 | 198,800 | 15 | (UNEP, 2011) |
| Beryllium | Be | 240 | 60 | 300 | 20 | (UNEP, 2011) |
| Cadmium | Cd | 21,500 | 9,200 | 30,700 | 30 | (UNEP, 2011) |
| Chromium | Cr | 7,320,000 | 1,825,000 | 9,145,000 | 20 | (UNEP, 2011) |
| Cobalt | Co | 98,000 | 32,700 | 130,700 | 25 | (UNEP, 2011) |
| Copper | Cu | 16,100,000 | 3,677,000 | 19,777,000 | 19 | (USGS, 2011a) |
| Gallium | Ga | 216 | 72 | 288 | 25 | (International Study Group for Nickel et al., 2012) |
| Germanium | Ge | 118 | 79 | 197 | 40 | (International Study Group for Nickel et al., 2012) |
| Gold | Au | 2,700 | 1,610 | 4,310 | 37 | (Thomson Reuters GFMS, 2012) |
| Indium | In | 640 | 720 | 1,360 | 53 | (International Study Group for Nickel et al., 2012) |
| Lead | Pb | 4,500,000 | 5,156,000 | 9,656,000 | 53 | (USGS, 2011a) |
| Magnesium | Mg | 780,000 | 334,300 | 1,114,300 | 30 | (UNEP, 2011) |
| Manganese | Mn | 14,000,000 | 6,895,500 | 20,895,500 | 33 | (UNEP, 2011) |
| Molybdenum | Mo | 250,000 | 83,300 | 333,300 | 25 | (UNEP, 2011) |
| Nickel | Ni | 1,800,000 | 886,500 | 2,686,500 | 33 | (UNEP, 2011) |
| Niobium | Nb | 63,000 | 15,750 | 78,750 | 20 | (UNEP, 2011) |
| Rhenium | Re | 49 | 16 | 65 | 25 | (International Study Group for Nickel et al., 2012) |
| Silver | Ag | 23,800 | 8,250 | 32,050 | 26 | (Silver Institute & GFMS, 2012) |
| Tantalum | Ta | 790 | 198 | 988 | 20 | (UNEP, 2011) |
| Tellurium | Te | 683 | 59 | 742 | 8 | (International Study Group for Nickel et al., 2012) |
| Tin | Sn | 253,000 | 81,150 | 334,150 | 24 | (USGS, 2011a) |
| Titanium[#] | Ti | 6,000,000 | 0 | 6,000,000 | 0 | (UNEP, 2011) |
| Tungsten | W | 72,000 | 48,000 | 120,000 | 40 | (UNEP, 2011) |
| Zinc | Zn | 12,400,000 | 3,100,000 | 15,500,000 | 20 | (UNEP, 2011) |
| | | | | | | |
| Platinum | Pt | 195 | 64 | 259 | 25 | (Johnson Matthey, 2012) |
| Palladium | Pd | 204 | 73 | 277 | 26 | (Johnson Matthey, 2012) |
| Rhodium | Rh | 31 | 9 | 40 | 22 | (Johnson Matthey, 2012) |
| Ruthenium | Ru | 34 | 34 | 67 | 50 | (UNEP, 2011) |
| Iridium | Ir | 8 | 1 | 9 | 15 | (UNEP, 2011) |
| | | | | | | |
| Lanthanum | La | 33,896 | 1,784 | 35,680 | 5 | (UNEP, 2011) |
| Cerium | Ce | 45,923 | 2,417 | 48,340 | 5 | (UNEP, 2011) |
| Praseodymium | Pr | 6,451 | 340 | 6,790 | 5 | (UNEP, 2011) |
| Neodymium | Nd | 21,869 | 1,151 | 23,020 | 5 | (UNEP, 2011) |
| Dysprosium | Dy | 1,748 | 92 | 1,840 | 5 | (UNEP, 2011) |

*# Estimate for titanium recycled content from (UNEP, 2011) was not applied, as primary production is for $TiO_2$ content not titanium*

*Sources: See references in Chapter 4 and Appendix 4 for data referring to primary production*

# Appendix 5: Political Risk Ratings

This appendix provides the political risk ratings that have been derived from Fund for Peace Failed States Index and World Bank Worldwide Governance Indicator for 2011. The original scores have been rescaled to ensure that they are between 0 and 100, with a high score corresponding to a high risk.

*Table A5.1: Failed States Index (FSI), 2011*

| Country | FSI |
|---|---|
| Somalia | 100.0 |
| Chad | 96.6 |
| Sudan | 95.0 |
| Congo (Kinshasa) | 94.4 |
| Haiti | 94.2 |
| Zimbabwe | 94.1 |
| Afghanistan | 93.7 |
| Central African Republic | 91.0 |
| Iraq | 90.8 |
| Côte d'Ivoire | 88.6 |
| Guinea | 88.3 |
| Pakistan | 88.1 |
| Yemen | 86.0 |
| Nigeria | 85.5 |
| Niger | 84.7 |
| Kenya | 84.2 |
| Burundi | 84.2 |
| Myanmar | 83.8 |
| Guinea Bissau | 83.8 |
| Ethiopia | 83.7 |
| Uganda | 81.7 |
| North Korea | 81.0 |
| Timor-Leste | 80.3 |
| Cameroon | 79.9 |
| Bangladesh | 79.7 |
| Liberia | 79.2 |
| Nepal | 78.9 |
| Eritrea | 78.8 |
| Sri Lanka | 78.3 |
| Sierra Leone | 77.2 |
| Kyrgyzstan | 77.0 |
| Congo (Republic) | 76.5 |
| Malawi | 76.2 |
| Rwanda | 76.1 |
| Iran | 75.2 |
| Togo | 74.3 |
| Burkina Faso | 73.5 |
| Cambodia | 73.4 |
| Tajikistan | 73.2 |
| Uzbekistan | 73.1 |
| Equatorial Guinea | 72.9 |
| Mauritania | 72.8 |
| Lebanon | 72.6 |
| Colombia | 71.8 |
| Egypt | 71.6 |
| Laos | 71.5 |
| Georgia | 71.1 |
| Syria | 70.6 |
| Solomon Islands | 70.6 |
| Bhutan | 69.7 |
| Philippines | 69.7 |
| Angola | 69.3 |
| Israel | 69.1 |
| Papua New Guinea | 68.8 |
| Zambia | 68.4 |
| Comoros | 68.4 |
| Mozambique | 68.2 |
| Madagascar | 67.8 |
| Bolivia | 67.4 |
| Djibouti | 67.1 |
| Swaziland | 67.0 |
| Ecuador | 66.7 |
| Azerbaijan | 66.4 |
| Indonesia | 66.0 |
| Tanzania | 65.7 |
| Moldova | 65.6 |
| Nicaragua | 65.6 |
| Fiji | 65.5 |
| Gambia | 65.3 |
| Bosnia and Herzegovina | 65.3 |
| Lesotho | 64.7 |
| China | 64.4 |
| Guatemala | 64.4 |
| Benin | 64.4 |
| Turkmenistan | 64.0 |
| India | 63.6 |
| Mali | 63.5 |
| Honduras | 62.6 |
| Thailand | 62.5 |
| Venezuela | 62.4 |
| Algeria | 62.2 |
| Russia | 61.9 |
| Belarus | 61.8 |
| Dominican Republic | 61.0 |
| Senegal | 60.9 |
| Cuba | 60.7 |
| Morocco | 60.3 |
| Vietnam | 60.1 |

| Country | FSI |
|---|---|
| El Salvador | 60.1 |
| Cape Verde | 59.9 |
| Maldives | 59.7 |
| Gabon | 59.3 |
| Saudi Arabia | 59.2 |
| Mexico | 59.1 |
| Turkey | 58.9 |
| Jordan | 58.5 |
| Sao Tome | 58.5 |
| Serbia | 58.3 |
| Peru | 57.5 |
| Guyana | 56.4 |
| Paraguay | 56.2 |
| Armenia | 56.1 |
| Micronesia | 55.7 |
| Namibia | 55.5 |
| Suriname | 54.8 |
| Macedonia | 54.7 |
| Kazakhstan | 53.9 |
| Tunisia | 53.8 |
| Samoa | 53.1 |
| Ukraine | 52.6 |
| Libya | 52.3 |
| Malaysia | 52.3 |
| Botswana | 51.4 |
| Belize | 51.2 |
| Ghana | 51.2 |
| Cyprus | 51.1 |
| South Africa | 51.1 |
| Jamaica | 50.6 |
| Seychelles | 50.4 |
| Grenada | 49.8 |
| Albania | 49.5 |
| Brunei | 49.2 |
| Brazil | 48.4 |
| Trinidad and Tobago | 46.9 |
| Antigua & Barbuda | 42.8 |
| Romania | 42.8 |
| Mongolia | 42.6 |
| Kuwait | 42.5 |
| Bahrain | 41.9 |
| Bulgaria | 41.9 |
| Panama | 40.6 |
| Croatia | 40.1 |
| Bahamas | 39.3 |
| Montenegro | 39.0 |
| Latvia | 36.8 |
| Barbados | 35.3 |
| Costa Rica | 33.0 |
| United Arab Emirates | 32.7 |
| Qatar | 31.8 |

| Country | FSI |
|---|---|
| Estonia | 31.6 |
| Oman | 31.5 |
| Hungary | 30.9 |
| Greece | 29.6 |
| Slovakia | 29.3 |
| Argentina | 28.9 |
| Poland | 28.9 |
| Italy | 27.8 |
| Malta | 27.5 |
| Lithuania | 27.3 |
| Mauritius | 26.1 |
| Spain | 25.0 |
| Czech Republic | 24.2 |
| Chile | 22.4 |
| Uruguay | 22.1 |
| South Korea | 20.4 |
| Slovenia | 16.9 |
| Singapore | 16.4 |
| United States | 16.1 |
| United Kingdom | 15.3 |
| Belgium | 15.3 |
| France* | 15.3 |
| Germany | 15.2 |
| Portugal | 13.5 |
| Japan | 12.0 |
| Iceland | 11.1 |
| Netherlands | 9.2 |
| Australia | 9.0 |
| Canada | 8.5 |
| Austria | 8.1 |
| Luxembourg | 6.8 |
| Ireland | 6.0 |
| New Zealand | 5.5 |
| Denmark | 4.4 |
| Switzerland | 3.7 |
| Sweden | 3.3 |
| Norway | 0.8 |
| Finland | 0.0 |

*New Caledonia as overseas territory

Source: (Fund for Peace, n.d.)

Table A5.2: Worldwide Governance Indicators, 2011

| Country | WGI |
|---|---|
| Somalia | 99.5 |
| Myanmar | 96.8 |
| Afghanistan | 96.6 |
| Congo (Kinshasa) | 96.4 |
| Sudan | 95.1 |
| Zimbabwe | 94.9 |
| North Korea | 93.1 |
| Chad | 92.6 |
| Iraq | 91.7 |
| Venezuela | 89.9 |
| Uzbekistan | 89.5 |
| Guinea | 89.4 |
| Central African Republic | 88.9 |
| Turkmenistan | 88.8 |
| Côte d'Ivoire | 88.6 |
| Eritrea | 87.5 |
| Equatorial Guinea | 87.4 |
| Haiti | 87.3 |
| Burundi | 87.3 |
| Tajikistan | 86.4 |
| Yemen | 86.1 |
| Libya | 85.2 |
| Nigeria | 84.8 |
| Iran | 84.6 |
| Congo (Republic) | 84.3 |
| Angola | 84.3 |
| Guinea-Bissau | 84.2 |
| Belarus | 82.1 |
| Laos | 81.4 |
| Comoros | 81.3 |
| Cameroon | 80.0 |
| Togo | 79.9 |
| Pakistan | 79.8 |
| Mauritania | 78.9 |
| Cambodia | 78.5 |
| Timor-Leste | 78.4 |
| Syria | 78.3 |
| Nepal | 78.2 |
| Kyrgyzstan | 77.8 |
| Bangladesh | 77.6 |
| Ecuador | 77.4 |
| Ethiopia | 77.3 |
| Azerbaijan | 77.3 |
| Algeria | 76.7 |
| Liberia | 75.3 |
| Fiji | 74.7 |
| Russia | 73.6 |
| Sierra Leone | 73.6 |
| Papua New Guinea | 73.1 |
| Nicaragua | 72.8 |
| Paraguay | 72.2 |
| Madagascar | 71.6 |
| Niger | 71.5 |
| Kenya | 71.1 |
| Honduras | 69.9 |
| Gabon | 69.4 |
| Guatemala | 69.4 |
| Ukraine | 69.0 |
| Djibouti | 68.6 |
| Cook islands | 67.9 |
| Lebanon | 67.9 |
| Bolivia | 67.9 |
| Uganda | 67.5 |
| Kosovo | 66.1 |
| Gambia | 66.0 |
| Egypt | 65.9 |
| Philippines | 65.6 |
| Vietnam | 65.5 |
| Solomon Islands | 65.3 |
| Kazakhstan | 65.1 |
| Swaziland | 64.9 |
| China | 64.8 |
| Indonesia | 64.4 |
| Mali | 64.0 |
| Cuba | 63.6 |
| Senegal | 63.2 |
| Dominican Republic | 63.0 |
| West bank Gaza | 62.3 |
| Moldova | 61.9 |
| Zambia | 61.2 |
| Sao tome and Principe | 61.2 |
| Guyana | 60.7 |
| Bosnia and Herzegovina | 59.9 |
| Sri Lanka | 59.8 |
| Tanzania | 59.8 |
| Niue | 59.6 |
| Benin | 59.5 |
| Argentina | 58.5 |
| Maldives | 58.1 |
| Armenia | 58.0 |
| Thailand | 57.6 |
| India | 57.5 |
| Burkina Faso | 57.4 |
| Mongolia | 57.1 |
| Morocco | 57.0 |
| Malawi | 56.9 |
| Colombia | 56.9 |
| Mozambique | 56.5 |
| Peru | 55.6 |
| Saudi Arabia | 55.1 |
| Rwanda | 54.8 |
| Mexico | 54.4 |
| Albania | 54.0 |
| Suriname | 52.8 |
| Lesotho | 52.6 |
| Serbia | 52.2 |
| Belize | 51.9 |
| El Salvador | 51.7 |
| Tunisia | 51.4 |
| Macedonia | 51.2 |

| Country | WGI |
|---|---|
| Marshall Islands | 50.8 |
| Jordan | 50.7 |
| Jamaica | 50.5 |
| Turkey | 49.6 |
| Georgia | 49.2 |
| Kiribati | 48.7 |
| Tonga | 47.9 |
| Bhutan | 47.0 |
| Micronesia | 46.4 |
| Panama | 45.0 |
| Bahrain | 44.7 |
| Montenegro | 44.7 |
| Ghana | 44.2 |
| Trinidad and Tobago | 44.2 |
| Palau | 43.6 |
| Brazil | 43.4 |
| Kuwait | 43.3 |
| Seychelles | 42.7 |
| Tuvalu | 42.0 |
| Romania | 41.6 |
| Nauru | 41.3 |
| Bulgaria | 41.1 |
| South Africa | 40.7 |
| Vanuatu | 40.5 |
| Oman | 39.7 |
| Malaysia | 39.4 |
| Namibia | 38.5 |
| Samoa | 38.4 |
| Greece | 37.0 |
| United Arab Emirates | 36.4 |
| Croatia | 35.3 |
| Cape Verde | 34.6 |
| Grenada | 34.6 |
| Israel | 33.8 |
| Italy | 32.8 |
| Puerto Rico | 30.0 |
| Costa Rica | 30.0 |
| Botswana | 29.9 |
| Qatar | 29.8 |
| Guam | 29.6 |
| Latvia | 29.3 |
| South Korea | 27.9 |
| Brunei | 27.7 |
| Lithuania | 27.4 |
| Mauritius | 27.4 |
| Martinique | 27.2 |
| Hungary | 26.8 |
| Dominica | 26.3 |
| American Samoa | 26.1 |
| Macao | 25.5 |
| Slovakia | 25.3 |
| Virgin islands | 24.6 |
| Antigua and Barbuda | 24.6 |
| Netherlands Antilles | 24.3 |
| Uruguay | 24.1 |
| Spain | 24.0 |
| Poland | 24.0 |
| St. Vincent and the Grenadines | 22.9 |
| Bahamas | 22.8 |
| St. Kitts and Nevis | 22.6 |
| St. Lucia | 22.3 |
| Slovenia | 22.0 |
| Reunion | 21.6 |
| Taiwan | 21.6 |
| Czech Republic | 21.3 |
| French Guiana | 20.7 |
| Portugal | 20.5 |
| Cayman Islands | 18.7 |
| Cyprus | 18.2 |
| Estonia | 17.8 |
| United States | 16.4 |
| Chile | 16.1 |
| Bermuda | 16.1 |
| Barbados | 15.9 |
| Japan | 15.2 |
| France* | 14.0 |
| Singapore | 13.7 |
| Malta | 13.3 |
| Hong Kong | 12.6 |
| United Kingdom | 12.6 |
| Belgium | 12.3 |
| Aruba | 12.1 |
| Anguilla | 10.9 |
| Greenland | 10.8 |
| Iceland | 10.3 |
| Germany | 10.3 |
| Andorra | 9.4 |
| Ireland | 9.2 |
| Australia | 7.9 |
| Canada | 6.6 |
| Netherlands | 6.2 |
| Austria | 5.9 |
| Liechtenstein | 4.8 |
| Switzerland | 4.3 |
| Luxembourg | 4.1 |
| Norway | 3.7 |
| New Zealand | 3.4 |
| Denmark | 3.2 |
| Sweden | 3.2 |
| Finland | 2.0 |

*New Caledonia as overseas territory

Source: (World Bank, 2011)

# Appendix 6: Summaries of High-Rated Critical Metals

## A.6.1 Rare earth elements

### Supply

***Common sources***

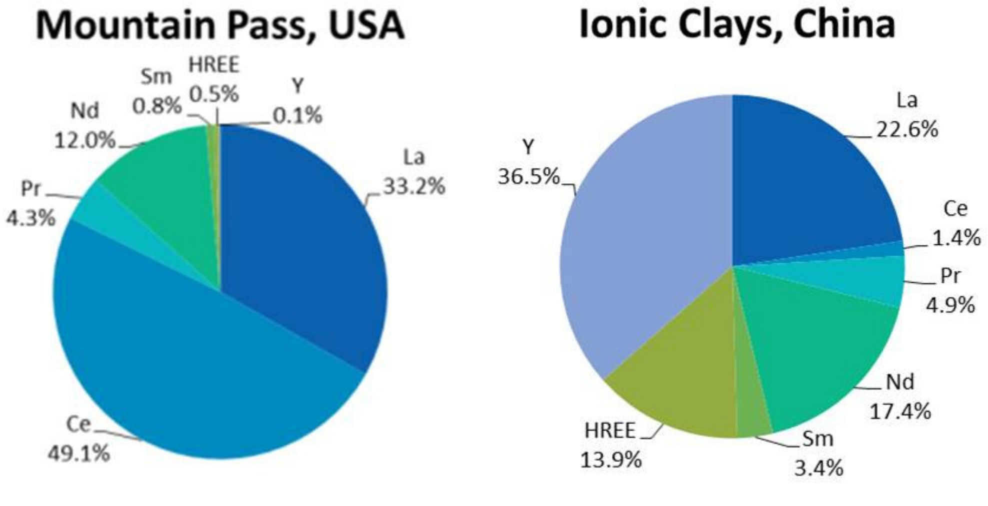
Rare earth elements are a group of metallic elements, which include lanthanum and the 14 lanthanides. Due to some chemical and physical properties, scandium and yttrium are often considered as rare earth elements as well, with yttrium generally classed as a heavy rare earth element. Rare earth elements are all metallic in nature and are typically discussed together due to their similar chemical and physical properties, and because they are often obtained from the same ore deposits, although the ratios do differ considerably between different deposit types. See for example the comparison between the rare earth composition of the Mountain Pass deposit in the United States to that of the heavy rare earth enriched Chinese ionic clays deposits (Figure A6.1).

Despite their name, rare earth elements are not particularly uncommon, just relatively widely distributed in the earth's crust. Rare earth reserves are estimated at 110 million tonnes (Table A6.1), with world resources of over 160 million tonnes (USGS, 2010b).

The major ore types from which rare earths are currently produced are bastnäsite, ionic clays and monazite. Rare earth elements are sometimes produced as a by-product from other metals. The world's largest rare earth mine, Bayan Obo in Inner Mongolia, China, produces rare earths as a by-product of iron ore mining. Bayan Obo represented around 45% of world supply of rare earths in 2010, with the remaining 55% of world rare earth production obtained from primary production (Lynas Corporation Ltd, 2010). A number of potential rare earth producers would also be from various poly-metallic or by-product sources including zirconium-hafnium, niobium-tantalum, phosphates, tin and titanium.

Within this Appendix the focus will be on six specific rare earth elements, namely: praseodymium, neodymium, europium, terbium, dysprosium and yttrium, which were identified as being the critical for the implementation of the EU path to the decarbonisation of the energy sector.

*Figure A6.1: Rare earth compositions of Mountain Pass versus Chinese Ionic Clays*



*Source: USGS, 2011c; Rare Earths 2009 Minerals Yearbook; HREE =Heavy Rare Earth Elements*

### *World production*

Mine production of rare earths was estimated by the USGS at 133,000 tonnes in 2010, of which over 95% originated in China (Table A6.1). Other producing countries include India, Brazil and Malaysia. The estimated elemental composition of world rare earth supply is shown in Figure A6.2, based upon a world production of 125,000 tonnes as estimated by Lynas. For the rare earth elements of interest estimated world production is the following:

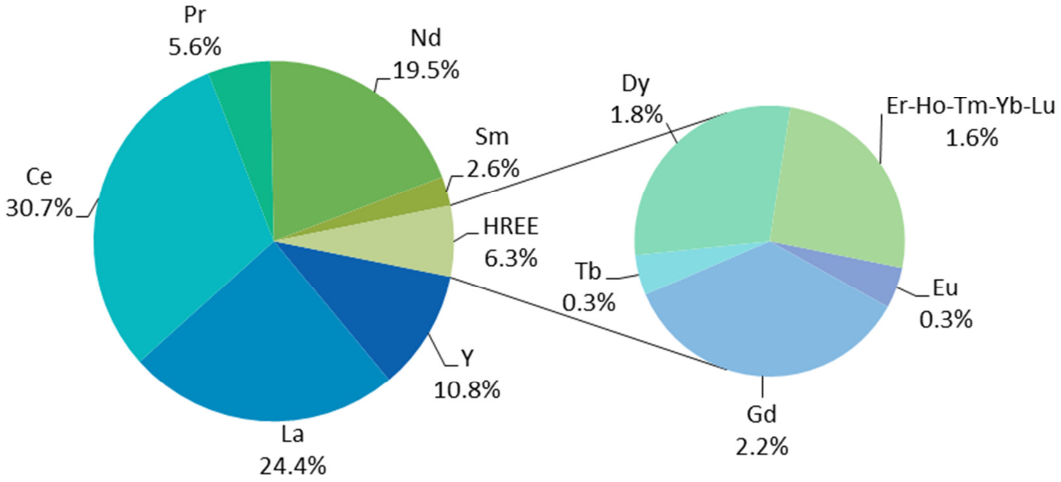
- Neodymium and praseodymium represent 25% of world rare earths supply or 31,400 tonnes.
- Yttrium supply is estimated at 13,500 tonnes or 11% of world rare earth supply.
- Europium, terbium and dysprosium supply totals only around 3,000 tonnes per year.

*Table A6.1: Worldwide rare earth mine production and reserves, 2010 & 2011 (tonnes)*

| **Country** | **Mine Production** | | **Reserves** |
|---|---|---|---|
| | **2010** | **2011e** | |
| Australia | — | — | 1,830,000 |
| Brazil | 550 | 550 | 48,000 |
| China | 130,000 | 130,000 | 55,000,000 |
| CIS | NA | NA | 19,000,000 |
| India | 2,800 | 3,000 | 3,100,000 |
| Malaysia | 30 | 30 | 30,000 |
| Other countries | NA | NA | 22,000,000 |
| United States | — | — | 13,000,000 |
| **World total** | **133,000** | **133,000** | **110,000,000** |

*Source: USGS, 2012*

*Figure A6.2: Rare earth supply by element, 2010 (tonnes)*



*Source: Lynas Corporation Ltd, 2010*

In terms of the supply outlook, some expansions in capacity are expected at the Chinese mines in Inner Mongolia (Baotou) and Sichuan, although considerable uncertainty exists regarding production in the Ionic clays regions of Southern China. Currently a considerable proportion of this production comes from small or illegal mines, which are coming under regulation and may lead to a large reduction in supply from these sources (Table A6.2). As might be expected given the recent high prices in rare earth elements, there is considerable exploration activity underway with dozens of prospects currently being explored. World supply is forecast to expected increase to at least 175,000 tonnes by 2014 (Table A6.3), although some other forecasters are more optimistic (Hatch, 2011).

*Table A6.2: Outlook for rare earths supply 2010 to 2014 (tonnes)*

| Mine | 2010 | 2014 | Comments |
|---|---|---|---|
| Baotou | 55,000 | 60,000 | Tailing facilities near capacity, limited by iron ore mining |
| Sichuan | 10,000 | 15,000 | Target to increase separation following refurbishment |
| Ionic clay regions | 45,000 | 40,000 | Large amount of illegal mining – but could be reduced to 20,000t |
| Mountain Pass | 3,000 | 20,000 | Molycorp, United States, expansion and reopening of the mine |
| Mount Weld | | 22,000 | New mine under construction and near start-up by Lynas, Australia |
| Recycling | 5,000 | 6,000 | |
| Russia | 4,000 | 4,000 | |
| India | 3,000 | 4,000 | Indian Rare Earths Ltd. |
| Vietnam | | 4,000 | Toyota led Joint Venture |
| Total | 125,000 | 175,000 | |

*Source: Lynas Corporation Ltd, 2010*

***Leading companies***

The two largest producers of rare earths in China are Baotou Rare Earth Group in Inner Mongolia, with an estimated production of 55,000 tonnes for 2010, and Hanglong Group in Sichuan at 10,000 tonnes (Table A6.2). Rare earth production in the Ionic clays regions of Southern China in highly fragmented, with at least 30 other companies listed within official production or export quotas, and further illegal production widely reported. The leading current rare earths producers outside of China are Lovozersky Mining Company (Russia), Indian Rare Earths and Industrias Nucleares do Brasil.

Given the level of exploration and mine development activity underway for rare earths, it is useful to provide commentary regarding the major future suppliers. There are dozens of prospects currently being explored, although in reality, given the size of the rare earths market and the economic viability of each of these, only a limited number can be expected to reach commercialisation. A complete list of the most advanced rare earth projects[23] is provided by Technology Metals Research, and consists of 43 advanced rare earth projects by 40 different companies in 13 different countries (Technology Metals Research, n.d.). In addition, at least four different joint venture projects involving major Japanese corporations are known to be in the pipeline (Ernst & Young, 2011). Norra Kärr, owned by Tasman Metals, is of note as the only advanced rare earths project located within the EU.

In an assessment of the most likely commercial mines, IMCOA identify Mountain Pass owned by Molycorp (United States) and Mount Weld owned by Lynas (Australia), as representing the most important new suppliers (Kingsnorth, IMCOA, 2012). Table A6.2 includes these tonnages in projected 2014 world supply estimates, alongside a Toyota-led joint venture in Vietnam. Other projects that are deemed to be closest to commercial production or more near-to-market prospects include: Steenkampskraal owned by Great Western Minerals Group (South Africa); a Sumitomo led joint venture in Kazakhstan; and Dubbo owned by Alkane Resources (Australia). Dubbo is noted as being the only project from these with a significant proportion of heavy rare earth elements within its composition.

***Processing routes***

Extraction and refining of rare earths from ore is complex due to the similar properties of the metals. This processing for each ore body requires specific technology unique for that particular deposit to be developed in order to extract and separate the individual rare earth elements. Once the rare earth-containing

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[23] Advanced projects are defined as where either the mineral resource or reserves have been formally defined or where the project has been subject to past mining campaigns for which reliable historic data is available

ore is obtained, a complex multistage process is required, which uses small differences in solubility to isolate each metal as its oxide; rare earths are typically supplied as an oxide. Bastnäsite (RE-$CO_3F$) is the most important mineral source of Rare Earth oxide (REO) production, representing the majority of Rare Earth resources worldwide. Extraction can occur through typical mining processes, however other techniques are also used which employ acid leeching to extract the rare earth ores in situ, causing environmental concern over the production of these metals.

For the bastnäsite, the process of mining and beneficiating of REO consists of the following steps:

- mining of the ore
- mineral concentration by froth floatation
- extraction of Rare Earth into concentrate subgroups (cracking)
- separation of individual Rare Earth by solvent extraction.

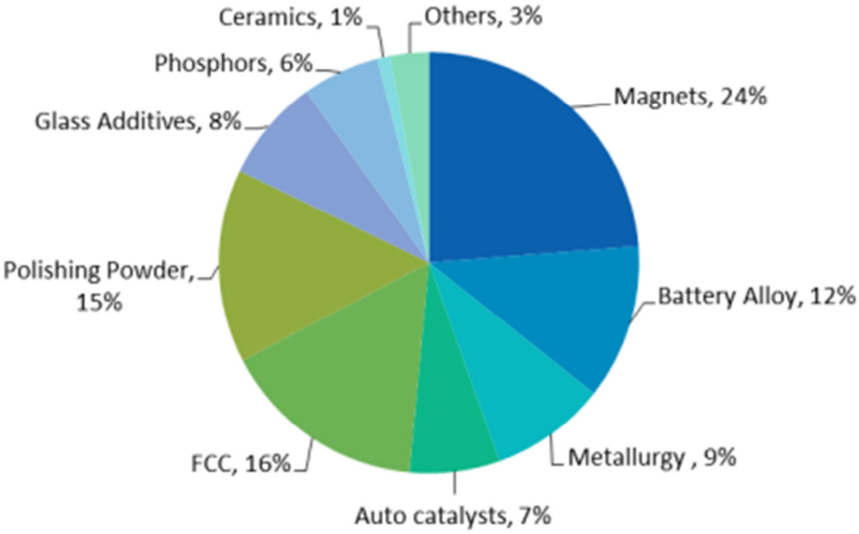
The most important rare earth deposits in hard rock are mined as open-pit operations by drilling, blasting, loading and hauling to the mill. Steam is used to condition the ore before flotation for bastnäsite recovery. The flotation concentrate contains typically 60% REO. This is leached by 10% hydrochloric acid (HCl) to remove the calcite, which raises the REO content to 68-73%. Various process routes may be used for cracking and separating individual Rare Earths from the concentrate. For bastnäsite, roasting at 500°C in concentrated sulphuric acid is use to remove fluoride and $CO_2$. Chloride solutions are also used in further purification processes. In other processes, nitric acid solutions might also be used. The end-product mixture from the mineral cracking process is further processed to separate the individual elements. A solvent extraction process is used for the initial stages of the separation and results in materials up to 99.9% purity. Additional complexity is added where other metals are present; for example, some deposits also contain the radioactive element thorium, which needs to be safely separated and stored as part of the extraction process.

## Demand

### *Applications*

Rare earth elements are used for a wide variety of applications, although four markets (magnets, fluid cracking catalysts (FCC), polishing powder and batteries), accounted for two thirds of total rare earth demand in 2010 (Figure A6.3). However each of the rare earth elements possesses slight differences in its properties such that each has a unique use, and substitution of one for another is often not possible.

Figure A6.3: Rare earth demand by application, 2010 (tonnes)

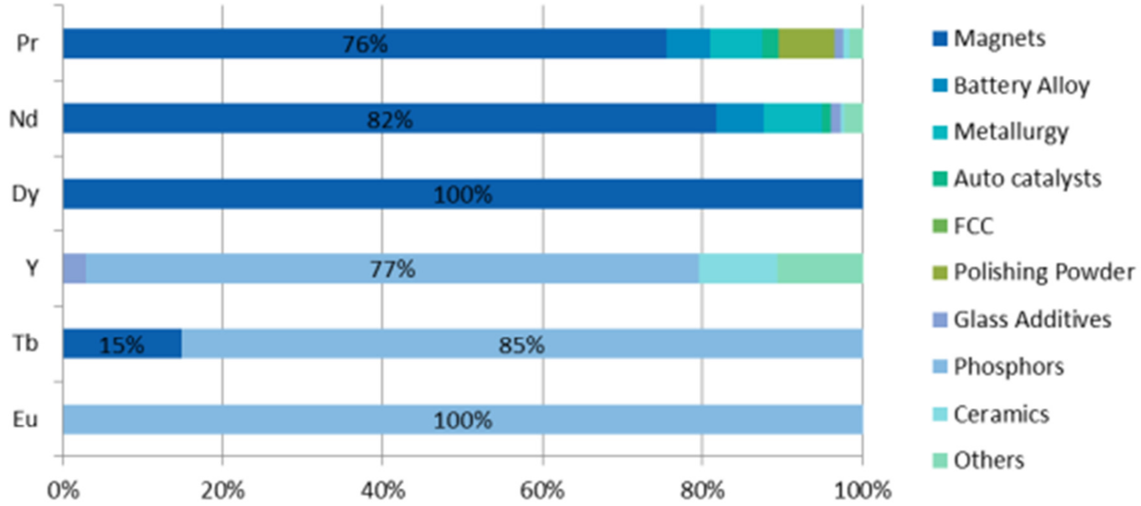


*Source: Lynas Corporation Ltd, 2010*

Figure A6.4 shows the applications for the six focus rare earth elements of this report. This figure confirms the key markets of magnets for praseodymium, neodymium and dysprosium; and of phosphors for yttrium, terbium and europium. In terms of the geographic distribution of rare earth demand, 60% of overall rare earth oxide demand is within China, as of 2010. Japan and North East Asia account for 20%, the USA 12% and others the remaining 8% (Kingsnorth, IMCOA, 2012). Some differences are apparent for specific sub-markets however:

- for rare earth magnets, where China's market share is around 80%
- for phosphors, where China's market share is around 65%.

*Figure A6.4: Selected elemental rare earth demand by application, 2010 (tonnes)*



*Source: Lynas Corporation Ltd, 2010*

***Principal users***

In order to identify the principal users for rare earth magnets and phosphors, some additional data is required on the specific markets for these intermediate products. Table A6.3 provides considerable details on the applications for rare earth magnets for 2008 and projections for 2014. It also contains useful information on the dysprosium content of different types of magnets, which varies considerably from <0.1% in hard disc drives to up to 8.7% in hybrid and electric vehicles. Average dysprosium content is approximately 3% across all of the applications. Motors, hard disc drives, electric bikes and loudspeakers are currently the largest applications for rare earth magnets; with wind power generators and hybrid and electric vehicles are two important emerging applications.

- For automobiles, the EU trade association ACEA has 16 companies that are full members (ACEA, n.d.). Toyota, Honda and Nissan are among the leading companies for sales of hybrid and electric vehicles.
- For hard disc drives the three leading manufactures are Seagate, Western Digital and Toshiba; although all major computers e.g. Dell, Apple and Hewlett Packard; can be considered principal users.
- For wind power generators important users include General Electric, Siemens, Vestas and Enercon (Oakdene Hollins, 2010).

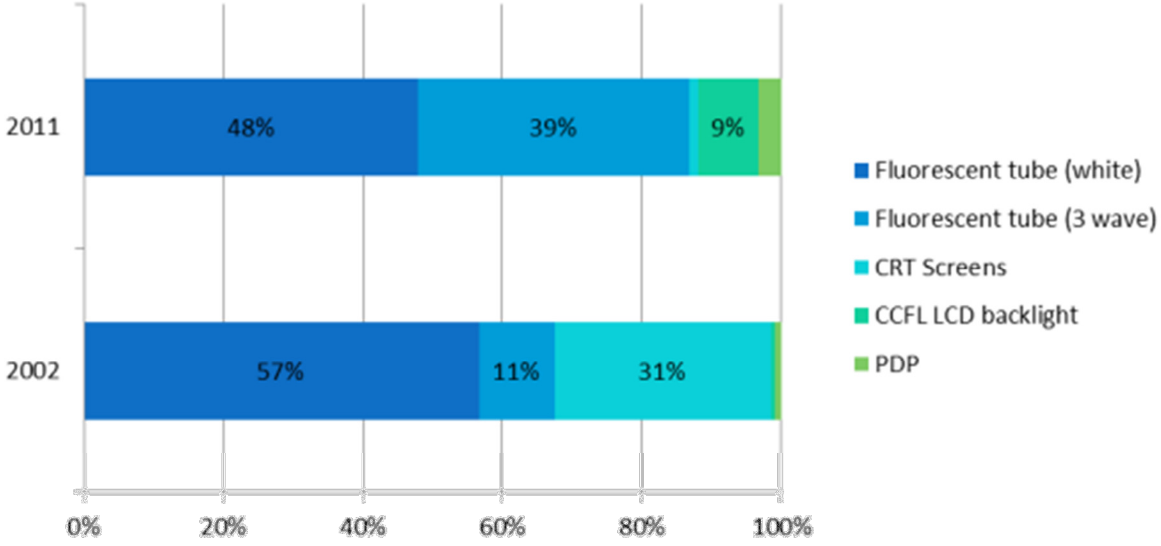
Figure A6.5 shows the breakdown for world phosphors markets for 2002 and 2011. Fluorescent tubes represent nearly 90% of the total market, although CCFL LCD backlights have emerged an important market following the demise of CRT screens. The EU trade association lists 12 companies among its membership, including General Electric, Phillips Lighting and Osram (European Lamp Companies Federation, n.d.), which can be considered to be the principal users for rare earth phosphors.

*Table A6.3: Rare earth magnet applications*

| Applications | Typical Dy Content (%) | Applications 2008 (% of mix) | Applications 2014e (% of mix) |
|---|---|---|---|
| Motors, industrial, general auto, etc. | 4.1 | 26.0 | 23.0 |
| HDD, CD, DVD | <0.1 | 14.8 | 18.0 |
| Electric bicycles | 4.1 | 9.2 | 11.4 |
| Wind power generators | 4.1 | 0.5 | 9.6 |
| Hybrid & electric traction drive | 8.7 | 3.0 | 6.1 |
| Transducers, loudspeakers | <0.1 | 9.0 | 6.0 |
| Magnetic separation | 2.8 | 5.0 | 3.5 |
| MRI | 1.4 | 4.0 | 1.5 |
| Sensors | 1.4 | 3.0 | 1.5 |
| Torque-coupled drives | 4.1 | 3.0 | 2.5 |
| Generators | 6.4 | 2.5 | 1.0 |
| Hysteresis clutch | 2.8 | 2.5 | 1.5 |
| Energy storage systems | 4.1 | 2.0 | 2.5 |
| Gauges | 2.8 | 1.5 | 0.8 |
| Magnetic braking | 4.1 | 1.5 | 0.8 |
| Relays and switches | 4.1 | 1.2 | 0.2 |
| Pipe inspection systems | 4.1 | 1.0 | 1.0 |
| Wave Guides: TWT, undulators, wigglers | 6.4 | 1.0 | 1.0 |
| Magnetically levitated transportation | 4.1 | 1.0 | 1.0 |
| Reprographics | 4.1 | 0.7 | 0.5 |
| Magnetic refrigeration | 1.4 | 0.3 | 0.5 |
| Advertising | <0.1 | 0.1 | <0.1 |
| Unidentified and all other | 1.4 | 7.2 | 6.0 |

*Source: Arnold Magnetic Technologies, 2011*

*Figure A6.5: World phosphor market 2002 and 2011 (%)*



*Source: Roskill, 2012*

***Market pricing***

Rare earth elements are traded through long-term supply contracts and individual trades between large consumers and suppliers as well as private trading houses. Potential buyers and sellers can also list proposals on specialist websites that attempt to match counterparties together. The terms of such trades are generally unavailable publicly and a 'market price' in the conventional sense does not exist. Publicly available price quotes actually represent expert estimates of representative prices in trades being executed on a particular day, which are compiled through recurring interviews with individual traders. These markets are therefore by their nature much smaller and more opaque than the exchange traded markets.

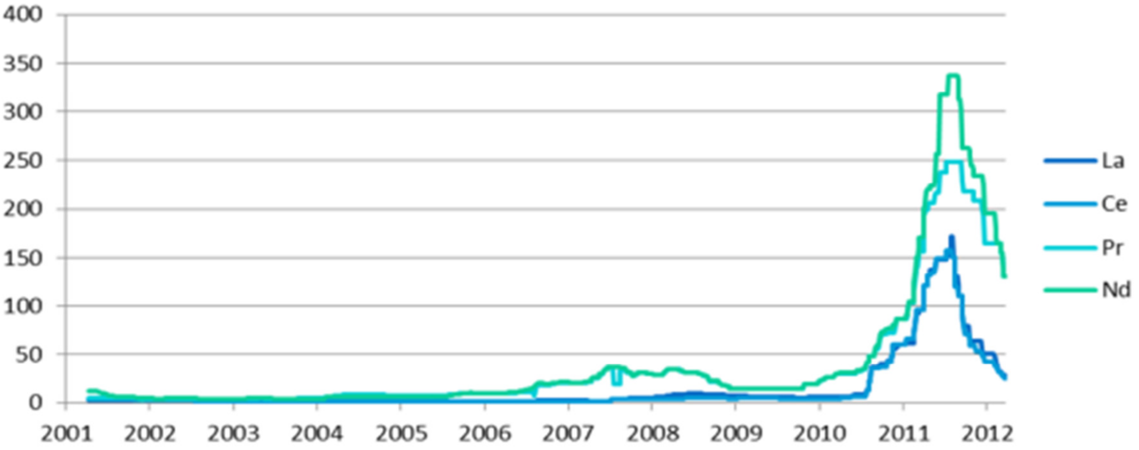
Historic prices for rare earth elements are given in Figure A6.6 (light rare earth elements) and Figure A6.7 (heavy rare earth elements). There has been considerable interest around the world in rare earth elements, following China's systematic tightening of export quotas and subsequent supply bottlenecks witnessed by many industries during 2010 and 2011. As a result rare earth oxide prices rose dramatically. Prices are also commonly quoted for rare earth carbonates, which can be considered the raw material for mixed rare earths and for mischmetal and didymium (which are mixtures of the quoted rare earths).

Figure A6.8 shows the trends for specific rare earth prices. This shows that price of light rare earths have rose the sharpest, but have recently fallen back to near their 2009 levels. In contrast, prices for heavy rare earth elements rose more steadily and have since been much more resilient. This in part reflects the distortions of the Chinese rare earth export quota system that originally did not distinguish between specific rare earth, and hence encouraged traders to sell the more expensive (heavy) rare earths to the rest of the world, pushing up the price of light rare earths more as a result. However, changing the export quota system to differentiate between specific rare earths, and the supply-demand dynamics for light versus heavy rare earths, are now more effectively represented in the prices.

Based on 2010 prices and production, the value of production is estimated at approximately US$5 billion for rare earth elements in total. The value of production for each of the focus rare earth elements is:

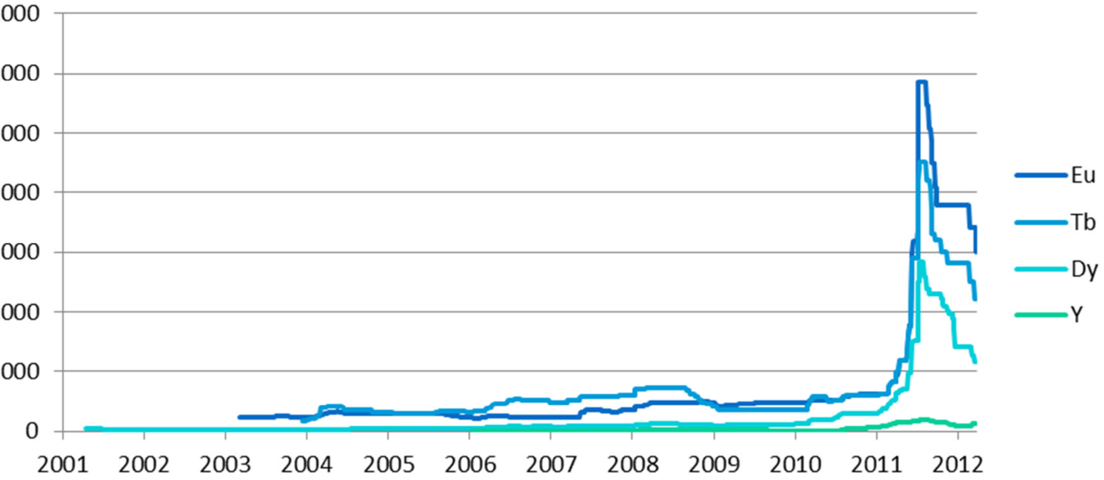
- lanthanum at $690m
- cerium at $825m
- praseodymium at $320m
- neodymium at $1,160m
- europium at $215m
- terbium at $200m
- dysprosium at $525m
- yttrium at $350m.

*Figure A6.6: La, Ce, Pr, and Nd oxide prices, min 99% purity, FOB China basis (US$/kg)*



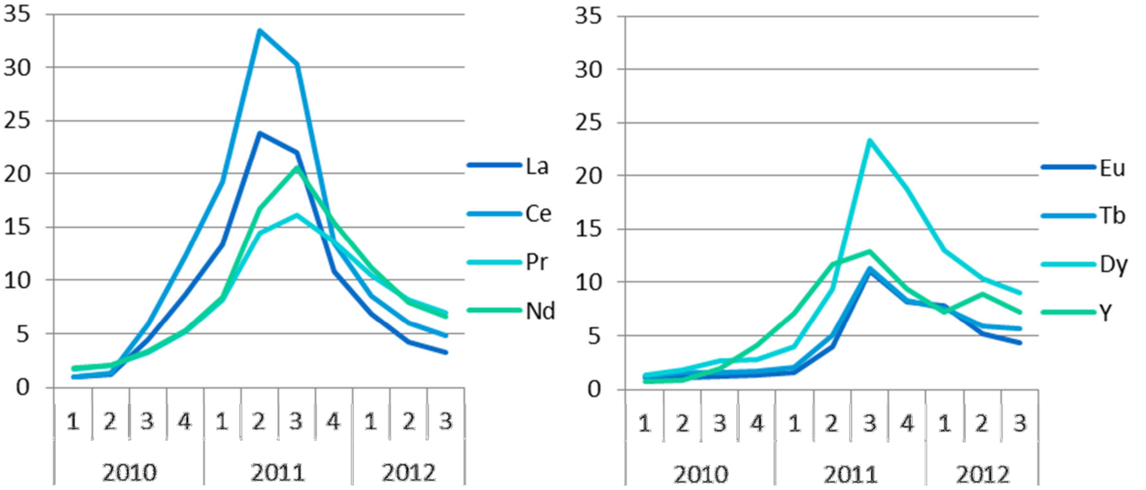
*Source: Metal Pages, n.d.*

*Figure A6.7: Eu, Tb, Dy, and Y* oxide prices, min 99% purity, FOB China basis (US$/kg)*



** Y oxide, min 99.999% purity; Source: Metal Pages, n.d.*

*Figure A6.8: Price multiples for rare earth oxides, versus 2009*



*Source: Metal Pages, n.d.*

## A.6.2 Gallium

### Supply

***Common sources***

Gallium (Ga) is a silvery metal with one of the lowest melting points (29.78°C) of all metals but it has a high boiling point of 2403°C. It therefore has the longest liquid range of all elements (Vulcan, 2009). Its density is 6.095 g/cm$^3$ at 29.8°C (liquid) and 5.904 g/cm$^3$ at 24.6°C (solid) (Greber, 2012). The metal expands in the phase transition from liquid to solid (like water). With a density higher than 5 g/cm$^3$, gallium ranks among the heavy metals. Gallium is a metalloid with a good electrical conductivity. Although gallium is quite soft and can be cut with a knife, it has the peculiarity that compact pieces can splinter under sudden mechanical stress with conchoidal fracture forming small, sharp-edged chips (Angerer et al., 2009).

The average concentration in earth's crust is 19 ppm and it ranks 34th-35th in order of abundance (Enghag, 2004). Elemental gallium does not occur in nature and gallium minerals (e.g. gallite, $CuGaS_2$) are very rare (Enghag, 2004). Gallium occurs in trace amounts in bauxite (aluminium ore), zinc blende and coal, probably due to similar lattice constants (Enghag, 2004). The gallium content in bauxite varies from 30-80 ppm, on average 50 g gallium per tonne of bauxite (Greber, 2012). The largest reserves of gallium are contained in phosphate ores and coal of various kinds. Gallium is concentrated in flue dust of phosphorous production and fly ash of coal. The total gallium reserves in phosphates and coals have been estimated at several million tonnes and thus exceed those in bauxite (Greber, 2012).

Gallium's world resources in bauxite alone are estimated to be 1 million tonnes (Moss et al., 2011). Since gallium is finely dispersed, estimation of gallium occurrence is difficult. Considering e.g. bauxite reserves implies a rough estimation of gallium reserves. According to the Indium Corporation, gallium reserves amount to 760,000 tonnes. With a production of about 150 tonnes per year, the reserves are sufficient for decades (Indium Corporation, 2011).

***World production***

Due to its low concentration, gallium is recovered as a by-product during the production of aluminium, zinc and copper, and is not mined as a primary commodity. Nowadays, gallium is mostly recovered during the refining of alumina that principally uses the Bayer liquor process (Indium Corporation, 2010). In 2011, the estimated world primary gallium production was 216 t, up from approximately 182 t in 2010 (Figure A6.9). The principal producing countries are listed in Table A6.4 (USGS, 2010a; USGS, 2012).

About 50% of the worldwide supply of gallium came from recycled new scrap, amounting to approximately 310 tonnes in 2011 (USGS, 2012a; Roskill, 2011). Gallium was recycled from new scrap in Canada, Germany, Japan, the UK, and the US (USGS, 2010a).

There was a remarkable change of key producer countries during the past 15 years. In 1999, Australia, Kazakhstan and Russia were alongside China, Germany, Hungary, Japan, Slovakia and Ukraine as the key producing countries for gallium (USGS, 2012). Today, China, Germany and Kazakhstan are the top three producers. Although China is the major supplier of gallium, supply risk is limited since there are other large, reliable producers (e.g. Japan, US). Furthermore, there are very large gallium reserves (21,400 t) in bauxite ores in Europe (Moss et al., 2011).

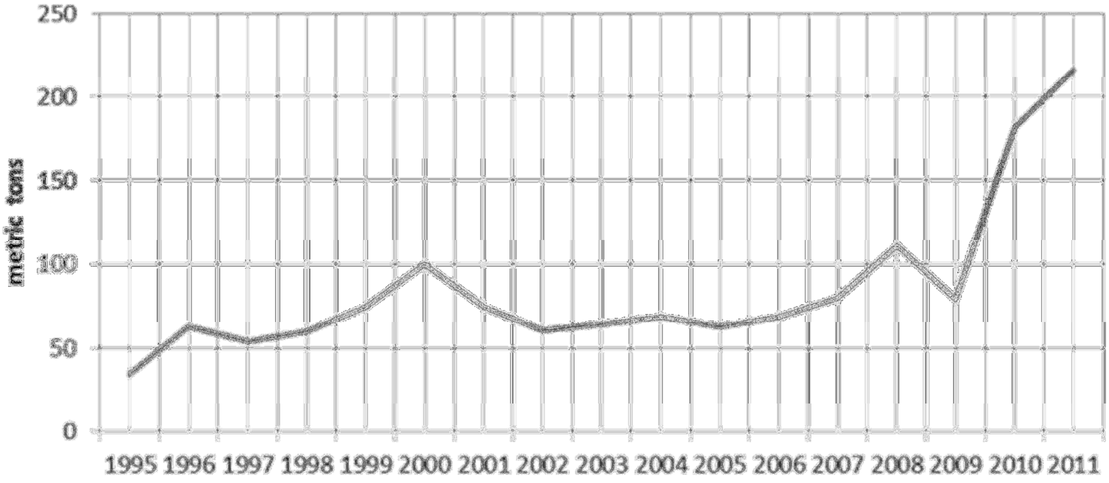
*Table A6.4: Estimated world annual primary gallium production capacity (December 2010)*

| Country | Capacity (metric tons) |
|---|---|
| China | 141 |
| Germany | 35 |
| Kazakhstan | 25 |
| Republic of Korea | 16 |
| Ukraine | 15 |
| Japan | 10 |
| Russia | 10 |
| Hungary | 8 |
| **Total** | **260** |

*Includes operating plants as well as at plants on standby basis*

*Source: USGS, 2010a*

*Figure A6.9: World primary production of gallium*



*Source: USGS, 2011a, estimated values*

***Leading companies***

The number of companies that are currently separating out gallium is low (Moss et al., 2011). In the top three producing countries, only 10% of the companies recover gallium from bauxite (Indium Corporation, 2010). China's leading gallium manufacturers were: the Aluminium Corporation of China Ltd., Beijing JiYa Semiconductor Material Co. Ltd, China Crystal Technologies Ltd, East Hope Mianchi Gallium Industry Co, and Zhuhai Fangyuan (USGS, 2010a).

Europe's share of primary gallium production capacity is about 12% of world capacity: 30 tonnes per year in Europe compared to 260 tonnes worldwide. Two companies within Europe are known to be active in recovering gallium: AOS Ingal in Germany at their Stade plant (25-30 tonnes of gallium per year) and MAL Magyar in Hungary (around 4 tonnes of gallium per year) (Moss et al., 2011). Gallium recovery only represents a small share of the revenue at an alumina refinery. There are a number of other active alumina refineries in Europe which do not recover gallium at their facilities.

***Processing routes***

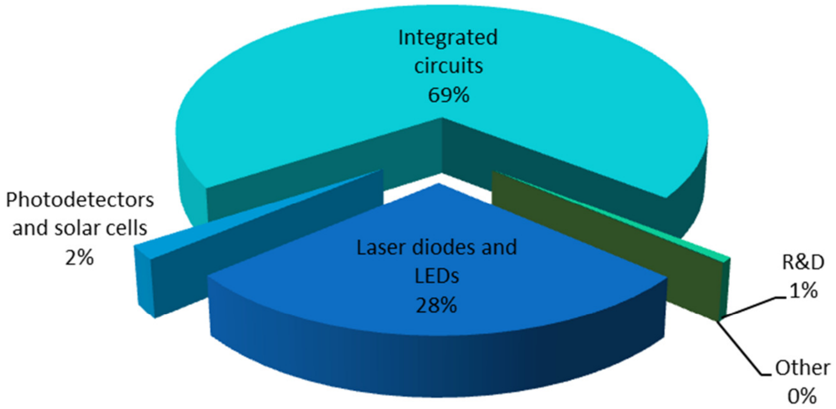
The main process for gallium manufacture is the extraction of the metal from the circulating liquors in the Bayer process for aluminium oxide manufacture. There are three types of process which are used to extract gallium: Fractional precipitation, electrolytic processes and extraction with chelating agents. Crude gallium from extraction processes has a purity of 99-99.9% (2-3N). However, for many applications - such as for semiconductor manufacture - much higher purities (up to 99.999999%, 8N) are necessary. A range of procedures is applied to remove the impurities: washing with aqueous acids and alkalis, fractional crystallization, zone melting and single crystal growth or distillation of volatile metals under vacuum (Greber, 2012).

## Demand

### *Applications*

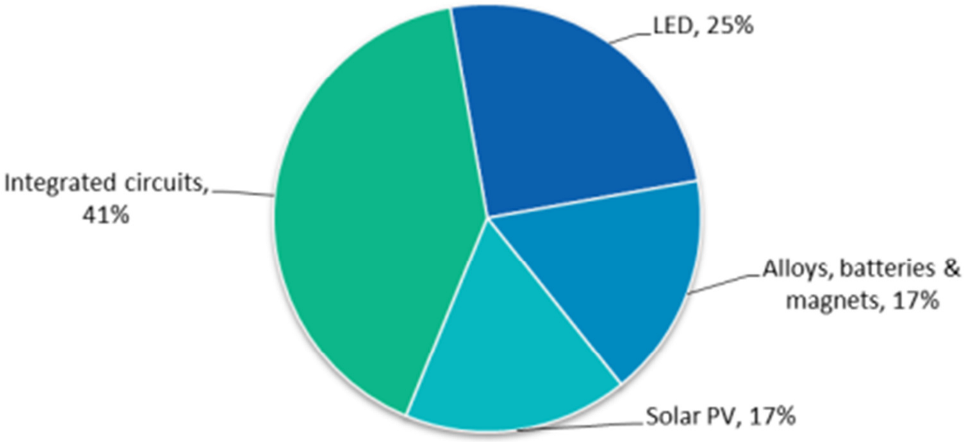
Gallium is mainly used for semiconductors as a compound with arsenic (as gallium arsenide, GaAs) and in light-emitting diodes (LEDs) (as gallium arsenide or gallium phosphide, Greber, 2012). It is used for integrated circuits (chips) especially for mobile phones, LEDs, laser diodes, photo-detectors, solar cells, amplifiers, transistors, blue laser diodes for Blu-ray DVD devices, high-temperature thermometers, high-quality mirrors, dental applications, magnets and catalysts (Vulcan, 2009). The distribution of end uses in 2010 for the US is shown in Figure A6.10. Alternative estimates of the uses of gallium are shown in Figure A6.11, courtesy of Indium Corporation. The value of worldwide GaAs device consumption increased to US$4.9 billion in 2010 (+32% compared to 2009), the value of GaN LED consumption increased to US$8.4 billion (+75%) and the high-brightness LED market increased to US$10.8 billion (+93%) (USGS, 2010a).

*Figure A6.10: US Consumption of gallium metal and compounds in 2010 by end use in kg*



*Source: USGS, 2010a*

*Figure A6.11: Uses of virgin Gallium, 2010*



*Source: Indium Corporation, 2010*

***Principal users***

The principal users of gallium are to be found in the integrated circuits (ICs) sector as well as among manufacturers of LEDs and Laser diodes (e.g. Aixtron AG, Veeco Instruments). Consumption in 2010 in the US for gallium use in ICs increased by 26% (due to GaAs-rich smartphones) and gallium use in LEDs and laser diodes increased by 75%, whereas gallium consumption in solar cells and photo-detectors decreased by 28% due to the worldwide economic downturn and decreasing prices of silicon-based solar cells (USGS, 2010a).

Further substitution possibilities for gallium are liquid crystals for use in LEDs, indium phosphide components for substituting GaAs in infrared laser diodes, and the substitution of GaAs by helium-neon lasers in visible laser applications. Gallium for GaAs-based integrated circuits in many defence-related applications cannot be substituted thus far (USGS, 2012).

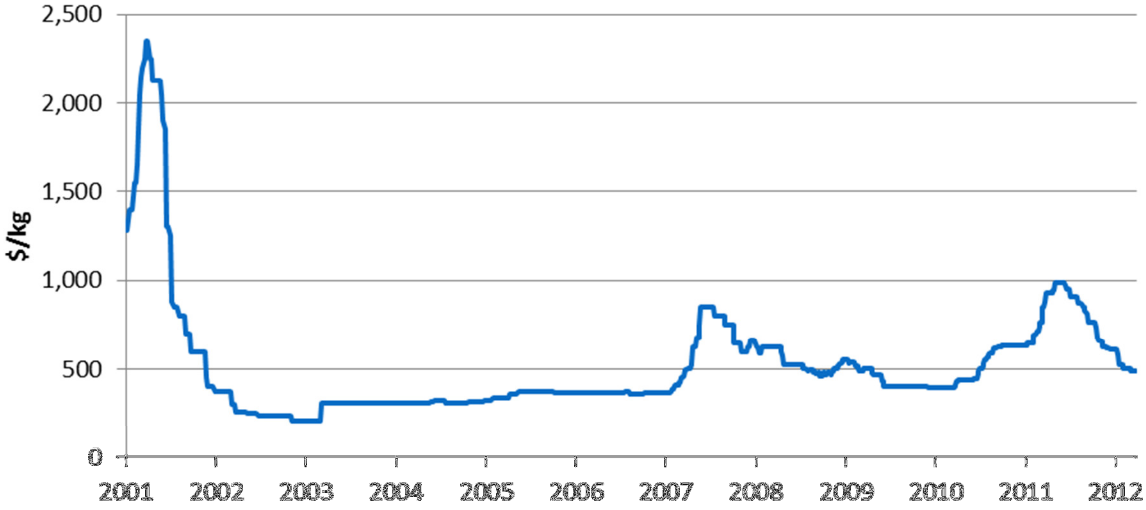
The European Commission classified gallium and 13 other raw materials as critical (EC, 2010a). The high supply risk results from China's dominating position in gallium manufacture. Besides this, there are few substitutes for gallium and there is no recycling from post-consumer products (Buchert et al., 2009). Thus, a heavy reliance on primary resources arises. Demand growth for gallium is forecast to be around 10% per annum, driven mainly by fast growth in photovoltaic applications (EC, 2010a).

***Market pricing***

Gallium is traded through long-term supply contracts and individual trades between large consumers and suppliers as well as private trading houses. Potential buyers and sellers can also list proposals on specialist websites that attempt to match counterparties together. The terms of such trades are generally unavailable publicly and a 'market price' in the conventional sense does not exist. Publicly available price quotes, actually represent expert estimates of representative prices in trades being executed on a particular day, which are compiled through recurring interviews with individual traders. These markets are by their nature much smaller and more opaque than the exchange traded markets.

The development of the gallium price over the past ten years is shown in Figure A6.12. Following a sharp increase in 2001, the price for gallium continued on a rather moderate level until 2006. In 2007 and 2011 gallium price reached two smaller peaks, which were considerably lower than the peak in 2001.

*Figure A6.12: Price of gallium (99.99% Purity, CIF Main Airport (EU))*



*Source: Metal Pages*

## A.6.3 Tellurium

### Supply

***Common sources***

Tellurium (Te) is a brittle, silver-white metal is closely associated with selenium, its periodic table neighbour, and the two metals are often found together. Tellurium is an element widely distributed throughout the Earth's crust; however, it is rarely found in its pure state but often as a compound in ores of bismuth, copper, gold, lead, mercury, nickel, silver and zinc. Tellurium rarely occurs in concentrations high enough to justify mining solely for its content, although some primary deposits do exist in China and Mexico. The element is mainly accumulated as a by-product during the copper refining process. The USGS estimates that tellurium reserves (contained within copper reserves) at 24,000 tonnes (USGS, 2012).

***World production***

Due to secrecy, official data on the tellurium production are only available for few states, although production of tellurium containing products is known to exist in a number of different countries. For 2011, the USGS estimated world production in Canada, Japan, Peru and Russia to be 115 tonnes. USGS's longstanding estimate for global tellurium production is that it has been between 450 and 500 tonnes per year (USGS, 2008).

However, in a recent publication the USGS has revised its view upwards, estimating world tellurium production at 630 tonnes in 2010 (Bauer et al., 2011). A range of other estimates exist:

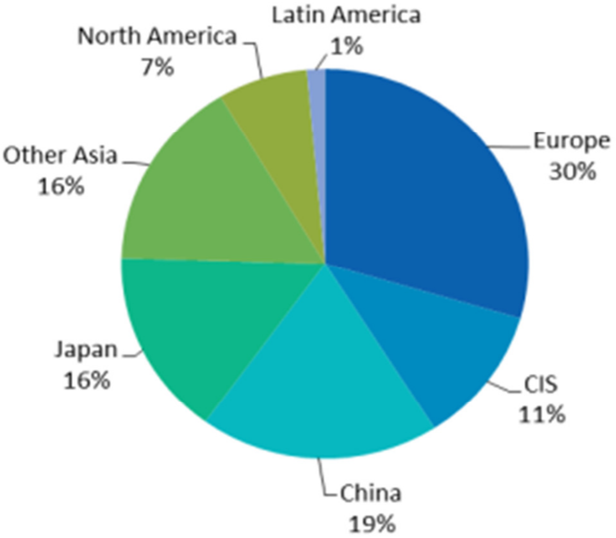
- Data compiled on behalf of the ICSG, estimates world tellurium production at 450-470 tonnes for 2011. The major producing countries include China, Japan, Belgium and Germany (Table A6.5). Tellurium production for the EU is estimated at 120-125 tonnes or 30% of world supply (Figure A6.13).
- First Solar, a leading manufacturer of CdTe Solar panels, estimate world current tellurium supply at 770 tonnes, rising to 1,460 tonnes in 2020. Their methodology takes a top-down approach considering the likely supply from copper, lead, directly mined and recycled sources (Table A6.6).
- Naumov offers a wide range for world tellurium production of 400-700 tonnes (Naumov, 2010).

*Table A6.5: Estimated world tellurium refinery production by country, 2011*

| Country | Refinery production (tonnes of Te content) |
|---|---|
| Belgium | 60 |
| Canada | 25 |
| China | 80-100 |
| Germany | 30-35 |
| India | 10-12 |
| Indonesia | 15 |
| Japan | 65 |
| Kazakhstan | 20 |
| Philippines | 20 |
| Russia | 25 |
| South Korea | 20 |
| Sweden/Finland | 20 |
| Others | 50 |
| Total | 450-470 |

*Source: International Study Group for Nickel et al., 2012*

*Figure A6.13: Estimated world tellurium refinery production by region, 2011 (tonnes of Te content)*



*Source: International Study Group for Nickel et al., 2012*

*Table A6.6: Long-term supply of tellurium (tonnes)*

| Type | 2010-2012 | 2014-2016 | 2020 |
|---|---|---|---|
| via Copper | 650 | 850 | 1,200 |
| via Lead & others | 40 | 44 | 64 |
| direct mined | 15 | 40 | 85 |
| via recycling | 65 | 76 | 111 |
| **Total** | **770** | **1,010** | **1,460** |

*Source: First Solar, 2012*

***Leading companies***

The supply of crude tellurium products is highly fragmented, with over 30 important suppliers identified in the survey conducted by the ICSG and only identified as possessing a market share greater than 10% of world supply for tellurium (International Study Group for Nickel et al., 2012).

However of these listed producers, it should be noted that many of the companies do not produce refined tellurium metal. The majority produce crude tellurium dioxide or copper telluride, which needs further upgrading. Important European players include Umicore (Belgium), Aurubis (Germany) and Boliden (Sweden and Finland). Outside Europe the largest players include Jiangxi Copper (China), Pan Pacific Copper (Japan), Xstrata (Canada), Sumitomo (Japan), Kazakhmys (Kazakhstan), Pasar (Philippines), Ural Electromed (Russia) and LS-Nikko Copper (South Korea).

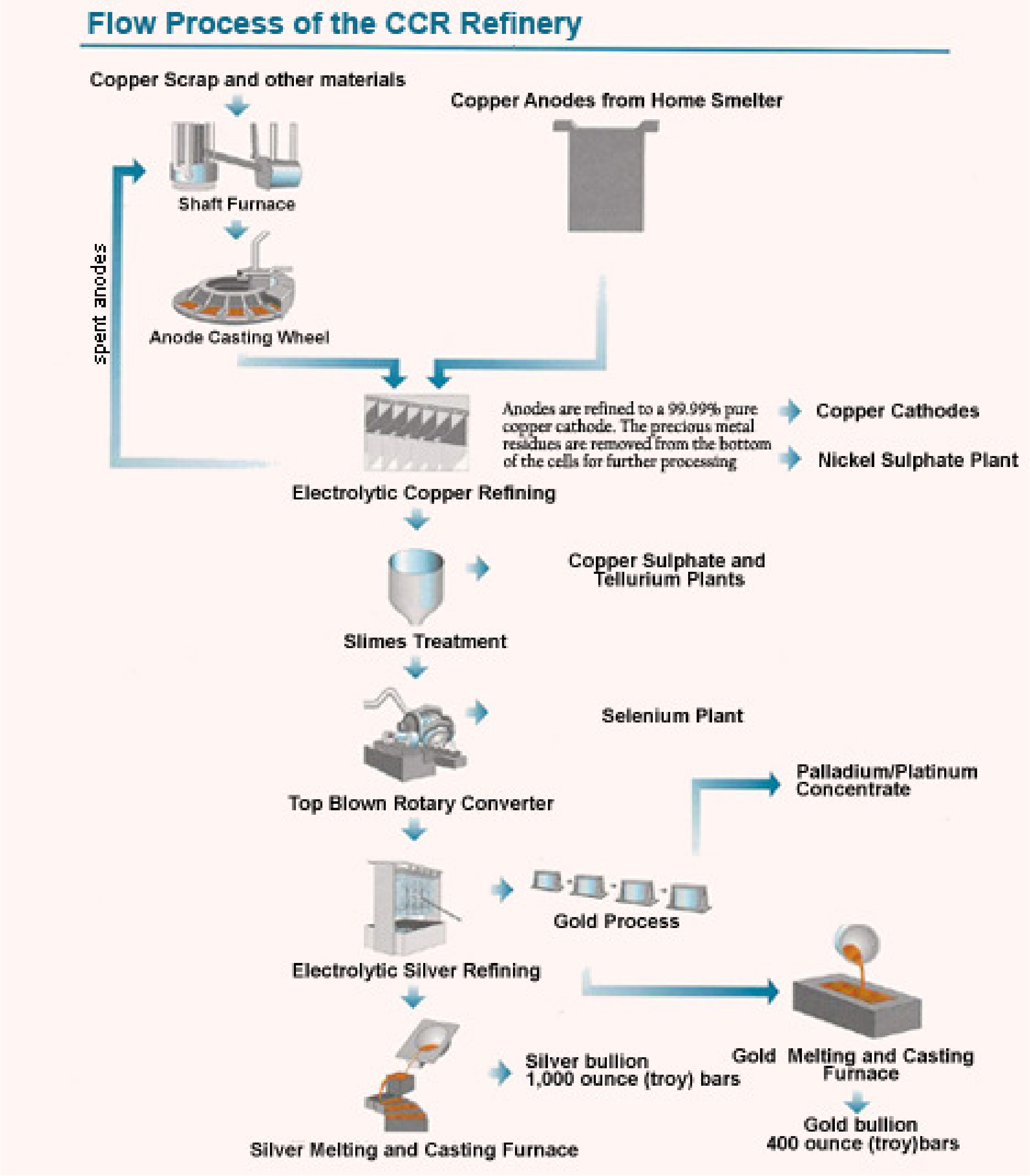
In terms of the production of refined tellurium metal and CdTe, evidence suggests that supply is significantly more concentrated compared to that the supply of tellurium containing production (International Study Group for Nickel et al., 2012):

- The leading supplier for tellurium metal is said to be 5N Plus, although the company does not release any production figures. 5N Plus is the supplier of choice to the world’s largest producer of CdTe Photovoltaic Solar, First Solar.
- The second largest producer of tellurium metal would seem to be Pacific Rare Speciality Metals & Chemicals in the Philippines, which reports its production of refined tellurium metal as 130-150 tonnes per year.

***Processing routes***

The main source of tellurium production is from copper refining. Figure A6.13 provides an overview of the processes involved at Xstrata's Canadian Copper Refinery. The USGS estimates that more than 90% of world tellurium is produced from anode slimes collected from electrolytic copper refining. The remainder is derived from skimmings at lead refineries and from flue dusts and gases generated during the smelting of bismuth, copper, and lead ores (USGS, 2012).

*Figure A6.14: Flow process of Xstrata's Canadian copper refinery*



*Source: Xstrata, n.d.*

It should be noted, however, that not all copper mines contain tellurium. In general terms it is the copper sulphide ores that contain the greatest tellurium content, although there is considerable variability in the tellurium content of ores. In a 2006 survey by the USGS of 56 worldwide copper refineries, 45 plants reported tellurium content in the slimes, at an average of 2% concentration (U.S. Geological Survey, 2008). However, many refineries in the CIS reported tellurium content in excess of 4%, with some at 8% or more (Moats et al, 2007).

Tellurium is recovered from copper anode slimes collected from the electrolytic refining of smelted copper. In this process, crude copper from a smelter is used as the anode in a bath of sulphuric acid. The copper is plated onto a thin pure copper or stainless steel cathode. In this operation impurities that may be present in the crude copper anodes such as the gold, silver, platinum, arsenic, molybdenum, selenium and tellurium can be made either to dissolve in the acid or fall out as anode slime, which can then be collected and processed for trace metals that have been concentrated by this process (Lifton, 2009). The slimes undergo a number of treatment processes such as auto-copper roasting, de-copperising and further refining in order to produce the different tellurium containing products. Different tellurium precipitation processes exist for refining the anode slimes, which can be used to optimise the trade-off between tellurium recovery against recovery of precious metals, notably gold and silver. The tellurium containing products: crude tellurium dioxide (≈70% Te), copper telluride (≈20-45% Te) or low grade tellurium concentrate (≈10% Te), then require further upgrading to produce tellurium metal.

There has been considerable recent comment on the shift of copper refining towards new processes that are more suitable for extracting copper from lower grade ores, notably the hydro-metallurgic process Solvent Extraction Electro-Winning (SX-EW). These processes may actually be more efficient at recovering molybdenum; however, the solvent leach technology does not lend itself to capturing the selenium or tellurium. There is therefore concern that as the higher grades of copper ore are being exhausted, this could affect future tellurium supply. The USGS comments that the increased use of leaching SX-EW processes for copper extraction has limited the future supply of tellurium supply from certain copper deposit types. However, this concern may have been somewhat exaggerated. This is because the copper sulphide ores that generally contain the higher tellurium content cannot be refined using the SX-EW process because of the sulphur content; therefore the actual tellurium being lost to the market as a result of SX-EW is probably quite low (International Study Group for Nickel et al., 2012).

## Demand

### *Applications*

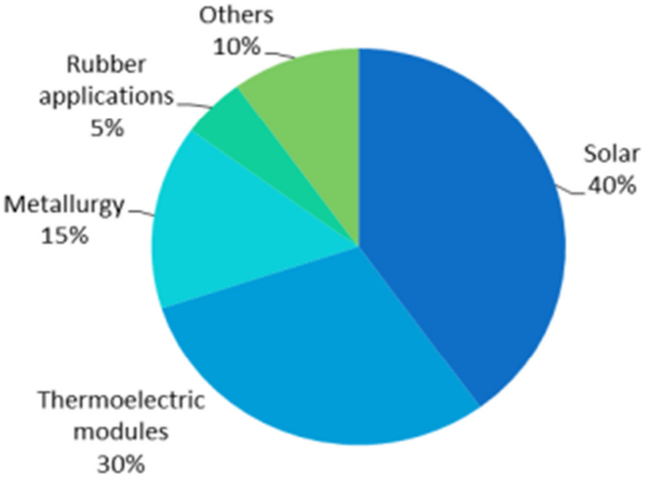
For tellurium usage, according to the latest statistics provided by the Selenium Tellurium Development Association (STDA), two applications for tellurium account for an estimated 70% its usage (Figure A6.15):

- In photovoltaic solar (40%), tellurium is used alongside cadmium in cadmium telluride (CdTe) thin films, which are becoming increasingly efficient and cost-competitive.
- In thermoelectric modules (TEM) (30%) tellurium is used in an alloy. By applying a low voltage DC power source to TEM semiconductor components, heat will be moved through the module from one side to the other, i.e. one side will be cooled while the opposite side will be heated.
- Other applications for tellurium include metallurgy where tellurium is included as an alloying additive to improve machining characteristics, as a vulcanising accelerator in the rubber industry and some other usages in the chemicals and pharmaceutical industries.

In terms of trends in tellurium usage, it is noticeable that in earlier sources metallurgy is commonly quoted as the most significant application with 42% of usage, followed by photovoltaic solar (26%) and chemicals and pharmaceuticals (21%) (EC, 2010a). The growth in the use of tellurium in solar PV is striking, as is its relative decline in some of the traditional applications. However, the current outlook for tellurium in this market is weak. Traders report that the PV solar industry is currently taking a ‘holiday’ in purchasing new material, instead of using up existing inventories which could last several years, to improve their cash-flow situation amidst highly competitive market conditions for panels (see Figure A6.16).

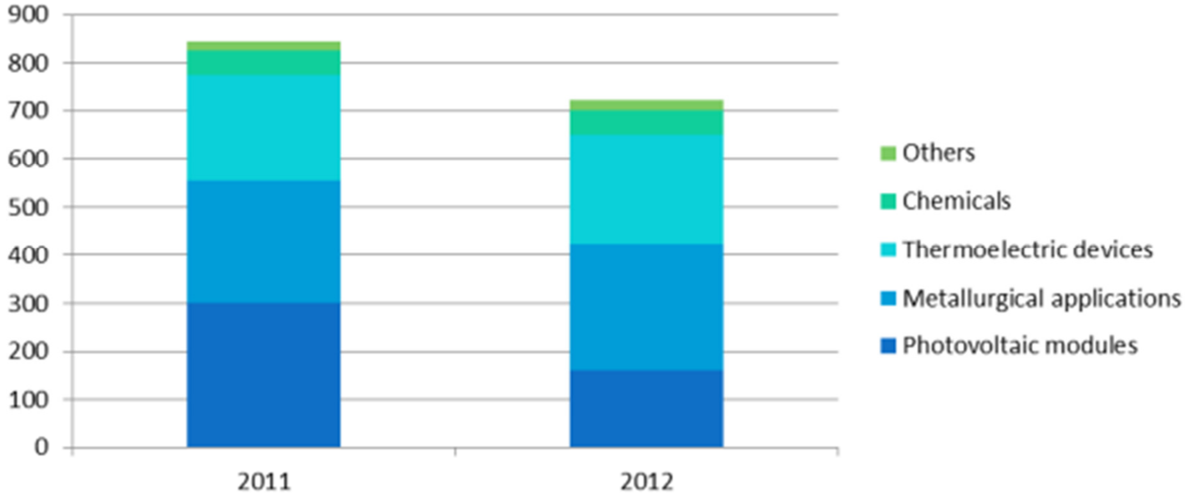
The STDA comments that tellurium’s use in the rubber industry is price-sensitive and long term substitution is possible in metallurgy (although this is more for the long term, as it requires formulation changes in steel) (International Study Group for Nickel et al., 2012). Much of tellurium usage in TEMs is also price-sensitive; although at the high end - for example mobile devices, laptops and phase change memory - the price sensitivity is lower.

*Figure A6.15: Major applications for tellurium, 2011*



*Source: International Study Group for Nickel et al., 2012*

*Figure A6.16: Tellurium demand profile 2011 & projected 2012*



Source: First Solar, 2012

***Principal users***

Attention here is focused on the two largest markets for tellurium. For photovoltaic solar, First Solar is the world's largest user of tellurium in its thin film CdTe solar panels. It is the dominant player for CdTe with a market share of near 90% for this technology, with installations and manufacturing across the US, Europe and Asia (NREL, 2007). Other market players include: Antec Solar, Clyxco (both Europe), AVA Solar and Primestar Solar (both United States).

For the second largest market for tellurium, i.e. thermoelectric modules, the International Thermoelectric Society lists over 30 module manufacturers on its company directory. Most of these are located in the US, China, Russia or Ukraine (Table A6.7). There are also several manufacturers within Europe.

*Table A6.7: List of thermoelectric module manufacturers by country*

| United States | China | Russia or Ukraine | Others |
|---|---|---|---|
| Custom Thermoelectric | Beijing Huayu-Landian Refrigeration Technology | Adv-Engineering | AMS ThermoTech (Germany) |
| Ferrotec | Beijing Huimao Cooling Equipment | Crystal | Aquaport International (Australia) |
| HiTECH Technologies | Fujitaka | Kryotherm | Cidete (Spain) |
| Magaland Technology | Hicooltec Electronic | Modul | EURECA Messtechnik (Germany) |
| Marlow Industries | Hui Mao Cooling Equipment | Osterm | Komatsu Group (Japan) |
| Melcor Corporation | Shenzhen Wellen Technology | RMT | SIREC Thermoelectric Products (Germany) |
| TE Technology | Thermonamic Electronics | S&PF Module | Supercool (Sweden) |
| Tellurex | | Thermion | TE Energy (Finland) |
| ThermoTek | | Thermix | |

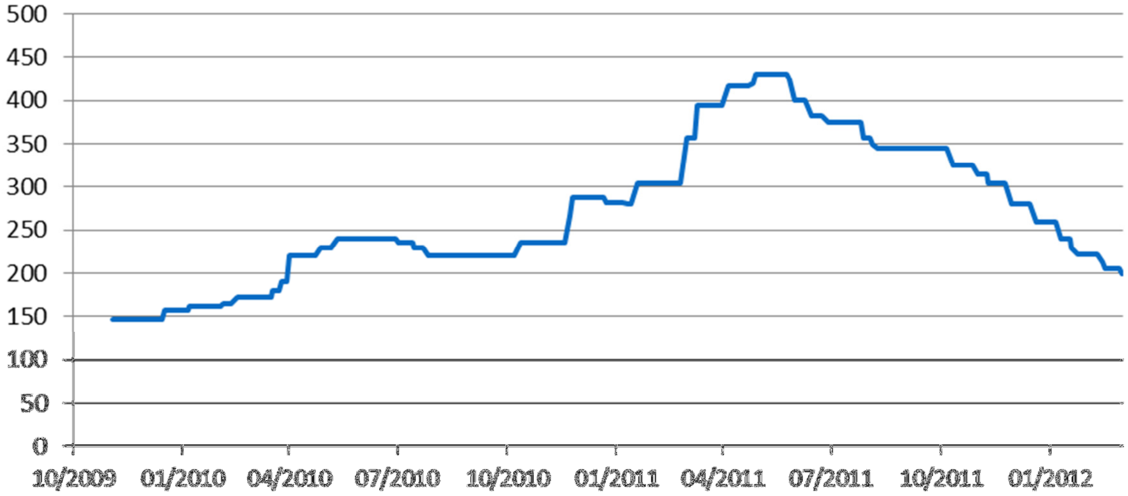
*Source: International Thermoelectric Society, n.d.*

***Market pricing***

Tellurium is traded through long-term supply contracts and individual trades between large consumers and suppliers as well as private trading houses. Potential buyers and sellers can also list proposals on specialist websites that attempt to match counterparties together. The terms of such trades are generally unavailable publicly and a 'market price' in the conventional sense does not exist. Publicly available price quotes actually represent expert estimates of representative prices in trades being executed on a particular day, which are compiled through recurring interviews with individual traders. These markets are by their nature much smaller and more opaque than the exchange traded markets.

The price of tellurium has fallen considerably from its high of nearly US$450 per kg in mid-2011 to a current (2012) level of US$200 per kg. This has unwound much of the increase that occurred during 2010 and 2011, which saw a trebling of prices from US$150 per kg. Based upon an average price of around US$300 per kg, this implies a market size of around US$150 million.

*Figure A6.17: Tellurium metal prices, 99.99% purity IWH Rotterdam (US$/kg)*



*Source: Metal Pages, n.d.*

**European Commission**

**EUR 25994 EN – Joint Research Centre – Institute for Energy and Transport**
Title: Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector:
Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies
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## Abstract

In order to tackle climate change, to increase energy supply security and to foster the sustainability and competitiveness of the European economy, the EU has made the transition to a low-carbon economy a central policy priority. This report builds on the first study conducted by the JRC in 2011 (Critical Metals in Strategic Energy Technologies), where critical metals were identified, which could become a bottleneck to the supply-chain of the low-carbon energy technologies addressed by the Strategic Energy Technology Plan (SET-Plan), namely: wind, solar (both PV and CSP), CCS, nuclear fission, bioenergy and the electricity grid. Fourteen metals were identified to be a cause for concern. After taking into account market and geopolitical parameters, five metals were labelled 'critical', namely: tellurium, indium, gallium, neodymium and dysprosium. The potential supply chain constraints for these materials were most applicable to the deployment of wind and PV energy technologies.

In the follow-up study reported here, other energy and low-carbon technologies are investigated that not only play an important role in the EU's path towards decarbonisation but also may compete for the same metals as identified in the six SET-Plan technologies. Eleven technologies are analysed including fuel cells, electricity storage, electric vehicles and lighting. As in the first report, sixty metals, i.e. metallic elements, metallic minerals and metalloids are considered; only iron, aluminium and radioactive elements (used as fuel in nuclear plants) were specifically excluded. Graphite was also included, reflecting its status as one of the critical raw materials identified by the EU Raw Materials Initiative. Where possible, the study models the implications for materials demand as a result of the scenarios described in the EU Energy Roadmap 2050. Consequently, the results obtained in the first study are updated to reflect the data that has become available in the roadmap. This second study found that eight metals have a high criticality rating and are therefore classified as 'critical'. These are the six rare earth elements (dysprosium, europium, terbium, yttrium, praseodymium and neodymium), and the two metals gallium and tellurium. Four metals (graphite, rhenium, indium and platinum) are found to have a medium-to-high rating and are classified as 'near critical', suggesting that the market conditions for these metals should be monitored in case the markets for these metals deteriorate thereby increasing the risk of supply chain bottlenecks. The applications, i.e. technologies, of particular concern are electric vehicles, wind and solar energy, and lighting. As in the first report, ways of mitigating the supply-chain risks for the critical metals are considered. These fall into three categories: increasing primary supply, reuse/recycling and substitution. In addition, a number of topics were identified as possibly meriting further research, but could not be considered within the immediate scope of this study. These include conducting further studies to look at raw materials requirements for hybrid and electric vehicles for a wider range of technology uptake and penetration scenarios; developing new and more detailed scenarios for the uptake and technology mix of options for stationary energy storage; undertaking similar studies in defence and aerospace; improving statistics on the contribution of recycling to world production for a number of metals; and investigating the contribution of greater traceability and transparency to reducing raw materials supply risk. Finally, it is important not to overstate the bottlenecks due to the risks of raw material shortages for key technologies. This is because there are still many years before the large uptake of some technologies and in the coming years, there are numerous options that will become available to mitigate the identified risks.

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