JRC Scientific and Technical Reports

Critical Metals in Strategic Energy Technologies

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

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EUR 24884 EN - 2011

JRC EUROPEAN COMMISSION

Institute for Energy and Transport

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European Commission
Joint Research Centre
Institute for Energy and Transport

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JRC 65592

EUR 24884 EN-C
ISBN 978-92-79-20698-6
ISSN 1018-5593
doi: 10.2790/35600

Luxembourg: Publications Office of the European Union

Printed in The Netherlands

Cover photograph: Mount Weld Rare Earths Mine, Australia (courtesy of Lynas Corporation Ltd.)

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ABSTRACT

Due to the rapid growth in demand for certain materials, compounded by political risks associated with the geographical concentration of the supply of them, a shortage of these materials could be a potential bottleneck to the deployment of low-carbon energy technologies. In order to assess whether such shortages could jeopardise the objectives of the EU's Strategic Energy Technology Plan (SET-Plan), an improved understanding of these risks is vital. In particular, this report examines the use of metals in the six low-carbon energy technologies of SET-Plan, namely: nuclear, solar, wind, bioenergy, carbon capture and storage (CCS) and electricity grids. The study looks at the average annual demand for each metal for the deployment of the technologies in Europe between 2020 and 2030. The demand of each metal is compared to the respective global production volume in 2010. This ratio (expressed as a percentage) allows comparing the relative stress that the deployment of the six technologies in Europe is expected to create on the global supplies for these different metals. The study identifies 14 metals for which the deployment of the six technologies will require 1% or more (and in some cases, much more) of current world supply per annum between 2020 and 2030. These 14 metals, in order of decreasing demand, are tellurium, indium, tin, hafnium, silver, dysprosium, gallium, neodymium, cadmium, nickel, molybdenum, vanadium, niobium and selenium. The metals are examined further in terms of the risks of meeting the anticipated demand by analysing in detail the likelihood of rapid future global demand growth, limitations to expanding supply in the short to medium term, and the concentration of supply and political risks associated with key suppliers. The report pinpoints 5 of the 14 metals to be at high risk, namely: the rare earth metals neodymium and dysprosium, and the by-products (from the processing of other metals) indium, tellurium and gallium. The report explores a set of potential mitigation strategies, ranging from expanding European output, increasing recycling and reuse to reducing waste and finding substitutes for these metals in their main applications. A number of recommendations are provided which include:

- ensuring that materials used in significant quantities are included in the Raw Materials Yearbook proposed by the Raw Materials Initiative *ad hoc* Working Group,
- the publication of regular studies on supply and demand for critical metals,
- efforts to ensure reliable supply of ore concentrates at competitive prices,
- promoting R&D and demonstration projects on new lower cost separation processes, particularly those from by-product or tailings containing rare earths,
- collaborating with other countries/regions with a shared agenda of risk reduction,
- raising awareness and engaging in an active dialogue with zinc, copper and aluminium refiners over by-product recovery,
- creating incentives to encourage by-product recovery in zinc, copper and aluminium refining in Europe,
- promoting the further development of recycling technologies and increasing end-of-life collection,
- measures for the implementation of the revised WEEE Directive, and
- investing broadly in alternative technologies.

It is also recommended that a similar study should be carried out to identify the metal requirements and associated bottlenecks in other green technologies, such as electric vehicles, low-carbon lighting, electricity storage and fuel cells and hydrogen.

Contents

Glossary

AC	alternating current
AGR	advanced gas cooled reactor
a-Si	amorphous silicon
ASTM	American Society for Testing and Materials
ATO	antimony tin oxide
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Geological Survey)
BWR	boiling water reactor
CAGR	compound annual growth rate
CCS	carbon capture and storage
CdTe	cadmium telluride
CIF	cost insurance and freight
CIS *or* CIGS	copper indium (gallium) diselenide
CPV	concentrated photovoltaics
c-Si	crystalline silicon
CSP	concentrated solar power
DC	direct current
EBRD	European Bank for Reconstruction and Development
EII	European Industrial Initiative
ENTSO-E	European Network of Transmission System Operators for Electricity
EPA	Environment Protection Agency
EPIA	European Photovoltaic Industry Association
EPR	European Pressurised Reactor
EVA	ethylene vinyl acetate
EWEA	European Wind Energy Association
EWI	European Wind Initiative
FoB	free on board
FPD	flat panel display
F-T	Fischer–Tropsch
GCR	gas cooled reactor
GDP	gross domestic product
GHG	greenhouse gas emissions
HCSS	Hague Centre for Strategic Studies
HDDR	hydrogenation disproportionation desorption recombination
HSLA	high strength low alloy
HTGCR	high temperature gas cooled reactor
HTS	high temperature super conductors
HV	high voltage
HVAC	high voltage alternating current
HVDC	high voltage direct current
ICT	information and communications technology
IMCOA	Industrial Minerals Company of Australia
ITO	indium tin oxide
LCD	liquid crystal display
LCM	less common metals
LED	light emitting diode
Li-Ion	lithium-ion
LME	London Metals Exchange
MRI	magnetic resonance imaging
NAMTEC	British National Metals Technology Centre
NiMH	nickel metal hydride

n/a	not applicable (or not available)
PCB	printed circuit board
PGM	platinum group metals
PHWR	pressurised heavy water reactor
PMG	permanent magnet generator
PV	photovoltaic
PWR	pressurised water reactor
R&D	Research and Development
RDD	R&D and Demonstration
REE	rare earth elements
REO	rare earth oxide
SETIS	SET-Plan Information System
SET-Plan	Strategic Energy Technology Plan
SOX	sodium oxide
STDA	Selenium Tellurium Development Association
TCO	transparent conductive oxide
toe	tonnes of oil equivalent
USGS	US Geological Survey
WEEE	Waste Electrical & Electronic equipment
WNA	World Nuclear Association
WRAP	Waste & Resources Action Programme, UK

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};
Hence, kg/MW=kilograms per megawatt

Acknowledgements

The authors would like to extend their gratitude to the following individuals and their organisations for generously sharing their support, advice and data. Without these contributions, this report would not have been possible. In particular, the authors thank Panagiota Ntagia for her rigorous data validation and editing skills.

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1 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 has set the creation of a low-carbon economy as a central policy priority. The EU has therefore created the Strategic Energy Technology Plan (SET-Plan) to enhance Research, Development and Demonstration in key Low-Carbon Technologies and hence to help Europe meet its ambitious 2020 targets for reducing greenhouse gas emissions and increasing European energy supply through the promotion of renewable resources and the improvement of energy efficiency. In this context, previous work by the JRC has identified potential bottlenecks in the supply chains for various metals as a possible obstacle to the deployment of SET-Plan technologies. Many metals are essential for manufacturing low-carbon technologies and Europe depends on imports for many of them. As demand grows rapidly, limited global supplies and competition over the control of resources have created concerns that limited metal availability might slow the deployment of low-carbon technologies.

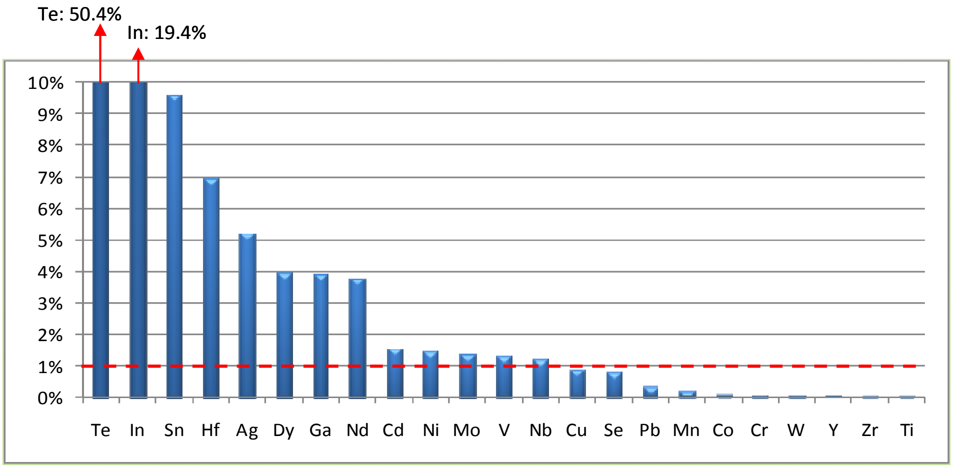
To improve the understanding of these risks, this report examines the use of metals in the six low-carbon energy technologies of the SET-Plan: nuclear, solar, wind, bioenergy, carbon capture and storage (CCS) and electricity grids. The broadest selection of metallic elements has been considered, with 60 elements included in the study. Quantitative estimates are provided for the metal requirements of each technology in terms of:

- kg per megawatts (of new) nuclear, wind and solar power installed capacity
- kg per million tonnes of oil equivalent that is generated from bioenergy
- kg per megawatt of fossil fuel electricity generation capacity to which CCS is applied
- kg per kilometre of electricity grid cables that are laid.

This allows estimating the metal demand from various scenarios for the deployment of each technology. The demand for metals has first been calculated for the most optimistic deployment-scenario for the technologies in Europe in order to identify those metals with the greatest usage in the SET-Plan. However, *absolute* volumes do not provide an informative comparison because production volumes for different metals differ considerably. Instead, the average annual demand from the deployment of the technologies in Europe between 2020 and 2030 for each metal is estimated and then compared to the global production volume of this metal in 2010. This ratio (expressed as a percentage) allows comparing the *relative* stress that the deployment of the six technologies in Europe is expected to create on the global supplies for these different metals. The figure below shows the results of these calculations for several metals. Of these, 14 are identified for which the deployment of the six technologies in Europe will require 1% or more of current world supply per annum between 2020 and 2030. For the purposes of this report, these 14 metals are designated as the group of significant metals to the SET-Plan technologies.

The 14 metals, in order of decreasing demand, are tellurium, indium, tin, hafnium, silver, dysprosium, gallium, neodymium, cadmium, nickel, molybdenum, vanadium, niobium and selenium. The deployment of these technologies also requires other metals, but these are needed in such small quantities compared to current world supply (i.e. less than 1% of current world supply) that their sourcing is extremely unlikely to constitute a significant problem for the deployment of the six SET-Plan technologies in Europe. Significant additional future demand for a metal does not necessarily constitute a problem, as supply in principle is likely to adjust over time. However, such adjustment processes are not always smooth and temporary supply-chain bottlenecks associated with price hikes and supply disruptions may occur in the future. Next the report therefore examines the risk of future supply-chain bottlenecks over the coming decade for each of the 14 metals, by analysing in detail the likelihood of rapid future global demand growth, limitations to expanding supply in the short to medium term, the concentration of supply and political risks associated with key suppliers for each of these metals.

Figure 1: Metals Requirements of SET-Plan in 2030 as % of 2010 World Supply



Key: Te=tellurium, In=indium, Sn=tin, Hf=hafnium, Ag=silver, Dy=dysprosium, Ga=gallium, Nd=neodymium, Cd=cadmium, Ni=nickel, Mo=molybdenum, V=vanadium, Nb=niobium, Cu=copper, Se=selenium, Pb=lead, Mn=manganese, Co=cobalt, Cr=chromium, W=tungsten, Y=yttrium, Zr=zinc and Ti=titanium

Measuring such future risks is a complex challenge and is not an exact science. The present study however improves on several existing studies by putting more emphasis on actual market dynamics, global supply and demand forecasts. The scoring of these factors abstains from using precise numeric risk measures and instead employs a simple low-medium-high scale, to emphasize the large margins of uncertainty associated with such assessments of future developments. Table 1 shows the results which identify 5 of the 14 to be at high risk for future supply-chain bottlenecks, which are the rare earths, neodymium and dysprosium, and the by-products (from the processing of other metals) indium, tellurium and gallium.

Table 1: Summary of Bottleneck Analysis

Metal	Market Factors		Political Factors		Overall risk
	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	
Dysprosium	High	High	High	High	**High**
Neodymium	High	Medium	High	High	
Tellurium	High	High	Low	Medium	
Gallium	High	Medium	Medium	Medium	
Indium	Medium	High	Medium	Medium	
Niobium	High	Low	High	Medium	**Medium**
Vanadium	High	Low	Medium	High	
Tin	Low	Medium	Medium	High	
Selenium	Medium	Medium	Medium	Low	
Silver	Low	Medium	Low	High	**Low**
Molybdenum	Medium	Low	Medium	Medium	
Hafnium	Low	Medium	Medium	Low	
Nickel	Medium	Low	Low	Medium	
Cadmium	Low	Low	Low	Medium	

Source: Chapter 5

Over the coming decade, continued rapid demand growth is expected to keep supplies of these metals under pressure. In each case, there are also significant obstacles to expanding output in the short to medium term, resulting in high overall market risk. In the case of the rare earths, these difficulties are related to the commercial and technical challenges in bringing new mines to the market. For indium, tellurium and gallium, it is the by-product character that poses obstacles to the expansion of supply. in the rare earths case, these market risks are compounded by high political risks due to the concentration of supply in China. Political risks are less prominent for indium, tellurium and gallium, as supply is less concentrated and in each case there is significant production which is associated with low political risks.

In the six SET-Plan technologies, the five, high-risk metals are mainly used in various wind and solar energy generation technologies, although in differing quantities within the technology mix. Therefore an assessment is conducted of the impact of variations in the assumptions of future technology uptake, as well as the technology mix in the wind and solar sector, upon the demand for the five bottleneck metals. It shows that depending on the precise technology mix, demand could vary significantly, indicating a considerable degree of uncertainty. An important conclusion is that if bottlenecks for particular technologies do materialise, then alternative technologies are in principle able to substitute potential bottleneck technologies and help to nonetheless achieve the SET-Plan targets. For companies who are committed to particular technologies, the implications of metal bottlenecks are likely to be much more serious. Consequently it is recommended that in order to increase resilience, the SET-Plan avoids such technology 'lock-in', and does not attempt to 'pick-winners' by favouring particular technologies, for example, through highly targeted research or subsidies. However, due to the additional performance that may be achieved, as well as the high uncertainties related both to metal demand and the risks of future bottlenecks, it is not suggested that technologies with potential metal bottlenecks should be discouraged.

Finally a set of potential mitigation strategies is explored, ranging from expanding European output for these metals, increasing recycling and reuse to reducing waste and finding substitutes for these metals in their main applications. The results show that while some solutions are not realistic for particular metals, a range of promising options is available to mitigate risks for future bottlenecks. Many would however require additional research efforts and investments and would only begin to contribute substantially to reducing the risk for future supply-chain bottlenecks towards the middle of this decade at the earliest.

Recommendations are to:

1. Collect more data and provide better information on the demand, supply and price trends for metals that are used in significant quantities in SET-Plan technologies. Bottleneck risks are reduced by a faster flow of information between decision-makers and market participants both in metal markets as well as in the consuming industries. This can be achieved by:
    i. ensuring that materials used in significant quantities are included in the Raw Materials Yearbook proposed by the Raw Materials Initiative *ad hoc* Working Group
    ii. the publication of regular studies on supply and demand for bottleneck metals
    iii. ensuring that any informational actions for the "critical" materials gallium, indium and the rare earths are also duplicated for tellurium, which falls outside this group.
2. Support and sustain the existing rare earths supply chain in Europe, including efforts to ensure reliable supply of ore concentrates at competitive prices through:
    i. feasibility studies on bringing back into use and updating existing assets,
    ii. R&D and demonstration projects on new, lower-cost separation processes, particularly those from by-product or tailings containing rare earths,
    iii. collaboration with other countries/regions with a shared agenda of risk reduction such as the USA and Japan in exchange of information on underpinning science or in pre-competitive research.
3. Support junior miners, possibly via EBRD co-funding of feasibility studies, in exploration of promising European rare earth deposits as well as the respective permitting processes.

4. Raise awareness and engage in an active dialogue with zinc, copper and aluminium refiners over by-product recovery. For tellurium and gallium in particular there is scope to increase European recovery rates. This can be achieved by funding workshops and networks via the appropriate metal industry study group or development association to identify risks, barriers and benefits to further investment.
5. Create incentives to encourage by-product recovery in zinc, copper and aluminium refining in Europe, possibly via funding of feasibility studies or loans by EBRD.
6. Promote the further development of recycling technologies and especially increased end-of-life collection and processing for a number of particular components and products, notably permanent magnets in hard disc drives and flat panel displays. Funding should be provided for demonstration projects in hard disc drive and flat panel display disassembly and recycling, where it is proposed to recover high percentages of rare earths and indium, and for innovative design that enables easier and quicker disassembly whilst retaining product integrity and functionality.
7. Include measures for the implementation of the revised WEEE Directive in order to encourage recovery of such less common metals alongside the main metals that are usually targeted in mass-based recovery systems.
8. Invest broadly in alternative technologies that can provide system-level substitutes to technologies that rely heavily on bottleneck metals whilst retaining performance advantages. This includes alternative systems for wind-turbines.
9. Funding of further R&D into substituting indium in indium tin oxides.
10. Encourage the substitution of tellurium use in low-value applications via innovation funding.

Future research is proposed in order to identify the metal requirements and associated bottlenecks from green technologies other than the six SET-Plan technologies that were examined within the scope of this study. Important demand-side ‘green’ technologies such as electric vehicles, low carbon lighting, but also electricity storage or fuel cell and hydrogen technologies—which are key to Europe’s green energy transition and the attainment of the SET-Plan targets—should be examined for their metal use and associated risks for supply-chain bottlenecks. Such studies should be periodically updated at a timescale appropriate to the development of the technology, which is likely to be every 5-10 years.

2 Introduction

2.1 Background

In order to tackle climate change, to increase energy supply security and to foster the sustainability and competitiveness of the European economy, the European Union has set the creation of a low-carbon economy as a central policy priority. The deployment of low-carbon energy technologies lies at the heart of this transition. The EU therefore created the Strategic Energy Technology Plan (SET-Plan) to accelerate the development and large scale deployment of low-carbon energy technologies, drawing upon the current R&D and Demonstration (RDD) activities and achievements in Europe. SET-Plan oversees that Europe meets its ambitious targets for 2020, namely: a 20% reduction of CO_2 emissions from 1990 levels; a 20% share of energy from renewable energy sources in the gross energy demand; and a 20% reduction in the use of primary energy by improving energy efficiency. This will be largely achieved by enhancing RDD in the six selected, SET-Plan technologies (nuclear, solar, wind, bioenergy, carbon capture and storage (CCS) and electricity grids).

Previous JRC work has identified potential bottlenecks in the supply chains for various metals as obstacles to the deployment of SET-Plan technologies and consequently, the realisation of the 2020 targets. Many speciality metals are essential for manufacturing many low-carbon energy technologies, and Europe is 100% import-dependent for many of these metals. As demand grows rapidly, limited global supplies and competition over the control of resources have created concerns that limited metal availability might slow the deployment of low-carbon technologies.[a] Particular metals identified for inclusion within this study were bismuth, cadmium, copper, gallium, hafnium, indium, lithium, nickel, niobium, palladium, platinum, rare earth elements (notably dysprosium, lanthanum, neodymium and yttrium), scandium, silver and zirconium.

2.2 Scope and Approach

The approach taken in this study has been to identify and quantify the metal requirements of each of the six SET-Plan technologies in "kilogram per megawatt" (kg/MW) terms or an appropriate equivalent. The broadest selection of metallic elements has been considered for this process, with 60 elements included in the study and only iron, aluminium and radioactive elements being excluded from this process. The six SET-Plan technologies that have been considered are:

- Nuclear energy (fission)
- Solar energy (photovoltaics and concentrated solar power)
- Wind energy
- Bioenergy
- Carbon Capture and Storage
- Electricity Grids.

The quantitative estimates used to calculate the metal requirements for different deployment scenarios for the six technologies are:

- kg per megawatts (of new) nuclear, wind and solar power installed capacity
- kg per million tonnes of oil equivalent that is generated from bioenergy
- kg per megawatt of fossil fuel electricity generation capacity to which CCS is applied
- kg per kilometre of electricity grid cables that are laid.

Average annual requirements for each metal between 2020 and 2030 are then expressed in relative terms as percentages of current world supply, to allow a comparison of the material requirements of the

a See US Department of Energy (2010), Critical Materials Strategy; EU (2011) Commission Communication, Tackling the Challenges in Commodity Markets and on Raw Material.

SET-Plan on the various metals which have very different annual production volumes. Metals for which the deployment of the six SET-Plan technologies in Europe is expected to generate an average annual demand between 2020 and 2030 that exceeds 1% of current world supply are defined as significant, on the basis that a usage below 1% of current supply even under the most optimistic uptake scenarios constitutes a very marginal demand. The deployment of these technologies also requires other metals, but these are needed in such small quantities compared to current world supply that their sourcing is extremely unlikely to constitute a significant problem for the deployment of SET-Plan technologies.

High demand for a metal does not necessarily constitute a problem as it stimulates increasing supply. Metal supply has expanded significantly in the past and there is no reason to assume *a priori* that rapid demand will necessarily constitute a problem. Nonetheless, there is potential for supply-chain bottlenecks to occur which could result in price rises and supply disruptions. This could slow the deployment of the SET-Plan technologies and endanger the achievement of Europe's 2020 targets.

The structure and future trends in global supply and demand for each of the metals that are used in significant quantities by the six SET-Plan technologies is therefore analysed in detail, in order to assess the risk for the occurrence of such future supply-chain bottlenecks. This risk assessment relies on four key criteria that are scored on a low-medium and high scale. These criteria are:

- the likelihood of rapid global demand growth
- limitations on expanding supply in the short to medium term
- the cross-country concentration of supply and
- political risks associated with major producers.

In scoring, a wide range of secondary sources has been considered. Extensive interviews with key companies and industry experts have been a particularly valuable source of information, as for many metals that were considered, public sources provide only very limited information, particularly on market dynamics and future trends. As a result of this bottleneck metals with the highest risks for future price hikes and supply disruptions are identified. Focusing on metals with the highest risks and particularly vulnerable technologies, low and high scenarios until 2030 have then been explored in depth to detect the vulnerability to metal supply-chain bottlenecks for the European deployment of SET-Plan technologies including different uptake scenarios of SET-Plan technologies and different technology mixes within SET-Plan technologies.

Finally the study investigates what opportunities exist to mitigate potential metal bottlenecks in the implementation of the SET-Plan. This is conducted on the basis of mapping and analysing the supply chains for each of the bottleneck metals. Interventions to mitigate the metals risks are explored at each stage of the supply chain including:

- the potential to increase European mine production or by-product extraction
- the role that reuse, recycling and waste reduction can play, and
- the extent to which bottleneck metals can be substituted in some applications.

In a number of ways, this study has much in common with that undertaken by the US Department of Energy in their *Critical Materials Strategy* (2010), which assessed the role of certain metals, in terms of their importance to clean energy and supply risk, both for the short term (0-5 years) and medium term (5-15 years). Similarities include the modelling of different technology uptake and technology mix scenarios, and the types of indicators used in the assessment of supply risk (captured within this study in the Bottleneck Screening). However the technologies considered in the two studies differ somewhat; within the US Study, the technologies included were solar, wind, vehicles (magnets and batteries) and lighting. A second major difference with this is the methodologies for analysing the importance of the metals, with a bottom-up approach being employed here to quantify each of the metal requirements rather than starting with a list of metals to discuss. Finally, the risk assessment methodology employed here puts greater emphasis on analysing the combination of actual market dynamics as opposed to relying mainly on individual risk factors, such as the reserve range or recycling possibilities.

2.3 Structure of the Report

The structure of this report is as follows:

- Chapter 3 introduces and describes the Strategic Energy Technology Plan (SET-Plan), with a particular focus on each of the six low-carbon energy technologies.
- Chapter 4 quantifies all metal requirements for each of the six technologies and identifies for which metals the deployment of these technologies in Europe creates significant pressure on global supplies.
- Chapter 5 evaluates the risks for future supply-chain bottlenecks for the group of the 14 significant metals, considering a wide range of market and political factors that can contribute to bottleneck risks.
- Chapter 6 sets out the low- and high-technology scenarios to investigate the effects of different uptakes and technology mixes upon demand for the bottleneck metals in particularly vulnerable SET Plan technologies.
- Chapter 7 discusses possible risk mitigation strategies for the bottleneck metals including increasing primary production, reuse, recycling and waste reduction, and substitution.
- Chapter 8 provides the conclusions & recommendations of the study.

The report also includes 3 appendices which supplement and provide additional information to that contained within the main body of the report:

- Appendix 1: Energy Mix Projections, which provide information regarding different uptake scenarios of SET-Plan Technologies.
- Appendix 2: Metal Composition of SET-Plan Technologies, which set out in detail the methodologies and sources used to quantify the metal requirements of SET-Plan Technologies.
- Appendix 3: Summaries of each metal belonging to the group of the 14 significant metals provide information regarding the supply, applications, political risks, prices and forecasts for supply and demand for each of the significant metals. This information forms the basis for much of the analysis conducted in Chapter 5: Bottleneck Screening.

3 Strategic Energy Technology Plan (SET-Plan)

The EU has created the Strategic Energy Technology Plan (SET-Plan) to help Europe meet its ambitious 2020 targets for reducing GHG emissions and increasing the European energy supply from renewable resources, namely: a 20% reduction of CO_2 emissions from 1990 levels, a 20% share of energy from renewable energy sources in the gross energy demand and a 20% reduction in the use of primary energy by improving energy efficiency.

In 2007, the SET-Plan Technology Map was published by the JRC that underlined the European Strategic Energy Technology Plan (SET-Plan). The Technology Map contributed to the identification of the SET-Plan technology priorities, i.e. the technologies with the greatest potential to contribute to the transition to a low-carbon economy. In 2009, the SET-Plan Information System (SETIS) updated the Technology Map: *2009 Technology Map of the European Strategic Energy Technology Plan (SET-Plan) Part – I: Technology Descriptions*. This Chapter draws extensively upon this source.

The 2009 Technology Map assesses the technological state of the art and the anticipated developments of 17 energy technologies, the status of the corresponding industries and their potential, the barriers to large scale deployment, the needs of the industrial sector to realise the technology goals and the synergies with other sectors. The technologies addressed are:

1. Wind power
2. Solar photovoltaics (PV)
3. Concentrated solar power (CSP)
4. Hydropower
5. Geothermal energy
6. Ocean energy
7. Cogeneration of heat and power
8. Carbon capture and storage (CCS)
9. Advanced fossil fuel power generation
10. Nuclear fission
11. Nuclear fusion
12. Electricity grids
13. Bioenergy for power generation
14. Biofuels for transport applications
15. Fuel cell and hydrogen technologies
16. Electricity storage
17. Energy efficiency in transport.

This study considers the metal requirements for a subset of the above list of technologies, which were identified as being priority technologies by the EC JRC's Institute for Energy, i.e. the six prioritised low-carbon energy technologies of SET-Plan. These technologies are:

- Nuclear energy (fission)
- Solar energy (PV and CSP)
- Wind energy
- Bioenergy
- CCS
- Electricity grids.

3.1 Nuclear Energy (Fission)

Nuclear fission is used to generate electricity through a controlled chain reaction of nuclear fuel within a reactor. This process generates large amounts of heat, which is used to generate steam to drive turbines for electricity production. The long-term sustainability of nuclear energy is the main driver of the European Industrial Initiative (EII) on nuclear fission. In particular, the EII is focused on a new generation of reactors –the so-called Generation IV nuclear reactor. Such reactors will operate in new ways that have the capability of exploiting the full energetic potential of uranium, thus greatly extending resource availability by factors of up to 100 over current technologies. They will maximise inherent safety and produce less radioactive waste. Some types will also have the ability to co-generate electricity and process heat for industrial purposes (e.g. in oil, chemical and metals industries, for hydrogen production, or seawater desalination).

Based upon the slow progress which is currently being made with regard to the new-build and operation of Generation III+ fission reactors, it seems highly unlikely that any Generation IV reactors will be operating on a commercial basis by 2030. Hence the metals requirements investigated in this project concentrates extensively on Generation III and III+ technologies as described below:

- Light Water Reactors – The collective name for the Boiling Water Reactors (BWRs) and Pressurised Water Reactors (PWRs). Both Westinghouse and Areva favour PWR technology for their AP1000 and EPR reactors respectively, as does Mitsubishi Heavy Industries for its EU-APWR system. In a PWR, heat from the primary reactor coolant system is transferred to a secondary circuit in which steam is generated. A BWR generates steam directly by boiling the primary reactor coolant. As of 2010, there were 265 PWRs and 94 BWRs in operation worldwide.
- Candu Pressurised Heavy Water Reactor (PHWR) – The heavy water moderator allows natural (or slightly enriched) uranium to be used as fuel. This reactor design is popular in its homeland of Canada and, with a slightly modified design, in India. There are currently 44 PHWRs in operation worldwide.
- Gas Cooled Reactors – GCRs (including the UK's ageing Advanced Gas Cooled Reactors, AGRs) use a graphite moderator and a carbon dioxide gas coolant. As with heavy water reactors, natural or slightly enriched uranium is used as a fuel. Worldwide there are approximately 18 GCRs in operation. It is anticipated that these reactors, which are of a Generation II design, will cease operation before 2030. No new GCRs of this design are planned.
- High Temperature Gas Cooled Reactors (HTGCRs) – This design of reactor is not yet in commercial operation but may be by 2030. They use graphite as the moderator and helium as the coolant. They gain their improved efficiency by operating at temperatures approaching 950°C.

To give an idea of the scale of the proposed plans for nuclear new build, it is interesting to consider the number of reactors currently in operation. At present, operating reactors number approximately 440, shared between 30 countries. A further 58 reactors are currently being constructed. Some of the current 440 reactors will be retired before 2030, but it is not clear exactly how many. Most nuclear power plants have an original nominal design life of 25 to 40 years. Within Europe the expected capacity loss from the retirement of nuclear reactors has been estimated at 17.7GW between 2011 and 2020, and 20.3GW between 2021 and 2030.[a] However, engineering assessments of many plants have established that longer operational lives are acceptable, resulting in licence renewals extending operational life by 20 years in many cases. About 150 new reactors are now at the advanced planning stage and 340 more have been proposed, although it is noted that the recent events in March 2011 involving the nuclear reactors at Fukushima in Japan may lead to some of these proposals being revisited.

a World Nuclear Association Nuclear Power Country Briefings. Available at: http://www.world-nuclear.org/. [Accessed 22/10/2010].

3.2 Solar Energy

Solar energy involves turning the energy contained in sunlight into electricity. Within this section two main types of systems are considered:

1. Photovoltaic (PV) systems
2. Concentrated solar power (CSP) systems.

The European Industrial Initiative (EII) on solar energy focuses on photovoltaics (PVs) and concentrating solar power (CSP) technologies. The PV component is expected to contribute up to 12% of European electricity demand by 2020. The CSP component is expected to contribute around 3% of European electricity supply by 2020, with a potential of at least 10% by 2030.

3.2.1 Photovoltaic systems

PV systems collect sunlight through absorption and conversion of sunlight to electricity. The individual cells linked together to create solar panels consist of layers of materials designed to absorb light, and transfer the energy as electricity to the attached circuitry. The core component of a PV system is the materials used to absorb energy from sunlight, which are split into three main competing technologies: crystalline silicon (c-Si), thin film and electrochemical.

Crystalline silicon

Two types of crystalline silicon are used in the industry. The first is monocrystalline, produced by slicing wafers (up to 150mm diameter and 150 to 200 microns thick) from a high-purity single crystal boule. The second is multicrystalline silicon, made by cutting a cast block of silicon first into bars and then wafers. Multicrystalline technology is currently in trend for silicon cell manufacture. Energy efficiencies change from 11 to 16%, half to two-thirds of the theoretical maximum.

For both mono- and multicrystalline Si, a semiconductor homojunction is formed by diffusing phosphorus (an n-type dopant) into the top surface of the boron doped (p-type) Si wafer. Screen-printed contacts are applied to the front and rear of the cell, with the front contact pattern specially designed to allow maximum light exposure of the Si material with minimum electrical (resistive) losses in the cell.

Each c-Si cell generates about 0.5V, but to be useful higher output voltages are required so cells are usually soldered together in series to produce a module with a more useful output. For example, to charge a 12V battery a module containing 36 cells is typically used. The cells are hermetically sealed under toughened, high transmission glass to produce highly reliable, weather resistant modules that may be warranted for up to 25 years. Crystalline silicon has a market share of 78-80%.

Thin film

Thin film technologies are developed to respond to cost reduction efforts as crystalline silicon wafers make up about 26-30% of the cost of a finished module. Potential to reduce the cost is substantial since there is only about 1 micron thickness to absorb the light. The most common materials are amorphous silicon (a-Si), or the polycrystalline materials: cadmium telluride (CdTe) and copper indium (gallium) diselenide (CIS or CIGS).

Large area deposition is viable for each of these technologies hence high volume manufacturing. The thin film semiconductor layers are deposited on to either coated glass or stainless steel sheet. A transparent conducting oxide layer (such as tin oxide) forms the front electrical contact of the cell, and a metal layer forms the rear contact.

Although thin films are less efficient (production modules range from 8 to 11%), they are potentially cheaper than c-Si because of their lower materials costs and larger substrate size. Many thin film technologies have demonstrated best cell efficiencies at research scale above 18%, and best prototype module efficiencies above 12%.

There are several elements used in thin film PV production. Among the elements used include cadmium and tellurium (CdTe), copper, indium and selenium (CIS), and copper, indium, gallium and selenium (CIGS). These various elements are used to improve operating efficiencies and lower production costs of PV devices. In general, crystalline PV devices have higher solar efficiencies, but materials cost more due to their material thickness of 150 to 200 microns, whereas, thin film PV are usually about 3 microns deep offering potentially, significantly lower production costs. However, so far in the market place, only CdTe-based thin film solar modules are cheaper than that of polycrystalline silicon. Thin film technologies currently have 18-20% of the market share.

Electrochemical

Unlike the crystalline and thin film solar cells that have solid-state light absorbing layers, electrochemical solar cells have their active component in a liquid phase. They use a dye sensitizer to absorb the light and create electron-hole pairs in a nanocrystalline titanium dioxide semiconductor layer. This is sandwiched between a tin oxide coated glass sheet (the front contact of the cell) and a rear carbon contact layer, with a glass or foil backing sheet.

These cells have the potential to offer lower manufacturing costs in the future because of their simplicity and use of cheap materials. The challenges of scaling up manufacturing and demonstrating reliable field operation of products lie ahead. However, prototypes of small devices powered by dye-sensitised nanocrystalline electrochemical PV cells are now appearing in the market.

3.2.2 Concentrated solar power

CSP is a term for technologies that concentrate the sun's rays to heat a medium (usually liquid or gas) that is then used in a heat engine process (steam or gas turbine) to generate electricity, which can be stored for later use or used to supply heat for industrial processes.

There are four main CSP designs currently in use at the utility scale: parabolic troughs, tower systems, parabolic dishes and linear (Fresnel) troughs. Parabolic troughs currently account for over 90% of the generation capacity in installed CSP, however many in the solar industry speculate that tower systems will become more widely used than parabolic troughs in the future.

The scale of concentrated solar is set to increase dramatically as projects in the planning and construction stage come online. As of 2010, more than 800MW of CSP plants were operational, and this number is likely to exceed 1GW by 2011, as Spain already has 1GW of installed CSP capacity. As for the future, the United States and Spain alone have 17GW of plants that are planned or under construction.[a] Most of this total (about 14.5GW) consists of planned projects.

Up to 90% of operational CSP plants are located in the United States and Spain.[b] The American Southwest has greater potential and the United States has a slightly larger total installed capacity; however on a per capita basis Spain produces far more power with CSP than the United States. Spain has ten operational CSP plants between 1 and 50MW.[c]

CPV applies the law of refraction to focus sunlight on a solar cell with a lens. Cell materials include Polysilicon and III-V Compound Semiconductor (mainly Gallium Arsenide: GaAs). The latter multi-junction design, for example, has a maximum conversion efficiency of 45.5%.

Part of the CSP generation is storage of electricity to make it available when sunlight is not available. There are a number of solutions to these:[d]

a Greenpeace, ESTELA, Solar PACES. Concentrating Solar Power Global Outlook 2009, p.7.
b International Energy Agency, 2009. Renewable Energy Essentials: Concentrating Solar Power.
c Protermo Solar map of solar installations, 2010. Available at: http://protermosolar.com/boletines/boletin24.html#destacados03.
d Solar Thermal Storage Technologies, Doerte Laing, German Aerospace Centre(DLR), Energy Forum Hannover 2008.

- Steam accumulators
- Molten salt storage
- Solid media concrete storage
- Phase change storage
- Combined concrete and Phase change storage.

As all of these solutions require structural materials, they have not been included in this study. In fact, electricity storage is one of the 17 technologies in the Technology Map 2009, which, as it covers from battery storage to molten salts, would require a more detailed study. Examples of materials used in these technologies include sodium nitrate and potassium nitrate for molten salt storage, cobalt and lithium or rare earth elements for battery technologies, as well as bulk materials such as steel alloys and concrete.

3.3 Wind Energy

Wind turbines generate electricity by capturing the wind energy as mechanical energy through blades attached to a rotating shaft. This mechanical energy is converted to electrical energy by a generator driven by the shaft. Wind turbines are normally grouped in wind farms in order to obtain economies of scale. Wind speed is the most important factor affecting wind turbine performance. A small difference in wind speed gives a large difference in available energy and in electricity produced, and eventually in the cost of the electricity generated. Generally, utility-scale wind power plants require minimum average wind speeds of 6 ms^{-1}.

There are two main market sectors: onshore wind, which includes both inland and shoreline installations, and offshore wind, away from the coast. The differences are remarkable, due to the different working environment (saline and tougher in the sea) and facility of access for installation and maintenance. In addition, as the wind is stronger and more stable at sea, wind turbine electricity production is higher offshore. Current onshore wind energy certainly has room for further technology improvement, for example, locating in forests or facing extreme weather conditions. Wind energy is a mature technology, however offshore wind power still faces many challenges.

The trend towards ever larger wind turbines (20 kW in the 1980s to a maximum of 7.5 MW today) has stabilised during recent years. Currently land-based turbines (98 % of all installed capacity) are mostly rated either at the 750 – 850 kW, the 1.5 – 2 MW or the 3 MW range. For offshore machines however, both industry and academia see larger turbines (10 – 20 MW) as the future. The main lines of research include larger turbines, drive-train innovations and offshore installation. Drive research includes direct drive, leading to simpler nacelle systems, increased reliability, increased efficiency and absence of gearbox issues; and hybrid drive trains, generally leading to very compact drive. Direct-drive solutions may use permanent magnets that contain rare earth metals, which are of interest for this study, although other technologies include copper electromagnets and (not yet commercial) High Temperature Superconductor (HTS) systems.

The European Wind Initiative (EWI) is the technology roadmap to reduce the cost of wind energy. Its implementation will help improve the competitiveness of the industry by ensuring the large-scale deployment of wind energy worldwide and securing long-term European technological and market leadership. In addition the EWI aims at ensuring that aspects other than technology are met in order to facilitate the deployment of wind energy. The strategic objectives of the EWI are:

- to maintain Europe's technology leadership in both onshore and offshore wind power
- to make onshore wind the most competitive energy source by 2020 with offshore following by 2030
- to enable wind energy to supply 20 % of Europe's electricity in 2020, 33 % in 2030 and 50 % in 2050.

3.4 Bioenergy

Bioenergy involves converting the energy contained within organic sources into energy. Bioenergy can be divided into electricity and/or heat generated by biomass, and the production of biofuels from plant feedstocks (biomass). These are associated with separate areas of the energy supply, and are dealt with separately below.

Biomass is used for electricity generation in biomass boilers specifically designed for this purpose. Though the design of biomass boilers differs to those used for fossil fuel combustion, the metals and scale of equipment is similar, therefore no metal supply issues are expected.

Biofuels (sometimes denoted as agrofuels to make reference to biofuels from agriculture and forestry) can be broadly defined as any sort of fuel that is made from biomass. The most common biofuels are biodiesel and bioalcohols, including bioethanol and biobutanol (also called biogasoline).

Biofuel production usually involves catalysts which are environmentally benign and can be operated in continuous processes. Moreover they can be reused and regenerated. However, due to a high molar ratio of alcohol to oil, large amounts of catalyst and high temperature and pressure are required when utilising heterogeneous catalysts to produce biodiesel.

Several heterogeneous catalysts have been employed in the biodiesel production, for example magnesium oxide, calcium oxide and hydrotalcites. Fischer-Tropsch catalysts are very well known for the syngas synthesis to produce diesels and gasoline. These catalysts are relevant if the fuel sources are biomass based. The most common Fischer-Tropsch catalysts use Group VIII Metals (cobalt, ruthenium and iron). Iron catalysts are commonly used because of their low costs in comparison to other active metals. Cobalt catalysts give the highest yields and longest life-time while ruthenium is very active but expensive. These metals are used as low concentration dopants in some oxide-based substrates, such as alumina and silica.

The European Industrial Initiative on bioenergy addresses the technical and economic barriers to the further development and accelerated commercial deployment of bioenergy technologies. This should lead to the widespread sustainable exploitation of biomass resources, with the aim of ensuring at least 14% bioenergy in the EU energy mix by 2020, and at the same time achieving a reduction of greenhouse gas emissions by 60% for biofuels and bio-liquids under the sustainability criteria of the RES Directive.[a]

3.5 Carbon Capture and Storage (CCS)

Carbon Capture and Storage (CCS) involves three distinct stages for its application to fossil fuel power stations in capturing carbon dioxide emissions and preventing their release to the atmosphere:

- Capture – the capture and isolation of CO_2 emitted from fossil fuel combustion
- Transport – the transfer of the captured CO_2 from the source site to long-term storage
- Storage – long-term storage for CO_2.

The implementation of these components requires distinct technologies, with further variations existing within each category.

Capture

Three alternative technologies for CO_2 capture are currently being tested for potential commercial application, each using a different mechanism to capture CO_2 emissions:

- Pre-combustion technology – In the first place the fossil fuel is converted to syngas (a mixture of carbon monoxide and hydrogen), which is then 'shifted' to CO_2 and H_2 prior to

a Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources combustion taking place. The CO_2 is then extracted and sequestered, and the H_2 is used as fuel for power generation.

- Post-combustion technology – this technology removes the CO_2 from the flue gas emissions generated during the combustion process. The CO_2 is most commonly sequestered by absorption with an amine-based solvent. Desorption then occurs by altering the conditions and the CO_2 separates off. The solvent can be cycled repeatedly in a continuous process.
- Oxy-combustion – this method requires combustion to take place with pure oxygen, generating a flue gas composition of almost pure CO_2. This technology requires an on-site plant to produce an oxygen stream from air and produces a much hotter combustion process.

At this stage all these technologies are still in consideration for commercial use, though post-combustion and pre-combustion technologies are more fully developed, as they have been used previously in industry, though on a much smaller scale.

Transport

Two alternatives for CO_2 transport are under consideration: pipelines and ships. For large scale CCS, involving the transport of CO_2 from power stations to large storage sites, permanent pipelines are viewed as the most suitable system. Shipping may still be utilised on a small scale, but this is unlikely to be viable for power generation scale operations, and is therefore not considered within this study.

Storage

Several storage options are being investigated. Under current plans the highest capacity of CO_2 will be stored in rock formations which, being rigid will hold high pressures of CO_2. Other options include storage in the deep oceans (either dispersed in the water or as a lake under pressure) or mineral carbonation. Both of these options are at the experimental stage.

In addition to the technologies directly associated with CCS, improvements to the energy generation efficiency of turbines are also likely to be implemented as a result of CCS. CCS utilises a significant proportion of the total energy output of power generation (current estimates are between 10 to 40%). Therefore gains in efficiency resulting from improved turbines have a double benefit in this case. These improvements are often planned to be implemented in parallel to CCS, therefore these have also been examined in this study.

The objective of the European Industrial Initiative on carbon capture and storage is to demonstrate the commercial viability of CCS technologies in an economic environment driven by the emissions trading scheme. In particular, it aims to enable their cost-competitive deployment in coal-fired power plants by 2020 or soon thereafter, and to further develop CCS-technologies to allow for their subsequent wide-spread use in all carbon-intensive industrial sectors.

Targets in the SET-Plan aim at 3,600 MW of power generation, via demonstration plants, to be CCS-enabled by 2020. This scale of further envisaged deployment requires installation of a large-scale infrastructure to provide the sequestration at a large enough capacity for this level of power generation.

3.6 Electricity Grids

The objective of the European Industrial Initiative on electricity grids is to enable the transmission and distribution of up to 35% of electricity from dispersed and concentrated renewable sources by 2020, and a completely decarbonised electricity production by 2050. This is to be achieved through further integrating national networks into a market-based, truly pan-European network guaranteeing a high quality of electricity supply to all customers and engaging them as active participants in energy efficiency, while anticipating new developments such as the electrification of transport.

An electricity grid is defined to include:

- greater use of ICT to monitor and manage flows of electricity in the transmission and distribution grid and in the home environment;
- adaption of the distribution and transmission grid to greater proportions of renewable energy and greater distributed energy generation;
- investments in the power transmission grid to enable connectivity to new generation assets, and between countries and regions.

Control and management systems, often referred to as the “smart” contribution, i.e. Smart Electricity Grid, incorporate conventional ICT materials found in computers and telecommunications equipment – small quantities of silicon, copper and a large variety of speciality metals and materials in very small quantities. Greater use is made of power electronics in Smart Electricity Grids, which incorporate silicon or silicon carbide semiconductor devices. Whilst the number of facilities able to fabricate such large-scale devices may be limited, the supply of metals is not significant compared to world usage. Monitoring of power cables may require fibre-optic cable, but again not in quantities that are significant compared to total world production of fibre-optic material.

Hence the introduction of “smartness” into the grid does not introduce any speciality metal requirements. The sensitivities are present in the conventional investment in cabling and transformers to extend the grid to new sources of power, notably offshore wind in the period to 2020, and to interlink European countries to a greater extent.

For the purposes of this study the conventional replacement investment in the transmission and distribution grids is included.

Overhead cables

For 2020, it is likely that high voltage AC (HVAC) cables will only be constructed using an aluminium conductor and a conventional steel cabling core to provide tensile strength.[a] Future developments include carbon-fibre cores to increase the lightness of the cable and hence enable greater spacing of supporting pylons. Monitoring techniques using fibre optics are under development to monitor the sag of cables, which increases with temperature, and hence to optimise the current carrying capacity of the line under different environmental conditions. However, none of these innovations has speciality metal implications.

Submarine cables

Submarine cables are required for increasing offshore wind capacity, also for certain large scale international interconnector projects such as those proposed for the North Sea and for the Mediterranean. These cables may be AC, although there is increasing use of HVDC for long distance submarine cables, and this trend is expected to continue. However there is little difference in metal requirements between the two approaches: copper or aluminium conductors may be used, or a combination of the two. In addition, a copper mesh surrounding the insulators may be used. Lead sheathing has been traditionally used to help protect submarine cable integrity, although it now exists in competition with plastic sheathings.

[a] ENTSO-E Project of European Significance up to 2020

Superconducting cables
Demonstration projects have existed for some time using conventional high temperature superconductors. The consensus view of researchers and commercial organisations is that superconductors will have very limited penetration of the power cable market by 2020. Applications will be limited to high power, short distance applications where the minimisation of cabling infrastructure is particularly attractive (for example urban environments). Superconducting cables are not forecast to be used in long distance cables that might consume significant quantities of the constituent metals compared to current world production.

Transformers, switchgear
Conventional construction using copper, aluminium and steel is expected to continue. Typical steel alloys have high silicon contents, but have no unusual alloying elements. Superconducting windings have been experimentally trialled in transformers, but are not expected to be deployed by 2020.

3.7 Conclusion

This Chapter has provided an overview of the SET-Plan for the implementation of renewable energy technologies within Europe. Within this study the focus has been placed upon the six SET-Plan technologies:

- Nuclear energy (fission)
- Solar energy (PV and CSP)
- Wind energy
- Bioenergy
- Carbon Capture and Storage
- Electricity Grids.

As this Chapter has outlined, each of these six technologies have their own roadmaps and implementation plans.

The Chapter has also provided a technical illustration of each of the six technologies. This demonstrates that each of the technologies have different components, each of which has their different metal requirements. Additionally, a number of the technologies have a number of possible sub-technologies that will collectively contribute towards achieving the SET-Plan. As each of these sub-technologies have differing metals requirements, it is crucial that any analysis of SET-Plan metals requirements considers the possibility of alternative technology mixes.

The next Chapter estimates the metals demand under the most optimistic uptake scenario for the six SET-Plan technologies and identifies on this basis for which metals demand is likely to increase most significantly due to the deployment of these technologies.

4 Metal Requirements of SET-Plan

This study has taken a bottom-up approach of identifying and quantifying the metals requirements of the SET-Plan technologies, creating an inventory of all of the metals required for each of the technologies that have been discussed in the previous Chapter. The broadest possible range of metals was considered at this stage to ensure comprehensive coverage ahead of the screening process: 60 metallic elements in all – only iron, aluminium and radioactive elements were excluded. Table 2 gives details of the metals considered and required for each SET-Plan technology, as indicated by the research presented in Appendix 2. Those metals that have been ticked in brackets denote very small or occasional usage which has not been quantified. With respect to rare earth metals (REM) and the platinum group of metals (PGM), Table 3 provides a list of these separate metals and their usages in wind and biofuels respectively.

Nuclear fission was the technology with the greatest number of required metals at 17; conversely Electricity Grids had the fewest at 2. It was noted that a number of the metals had uses across more than one SET-Plan technology, for example copper (five technologies), molybdenum and nickel (four technologies). These cross-technology sensitivities are taken into account in the screening process. It is also observed that some of the metals listed within the scope of the study such as bismuth, lanthanum, lithium, platinum and palladium were not identified as being used within the six SET-Plan Technologies.

The analysis in this Chapter provides quantitative estimates for the annual metal requirements of each of the six technologies and sub-technologies. These have been calculated based on a detailed assessment of metal requirements of each sub-technology and their individual components, which can be found in Annex 2. Based on assumptions about the future mix of sub-technologies which are discussed below, aggregate metal requirements for each of the technologies are presented here in terms of:

- kilogram per megawatts (of new) nuclear, wind and solar power installed capacity
- kilogram per million tonnes of oil equivalent that is generated from bio energy
- kilogram per megawatt of fossil fuel electricity generation capacity to which CCS is applied
- kilogram per kilometre of electricity grid cables that are laid.

This allows estimating and comparing the metal demand from various scenarios for the deployment of SET-Plan technologies. In this Chapter the technology mix for wind and solar energy is kept fixed, however Chapter 6 examines the demand sensitivities associated with varying the technology mix.

In section 4.1, the demand for the 60 different metals in the most optimistic scenario for the deployment of the SET-Plan technologies is calculated and finds that metal requirements in this scenario are most demanding between 2020 and 2030. However, these *absolute* volumes are not a useful metric for comparison because global production volumes for metals differ considerably ranging from tens of millions of tonnes for some metals to less than a hundred tonnes per annum for others. Instead, the additional average annual demand from the deployment of SET-Plan technologies in Europe between 2020 and 2030 for each metal in this optimistic scenario is compared to the global production volume of this metal in 2010. This ratio (expressed as a percentage) allows comparing the *relative* stress of the deployment of SET-Plan technologies on the demand for different metals. Additional and different technology uptake scenarios are later modelled in Chapter 6 to explore the impact of such variations on the demand for key metals.

The results show that the deployment of SET-Plan technologies in Europe creates very different challenges for different metals. For some, the average annual demand between 2020 and 2030 from the deployment of SET-Plan technologies in Europe has a negligible impact on the global demand for that metal (less than a tenth of a percent) to others for which it will imply a major challenge for suppliers.

Table 2: List of Metals Considered in This Study

Element Name	Symbol	Nuclear	Solar	Wind	Biofuels	CCS	Grids
Antimony	Sb	✗	✗	✗	✗	✗	✗
Barium	Ba	✗	✗	✗	✗	✗	✗
Beryllium	Be	✗	✗	✗	✗	✗	✗
Bismuth	Bi	✗	✗	✗	✗	✗	✗
Cadmium	Cd	✓	✓	✗	✗	✗	✗
Calcium	Ca	✗	✗	✗	✗	✗	✗
Caesium	Cs	✗	✗	✗	✗	✗	✗
Chromium	Cr	✓	✗	✓	✗	✓	✗
Cobalt	Co	✓	✗	✗	✓	✓	✗
Copper	Cu	✓	✓	✓	✗	✓	✓
Gallium	Ga	✗	✓	✗	✗	✗	✗
Germanium	Ge	✗	✓	✗	✗	✗	✗
Gold	Au	✗	✗	✗	✗	✗	✗
Hafnium	Hf	✓	✗	✗	✗	(✓)	✗
Indium	In	✓	✓	✗	✗	✗	✗
Lead	Pd	✓	✗	✗	✗	✗	✓
Lithium	Li	✗	✗	✗	✗	✗	✗
Magnesium	Mg	✗	✗	✗	✗	✗	✗
Manganese	Mn	✗	✗	✓	✗	✓	✗
Molybdenum	Mo	✓	✗	✓	✗	✓	✗
Nickel	Ni	✓	✗	✓	(✓)	✓	✗
Niobium	Nb	✓	✗	✗	✗	✓	✗
Platinum Group	PGM	✗	✗	✗	✓	✗	✗
Potassium	K	✗	✗	✗	✗	✗	✗
Rare Earth Elements	REE	✗	✗	✓	✗	✗	✗
Rhenium	Re	(✓)	✗	✗	✗	(✓)	✗
Rubidium	Rb	✗	✗	✗	✗	✗	✗
Scandium	Sc	✗	✗	✗	✗	✗	✗
Selenium	Se	✗	✓	✗	✗	✗	✗
Silver	Ag	✓	✓	✗	✗	✗	✗
Sodium	Na	✗	✗	✗	✗	✗	✗
Strontium	Sr	✗	✗	✗	✗	✗	✗
Tantalum	Ta	✗	✗	✗	✗	(✓)	✗
Tellurium	Te	✗	✓	✗	✗	✗	✗
Thallium	Tl	✗	✗	✗	✗	✗	✗
Tin	Sn	✓	✓	✗	✗	✗	✗
Titanium	Ti	✓	✗	✗	✗	✗	✗
Tungsten	W	✓	✗	✗	✗	✗	✗
Vanadium	V	✓	✗	✗	✗	✓	✗
Yttrium	Y	✓	✗	✗	✗	(✓)	✗
Zinc	Zn	✗	✗	✗	✗	✗	✗
Zirconium	Zr	✓	✗	✗	✗	✗	✗

(Metals that have been ticked in brackets denote very small or occasional usage which has not been quantified)

Table 3: List of Rare Earth Elements and Platinum Group Metals Considered in this Study

Rare Earth Elements	Symbol	Wind
Lanthanum	La	×
Cerium	Ce	×
Praseodymium	Pr	(✓)
Neodymium	Nd	✓
Samarium	Sm	×
Europium	Eu	×
Gadolinium	Gd	×
Terbium	Tb	(✓)
Dysprosium	Dy	✓
Holmium	Ho	×
Erbium	Er	×
Thulium	Tm	×
Ytterbium	Yb	×
Lutetium	Lu	×

Platinum Group Metals	Symbol	Biofuels
Ruthenium	Ru	✓
Rhodium	Rh	×
Palladium	Pd	×
Osmium	Os	×
Iridium	Ir	×
Platinum	Pt	×

(Metals that have been ticked in brackets denote very small or occasional usage which has not been quantified)

4.1 Significance Screening

In this section the metal requirements of each of the SET-Plan technologies is quantified using the functional units discussed in the previous section. Full details on these calculations can be found in Appendix 2. A summary of the key references and assumptions can be found in the Appendix, for each of the SET-Plan technologies in turn. The quantification by functional units then enabled the total metal requirements to be calculated for the different uptake scenarios of each SET-Plan technology. In order not to exclude any important metals, the most optimistic projections for technology uptake were modelled in the screening process (see Appendix 1 for more details), and compared to current world supply of the metal. For each technology, the reference scenario for 2010 from the European Energy Outlook was used as the starting point. The main source used for the supply data was USGS Mineral Commodity Summaries 2011 and it is noted where available secondary production has been included. Supplementary data sources were required for some elements, as the USGS did not attribute production for some specific metals or take secondary production into account.[a]

It is recognised that the most optimistic projections are likely to be unrealistic in some cases. Additionally, it is likely that world production of the relevant metals will grow as demand increases.[b] Therefore comparing the most optimistic demand scenario for the SET-Plan technologies with current world supply provides a criterion that is much more likely to overestimate rather than to underestimate the risks for potential supply shortfalls. Where European average annual demand from SET-Plan technologies between 2020 and 2030 is estimated to exceed 1% of current world supply, the additional demand for a specific metal from the deployment of these technologies is classified as *significant*. While there is no 'natural' choice for such a threshold, usage below 1% of current supply even under the most optimistic uptake scenarios constitutes a very marginal demand and is highly unlikely to materially impact on future deployment of the six SET-Plan technologies. All metals for which this method detects significant additional demand from the deployment of the six SET-Plan technologies in Europe are subject to more in-depth scrutiny in the following Chapter.

a These elements were dysprosium, gallium, hafnium, indium and neodymium. See Appendix 3 for more details.
b Appendix 3 does provide supply forecasts for those metals up to 2020 that were identified as being significant for the SET-Plan, which are then used in Chapter 5 in the Bottleneck Analysis.

4.1.1 Nuclear energy

The metals requirements for nuclear energy are presented in Table 4. The metals demand (kg/MW) has been calculated on the basis that reactors to be built will be either Westinghouse AP1000 or Areva EPR designs and this provides the source of much of the data, with remaining gaps filled by US Environmental Protection Agency Data on Scrap Metal Inventories at US nuclear power plants. Full details on the model systems can be found in Appendix 2.

The uptake assumptions used are the World Nuclear Association, High Projections, and assume that no recycling takes place for nuclear reactors scheduled to be shutdown (38 GW of capacity by 2030). This projection is for 198 GW of nuclear capacity for 2020 and 297 GW for 2030. Using these calculations, the largest metals requirements in 2030 as a percentage of 2010 world supply are for hafnium (7.0%) and indium (1.4%), both of which are used for reactor control rods.

Table 4: Nuclear Metals Requirements

Element	World Supply - 2010 (kt)	Metals Demand (kg/MW)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
Hf	0.082	0.48	0.004	0.006	5.2%	7.0%
In	1.35	1.6	0.01	0.02	1.0%	1.4%
Ag	22	8.3	0.07	0.10	0.3%	0.4%
Mo	234	70.8	0.6	0.8	0.3%	0.4%
Ni	1,550	255.5	2.3	3.0	0.1%	0.2%
W	61	5.0	0.04	0.06	<0.1%	<0.1%
Y	8.9	0.5	0.004	0.006	<0.1%	<0.1%
Nb	63	2	0.02	0.02	<0.1%	<0.1%
Zr	1,190	30.5	0.3	0.4	<0.1%	<0.1%
Cd	22	0.5	0.005	0.006	<0.1%	<0.1%
Cr	22,000	426.7	3.8	5.1	<0.1%	<0.1%
Sn	261	4.6	0.04	0.05	<0.1%	<0.1%
V	56	0.6	0.005	0.007	<0.1%	<0.1%
Cu	16,200	59.6	0.5	0.7	<0.1%	<0.1%
Pb	4,100	4.3	0.04	0.05	<0.1%	<0.1%
Ti	5,720	1.5	0.01	0.02	<0.1%	<0.1%
Co	88	0	0	0	<0.1%	<0.1%

World Supply 2010 Data: USGS, except for Hf (own calculations from USGS/Roskill) & In (US DoE 2010)
Key References for Metals Demand: Arreva, UK Equipment Suppliers, US EPA
Uptake Assumptions: World Nuclear Association – High Projections; no recycling of shut down plants

4.1.2 Solar energy

The metals requirements for PV and CSP are presented in Table 5 and Table 6 respectively. For solar PV the assumptions used are the Maximum potential Penetration Scenario in the 2007 SETIS Technology Map, with a technology mix of 80% c-Si, 10% a-Si, 5% CdTe and 5% CIGS. For CSP the assumptions for uptake are taken from the Solar Thermal Electricity European Industrial Initiative from JRC-SETIS (2009). The largest metals requirements as a percentage of world supply in 2010 are in the thin film technologies for tellurium (50.4%), indium (18.0%) and gallium (3.9%) for 2030. The results also show that there are not insignificant raw metals requirements within crystalline silicon for tin (9.6%) and silver (4.7%), in 2030. Additionally, the sensitivity analysis on the solar technology mix highlighted that selenium (also used in thin films) could have significant usage for the SET-Plan, where CIGS to have a larger than expected share of the technology mix.

Table 5: Solar PV Metals Requirements

Element	World Supply - 2010 (kt)	Metals Demand (kg/MW)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
Te	0.50	4.7	0.04	0.25	8.1%	50.4%
In	1.35	4.5	0.04	0.24	2.9%	18.0%
Sn	261	463.1	4.03	25.01	1.5%	9.6%
Ag	22	19.2	0.17	1.04	0.8%	4.7%
Ga	0.16	0.12	0.001	0.006	0.6%	3.9%
Cd	22	6.1	0.05	0.33	0.2%	1.5%
Se	3.25	0.5	0.004	0.026	0.1%	0.8%
Cu	16,200	2194.1	19.09	118.48	0.1%	0.7%
Pb	4,100	269.3	2.34	14.54	<0.1%	0.4%

World Supply 2010 Data: USGS, except In & Ga (US DoE 2010), Hf (own calculation from Rpskill)
Key References for Metals Demand: Academic Sources (Materials Sciences, Energy Materials, Utrecht University); Ökopol, National Renewable Energy Laboratory
Uptake Assumptions: SETIS (2007) – Maximum potential Penetration Scenario
Technology Mix 80% c-Si, 10% a-Si, 5% CdTe, 5% CIGS.

Table 6: Solar CSP Metals Requirements

Element	World Supply - 2010 (kt)	Metals Demand (kg/MW)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
Ag	22	6.5	0.02	0.02	<0.1%	<0.1%

World Supply 2010 Data: USGS
Uptake Assumption: JRC-SETIS (2009): European Solar Industry Initiative

4.1.3 Wind energy

The metals requirements for wind energy are presented in Table 7. The metals demand (kg/MW) has been calculated on the assumption that the technology mix will be 15% permanent magnet in 2020 and 20% in 2030. This penetration of permanent magnetic adoption is lower than that expected for the world as a whole due to the existence of a European manufacturer of non-permanent magnet gearless systems and relatively slow uptake of permanent magnet turbines in Europe to date. Clearly this is an important sensitivity and the reasoning behind it, is discussed in Appendix 2, together with details on the model systems and the analysis used to calculate the metal composition of turbines.

The uptake assumptions used are from the EWEA (2010) projections for long-term take-up. This assumes wind capacity of 230 GW for 2020 and 400 GW for 2030. Using these calculations, the largest metals requirements for 2030 as a percentage of 2010 world supply are for the rare earth elements dysprosium (4.0%) and neodymium (3.8%), which are used in permanent magnet generators (PMG) and for molybdenum (1.0%), which is used as a steel alloying element.

It is noted that the results presented here are in line with separate modelling undertaken internally by the EWEA.[a] In the EWEA modelling similar assumptions were made regarding neodymium usage per MW and penetration of permanent magnets in the technology. Within their analysis however the EWEA noted a number of caveats:

- The 2009 direct drive market share was split between two manufacturers, one of which does not use permanent magnets.
- The specific amount of rare earth elements used varies significantly with the speed of the turbines.
- No innovation has been factored into the modelling

These issues are discussed and modelled within the technology sensitivity analysis contained within Section 6.2. However for the purposes of the significance screening, which has been conducted on the basis of quantifying the most demanding scenario for metal demand, these issues have not been included in this section.

Table 7: Wind Energy Metals Requirements

Element	World Supply - 2010 (kt)	Metals Demand (kg/MW)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
Dy	1.2	2.8	0.03	0.05	2.5%	4.0%
Nd	18	40.6	0.43	0.69	2.4%	3.8%
Mo	234	136.6	1.95	2.32	0.8%	1.0%
Ni	1,550	663.4	9.46	11.28	0.6%	0.7%
Cu	16,200	1142.9	16.13	19.43	<0.1%	0.1%
Cr	22,000	902.4	12.83	15.34	<0.1%	<0.1%
Mn	13,000	80.5	1.18	1.37	<0.1%	<0.1%

World Supply 2010 Data: USGS, except for Dy & Nd (US DoE 2010)
Key References for Metals Demand: BVG Associates &UK Renewables, Corus Speciality Steels, General Electric, Shin Etsu, Avalon Rare Metals, Great Western Minerals Group and Technology Metals Research
Uptake Assumptions: EWEA (2010) long-term take-up
Technology Mix: 15% low speed permanent magnet in 2020 and 20% in 2030

a Wilkes, Justin. EWEA. (Personal communication)

4.1.4 Carbon capture and storage

The metals requirements for CCS are presented in Table 8. As little is known about the metals required within CCS, the metals demand (kg/MW of fossil fuel generation fitted with CCS) has been calculated based upon assumptions on the additional high specification steel alloys needed to upgrade existing generators. For the pipelines, the compositions of the steels have been modelled on those currently used within the oil and gas industry. More details can be found in Appendix 2. It should be noted that the metals demand (kg/MW) is not a constant relationship, and depends upon the actual length of pipeline constructed, with Table 8 showing the metals demand (kg/MW) for 2030.

Table 8: Carbon Capture and Storage Metals Requirements

Element	World Supply - 2010 (kt)	Metals Demand (kg/MW)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
V	56	100	0.080	0.730	0.1%	1.3%
Nb	63	100	0.080	0.730	0.1%	1.2%
Ni	1,550	1,145	0.926	8.336	<0.1%	0.5%
Mn	13,000	3,761	3.011	27.380	<0.1%	0.2%
Co	88	7.5	0.006	0.055	<0.1%	<0.1%
Cu	16,200	692	0.559	5.034	<0.1%	<0.1%
Mo	234	7.5	0.006	0.055	<0.1%	<0.1%
Cr	22,000	326	0.261	2.373	<0.1%	<0.1%

World Supply 2010 Data: USGS
Uptake assumptions: JRC-SETIS (2009) – Maximum potential Penetration Scenario
Note: Ta, Hf, Re and Y may also be required but demand is uncertain

The uptake assumptions modelled are the JRC-SETIS (2009) Maximum potential Penetration Scenario, which is for a capacity of 3.6 GW in 2020 (demonstration plants) and 80 GW (commercial plants) for 2030. Using these calculations the largest metals requirements as a percentage of current world supply in 2030 are for vanadium (1.3%) and niobium (1.2%), which are used as steel alloying elements within the pipelines. It was noted that small quantities of some other metals may also be required, but the demand for these is uncertain.

4.1.5 Electricity Grids

The metals requirements for Electricity Grids are presented in Table 9. The assumptions used are the ENTSO-E Project of European Significance up to 2020; with copper being used for underground cables only (aluminium is used for overground) and lead sheathing used for submarine cables. More details can be found in Appendix 2. Neither have particularly stringent metals requirements.

Table 9: Electricity Grids Metals Requirements

Element	World Supply - 2010 (kt)	Metals Demand (kg/km)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
Cu	16,200	8,200	78.72	N/A	0.5%	N/A
Pb	4,100	2,000	19.2	N/A	0.5%	N/A

World Supply 2010 Data: USGS
Uptake assumptions: ENTSO-E Projects of European Significance;
Assumptions: Cu for underground only, Pb sheathing for submarine cables

4.1.6 Biofuels

A variety of catalysts can be used for the Fischer–Tropsch (F-T) process, but the most common are the transition metals cobalt, iron and ruthenium. Cobalt-based catalysts are highly active. In addition to the active metal, the catalysts typically contain a number of 'promoters' including potassium and copper. Catalysts are supported on high-surface-area binders/supports such as silica, alumina or zeolites. Cobalt catalysts are more active for F-T synthesis when the feedstock is natural gas, while iron catalysts are preferred for lower quality feedstock such as coal or biomass.

Two types of F-T catalysts considered are 79%Fe, 20% Co, 1% Ru[a] on alumina substrate and 98% Co, 2% Ru.[b] The latter has been taken for the calculations as this is the scenario with the most demanding metal requirements due to its high composition of cobalt. For this, 20% metal loading, 0.8 compaction ratio and 0.15 tonnes biofuels product per m^3 catalysts per hour were taken. The lifetime for the catalyst is 10 years.[c] The results of the calculations are shown in Table 10. As shown, cobalt has no significant demand and ruthenium demand increases by only around 2-3% each year. However, the production of biofuel displaces the production of fossil-derived fuel using the same catalysts; hence for that reason, even this level of extra demand on ruthenium will not materialise. Furthermore, there are now recycling technologies for the recovery of F-T catalysts: hence ruthenium is not included in the significance list.

Table 10: Metal Requirement for Co-based F-T Catalysts.

Element	World Supply - 2010 (kt)	Metals Demand (kg/Mtoe)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply - 2010	
			2020	2030	2020	2030
Ru	0.03	0.12	0.001	0.001	1.8%	2.7%
Co	62	5.91	0.029	0.043	<0.1%	<0.1%

Co World Supply 2010 Data: USGS; Ru World Supply JM
Key References for Metals Demand: JM, F-T Technology Development
Uptake Assumptions: SETIS (2007) Maximum potential Penetration
Technology Mix: 98% Co, 2% Ru

4.2 Summary

To take into account cross-technology sensitivities, the metals requirements of the six SET-Plan technologies need to be added together. The results of this are shown in Figure 2 and Table 11, which have been ordered by the estimated average annual metals requirements for 2020-2030, as a percentage of current world supply. Any metals with requirements from the SET-Plan in 2030 accounting for more than 1% of current world supply were selected for further analysis. This 1% cut-off was selected on the basis that a usage below 1% of current supply even under the most optimistic uptake scenario constitutes a very marginal demand. The Chapter has demonstrated that deployment of these technologies also requires other metals, but these are needed in such small quantities compared to current world supply that their sourcing is extremely unlikely to constitute a significant problem for the deployment of SET-Plan technologies.

Additional sensitivity analysis on the solar technology mix highlighted that selenium could have significant usage for the SET-Plan were CIGS to have a larger than expected share of the technology mix (see Chapter 6); as a result selenium is included on the group of significant metals for further analysis.

The results show that the deployment of different SET-Plan technologies in Europe creates very different challenges for different metals. For most, the estimated average annual demand between 2020 and 2030 has a negligible impact on the global demand for that metal (less than a tenth of a percent). For others however, it is likely to imply more of a major challenge for suppliers. For example, more than 90% of

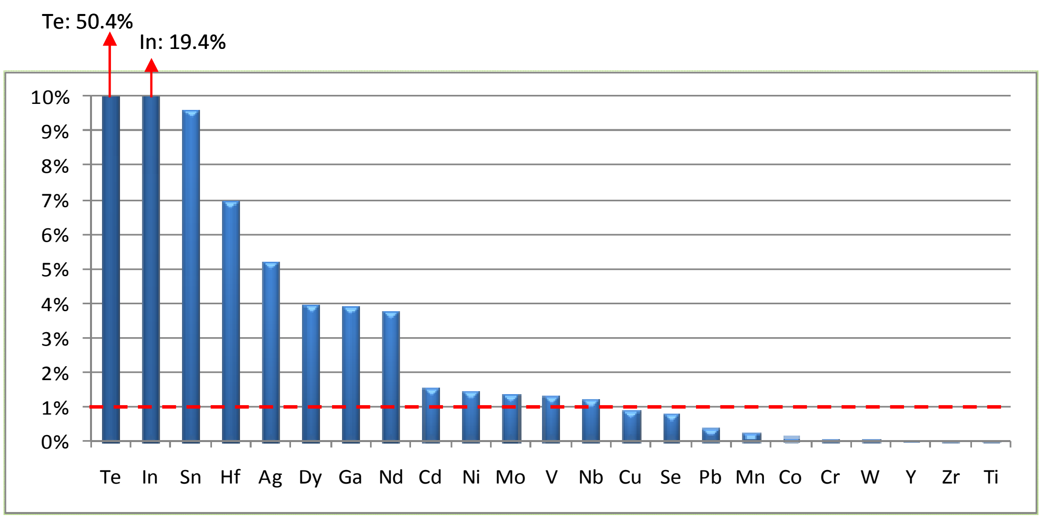
a Technology Development for Iron and Cobalt Fischer-Tropsch Catalysts. *Quarterly Report January 1, 1999 to March 31, 1999*.
b Johnson Matthey. (Personal communication)
c End of life management of GTL catalyst, tce, pp, 26-29, February 2007.

current global tellurium output per annum would be needed each year between 2020 and 2030 to satisfy only the demand generated from the deployment of PV thin-film technology in Europe. Note that this does not include the demand from applications other than these six technologies or the demand from countries outside of Europe.

In summary the results show that the deployment of the six SET-Plan technologies in Europe will require one percent or more of current world supply per annum between 2020 and 2030 for fourteen metals. These are designated as metals for which there is a significant additional demand from the deployment of these technologies in Europe. This group of "significant" metals and their major uses are:

1. Tellurium (solar thin films)
2. Indium (solar thin films & nuclear control rods)
3. Tin (solar crystalline silicon)
4. Hafnium (nuclear control rods)
5. Silver(solar crystalline silicon)
6. Dysprosium (wind permanent magnets)
7. Gallium (solar thin films)
8. Neodymium (wind permanent magnets)
9. Cadmium (solar thin films)
10. Nickel (various, steel alloys)
11. Molybdenum (wind steel alloys)
12. Vanadium (CCS pipelines)
13. Niobium (CCS pipelines)
14. Selenium (solar thin films).

Figure 2: Metals Demand of SET-Plan in 2030 as % of 2010 World Supply



Key: Te=tellurium, In=indium, Sn=tin, Hf=hafnium, Ag=silver, Dy=dysprosium, Ga=gallium, Nd=neodymium, Cd=cadmium, Ni=nickel, Mo=molybdenum, V=vanadium, Nb=niobium, Cu=copper, Se=selenium, Pb=lead, Mn=manganese, Co=cobalt, Cr=chromium, W=tungsten, Y=yttrium, Zr=zinc and Ti=titanium

It is therefore noted that the deployment of SET-Plan technologies can create some pressure on the supply of many minor metals. However, as the current output of many base metals is so large, the additional pressure from the deployment of SET-Plan technologies is small. In addition to their scale, base metals are typically well-developed and mature markets, while markets for minor metals are still under development, making the relative challenge created by additional demand from the deployment of new technologies much larger.

In the next Chapter, the risk of future supply-chain bottlenecks is examined for each of the 14 metals in the group of significant metals, in order to determine to what extent they represent potential risks with regards to the deployment of the six SET-Plan technologies. In particular, the global supply and demand situations are assessed to evaluate the likely stress on world demand, together with political factors. This will determine whether the significant SET-Plan demand for the fourteen metals constitutes a potential bottleneck.

Table 11: Total Metals Requirements of SET-Plan

Rank	Element	World Supply - 2010 (kt)	SET-Plan Demand (kt)		SET-Plan Demand / World Supply – 2010	
			2020	2030	2020	2030
1	Te	0.50	0.04	0.25	8.1%	50.4%
2	In	1.35	0.05	0.26	3.9%	19.4%
3	Sn	261	4.07	25.06	1.6%	9.6%
4	Hf	0.082	0.00	0.01	5.2%	7.0%
5	Ag	22	0.26	1.16	1.2%	5.2%
6	Dy	1.20	0.03	0.05	2.5%	4.0%
7	Ga	0.16	0.00	0.01	0.6%	3.9%
8	Nd	18	0.43	0.69	2.4%	3.8%
9	Cd	22	0.06	0.34	0.3%	1.5%
10	Ni	1,550	12.65	22.66	0.8%	1.5%
11	Mo	234	2.58	3.22	1.1%	1.4%
12	V	56	0.09	0.74	0.2%	1.3%
13	Nb	63	0.10	0.75	0.2%	1.2%
14	Cu	16,200	36.30	143.65	0.2%	0.9%
15	Se	3.3	0.00	0.03	0.1%	0.8%
16	Pb	4,100	2.38	14.59	<0.1%	0.4%
17	Mn	13,000	4.19	28.75	<0.1%	0.2%
18	Co	88	0.03	0.10	<0.1%	0.1%
19	Cr	22,000	16.88	22.80	<0.1%	0.1%
20	W	61	0.04	0.06	<0.1%	<0.1%
21	Y	8.9	0.00	0.01	<0.1%	<0.1%
22	Zr	1,190	0.27	0.36	<0.1%	<0.1%
23	Ti	5,720	0.01	0.02	<0.1%	<0.1%

5 Bottleneck Screening

5.1 Introduction

The findings of Chapter 4 demonstrate that SET-Plan technologies rely on a wide variety of different metals. The results further show that to realise the SET-Plan targets for the introduction of these technologies until 2030, 14 of these metals are required in significant quantities relative to their current production volumes. The aim of this Chapter is to provide an assessment of the risk for supply-chain bottlenecks to occur for each of these metals.

Such bottlenecks could disrupt a timely and affordable supply of these metals to Europe in the future and potentially hinder the smooth deployment of SET-Plan technologies and the realisation of the EU 2020 targets. In this context, it is important to note that significant SET-Plan demands for a specific metal on itself do not necessarily constitute a problem. Demand for raw materials changes constantly as technologies and consumption patterns change over time. This creates incentives for adapting supply, so that the market balance is restored.

However, such adaptation processes can be very time-consuming, for example, when it takes many years to open new mines. If demand expands rapidly and supply is unable to keep pace in the short to medium term, bottlenecks in the form of price rises and supply shortages can be the consequence.[a] In cases where only a few countries control the production of an individual metal under tight market conditions, bottlenecks can also be exacerbated through political interventions by governments. Dominant producers may, for example, use their market power to gain political or commercial advantages through influencing supply and prices or imposing trade restrictions.

A good example of how disruptive such bottlenecks can be is the case of rare earths. Given the challenging economic and technical obstacles involved in opening new rare earths mines, supply has struggled to grow considerably even though demand has been booming over the past decade.[b] In parallel, China has been systematically tightening export quotas that favour domestic rare-earth consuming industries over competitors in the rest of the world, resulting in 2010, in a tight market and driving up prices. China implemented strict measures to consolidate a weakly regulated industry with many small-scale operations that routinely ignore safety, environmental and export regulations; and a temporary halt of rare earth exports to Japan was imposed to exert political pressure in the context of a diplomatic dispute. Taken together, this combination of political and market factors have resulted in considerable supply shortages and price rises for rare earths over the course of 2010.[c] Indeed, even at the time of writing, there have been further substantial increases in the price of some rare earth oxides (especially dysprosium oxide) in 2011 alone.[d]

5.2 Approaches to Evaluating Risk for Supply-Chain Bottlenecks

It is not easy to evaluate the risk of such supply-chain bottlenecks occurring for individual metals in the future. Although several approaches have been developed over the past years to measure such supply risks, a widely accepted method does not exist. Table 12 below, lists the factors used to assess supply risks in several prominent studies.[e] It shows that while several factors are taken into account by most studies, many factors are also used only by a single study, such as for example, lead-times for expanding supply or vulnerability to climate change. Furthermore, the same factors are utilised differently: there is

a HCSS for TNO, 2010. Mineral Scarcity a strategic security issue.
b IMCOA Presentation at HCSS, Dec 2010. Meeting Rare Earths Demand in the next decade.
c New York Times, February 2011. China Acts to Tighten Grasp on Rare Earths Production.
d Metal-Pages
e It is important to note that most of these studies combine measures of 'supply risk' with an assessment of 'economic importance' and then combine both indicators to an overall criticality assessment (see e.g. EU 2010). The comparison here focuses only on the 'supply risk' dimension as the importance of the individual metals for the SET-Plan has been assessed in great detail in the previous Chapter and the study is not intended to evaluate the economic importance of these metals beyond the scope of the SET-Plan.

for example, no single way how to measure geological availability. Each study also uses different weighting factors to aggregate their results, for example, by first scoring each individual aspect and then aggregating the various factors through a formula or through descriptive accounts of each factor, which are then aggregated to an overall assessment through expert judgement.

Many of these studies then also use different scoring systems in their results about the supply risks concerning different metals. In order to make these comparable, the results from individual studies have been converted to a simple low-medium-high scale (Table 12). In addition to any disagreements on which factors constitute supply risk and using the appropriate measurement method, inconsistencies in the results are also likely to reflect a high degree of uncertainty about future supply and demand developments and limited availability of readily accessible data on supply risk factors for individual metals. Additionally, because much of the scoring within the studies is relative, for example, comparing the risks of one metal against the others, the assessments in part depend upon the metals analysed within each study. Notwithstanding these limitations, Table 12 also demonstrates that both the rare earths neodymium and dysprosium, as well as the by-products gallium and indium receive relatively high scores for supply risks across several prominent studies.

Table 12: Supply Risks Assessment in Earlier Studies

Study:	**US Department of Energy (2010)**	**European Commission (2010)**	**Oeko Institute (2009)**	**US National Resource Council (2008)**	**Oakdene Hollins (2008)**
Supply Risks Factors	• Geological availability • Political risk • By-product character • Concentration of supply • Competing demand	• Political risk • Concentration of supply • Ability to Substitute • Recycling potential	• Geological availability • By-product character • Concentration of supply • Lead times to expand production	• Geological availability • By-product character • US import-dependence • Recycling share	• Geological availability • Political risk • Concentration of supply • Vulnerability to climate change
Cadmium	N/A	N/A	N/A	N/A	Medium
Dysprosium	High	High	Medium	High	N/A
Gallium	Low	Medium	High	High	Medium
Hafnium	N/A	N/A	N/A	N/A	N/A
Indium	High	Medium	High	High	Medium
Molybdenum	N/A	Low	N/A	N/A	Medium
Neodymium	High	High	Medium	High	N/A
Nickel	N/A	Low	N/A	N/A	High
Niobium	N/A	Medium	N/A	High	High
Selenium	N/A	N/A	N/A	N/A	Medium
Silver	N/A	Low	N/A	N/A	High
Tellurium	Medium	Low	Medium	N/A	Medium
Tin	N/A	N/A	N/A	N/A	High
Vanadium	N/A	Low	N/A	Medium	Medium

5.3 *Criteria for Evaluating Bottleneck Risks*

Building on the insights from these previous studies, the approach taken here focuses on four criteria to evaluate risks for future supply-chain bottlenecks for individual metals, which are discussed in detail below. These four criteria are:

1. the likelihood of rapid global demand growth
2. limitations to expanding global production capacity in the short to medium term
3. the cross-country concentration of supply
4. political risk related to major supplying countries.

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. Different from several earlier studies, this report opts for a simple ordinal risk scale, instead of a numeric composite indicator, in order to avoid the misleading impression of a precise quantitative assessment of the risks for future bottlenecks. In the eyes of the authors, such precise estimates are difficult to make due to the complex set of dynamic factors that simultaneously affects the formation of future bottlenecks, 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 as described in greater detail in the following sections.

5.3.1 Market factors

A major weakness of many earlier studies is insufficient attention to actual market dynamics in evaluating the risk of future supply-chain bottlenecks. Of the studies presented in section 5.2, most, for example, fail to explicitly evaluate supply and demand side factors simultaneously, with the latest assessment by the US Department of Energy being a notable exception. Instead, they mostly rely on composite indicators that are assembled from data on potential for recycling or substitution, geological availability and supply concentration or political risks associated with major suppliers. While such factors are important driving factors for future demand and supply developments, by themselves they are insufficient to effectively assess the short- and medium-term evolution of this supply-demand balance. However, supply-chain bottlenecks result from the dynamic interplay of supply and demand and only occur when demand outpaces supply for some time.[a] Lack of substitutes, limited recycling potential and low known reserves, for example, do not necessarily imply that mine supply will be unable to meet demand, if major exploration projects are on the way and demand growth can be met from existing sources. (The issues of expanding primary output, recycling and substitution are all discussed further in Chapter 7 under Mitigation Strategies).

In contrast to many of the earlier studies, the approach taken here is therefore to focus explicitly on global demand and supply trends to identify bottleneck risks. The first two criteria used to evaluate bottleneck risks aim explicitly to capture these supply and demand dynamics that increase chances for supply-chain bottlenecks occurring.

First, bottlenecks are more likely to occur where global demand for a metal is forecasted to increase rapidly, because 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 (see Appendix 3). Note that while, for example, the theoretical potential for substitutability is not measured here directly, actual tendencies by industries to substitute the metal are typically taken into account by such demand forecasts. Obviously, a significant amount of uncertainty remains in these data, especially where the demand for a metal is driven by a few new applications with an uncertain future; nonetheless clear differences emerge between metals for

a HCSS for TNO, 2010. *Mineral Scarcity a Strategic Security Issue.*

which global demand is projected to expand at a rapid pace (for example neodymium) or for which relatively slow growth is expected (for example cadmium).

Second, the risk for bottlenecks is also higher wherever the short- to medium-term price elasticity of global supply is low, i.e. where *limitations to expanding global production capacity in the short to medium term* exist. This might be due to several reasons, for example, because existing projects are producing at full capacity and new projects are years away from production or because investors are reluctant to make large and risky long-term investments in new capacity in uncertain and volatile markets. The metal might also be a by-product, where production decisions are largely driven by the economics of the host-metal rather than by-product prices. The risk criterion is again scored as low, medium or high, based on supply forecasts from industry sources. Such forecasts typically evaluate the capacity of existing projects, secondary sources (i.e. recycling) and examine the exploration pipeline. Additionally, the scoring also takes into account currently available reserves and by-product character.

The interaction of these two risk criteria is then considered when assessing the overall market risk for a particular metal (rather than adding or averaging the two criteria in some way). 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 for a bottleneck 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. However, the risks for bottlenecks are considerable where market forecasts expect a rapid expansion of demand while the price elasticity of supply is low in the short to medium term. This can create situations where prices shoot up suddenly and if suppliers are unable or unwilling to react rapidly, this can leave customers unable to procure the quantities they want or force them to pay these inflated prices. The indium boom caused by the large scale introduction of LCD screens provides a good example, with prices increasing by 800% between 2002 and 2005 and producers nonetheless struggling to procure the desired quantities in the market.

Price forecasts have not explicitly been included within the bottleneck analysis for a number of reasons, (although prices are implicitly included, determined by the interaction of the other factors). Of the fourteen metals that are used in significant amounts in the six SET-Plan technologies, only three (nickel, tin and molybdenum) are traded on exchange-based markets, with the rest being traded through long-term supply contracts and individual trades between individual large consumers and suppliers as well as private trading houses. The terms of such trades are generally unavailable publicly and a 'market price' in the conventional sense does not exist. Publicly available price quotes, for example, through sources such as metal-pages.com, actually represent expert estimates of representative prices in trades being executed on a particular day, which are compiled through recurring interviews with individual traders. Given their small size and opaque nature, market and price forecasts for these metals in many cases do not exist, are not publicly available or are of questionable reliability, for example, where they are provided by parties with a commercial interest in specific forecasts, such as mining exploration companies. Nonetheless historical price graphs are available for the fourteen metals in Appendix 3.

5.3.2 Political Factors (including trade restrictions)

Beyond these market dynamics, political factors can also 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. The third risk criterion evaluates supply concentration as high, medium or low.

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 permits 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 (a phenomenon often referred to as 'resource nationalism')[a] and thereby exacerbate the risk of global supply-chain bottlenecks. Such interventions can take the form of *trade restrictions* that limit or tax exports of certain metals. Countries may implement them because they intend to subsidise domestic processing industries, as domestic supply is expanded at the expense of global supplies and a price differential emerges in favour of domestic consumers of the metals. Finally, it is also possible that countries use their power as suppliers as strategic bargaining in international relations, for example, to curry favours through long-term supply contracts or punishing through withholding supplies to specific countries.

While such political factors can clearly play a role in exacerbating risks for supply-chain bottlenecks, it is very difficult to measure these risks. The approach taken here follows the criticality study of the European Commission, by focusing on composite indicators measuring 'good governance' and political stability, such as the World Banks' Governance Indicator or the Failed State Index. They serve as - admittedly very crude - proxies for measuring the political stability of key suppliers and their inclination to intervene heavy-handedly in market processes, which, depending on the scores on these scales for major producers are again scored as low, medium or high.

It is important to stress that the risk for supply-chain bottlenecks to occur due to such political interventions remains contingent on both supply concentration and also overall market conditions. This is because if significant excess production capacity exists, it is likely to be very difficult, even for relatively large suppliers, to meaningfully intervene into markets as reductions in capacity or attempts to sell for higher prices are likely to be undercut by other competitor suppliers and resisted by customers who have alternative sources of supply. It is therefore only in a tight, supply-dominated environment that there is scope for effective political intervention by large suppliers, as buyers will find it difficult to replace supply from other sources and are often forced to accept higher prices as few alternatives exist.

5.3.3 Overall Scores

Table 13 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 of Table 13 provide an overview of the type of data that has been used to evaluate the individual risk factors, with a short explanation on what basis the high, medium or 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. In line with the above discussion, market risks are determined through the simultaneous evaluation of the likelihood of rapid demand growth and the extent of limitations on expanding supply in the short or medium term. Market risks are considered as high, if one or both factors are scored as high, with the others being scored at least as medium. Market risks are considered as medium, if both factors individually score as medium; otherwise, market risks are considered as low. 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.

a For a discussion of resource nationalism, see e.g. Bremmer & Johnston, 2010. *The Rise and Fall of Resource Nationalism.*

Table 13: Bottleneck Criteria Used in this Study

Criterion	Rationale	Basis of assessment	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 (close to or exceeding double-digit growth rates) **Medium**: Industry forecasts expect moderate and steady demand growth **Low:** Industry forecasts expect slow or stable demand from mature applications
Limitations to expanding global production capacity in the short to medium term	Risks are higher if suppliers are unable to expand output relatively easily in the short to medium term in response to demand and price increases (for example due to a lack of production capacity or reserves and investments, or because the metal is a by-product).	Reserve estimates, supply forecasts and evaluation by-product dependencies	**High:** There is a by-product dependency with little opportunity to increase extraction rates or low reserves. **Medium:** There is a by-product dependency or severe underinvestment. **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:** The majority supply is concentrated in one country **Medium:** The majority of supply is concentrated in two or three countries **Low:** Supply is dispersed among a number of countries
Political risk related to 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") as well as expert assessment	**High:** The major producing countries have all a high score for political risk **Medium:** The main producing countries have mixed scores for political risks **Low:** The main producing countries have low political risk scores

5.4 Assessment of Bottleneck Risks for Individual Metals

In this section, the risk of supply-chain bottlenecks is evaluated for each metal that is used in significant quantities in SET-Plan technologies. Taking each metal in alphabetical order, this assessment relies on extensive examinations of data on reserves, production, key applications, processing routes, dominant supplying countries and political risks, price developments, and supply and demand forecasts. These data have been collected from geological surveys and secondary sources. As much of the necessary data is not publicly available, additional information was collected were necessary through interviews with key producers and industry experts. An extensive overview of the collected data is presented in Appendix 3, and the bottleneck evaluations provided in the sections below are based on this information.

5.4.1 Cadmium

Cadmium demand has exhibited a slow decline over the past years,[a] as it is being phased out in a range of applications such as pigments, due to its toxicity. Also the major application for cadmium, NiCd batteries (≈80%), faces increasing competition from alternative technologies, such as NiMH and Li-Ion batteries.[b] The likelihood for rapid global demand growth over the coming five to ten years is therefore regarded as low by industry experts.[c] Large reserves represent considerable potential for future production.[d] While cadmium is a by-product of zinc refining, cadmium recycling is increasing and industry sources expect producers to struggle with overcapacity in the industry. Limitations on expanding output in the short to medium term are therefore scored as low. Cadmium production is not very concentrated, with the top three producing countries accounting for less than half of the refinery production in 2010.[e] Concentration of supply is therefore scored as low. Two of the largest producers, China and Kazakhstan score high on political risk measures, although this is somewhat offset by lower political risk for the second and third largest producers, Japan and South Korea.[f] Political risk is therefore scored as medium. Table 14 shows the results of the bottleneck evaluation for cadmium. Given the low market risk and low concentration of suppliers, the overall risk is scored as low.

Table 14: Cadmium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risks	Overall risk
Cadmium	Low	Low	Low	Medium	Low

5.4.2 Dysprosium

Demand growth for dysprosium is forecasted to be very strong by industry sources, due to competing pressures for rare earth magnets. The likelihood for rapid global demand growth over the coming five to ten years is therefore scored as high. There are considerable reserves available and several rare earths projects are under development.[g] Nonetheless, the limitations to expand production in the short to medium term are scored as high, due to the long lead times and complex commercial and technical challenges involved in bringing a rare earth mine to production. These problems for a smooth expansion of dysprosium supply are further exacerbated by the relative under-representation of dysprosium in rare earth ores as compared to the structure of demand.[h] Dysprosium production is concentrated almost entirely in China, a country that scores high on political risk indicators.[i] As a result, both the concentration of supply, as well as political risks are evaluated as high. Table 15 shows the results of the bottleneck evaluation for dysprosium. Given that high market risks are compounded by an extreme concentration of supply and high political risk for near-monopolist China, the overall risk is scored as high.

Table 15: Dysprosium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Dysprosium	High	High	High	High	High

a de Metz, Patrick. Corporate Environmental and Governmental Affairs Director at *Saft Batteries*. (Personal communication)
b Ibid.
c Based on Morrow, Hugh, October 2010. *Cadmium Market Report.*
d Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
e Ibid.
f Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).
g IMCOA Presentation at HCSS, Dec 2010. *Meeting Rare Earths Demand in the next decade*.
h Ibid, p. 10.
i Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).

5.4.3 Gallium

Demand growth for gallium is forecast to be around ten per cent per annum, driven mainly by fast growth in PV applications.[a] The likelihood of fast demand growth is therefore scored as high. Limitations to expand gallium output in the short to medium term is scored as medium, as gallium is a by-product of aluminium, but the number of alumina plants that are currently separating out gallium is low. There are limited incentives for aluminium refiners to increase output due to the very limited size of the market for gallium (about 100 tonnes of primary output compared to more than 40 million tonnes of aluminium annually).[b] There are few reliable sources of actual production statistics for gallium, however China is considered a key producer alongside Japan and Germany.[c] Concentration of supply is therefore scored as medium. Due to the high scores for political risk indicators for the dominant producer China, political risk is scored as medium, despite few political risks related to other significant producers.[d] Table 16 shows the results of the bottleneck evaluation for gallium. The overall risk is scored as high given the substantial market risks that are compounded by moderate political risks.

Table 16: Gallium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Gallium	High	Medium	Medium	Medium	High

5.4.4 Hafnium

Industry sources expect relatively moderate demand growth for hafnium over the coming decade, mainly in nuclear applications and super alloys.[e] The likelihood of demand shortages is therefore scored as low. Hafnium supply is a by-product of zirconium production, driven by demand in the nuclear industry for high purity zirconium metal alloys, but given industry expectations of considerable output expansion in zirconium production over the coming decade, limitations to expanding supply in the short to medium term are scored as medium. Hafnium production is quite concentrated, with France and the US dominating the production of high purity zirconium for nuclear applications, with hafnium as by-product.[f] The overall score for supply concentration is therefore assessed as medium. The political risks associated with the key producing countries are scored as low.[g] Table 17 shows the results of the bottleneck evaluation for hafnium. Given limited market and political risks, the overall score is assessed as low.

Table 17: Hafnium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Hafnium	Low	Medium	Medium	Low	Low

a Umicore, 2010, in European Commission, 2010. *Critical raw materials for the EU, Annex V*.
b Mikolajczak, Claire. Indium Corporation. (Personal communication)
c Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
d Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).
e Roskill, 2007. *The Economics of Zirconium*, 12th Edition.
f Minor Metals Trade Association Website: *Hafnium*. Available at: http://www.mmta.co.uk/metals/Hf/. [Accessed 01/02/2011].
g Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).

5.4.5 Indium

Indium demand is currently dominated by its application of flat display panels that use ca. 74% of indium output,[a] but this is now a relatively mature market. However indium demand within solar PV is forecast to grow rapidly over the coming decade.[b] The likelihood of rapid demand growth is therefore scored as medium. Despite available reserves,[c] limitations to expanding output in the short to medium term are assessed as high. Indium is a by-product of zinc refining and recovery rates are relatively low, although only certain zinc ores contain indium. Despite high prices, incentives for zinc refiners are limited to recover indium during refining due to the very small size of the market (about 600 tonnes of primary indium production annually compared to more that roughly 11 million tonnes of zinc).[d] Indium refinery production is relatively concentrated, with about half currently being located in China; significant secondary production takes place in Japan.[e] The remainder of world supply, however, is not very concentrated, so overall supply concentration is scored as medium. Political risks associated with the main producer China are high, but are somewhat mitigated by low scores for other significant producers.[f] Overall political risk is therefore scored as medium. Table 18 shows the results of the bottleneck evaluation for indium. Given considerable market risks which are compounded by additional political risks, overall score is given as high.

Table 18: Indium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Indium	Medium	High	Medium	Medium	High

5.4.6 Molybdenum

Molybdenum demand is expected to grow substantially but steadily over the coming decade, driven by expanding steel consumption and an increasing share of high-performance steels.[g] The likelihood of fast demand growth is therefore scored as medium. Substantial reserves are available and molybdenum is mined as both primary and by-product.[h] Industry sources expect considerable new capacity to come online over the coming decade.[i] Overall, limitations to expand production in the short to medium term are scored as low. The largest two producing countries, China and the US, account for over half global supply, but the remainder of world production is relatively diversified.[j] Political risks are scored as medium given the varied performance of key producers in political risk indicators.[k] Table 19 shows the results of the bottleneck evaluation for molybdenum. Given limited market risk and moderate political risks, overall bottleneck risks are scored as low.

Table 19 Molybdenum Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Molybdenum	Medium	Low	Medium	Medium	Low

a European Commission (2010), *Critical raw materials for the EU, Annex V.*
b Umicore, 2009, in European Commission,2010. *Critical raw materials for the EU, Annex V.*
c Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
d Mikolajczak, Claire. Indium Corporation. (Personal communication)
e Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
f Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see appendix 3).
g *Mining Engineering (October 2009)*, Molybdenum Supply Forecasting & Roskill Presentation (April 2010). *Global Molybdenum Market Outlook*, Minor Metals Conference.
h Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
i *Mining Engineering (October 2009*). Molybdenum Supply Forecasting.
j Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
k Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see appendix 3).

5.4.7 Neodymium

Demand growth for neodymium is forecast to be very strong by industry sources, due to competing pressures for rare earth magnets. The likelihood for rapid global demand growth over the coming five to ten years is therefore scored as high. There are considerable reserves available and several rare earths projects under development.[a] Nonetheless, the limitations to expand neodymium production in the short to medium term are scored as medium, due to the long lead times and complex commercial and technical challenges involved in bringing a rare earth mine to production (compared to dysprosium, risks are assessed as somewhat lower due to the fact that compared to demand, neodymium usually is less under-represented in rare earth deposits). Neodymium production is concentrated almost entirely in China, a country scoring high on political risk indicators.[b] As a result, both the concentration of supply as well as political risks are evaluated as high. Table 20 shows the results of the bottleneck evaluation for neodymium. Given that significant market risks are compounded by an extreme concentration of supply and high political risk for near-monopolist China, the overall risk is scored as high.

Table 20: Neodymium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Neodymium	High	Medium	High	High	High

5.4.8 Nickel

Nickel demand is expected to grow substantially over the coming decade, mainly driven by expanding stainless steel use.[c] The likelihood of fast demand growth is therefore scored as medium. Reserves are estimated to be large relative to current levels of production and significant capacity will be added over the coming years.[d] Limitations to expanding supply are therefore scored as low. Production is geographically quite dispersed.[e] Political risk of the largest producers (Russia, Indonesia and the Philippines) is relatively high although Canada, Australia and European producers - including New Caledonia – account for more than half of global production at a low political risk.[f] Supply concentration is therefore scored as low and political risks as medium. Reserves are estimated to be large relative to current levels of production. Table 21 shows the results of the bottleneck evaluation for nickel.

Table 21: Nickel Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Nickel	Medium	Low	Low	Medium	Low

a IMCOA, 2010. *Presentation: Meeting Rare Earths Demand in the next decade*. HCSS, Dec 2010. .
b Based on *Failed State Index – 2009* & *Worldwide Governance Indicator 2009* (for details see appendix 3).
c Kirves, Marja, MK Commodity Consulting (2010). *The Outlook for Nickel - Dichotomies of the Fundamentals, Nov. 2010.*
d Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
e Ibid.
f Based on Failed State Index, 2009 & Worldwide Governance Indicator, 2009 (for details see Appendix 3).

5.4.9 Niobium

Niobium demand is expected to grow substantially over the coming decade, driven by rapidly expanding markets for steels as well as an intensification effect towards greater usage of high-strength steels, which commonly use niobium as an alloying addition.[a] The likelihood of fast demand growth is therefore scored as high. Estimates of reserves are large,[b] and capacity expansion is currently underway, leading to a low score for short- to medium-term limitations to expand supply. Niobium production is highly concentrated, with more than 90% of it located in Brazil.[c] Supply concentration is therefore scored as high. Brazil scores moderately on political risk indicators,[d] leading to medium score. Table 22 shows the results of the bottleneck evaluation for niobium. Moderate market risks are somewhat compounded by relatively high political risks, leading to a medium overall bottleneck risk.

Table 22: Niobium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Niobium	High	Low	High	Medium	Medium

5.4.10 Selenium

Selenium demand is expected to grow at a moderate pace, as high growth in solar applications is partially off-set by low growth in traditional selenium applications such as glass manufacturing.[e] The likelihood of rapid demand growth over the coming decade is therefore scored as medium. Selenium output is a by-product of copper production. However, due to the very small scale of the selenium market (ca. 3,250 tonnes of selenium are produced from primary sources comparing to more than 15 million tonnes of copper), copper producers have limited commercial incentives to increase production, even if there is considerable scope to improve extraction rates.[f] Overall limitations to expanding production capacity are scored as medium. Global production is quite concentrated,[g] although much is located in countries with low political risk scores, such as Japan and Germany.[h] Concentration of supply is therefore scored as medium, with political risks being scored as low. Table 23 shows the results of the bottleneck evaluation for selenium. Given moderate market risks on both the supply and demand side and negligible political risks, overall bottleneck risk for selenium is scored as medium.

Table 23: Selenium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Selenium	Medium	Medium	Medium	Low	Medium

a Iamgold Investor Presentation, June 2009. Niobec Tour Presentation. Available at: http://www.iamgold.com/English/Investors/Presentations/default.aspx. [Accessed 09/11/2010].
b Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
c Ibid.
d Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).
e Owens-Illinois November, 2010. *Future usage of Se in CIGS*, Investor Presentation & Retorte Presentation, Minor Metals Conference April 2010.
f Hisshion, Daniel. President of the Selenium Tellurium Development Association. (Personal communication)
g Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
h Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).

5.4.11 Silver

Industry experts expect fast demand growth in new applications for silver, such as in electronics, to be balanced by traditional applications, where demand is largely stable.[a] 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.[b] About a third of silver supply comes from primary sources, with the remainder being a by-product of copper, lead and zinc refining.[c] Overall limitations to expanding supply are scored as medium. Silver production is not very concentrated and is rated as low. Political risks associated with the largest three producers (Peru, Mexico and China– accounting for 47% of world supply) are high.[d] Table 24 shows the results of the bottleneck evaluation for silver. Given the limited market risks and low supply concentration that mitigates political risks, overall bottleneck risk is scored as low.

Table 24: Silver Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Silver	Low	Medium	Low	High	Low

5.4.12 Tellurium

Demand in tellurium is expected to increase rapidly over the coming decade, especially due to solar PV applications.[e] Likelihood of rapid demand growth over the coming decade is therefore scored as high. Tellurium is quite a rare metal with significant geological constraints. It is produced as a by-product of copper refining. Given the very limited size of the tellurium market (only about 500 tonnes of tellurium metal are mined per annum compared to more than 15 million tonnes of copper),[f] expanding output has limited commercial appeal for copper refiners. Overall limitations to expanding tellurium supply in the short to medium term are therefore scored as high. Detailed production statistics are not available, but tellurium production is quite diversified.[g] Political risk scores are mixed for major producing countries including Japan, Russia and Peru.[h] Table 25 shows the results of the bottleneck evaluation for tellurium. While political risks are limited, there are strong market risks, resulting in a high overall score.

Table 25: Tellurium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Tellurium	High	High	Low	Medium	High

a Cross J., 2009. *Prospects for Silver Supply and Demand*. LBMA Precious Metals Conference, 2009.
b Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
c Ibid.
d Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).
e Öko-Institut for UNEP, 2009. *Critical Metals for Future Sustainable Technologies and their Recycling Potential.*
f Hisshion, Daniel. President of the Selenium Tellurium Development Association. (Personal communication).
g Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
h Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).

5.4.13 Tin

Tin demand is likely to keep growing at a slow but steady pace driven mainly by applications in the electronics industry.[a] The likelihood of rapid demand growth over the coming decade is therefore scored as low. Reserves for tin are large relative to current production.[b] While new supply is expected to come on the market in several years, global tin output is currently constrained by years of underinvestment.[c] Limitations to expanding supply in the short to medium term are therefore scored as medium. Supply is quite concentrated, with China and Indonesia alone accounting for over half of world supply.[d] Both of these countries score highly on political risk indicators.[e] Overall concentration of supply is scored as medium and political risk as high. Table 26 shows the results of the bottleneck evaluation for tin. The overall bottleneck risk is scored as medium, due to concerns about the relatively concentrated supply and high political risks associated with major producers, with some market risks especially in the short term.

Table 26: Tin Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Tin	Low	Medium	Medium	High	Medium

5.4.14 Vanadium

Vanadium demand is expected to experience robust growth based on growing steel production and an increasing share of high-strength steels, as well as new applications, for example, in redox batteries.[f] Overall likelihood of rapid demand growth is therefore scored as high. Considerable reserves are available and supply is expected to grow substantially over the next few years, both driven by expanding capacity of existing suppliers as well as new market entrants.[g] Overall limitations to expanding capacity in the short to medium term are therefore scored as low. Production is quite concentrated with the three largest producing countries, China, Russia and South Africa, accounting for over 90% of global supply.[h] Concentration of supply is therefore scored as medium. The three main producers all score relatively high on political risk indicators, resulting in a high political risk score.[i] Table 27 shows the results of the bottleneck evaluation for vanadium. Overall bottleneck risk is evaluated as medium.

Table 27: Vanadium Bottleneck Evaluation

Metal	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Vanadium	High	Low	Medium	High	Medium

a Economist Intelligence Unit forecast for the Tin Market.
b Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
c Reuters, March 22 2010. *Tin seen tight in 2011 despite Japan demand fall.*
d Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
e Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).
f Based on Byron Capital Markets Presentation, 2010. *Lithium and Vanadium – The metals of the electric Revolution,* Objective Capital Rare Earths, Speciality and Minor Metals Investment Summit, March 2010.
g Ibid.
h Based on *USGS Mineral Commodity Summaries 2011* and previous editions (for details see Appendix 3).
i Based on *Failed State Index, 2009* & *Worldwide Governance Indicator, 2009* (for details see Appendix 3).

5.5 Overview of the Bottleneck Screening

Table 28 summarises the risks for supply-chain bottlenecks for each of the 14 metals that are used in significant quantities in the SET-Plan technologies. The results have been colour-coded to aid viewing. Table 28 shows that for five of these fourteen metals (cadmium, hafnium, molybdenum, nickel and silver) the likelihood of supply-chain bottlenecks occurring over the next decade is found to be low. This is the case either because demand growth is expected to be relatively slow (e.g. in the case of cadmium, hafnium or silver) or because there are few serious obstacles on expanding output through bringing additional capacity into production (e.g. in the case of nickel or molybdenum). Political risks fail to change this assessment, with only molybdenum being associated with moderate political risks. For the others, political risks are low because production is either relatively diversified (e.g. in the case of cadmium, nickel and silver) or dominant producers are associated with low risks (e.g. hafnium).

The bottleneck screening finds moderate risks for supply-chain bottlenecks over the coming decade for four other metals: niobium, selenium, tin and vanadium. Demand for niobium, selenium and vanadium is expected to increase rapidly. However, only moderate growth is expected for tin and there are few limitations to expand niobium and vanadium output. Therefore, the bottleneck screening finds only limited market risks for these three metals. They are nonetheless assigned a medium risk score because of the presence of significant political risks. In the case of niobium, it is the very high supplier concentration (more than 90% of niobium production currently takes place in Brazil) that leads to concerns. For vanadium and tin, moderate supplier concentrations are compounded with high political risk scores for all major producers (China and Indonesia for tin, and China, South Africa and Russia for vanadium). In the case of selenium, there are no major political risks, but due to strong demand and its by-product character, market risks are assessed to be moderate, resulting in a medium overall bottleneck score. For these four metals, there is no immediate concern over supply-chain bottlenecks. However, supply and demand developments could deteriorate relatively easily in the future and could escalate risks for the formation of supply-chain bottlenecks. The markets for these metals should therefore be monitored regularly for signs of such deterioration.

Table 28: Summary of Bottleneck Analysis

Metal	Market Factors		Political Factors		Overall risk
	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	
Dysprosium	High	High	High	High	**High**
Neodymium	High	Medium	High	High	
Tellurium	High	High	Low	Medium	
Gallium	High	Medium	Medium	Medium	
Indium	Medium	High	Medium	Medium	
Niobium	High	Low	High	Medium	**Medium**
Vanadium	High	Low	Medium	High	
Tin	Low	Medium	Medium	High	
Selenium	Medium	Medium	Medium	Low	
Silver	Low	Medium	Low	High	**Low**
Molybdenum	Medium	Low	Medium	Medium	
Hafnium	Low	Medium	Medium	Low	
Nickel	Medium	Low	Low	Medium	
Cadmium	Low	Low	Low	Medium	

Finally, there are five metals for which the screening finds high risks for supply-chain bottlenecks. These metals are:

1. dysprosium
2. neodymium
3. tellurium
4. gallium
5. indium

For all these metals, industry sources expect over the coming decade a continuation of the rapid demand growth they have experienced over the past years, which puts the supply side under pressure. In most cases, these high growth rates are driven by strong growth in green-tech applications such as the SET-Plan technologies. However, in each of these cases, there are significant obstacles to expanding output in the short to medium term, resulting in high overall market risk. In the case of the rare earths neodymium and dysprosium, these difficulties are related to the commercial and technical challenges in bringing new rare earths mines to the market, including the need for considerable long-term investments and long-lead times. In the case of dysprosium (and to a lesser extent for neodymium), this market risk is further exacerbated because the metal is 'underrepresented' in most rare earth ores relative to market demand.

In the case of indium, tellurium and gallium, it is above all the by-product character that poses obstacles to the expansion of supply. These metals are mainly recovered during zinc, copper and aluminium refining, but the markets are tiny in comparison to the markets for the host metals. Primary production of roughly 600, 500 and 100 metric tonnes of indium, tellurium and gallium respectively per annum compares with more than 11, 15 and 36 million metric tonnes of primary production for zinc, copper and aluminium. This is a factor of 1:18,000, 1:30,000, and 1:360,000 in terms of quantity between the by-product and the host metal. Even with very high prices for the by-products, the small size of the markets creates only very limited commercial incentives for zinc, copper and aluminium refiners to pay strong attention to optimal by-product recovery. Supply expansion is therefore intermittent, with significant amounts of the by-product not being recovered due to lack of treatment or sub-optimal extraction rates.

These high market risks are compounded in the rare earths case by high political risks due to an extreme concentration of supply in China. Political risks are less prominent for indium, tellurium and gallium, as supply is less concentrated and in each case there is significant production in countries which are associated with low political risks. It is further interesting to note that for these five metals, geological availability is not a central issue as they are all relatively abundant in the earth's crust, except for tellurium which is also quite scarce in the physical sense. Given these high market and political risks identified in this study, it is not surprising that most of these metals have been associated with high supply risks in several previous studies (see Table 12). How real the risks for future supply-chain bottlenecks are is also demonstrated by the fact that over the past decade, the markets for each of these five metals have been rocked by crises triggered by supply-chain bottlenecks, which have been marked by price spikes and supply disruptions. Gallium prices spiked sharply in 2001 to over $2000 per kg before falling back to less than $300 per kg a year later and indium prices increased by 800% between 2002 and 2005. Tellurium prices have also increased roughly 10-fold over the past five years and the current rare earth crisis (which was already discussed at the beginning of this Chapter) sent neodymium prices soaring from about $30 in mid-2010 to more than $300 per kg at the time of writing. In many cases, downstream processors have also faced supply disruptions during such supply crises.

The analysis in this Chapter shows that a high risk for similar future bottlenecks persists for these five metals. Such supply disruptions and price rises could adversely affect the smooth deployment of SET-Plan technologies and the realisation of the SET-Plan targets. In Chapter 6, the reliance of SET-Plan technologies on these five bottleneck metals is examined in greater detail. Chapter 7 then examines possible mitigation strategies for each metal from a European policy-making perspective, including substitution, increasing European output, more efficient use and intensified recycling.

6 Technology Scenarios of Bottleneck Metals

Chapter 4 identified future metals demand from six SET-plan technologies under an optimistic uptake scenario and using "business-as-usual" assumptions about the mix of sub-technologies for solar and wind energy. Chapter 5 then identified five metals with the highest risk for future supply-chain bottlenecks, among the fourteen metals for which the deployment of the SET-Plan technologies in Europe will create the greatest pressures on global supplies. In this Chapter, the focus is on these five bottleneck metals and the assumptions about the speed and extent of European market penetration and technology mix for the SET-Plan technologies. This is important because these assumptions are subject to considerable uncertainty and —as this Chapter will demonstrate—in many cases have a large potential impact, both on the future demand for individual bottleneck metals, as well as the time path for demand peaks to occur.

Specifically, the next section examines how plausible alternative assumptions about speed and extent of market penetration of the six SET-Plan technologies could affect demand for the five bottleneck metals. Section 6.2 then explores how demand for these metals would be affected by variations of the technology mix in the European wind and solar energy sector. The Chapter focuses on these two technologies in detail, firstly because this is where the bottleneck metals are most extensively used, and secondly because of uncertainty associated with the future technology mix within the European wind and solar markets.

6.1 Uptake Scenarios

For the uptake scenarios, each is modelled with reference to a common 2010 baseline, which comes from *EU energy trends to 2030 — Update 2009, EC* (2010). More details for each scenario can be found in Appendix 1. It should be noted that the technology uptake scenarios modelled in Chapter 6, differ from those modelled in the significance screening in Chapter 4, which is why the SET-Plan demand estimates quoted between the two Chapters differ. This is due to the receipt of new data and also the moderation of the most optimistic uptake scenarios modelled during the significance screening into more reasonable scenarios. However the range of scenarios modelled in both Chapters 4 and 6 does serve to highlight the sensitivities of the uptake estimates on SET-Plan metal demand.

The technology mixes for solar and wind energy are kept constant across the scenarios in order to enable an effective comparison of the different uptake scenarios. These modelling assumptions on technology mix are common to those used in the significance screening in Section 4, i.e. for solar 80% c-Si, 10% a-Si, 5% CdTe, 5% CIGS; and for wind 15% low speed permanent magnet in 2020 and 20% in 2030. These modelling assumptions are modified within section 6.2, which investigates the sensitivities in the SET-Plan metal demand associated with changes in the technology mix (for the High scenario).

6.1.1 Low scenario

The Low scenario, which represents low uptake of SET-Plan technologies, comes from *EU energy trends to 2030 — Update 2009, EC* (2010). Wind and solar PV capacities increase significantly over the period, particularly in the first decade; nuclear capacity remains stable; CSP and CCS have minimal uptake in this scenario (Table 29).

The requirements of the bottleneck metals for the low uptake scenario are shown in Table 30:

- For solar, the metal requirements are higher for the second decade rather than the first. Tellurium has the largest SET-Plan metal requirement at 2.1% of current supply for 2030. Indium and gallium requirements however are quite small.

- For wind, the SET-Plan metal requirements are greatest in the first decade, where instalment of capacity is greatest. This amounts to 2.4% of current world supply of dysprosium and 2.3% of neodymium for 2020 within the EU SET-Plan.

Table 29: Electricity Generation Capacity and Installation for Low scenario (GW)

Energy Source	GW Capacity			GW Installed per annum	
	2010	2020	2030	2011-2020	2021-2030
Nuclear	127	123	124	1.4	2.1
Wind	86	222	280	13.6	5.8
Solar PV	38	49	72	1.1	2.3
CSP	0.7	1.2	3.6	0.1	0.2
CCS	0	5	6	0.5	0.1

Source: EC (2010)
Note: Nuclear installation includes the expected shutdown forecast by World Nuclear Association
Solar PV values (JRC 2011)

Table 30: Bottleneck Metal Requirements of Low scenario

Element	World Supply - 2010 (t)	Low scenario Demand (t)		Low scenario Demand / World Supply	
		2020	**2030**	**2020**	**2030**
Te	500	5	11	1.0%	2.1%
Dy	1,200	29	16	2.4%	1.4%
Nd	18,261	414	235	2.3%	1.3%
In	1,345	5	10	0.4%	0.8%
Ga	161	0.1	0.3	0.1%	0.2%

6.1.2 High scenario

The High scenario represents the industry estimates for uptake of SET-Plan technologies. In most cases these forecasts are the most optimistic (see Appendix 1 for a comparison). Strong implementation is projected for each of the technologies, particularly for solar; however for solar a more steady rate of adoption has been modelled compared to that analysed in Chapter 4 for the significance screening. Other than for solar, the uptake for all of the technologies accelerates between the first and second decades (Table 31).

The requirements of the bottleneck metals for the high uptake scenario are shown in Table 32:

- For solar the SET-Plan metal requirements are slightly higher for the first decade rather than the second, but are very large for both decades considering that the European Solar industry represents only one of many markets in the world for the metals. The SET-Plan tellurium requirements for 2020 are estimated at 30.0% of current world supply, with indium at 10.8% and gallium at 2.3%.
- For wind the SET-Plan requirements in 2020 for the rare earth elements, dysprosium and neodymium, are important, representing 4.0% and 3.8% of current world supply.

Table 31: Electricity Generation Capacity and Installation for High scenario (GW)

Energy Source	GW Capacity			GW Installed per annum	
	2010	2020	2030	2011-2020	2021-2030
Nuclear	127	198	297	8.9	11.9
Wind	86	230	400	14.4	17.0
Solar PV	38	360	630	32.2	27.0
CSP	0.7	30	60	2.9	3.0
CCS	0	7.2	80	0.7	7.3

Sources: see Appendix 1
Note: Nuclear installation includes the expected shutdown forecast by World Nuclear Association

Table 32: Bottleneck Metal Requirements of High scenario

Element	World Supply - 2010 (t)	High scenario Demand (t)		High scenario Demand / World Supply	
		2020	**2030**	**2020**	**2030**
Te	500	150	126	30.0%	25.2%
In	1,345	145	121	10.8%	9.0%
Dy	1,200	30	48	2.5%	4.0%
Nd	18,261	438	690	2.4%	3.8%
Ga	161	3.8	3.2	2.3%	2.0%

6.2 Technology Mix

As was identified in Chapter 3, both solar and wind have a number of competing sub-technologies able to contribute towards the SET-Plan, each of which has different metals requirements associated with them. This section models the effects on metals demand with respect to changes in the technology mix under the high uptake scenario. It should be noted that there are considerable uncertainties with regard to the expected penetrations within the technology mix, so results of this modelling should be seen as illustrative rather than definitive in highlighting the sensitivities associated with a changing technology mix.

6.2.1 Solar

Solar PV technologies are developing rapidly and it is not clear what the dominant PV technology will be in 2020 and 2030. In order to check the sensitivity of different market shares of the PV technologies two technology mixes have been developed: a continuation of the current dominance of c-Si and uptake of thin film solar technologies. These technology mixes are shown in Table 33 and in Table 34, with their respective market shares and installed capacity per annum. This is multiplied by the respective metal requirements of each technology, denoted in kg/MW terms to calculate the metal demand of the two mixes.[a] From this analysis, it is clear that uptake in thin film technologies like CIGS and CdTe, will further increase demand for tellurium, indium and gallium.

a The respective metal requirements are as follows: c-Si has no requirements of the bottleneck metals, a-Si uses 5.3 kg/MW of In, CdTe uses 93.3 kg/MW of Te & (in a limited number of cases, see Appendix A.2.2) 15.9 kg/MW of In; and CIGS uses 63.3 kg/MW of In & 2.3 kg/MW of Ga.

Table 33: Effect of Technology Mix Variation in PV on Yearly Metal Demand up to 2020 (t)

SET-Plan 2020 Energy Generation Metal Demand (t)												
Technology Mix	**c-Si dominant**						**Thin film uptake**					
Technology	c-Si	a-Si	CdTe	CIGS	**Total**	**% of 2010 Supply**	c-Si	a-Si	CdTe	CIGS	**Total**	**% of 2010 Supply**
Market share (%)	80%	10%	5%	5%	100%		59%	15%	8%	18%	100%	
Installed Capacity (GW)	288	36	18	18	360		212	54	29	65	360	
Average per annum (GW)	25.8	3.2	1.6	1.6	32.2		19.0	4.8	2.6	5.8	32.2	
Te			150		150	30%			240		240	48%
In		17	26	102	145	11%		26	41	367	434	32%
Ga				3.8	3.8	2.3%				14	14	8.4%

Table 34: Effect of Technology Mix Variation in PV on Yearly Metal Demand up to 2030 (t)

SET-Plan 2030 Energy Generation Metal Demand (t)												
Technology Mix	**c-Si dominant**						**Thin film uptake**					
Technology	c-Si	a-Si	CdTe	CIGS	**Total**	**% of 2010 Supply**	c-Si	a-Si	CdTe	CIGS	**Total**	**% of 2010 Supply**
Market share (%)	80%	10%	5%	5%	100%		59%	15%	8%	18%	100%	
Installed Capacity (GW)	504	63	32	32	630		372	95	50	113	630	
Average per annum (GW)	21.6	2.7	1.4	1.4	27.0		15.9	4.1	2.2	4.9	27.0	
Te			126		126	25%			202		202	40%
In		14	22	85	121	9%		22	34	308	364	27%
Ga				3.2	3.2	2.0%				11	11	7.0%

6.2.2 Wind

For wind, there are a wide range of potential systems, which are mainly based on a mix of geared / gearless transmission; with electromagnet (EM) / permanent magnet (PM) generators. Technologically, gearless transmission is therefore direct-drive (DD) and always linked to low-speed generators, but the latter may be based on EM or PM. Whilst the analysis thus far has concentrated on the installation of electromagnet (EM) generators and gearless (DD) / permanent magnet (PM) generator systems, it is useful to highlight the sensitivities associated when considering other combinations.

The technologies considered within this analysis are geared-EM, direct drive-EM, High Temperature Superconductor (HTS, not yet commercial), high/medium-speed PM and DD-PM systems. The rare earth magnet requirements of each of these are different, with some not using permanent magnets at all, others using relatively small proportions, while the DD-PM systems use the most. More information can be found in Appendix 2. Two technology mixes have been modelled. The first analyses the metal demands under a continued dominance of EM systems with a progression from geared to direct drive systems. The second analyses the effect of the take-up of permanent PM and HTS systems.

The results of the analysis show that a greater uptake of non-EM systems could significantly increase the demand for the rare earth elements, neodymium and dysprosium by at least twice that of the continued dominance of EM systems.

Table 35: Effect of Technology Mix Variation in Wind on Yearly Metal Demand up to 2020 (t)

SET-Plan 2020 Energy Generation Metal Demand (t)														
Technology Mix	**Dominance of EM Systems**							**Take-up of PM & HTS Systems**						
Technology	Gear-EM	DD-EM	HTS	H/M PM	DD-PM	**Total**	**% of 2010 Supply**	Gear-EM	DD-EM	HTS	H/M PM	DD-PM	**Total**	**% of 2010 Supply**
Market share (%)	64%	15%	1%	10%	10%	100%		40%	20%	5%	15%	20%	100%	
Installed Capacity (GW)	147.2	34.5	2.3	23	23	230		92	46	11.5	34.5	46	230	
Ave/yr (GW)	9.2	2.2	0.1	1.4	1.4	14.4		5.8	2.9	0.7	2.2	2.9	14.4	
Dy				2	20	22	1.9%				3	40	44	3.6%
Nd				33	292	326	1.8%				50	585	635	3.5%

Table 36: Effect of Technology Mix Variation in Wind on Yearly Metal Demand up to 2030 (t)

SET-Plan 2030 Energy Generation Metal Demand (t)														
Technology Mix	**Dominance of EM Systems**							**Take-up of PM & HTS Systems**						
Technology	Gear-EM	DD-EM	HTS	H/M PM	DD-PM	**Total**	**% of 2010 Supply**	Gear-EM	DD-EM	HTS	H/M PM	DD-PM	**Total**	**% of 2010 Supply**
Market share (%)	40%	40%	10%	5%	5%	100%		40%	10%	20%	10%	20%	100%	
Installed Capacity (GW)	160	160	40	20	20	400		160	40	80	40	80	400	
Ave/yr (GW)	6.8	6.8	1.7	0.9	0.9	17		6.8	1.7	3.4	1.7	3.4	17	
Dy				1	12	13	1.1%				3	48	50	4.2%
Nd				20	173	192	1.1%				39	690	730	4.0%

6.3 Conclusion

The analysis within the Chapter has shown the effects that both the technology uptake and technology mix can have upon the metals demand of the five bottleneck metals.

Table 37 summarises the results of the technology scenario modelling. This shows that the demand for the bottleneck metals varies considerably according to the technology uptake. For solar, moving from the Low scenario to the High scenario leads to a twenty- to thirtyfold increase in the metals demand for 2020 and a ten- to twentyfold increase for 2030. This takes the tellurium demand in 2020, (where the metal requirements are greatest) to 30% of world supply versus 1.0% for the Low scenario. Indium demand is greatest under the High scenario for 2020 at 10.8% of current world supply. For wind, the scenarios have similar demand for 2020, at around 2.5% of current world supply, but for 2030 the metal demand for the High scenario at around 4% of current supply is three times that for the Low scenario.

Table 38 summarises the results of the technology mix modelling. This shows that should thin film obtain a greater market share of the solar market, this will place even greater pressures on the tellurium, indium and gallium supply chains. Under the assumptions modelled, this increases tellurium demand by a factor of 1.6, trebles demand for both indium and gallium (albeit from a lower base). For wind, the PM and HTS uptake technology mix gives at least twice the demand for neodymium and dysprosium as the mix where EM systems remain dominant.

Table 37: Demand for Bottleneck Metals under the Low and High scenarios

Element	Low scenario Demand / World Supply		High scenario Demand / World Supply	
	2020	2030	2020	2030
Te	1.0%	2.1%	30.0%	25.2%
In	0.4%	0.8%	10.8%	9.0%
Dy	2.4%	1.4%	2.5%	4.0%
Nd	2.3%	1.3%	2.4%	3.8%
Ga	0.1%	0.2%	2.3%	2.0%

Table 38: Demand for Bottleneck Metals for the High scenario under different Technology Mixes

Element	Solar				Element	Wind			
	c-Si dominant		Thin film uptake			EM dominant		PM & HTS Uptake	
	2020	2030	2020	2030		2020	2030	2020	2030
Te	30%	25%	48%	40%	**Dy**	1.9%	1.1%	3.6%	4.2%
In	11%	9%	32%	27%	**Nd**	1.8%	1.1%	3.5%	4.0%
Ga	2.3%	2.0%	8.4%	7.0%					

The next Chapter considers what mitigation strategies could be employed to alleviate the metals bottlenecks identified, considering the role of additional primary production, reuse, recycling and waste reduction and substitution.

7 Mitigation Strategies

In Chapter 4, it was shown that significant quantities of 14 metals are likely to be needed to deploy SET-Plan technologies in Europe. In Chapter 5, it was found that for five of these metals, namely indium, tellurium and gallium and the rare earth elements neodymium and dysprosium, there are considerable risks for future bottlenecks. These are mainly related to market dynamics and, in the case of rare earths, exacerbated by political risks. In Chapter 6, the future technology uptake scenarios for all technologies and, in particular, the technology mixes for solar and wind energy were examined, where the five bottleneck metals are in most demand. It demonstrated how the variations create important uncertainties and could considerably increase or decrease the demand for the five bottleneck metals over the next two decades.

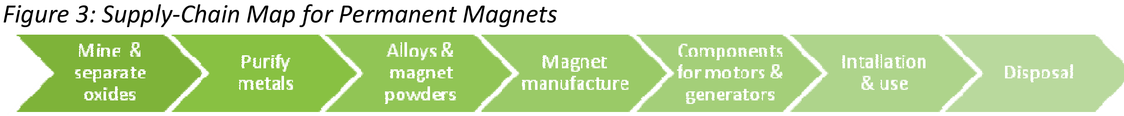
Against this background, in this Chapter possible measures are discussed that could decrease the risk of future bottlenecks for these metals from a European policy perspective. Such measures could be part of a European mitigation strategy to reduce risks from metal supply-chain bottlenecks to the realisation of the SET-Plan. To be successful, such mitigation measures must be based on a sound understanding of the complex supply chains of these metals. The next section therefore discusses these supply chains in greater depth. More details of the information contained in Section 7.1 can be found in Appendix 3.[a] To follow, European mitigation measures at each stage of the supply chain are discussed in detail, including increasing European primary production and by-product separation, encouraging reuse, recycling and waste reduction and examining the potential for substitution.

7.1 Supply-Chain Analysis

7.1.1 Neodymium and Dysprosium

Key to applications of rare earths in SET Plan technologies, especially for wind, is permanent magnets. The supply-chain map, see Figure 3, is common for neodymium and dysprosium in permanent magnets, so they are discussed together. At present, over 95% of the production of rare earth oxides takes place in China. The stages in production are the mining and concentration of the rare earth ores and the separation into the 17 different individual rare earth oxides by solvent extraction. This processing is complex as the individual rare earth elements are chemically similar and each ore body requires specific technology unique for that particular deposit to be developed in order to extract and separate the rare earth elements.[b] Common types of rare earth ores include bastnaesite, monazite, xenotime and ionic clays, and can be extracted either as a single product or as a by-product, for example, with iron ore in Inner Mongolia. The composition of the ore bodies varies considerably between different ore bodies. For example, Mountain Pass in California has neodymium content at around 12% and very low dysprosium content due to its high cerium content, whereas the ionic clays of Southern China have average neodymium content near 20% and dysprosium content near 4%.[c]

Figure 3: Supply-Chain Map for Permanent Magnets



The next stage is to refine and purify the rare earth oxides into their metals using ion-exchange purification to achieve the highest purities. For 2015, over 95% of dysprosium and over 90% of neodymium production is forecast to be consumed within permanent magnets.[d] For the forming of the

a For further reading: Ullmann's Encyclopaedia of Industrial Chemistry (7th Edition), Wiley for information on the processing steps and the USGS Mineral Commodity Yearbooks. Available at: http://minerals.usgs.gov/minerals/pubs/commodity/ for general information.
b OECD, October 2009. *Export restrictions on strategic raw material and their impact on trade and global supply*, Workshop on raw materials, 2009.
c USGS, 2010. *2008 Minerals Yearbook: Rare Earths.*
d Kingsnorth, Dudley. IMCOA. (Personal communication).

metals into magnet alloy powders and the manufacturing of the actual magnet, intellectual property plays a significant role in the supply chain. Two main types of permanent magnets are produced: higher performance sintered magnets for electric drive and wind turbine applications and bonded magnets for other applications such as electronics.[a] The respective master patents are controlled by two firms: Hitachi Metals (formerly Sumitomo) in Japan and Magnequench, a Chinese-backed consortium. There are a total of 10 firms located in China, Japan and Germany, licensed to produce sintered NdFeB magnets until 2014.[b] For locations of NdFeB magnet manufacture, it has been estimated that currently 75-80% occurs in China, 17-25% in Japan and 3-5% in Europe.[c]

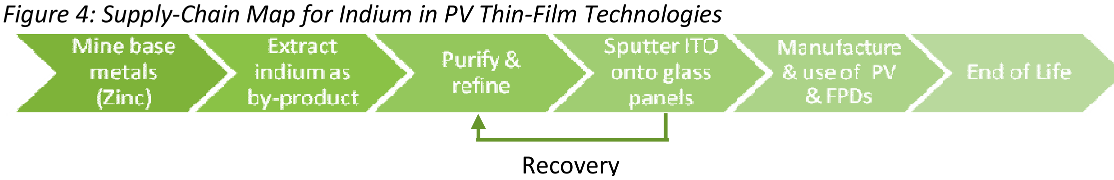
The magnets are then used as components for a range of applications of which hard disc drives (31%), generator motors (26%) and automobile (24%) are the major uses.[d] Other applications include optical devices, acoustic applications and MRI. With the exception of hard disc drives, most of these applications have long lifetimes, meaning that only limited volumes of permanent magnets are presently occurring in the waste stream.

7.1.2 Indium

The supply-chain map for indium PV thin films is shown in Figure 4. Indium is not mined as a primary product, but is produced as a by-product from the refining of base metals. Almost all commercially produced indium is extracted from zinc refining. Indium also occurs in deposits of copper, lead and tin, but mostly at sub-economic levels.

The USGS estimates that refinery production for virgin indium was 574 tonnes in 2010, of which China accounts for the largest proportion with 300 tonnes, which is consistent with China's leading position in zinc production.[e] It is worth noting that not all zinc deposits contain indium and for those that do, concentrations can vary considerably. The Indium Corporation estimates that 44% of zinc concentrates outside of China and the CIS contain indium. Of these, 54% originate from Peru, 22% from Bolivia, 12% from Canada and 9% from Australia.[f] There is a relative richness of indium content within the Peruvian and Bolivian zinc concentrates at 187ppm and 630ppm respectively (compared to an average level of 110ppm), which makes these two countries major indium players compared to their share of world zinc production.

Figure 4: Supply-Chain Map for Indium in PV Thin-Film Technologies



The zinc concentrates are then refined, at which point the indium is separated, but only if the zinc refinery has the required processes and equipment installed. It is estimated that only 26% of the zinc concentrates produced outside of China and CIS goes to indium capable refineries.[g] It is important to note that from a zinc producer perspective, indium and other by-products are essentially 'impurities' that need to be separated from the product during the refining process and that high concentrations of such impurities are therefore not necessarily desirable. However, where equipment for indium extraction is installed the by-product can produce valuable revenue and it is reported that some indium capable refineries are prepared to pay additional freight costs to source indium-containing zinc concentrates.[h] The indium is produced from residues collected from zinc refining and recycling of flue dusts and gases

a US Department of Energy (2010), Critical Materials Strategy.
b Ibid.
c Öko-Institut (2011), *Study on Rare Earths and Their Recycling*.
d Etsu, Shin, 2009. Presentation at 5th International Rare Earths Conference in 2009.
e USGS (2011), Mineral Commodity Summaries: *Indium*.
f Indium Corporation Presentation, October 2010. The *Relationship between Zinc and Indium Productions*.
g Ibid.
h Renewable Energy Focus, July 2008. *Indium and Gallium: Long term-supply*.

generated during smelting, which undergo electrothermic reduction and electrolytic treatment and are refined using leaching, solvent extraction and electro-refining process steps. The refining efficiency of the indium capable refineries is estimated at around 55% of the indium content (although in some cases this can be as high as 70%), with the remainder accumulating in the residues.[a]

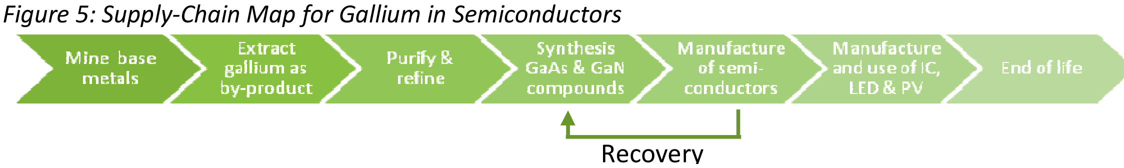
The major application for indium is within indium-tin oxide (ITO), with flat panel displays accounting for 74% of total indium consumption and other ITO uses accounting for a further 10%. The ITO is sputtered onto glass panels, although only 30% of the ITO sputtering targets are actually deposited onto the glass, with the other 70% left in used ITO targets, grinding sludge or on the shields of the sputtering chambers.[b] Recovery rates for the spent ITO are high at approximately 95%,[c] which makes reclaimed indium as important or even a greater source of indium than virgin production. At present, relatively few flat panel displays have yet reached their end-of-life and entering the waste stream. Flat panel displays and thin film PV were not launched until around the year 2000 and it is not anticipated that significant volumes will occur in the waste stream until 2012 and 2030 respectively.[d]

7.1.3 Gallium

Like indium, gallium is not mined as a primary commodity but is extracted as a by-product of the processing of other metals. Produced to a small extent as a by-product of zinc production by DOWA's Akita Zinc facility in Japan, gallium is mostly recovered during the refining of alumina from bauxite ores which are widely distributed globally.[e] Large economic deposits of bauxite can be found, among others, in Australia, Guinea, Brazil, Greece and China, which—with the exception of Greece—are also the top supplier countries for bauxite in 2010.[f] The production of alumina requires bauxite ores to be treated by the Bayer process. During this treatment gallium (which is found in average concentrations of roughly 50 ppm in bauxite ores) is extracted in a crude liquid form, which is then purified through solvent extraction and/or by ion exchange. Less than 10% of the gallium contained in bauxite is actually recovered, mainly due to the lack of gallium extraction equipment in many aluminium smelters.[g]

In 2010, primary gallium production was estimated at 106 tonnes with China, Germany, Ukraine and Kazakhstan being the major producers. To a lesser extent Hungary, Japan, Russia and Slovakia also contributed to gallium primary output.[h] It is worth noting that a significant share of the world's total gallium output comes from secondary production, i.e. from the recycling of scrap. In 2009, world gallium secondary production capacity has been estimated at 78t, which is a considerable amount compared to a total primary production capacity of 184t.[i] Recycling plants in Japan, UK and USA mainly recover gallium from new scrap and end-of-life recycling is currently not taking place.[j]

Figure 5: Supply-Chain Map for Gallium in Semiconductors



After purification, gallium is synthesised mainly with arsenide or nitrate to produce GaAs and GaN compounds which in turn are used as base materials in advanced semiconductors. Gallium-based semiconductors find use in a variety of technologies. GaAs is utilised in integrated circuits (chips/microchips) for wireless devices such as radio components, handsets and cellphones. In particular,

a Indium Corporation Presentation, October 2010. *The Relationship between Zinc and Indium Productions.*
b Mikolajczak, C., 2009. *Availability of Indium and Gallium*. Indium Corporation.
c:Mikolajczak, Claire. Indium Corporation. (Personal communication).
d Ademe, 2010. *Etude du Potentiel de Recyclage de Certains Metaux Rares.*
e Mikolajczak, C., 2009. *Availability of Indium and Gallium*. Indium Corporation.
f USGS, 2011. Mineral Commodity Summaries: Gallium.
g Mikolajczak, C., 2009. *Availability of Indium and Gallium*. Indium Corporation.
h USGS, 2011. Mineral Commodity Summaries: Gallium.
i Oko institute for UNEP, 2009. Critical metals for future sustainable technologies and their recycling potential
j Ibid.

the growing market share of third- and fourth-generation smartphones, which require significant higher amounts of GaAs content compared to regular cellphones, is likely to put pressure on the gallium supply chain. Gallium is also applied in light-emitting-diodes (LEDs) technologies for the backlighting of computer notebook displays, computer flat-screens and television flat-screens. Demand for LEDs is forecasted to grow steeply during the coming years, but liquid crystals made from organic compounds are currently being researched as a possible future substitute for LEDs.[a] Last but not least, thin films in advanced CIGS solar cell technologies also represent a growing consumer segment for gallium compounds.

7.1.4 Tellurium

Tellurium is a minor metal that is found in combination with several base metals such as copper, lead, gold, nickel, platinum and zinc. However, almost all tellurium currently produced is obtained as a by-product of copper refining. Copper ores, which are estimated to bear approximately 22,000t of tellurium reserves worldwide,[b] are fairly well distributed around the globe and, compared to other tellurium capable ores, contain on average the highest concentrations (according to estimates from the USGS ca. 80ppm).[c] While the theoretical maximum global production capacity p.a. is estimated at 1,500 tonnes,[d] exact global production figures for tellurium are hard to ascertain, as not all countries disclose their production data. However, industry sources estimate global production at about 500 tonnes annually,[e] a quarter of which is thought to take place in Europe.[f] Figures for tellurium secondary production are also unknown, although small quantities of new scrap from CdTe production are known to be recycled.[g] However, from the data available, it is safe to say that tellurium supply is quite diversified both geographically and politically with production taking place in Canada, Peru, Japan and Russia.

More than 90% of tellurium currently produced is extracted from anode slimes resulting from the electro-winning refining process of copper with the remaining 10% being recovered from lead refinery skimmings and from the flue dusts and gases generated during the smelting of copper.[h] Tellurium can only be extracted from copper that is refined by the electro-winning process, a technique that is cost-effectively applied to high-grade copper ores.[i] However, high grade ores are being exhausted and the most economical way to treat the remaining low grade ores is the solvent-leach refining process which does not lend itself to the recovery of tellurium. This may result in limitations in future tellurium supply.[j]

Figure 6: Suppy-Chain Map for Tellurium in PV Thin-Film Technologies

The next stage is the refining and purification of the extracted tellurium. The required purity degree varies depending on the specific application. Currently, 42% of tellurium is used as an alloy agent in stainless steel and copper to improve machinability and in lead to improve resistance to vibration and fatigue.[k] More than 25% of tellurium is synthesised with cadmium in the cadmium-telluride (CdTe) compound which is then used in a variety of semiconductor technologies, mainly in the solar sector. In 2009 solar thin films represented the second largest consumer segment for tellurium with a share of around a quarter of world consumption.[l]

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a Oko institute for UNEP, 2009. Critical metals for future sustainable technologies and their recycling potential.
b USGS (2011), Mineral Commodity Summaries: Tellurium.
c Edestein, Daniel. USGS. (Personal communication)
d Oko institute for UNEP, 2009. Critical metals for future sustainable technologies and their recycling potential.
e USGS (2010), 2009 Minerals Yearbook: Selenium and Tellurium.
f Hisshion, Daniel. President of the Selenium Tellurium Development Association. (Personal communication).
g Kammer, Dr. Ulrich. Technical director PPM Pure Metals GmbH. (Personal communication)
h Ayres, R.U., 2002. *The life cycle of copper, its co-products and by-products*. Available at: http://pubs.iied.org/pdfs/G00740.pdf. [Accessed 04/05/2011]
i Lifton, Jack. (July 2009) *The Tellurium supply conjecture*. Available at: http://www.techmetalsresearch.com/2009/07/the-tellurium-supply-conjecture/. [Accessed 04/05/2011].
j Ibid.
k USGS, 2011. Mineral Commodity Summaries: Tellurium.
l European Commission, 2010. *Critical raw materials for the EU, Annex V*.

High purity tellurium (up to 99.99999%) plays a prominent role in thin films for solar cells as its photosensitive properties are exploited to give solar panels high efficiency. Within the solar industry, two companies, 5N Plus and First Solar dominate the supply chain for CdTe-based thin-films. 5N Plus is active upstream with a fully integrated primary/secondary production facility of high-purity tellurium and CdTe.[a] First Solar, which is thought to account for the largest part of 5N Plus' sales, is active downstream being the leading producer of CdTe based thin films and PV solar panels.

7.2 Expanding Primary Output

One of the most obvious options to prevent the occurrence of supply-chain bottlenecks for a specific metal is to expand its output. In principle, expanding global supplies helps to alleviate risks for supply-chain bottlenecks. However, given the added supply security benefits, the section here focuses on expanding European output for the bottleneck metals. Additionally, European policymakers can obviously influence European developments more easily than those at the global level.

7.2.1 Neodymium and Dysprosium

Following the decision of the Chinese government to reduce its export quotas for rare earth elements in 2009 and 2010 and the subsequent large price rises, there has been a race amongst a large number of junior mining companies to open rare earth mines outside of China, notably in the US, Australia and Canada. While the European rare earths industry is currently very small, it is by no means non-existent. As a matter of fact, most steps in the rare earths supply chain are either currently performed in Europe or have been performed in Europe in the recent past. This includes:

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

Rare earths have even been mined in relatively small quantities throughout the 1960s in Finland as by-products of lead.[c]

However, with no direct access to rare earth elements, increasing export restrictions from China, and fierce international competition over new sources that are being developed outside of China, downstream processors and manufacturers of rare earths face limited incentives for significant long-term investments in Europe. For example, the only producing European rare earths separation facility, operated by the Estonian company Silmet has an annual production capacity of ca. 3 kt of REO (about 2.24% of current world production). While it has been unable to produce at capacity in the recent past due to limited access to REE concentrates on international markets, it was acquired by the US rare earths miner Molycorp in April 2011, creating prospects for further up-scaling of its activities.[d] Confronted by similar problems, the British alloy producer LCM has sought to vertically integrate with a Canadian junior REE mining company. European mining of REE's could potentially 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. This could help to stimulate European rare earths knowledge, expertise and production capacity, which could help to ensure adequate metal supply to SET-Plan technologies.

While the European geology is generally not very rich in rare earths, they are known to exist in Scandinavia and Greenland and several deposits are currently being explored by junior mining companies. Two of the most promising projects are perhaps the Kvanefjeld deposit in Greenland and the Nora Kärr project in Sweden, which are currently being developed by Greenland Energy and Minerals and

a Suys, M., 2010. Presentation: *Recycling Valuable Metals from Thin Film Modules.* EPIA, Jan 2010.
b Öko-Institut, 2010. *Study on Rare Earths and their Recycling*, p. 32, Table 5-5; personal communication: David O'Brooke, CEO of Silmet.
c Cassard, Daniel. BRGM PROMINE database. (Personal communication).
d O'Brooke, David. CEO of Silmet. (Personal communication). & Reuters, April 4, 2011. *Molycorp forays into Europe with $89 mln AS Silmet buy*.

Tasman Metals respectively.[a] Significant investments in the range of several hundred million euros would be necessary to bring these mines into production and concentrate the ores. However, different from rare earth projects currently being developed in Canada or Australia, such projects could potentially benefit from the modification of existing European separation capacities instead of having to rely on extremely costly greenfield investments. 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 11,000tpa of rare earths) is around €200m, or over three times the cost of the concentration plant.[b] 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.

Also, environmental management poses particular challenges in the rare earths mines due to the presence of radionuclides in some mine tailings.[c] A recent report by the German Öko-Institute, for example, raises such concerns with regards to the Kvanefjeld project.[d] Obtaining the necessary environmental permit would pose a significant hurdle for realising a European rare earths mining project. 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, alternative options to opening new mines could be to process rare earth-containing tailings, such as tin and titanium or from by-product sources; or to import rare earth concentrates from another mine opened outside of Europe for further processing in Europe.

It should also be noted that compared to neodymium, establishing European production of dysprosium faces additional challenges. First, not all rare earth deposits contain significant amounts of dysprosium. More importantly however, dysprosium and other heavy rare earths[e] require their own complex separation procedure and would require additional investments. While the French company Rhodia has operated a heavy rare earths separation facility in the past, the process is currently only in use in China and even new separation facilities currently under construction in Australia and the US will be unable to separate heavy rare earths.[f]

In summary, apart from the mining 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. Policy measures to strengthen this rare earths supply chain could increase supply security for SET-Plan technologies that rely on neodymium and dysprosium. Rare earths 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 permits. European policymakers and member country authorities should explore possibilities to support companies in fast-tracking exploration activities and regulatory procedures. An alternative mitigation option would be to process rare earth concentrates from tailings, by-product sources or another mine opened outside of Europe.

7.2.2 Indium, Gallium and Tellurium

Given their by-product character, boosting the output of indium, tellurium and gallium in Europe poses a very different type of challenge from increasing rare earths production. Possibilities to expand the European output for these three metals are discussed together here, because the basic problems involved are very similar. The key issue here is not to open new mines, but to increase by-product

a See the TMR Advanced Rare-Earth Projects Index. Available at: http://www.techmetalsresearch.com/metrics-indices/tmr-advanced-rare-earth-projects-index/. [Accessed 04/05/2011].
b Lynas Investor Presentation March 2011. Available at http://www.lynascorp.com/content/upload/files/Presentations/Investor_Presentation_March_2011_950850.pdf. [Accessed 04/05/2011]
c El-dine, N.W. et al, *Natural radioactivity and rare earth elements in feldspar samples, Central Eastern desert, Egypt*. Applied. Rad. Isotopes, 69, 2011, pp. 803-807.
d Öko-Institut, 2010. *Study on Rare Earths and their Recycling*, p. 58.
d Heavy rare earths: atomic numbers 65-71 (terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium)
f O'Brooke, David & Saxon, Mark. CEO of Silmet & CEO of Tasman Metals, respectively. (Personal communication).

recovery from base metal refining, most notably from zinc (for indium), copper (for tellurium) and aluminium (for gallium) refining. Also, given that a sizable refining industry already exists in Europe for all three of these host metals, the challenges to boost output are less significant than in the rare earths case. Several large European refiners already have by-product extraction equipment in use at their facilities and contribute significantly to global production for these three bottleneck metals. The challenge is thus mainly one of expanding and optimising existing by-product recovery in the European refining industry.

In principle, this challenge can be conceptualised to consist of four parts:[a]

1. The first issue concerns by-product presence in the ores that refiners process. Depending on the origin of the ore, concentrations of the by-product can vary considerably. For example, not all zinc ores contain indium. 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.[b] Most bauxite and copper ores do contain gallium or tellurium, but also here concentrations vary and do not always warrant economic extraction.[c]

2. The second issue concerns the technical capabilities 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 percent, but at many European copper refineries, the technologies and processes used allow for recovery only in the 30 – 40 percent range.[d] Indium, tellurium and gallium downstream industries such as advanced material producers for solar applications, which have a 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 agreements for the by-product to the refiners in order to increase the incentives to invest in by-product extraction.[e]

3. The third issue concerns financing, closely related to the previous issue. The differences between the different by-products are considerable here. Industry experts estimate the costs for installing an indium extraction unit as a sizable investment in the range of € 50 million, while a gallium extraction unit is considerably cheaper at roughly € 20 million and tellurium extraction equipment can already be installed for as little as less than € 1 million.[f] 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, but the numbers presented in Table 39 (which is discussed in greater detail below) provide a rough indication. Depending on the by-product, financing can thus be a significant issue or a negligible factor.

4. The fourth issue that regards the willingness of refiners to get involved into the production remains an issue. 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 about an adverse impact of switching to by-product recovery on the delicate and carefully calibrated processes for the refining of the main-product.

Taken together, these various obstacles lead to limited and in many cases suboptimal by-product extraction. There are no publicly available sources documenting which of these refineries are recovering

a The authors are indebted to Claire Mikolajczak, Indium Corporation, for suggesting this approach.
b Mikolajzcak, Claire. Indium Corporation. (Personal communication).
c Hisshion, Daniel. President of the Selenium Tellurium Advancement Association. (Personal communication).
d Ibid.
e Interviews with Claire Mikolajzcak and Daniel Hisshion.
f Ibid.

by-products and not all these companies are willing to publicly disclose their recovery capacities. Table 39 nonetheless attempts to provide a non-exhaustive overview of major European refining and by-product recovery, which has been compiled through a series of enquiries with companies and industry experts. While keeping the limitations of these data in mind, the right-most column of is indicative of the current extent of indium, tellurium and gallium recovery in European refining industries.

Table 39 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 zinc, copper and aluminium. In terms of the obstacles to by-product recovery that have been discussed above, the reasons for this limited recovery differ for indium, tellurium and gallium. In the case of the indium refiners, this is mainly due to the fact that many European zinc refiners are processing unsuitable ores that contain no or little indium and to the relatively high investments necessary to set up indium extraction equipment. 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 for gallium where 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.

Some additional sources for these metals come from the processing of smelter by-products (dross, slags, slimes, flue dust etc.). In Belgium, Umicore reports it produces around 20-30t per annum of indium from these sources and 50-100t per annum of tellurium, with some additional capacity available.[a] It should also be noted that high prices for indium, tellurium and gallium may also result in increasing recovery from other sources than zinc, copper and aluminium refining. For example, fly ash and urban coal ash, where gallium has been found at a concentration of 200 times that of primary refinery production, might also develop into viable economic sources for gallium.[b] Owing to growing concerns over tellurium supply, companies are also investigating the possibility to recover tellurium from other ore types such as gold-telluride and lead-zinc.[c] The Swedish company Boliden is planning to extract tellurium from a new gold-telluride mine from 2012 onwards, with a target capacity of 20tpa, which would be a significant contribution to world supply.[d]

In summary, there is considerable potential to increase the scope and effectiveness of by-product recovery in Europe, particularly for tellurium and gallium, and to a lesser extent for indium. To decrease risks for supply-chain bottlenecks for these three metals, European policymakers could focus on an active dialogue with refiners, as well as possible incentive schemes to promote optimal by-product recovery in the European refining industries. New sources for by-product recovery other than copper, aluminium and zinc refineries 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.

7.3 Reuse, Recycling and Waste Reduction

Policy measures aimed at increasing the reuse and recycling of the five bottleneck metals would also help to alleviate the risks of future supply crises for the five metals. In essence, increased reuse and recycling also expands the supply of these metals, albeit not from primary sources. Waste reduction, on the other hand, is a demand side measure, where less material is wasted, and the same amount of output is possible with less material, resulting in less pressure from demand on limited supplies. The following sections explore possibilities to expand recycling and reuse and to minimise waste for the rare earths neodymium and dysprosium, as well as indium, tellurium and gallium individually.

Within this section, the potential opportunities for recovery for both pre-consumer and post-consumer waste are explored. In general, the opportunities in pre-consumer waste are likely to be more exploitable as the material is typically much easier to collect and process as it is much less dispersed and

a Hagelüken, Christian, Feb 2011. (Personal communication).
b Moskalyk, R.R.. *Review of Germanium Processing Worldwide*, Minerals Engineering 17, pp 393–402, 2004.
c USGS (2011), Mineral Commodity Summaries: *Tellurium*.
d Heeroma, Pierre. Director Group Strategy and Business Development at Boliden. (Personal communication).

contaminated. 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 is more applicable in the medium to long term.

7.3.1 Neodymium and Dysprosium

In general the recycling and recovery of rare earth elements occurs at a low level and it is reported that less than 1% of REEs are recycled from old scrap, mainly from old magnets.[a] Pre-consumer waste is an issue for NdFeB magnets as they are brittle and fracture easily. An estimated 20-30% of the magnet material is scrapped during manufacturing due to breakages or waste cuttings.[b] At present it is cheaper to buy newly manufactured magnets than to reprocess the scrap material, and typically the scrap materials can end up in generic scrap metal waste streams.

As for post-consumer scrap, many of the products within which the magnets are contained have long lifetimes and are not expected to reach their 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.[c] 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. The permanent magnets used in small electrical items however are already reaching waste streams. These applications have a high turnover rate, but are dispersed into the waste stream at end of life. Recovery of these magnets is not practically or economically feasible due to their small size and because they are often glued to other components making separation impossible. When processed as WEEE, the metal in magnets enters light iron processing routes where it is diluted beyond recovery. Alternatively, smelting could provide another avenue for recycling but because the rare earth metals oxidise easily and they are dispersed amongst the low-grade slag, further recovery is extremely difficult to achieve.[d]

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. However, there is currently no evidence that the magnets are recovered for recycling. There is evidence though that novel research is on-going, for example, Birmingham University is involved in a project,[e] as are Hitachi in Japan.[f] Several technologies for recycling REE magnets have been described in the literature.[g] These may recycle the material itself as an alloy to form new magnets, or return the materials back to the individual metals for processing into new magnets.[h] These include hydrogenation disproportionation desorption recombination (HDDR),[i] dissolution in molten magnesium[j] and acid leaching.[k] These materials can be used in new magnets, but with a loss of performance.

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a European Commission (2010). *Critical raw materials for the EU*.
b Akai, T,. Recycling Rare EarthElements*, AIST Today, No29*, pp8-9, 2008.
c Oakdene Hollins for EPOW (2011), *Study into the Feasibility of Protecting and Recovering Critical Raw Materials through Infrastructure Development in the South East of England*.
d Hagelüken & Meskers, 2009. *Complex Life Cycle of Precious & Special Metals*. Gradel & Voet eds., *Linkages of Sustainability*. MIT Press. Nov 2009.
e Zakotnik, M., Harris, IR. & Williams, AJ. *Multiple recycling of NdFeB-type sintered magnets*. Journal of Alloys and Compounds, 469 (1-2), pp.314-321, 2009.
f *Hitachi's Involvement in Material Resource Recycling*. Available at http://www.hitachi.com/rev/archive/2010/icsFiles/afieldfile/2010/10/26/r2010_04_110.pdf.[Accessed 17/02/11].
g Oakdene Hollins for DfT, 2010. *Lanthanide Resources and Alternatives* & Öko Institute, 2011. *Study on Rare Earths and Their Recycling*.
h Hagelüken, Christian, February 2011. (Personal communication).
i Williams A., 2010. *Recycling of NdFeB - Turning Scrap into New Magnets*, UK Magnetics Society Presentation.
j Osamu Takeda et al., 2005. *Recovery of neodymium from a mixture of magnet scrap and other scrap*. Tokyo: The University of Tokyo.
k Tetsuji, Saito et al., 2006. Recovery of rare earths from sludges containing rare-earth elements. *Journal of Alloys and Compounds 425*, pp. 145–147.

Table 39: European Alumina, Zinc and Copper Refineries and their By-Product Extraction

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.**
Zinc refineries	Kokkola	300	Finland	Boliden	
	Odda	100	Norway	Boliden	
	Bukowno	100	Poland	Boleslaw ZGH	
	Porto Vesme	100	Italy	Glencore	
	Plovdiv	80	Bulgaria	KCM	
	Miasteczko	80	Poland		
	Copsa Mica	30	Romania	Mytilineos	
	Auby	300	France	Nyrstar	ca. 30-40t In p.a.
	Balen	300	Belgium	Nyrstar	
	Budel	300	Netherlands	Nyrstar	
	Kardjali	40	Bulgaria	OCK	
	Nordenham	200	Germany	Xstrata	
	San Juan de Nieva	600	Spain	Xstrata	
	Total	**2,530**			**ca. 30-40t In 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: Calculations based on expert interviews and various industry estimates

Costs of recycling rare earths are difficult to estimate since no commercial process exists at present. Greater disassembly and pre-processing of post-consumer WEEE would be required at around 100-1000 sites across Europe that carry out pre-processing of WEEE waste. This would then be followed by the metal recycling step, which 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 the individual element required, although some laboratory processes have achieved separate recovery of neodymium. Speculative capital costs might be €0.1-1.0m for each pre-processor and €10m-€100m for the recycling step.

Reuse is another potential option, as these magnets do not lose much strength over their lifetime. However, as the specification of the magnets in the original design is often exact, and the processes to change the properties of the magnets are complex and expensive, reuse does not occur.

7.3.2 Indium

For indium, recycling of post-industrial waste is common practice and already represents a major source of indium supply with production levels of secondary indium being at least as large as those for primary indium. This is because the inefficiencies of the sputtering process of ITO onto glass mean that only around 30% of the ITO is actually deposited. However much of the spent material can be collected for recycling. Indium Corporation report that recovery yields have increased from 55% to around 75-80% and more recently to 95% of the material[a] and turn-around times have been reduced to under 15 days. Therefore this process appears to have been fully optimised, although it is noted that geographically most of the activity is located in Asia, notably in Japan, Korea, Taiwan and also China.[b]

Recovery of indium from post-consumer flat panel display (FPD) glass does not appear to have been solved, with only an estimated 1% being recovered due to the dissipative use of indium in this application, as only low concentrations of ITO are present in FPDs.[c] Indeed a study by WRAP that examined the economics of recycling FPD considered the ITO-containing glass as a waste rather than a resource for recycling.[d] However, given that 74% of the world's indium production is consumed within FPDs, this makes these products an obvious target for indium recovery. Smelting is not seen as an attractive option to obtain the indium from these products. The relatively small quantities of indium are dwarfed by the amount of low-value glass substrate, making the economics of recovery less favourable. In addition, smelting would be inefficient with most of the energy focused on melting the glass.[e] Nonetheless Umicore (Belgium) have capacity to recover about 50 tonnes per annum of indium.[f] Current production levels are reported at 30-40 tonnes per annum of which 20-25% comes from recycled sources (mostly scrap from PV production – see below, but also indium contained within mobile phones and solders/alloys).[g] This facility also recovers the indium in conjunction with antimony and tellurium from WEEE waste streams and has been very well described.[h] A less conventional route however appears to be needed to increase the recovery of the indium from post-consumer FPDs. Presently, there does not appear to be any commercially available means to recycle post-consumer ITO from FPDs, which should be seen as a potential target for further research. FPDs should be easily separable from other types of WEEE because they are easily recognisable. This should enable sufficient concentration of material to enable more effective recycling methods to be developed. One process identified was by the Ashahi Pretec Group in Kobe, Japan, which recovers indium from FPDs by dissolution techniques.[i] It is noted that significant volumes will occur in the waste stream between 2012 and 2030.[j]

a *The Relationship between Zinc and Indium Productions*. Indium Corporation Presentation, October 2010.
b Mikolajczak, Claire. Indium Corporation. (Personal communication).
c European Commission, 2010. *Critical raw materials for the EU.*
d Oakdene Hollins for WRAP, 2010. *Demonstration of Flat Panel display recycling technologies*.
e *Technology challenges to recover precious and epical metals from complex products*. R'09 Twin World Congress And World Resources Forum, 2009.
f Oko institute for UNEP, 2009. Critical metals for future sustainable technologies and their recycling potential.
g Hagelüken, Christian, Feb 2011. (Personal communication).
h Hagelüken, Christian, 2006. *Recycling of Electronic Scrap at Umicore's Integrated Metals Smelter and Refinery*. Available at: http://www.preciousmetals.umicore.com/PMR/Media/e-scrap/show_recyclingOfEscrapAtUPMR.pdf. [Accessed 04/05/2011].
i Asahi Holdings Group, 2010. *Precious Metal Recycling Business*. Available at: http://www.asahiholdings.com/english/ir/report/document/pdf/environ08e/e_07_09.pdf. [Accessed 04/05/2011].
j BIOS for Ademe, 2010. *Etude du Potentiel de Recyclage de Certains Metaux Rares.*

For PV, recycling of pre-consumer production waste of CIGS already occurs at Umicore in Belgium, which recovers metals from high-grade PV residues. These are typically production scrap residues from CIGS (thin-film solar cells), which are processed to recover the copper, indium, selenium and gallium. This process is viable due to the concentrated nature of the waste feed. For post-consumer waste, arisings are almost non-existent,[a] although it is noted that the indium and gallium concentrations in general PV waste is too low to make the Umicore process for PV-manufacturing residues, sufficiently economic on a large scale at present, even with complete separation.[b] 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.[c] Processes also exist for the recovery of indium from CdTe PV, which is discussed in Section 7.3.4 on tellurium recycling.

Capital costs of an integrated metal recycling plant processing 300,000tpa of input material including PV and WEEE, and recovering 17 metals are put by Umicore as in excess of €1bn. The exact amount attributable to indium recovery (or to other metals recovered in this way) is difficult to estimate due to the integrated nature of the plant.

7.3.3 Gallium

The major usage of gallium is within semiconductors, which require that the refined material must have a very low concentration of impurities. Therefore sophisticated processing routes are required to ensure that this purity is produced. Only 15% of a GaAs ingot is actually used during electronics manufacture, and the remaining 85% can be recycled.[d] For 2010, world gallium recycling capacity was estimated at 141 tonnes (versus the 184 tonnes for primary production capacity), with recycling plants for new scrap located in Canada, Germany, Japan, the UK and USA.[e] At the height of the gallium price boom in 2001, GaAs-substrate maker Sumitomo Electric estimated that it was internally recycling 40% of the gallium used for crystal growth. A further 20% was retrieved from GaAs device makers in the form of broken wafers, sludge from wafer thinning and waste from epitaxial source material.[f] It is thought that the recycling of this internal scrap has been optimised at over 90% recovery due to the prices and maturity of the technology; and additionally the processing for LEDs has become much more efficient due to changes in processing techniques resulting in lower wastage.[g] A number of other companies and manufacturers have plants to recycle new gallium scrap in Japan, such as Dowa Mining and Asahi Holdings.

However, no recovery of gallium from post-consumer scrap is known to take place.[h] This is because the gallium contained within the semiconductors is highly dispersed due to their usage across printed circuit boards (PCBs), the recycling of which is mostly governed by the WEEE directive (although many non-WEEE directive products such as in the automotive and aviation industry will also contain 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; electronic waste, PGMs, indium and antimony are refined for reuse.[i] Other elements contained within the circuit board, including gallium, are generally disposed of as slag. Additionally there does not appear to be sufficient capacity to process the increasing collection of WEEE, as only around 6% of the feedstock can

a Gomez, Dr. Virginia, February 2011. (Personal communication).
b Hagelüken, Christian & Meskers, Christina, 2009. *Technology Challenges to Recover Precious and Special Metals from Complex Products*.
c Hageluken, Christian, February 2011. (Personal communication).
d Gallium, Minor Metals Trade Association. Available at http://www.mmta.co.uk/uploaded_files/GalliumMJ.pdf. [Accessed 25/02/2011].
e USGS (2011). Mineral Commodity Summaries: *Gallium*.
f Growth Predicted for Gallium Market, *Compound Semiconductor Magazine, May 2003*. Available at: http://compoundsemiconductor.net/csc/features-details.php?id=17430. [Accessed 04/05/2011].
g Mikolajczak, Claire. Indium Corporation. (Personal communication)
h Oko institute for UNEP, 2009. *Critical metals for future sustainable technologies and their recycling potential.*
i *Presentation: Electronic scrap recycling at Umicore*, *2007.* 3rd China International Metal Recycling Forum, 2007.

be fed into conventional integrated smelters and clearly barriers to entry exist with regards to the know-how and capital outlay.[a]

Research is ongoing for new technologies to extract further value from the scrap.[b] 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.[c]

The recycling of pre-consumer solar CIGS production waste is already occurring (see Section 7.1.2 on indium recycling). 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). 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.[d] In addition to the PV CYCLE scheme, initiatives by the German companies Saperatec and Loserchemie to recover end-of-life PVs are expected to start in 2011. Research is ongoing however on developing processes to recover from end-of-life CIGS (see Section 7.1.2 on indium recycling). 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.

7.3.4 Tellurium

For tellurium, each of the major applications have their own practices regarding recycling. The major application is metallurgy, with additions of 0.04% tellurium to improve its machinability, i.e. to make the metal easier to work with in terms of bending, cutting, shaping, finishing etc.[e] The dispersive nature of this application means that the tellurium contained will be diluted amongst a very much larger pool of ferrous scrap, meaning that although the tellurium will be ‘recycled’, it will not be available to replace virgin raw material. For tellurium-based copier drums, substitution to other materials has largely occurred, which has led to a fall in the amount of tellurium available for recovery from scrap tellurium-based copier drums.[f]

Some recycling opportunities do exist for the recovery of tellurium from electronic scrap where the scrap is processed at appropriate smelting plants. For example, recycling capacities for tellurium from electronic scrap exist at Umicore (Belgium), where tellurium is one of 17 metals that can be refined and is separated within its special metals refinery,[g] and also by Dowa in Japan. These facilities are available for use to recover any tellurium contained, such as within flash memory,[h] although actual production levels from recycling feed are currently low.

From PV, considerable opportunities exist in the recovery of material loss from the manufacture of CdTe solar cells. Estimates on the material utilisation 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.[i] 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.[j] The process is operated in the US and Germany and involves shredding,

a Plastics Europe, November 2006. *Using metal-rich WEEE plastics as feedstock / fuel substitute for an integrated metals smelter.*
b Hagelueken, Christian, 2011. (Personal communication).
c Oakdene Hollins for EPOW, 2011. *Study into the Feasibility of Protecting and Recovering Critical Raw Materials through Infrastructure Development in the South East of England*.
d Gomez, Dr. Virginia, Feb 2011. (Personal Communication)
e Chemistry Explained: Tellurium. Available at: http://www.chemistryexplained.com/elements/P-T/Tellurium.html#ixzz1HFFh4DSD. [Accessed 21/03/11].
f USGS, 2010. 2009 Minerals Yearbook: Selenium & Tellurium.
g UNEP (2009), *Recycling from E-Waste to Resources*.
h Oko institute for UNEP, 2009. Critical metals for future sustainable technologies and their recycling potential.
i Fthenakis, 2004. *Life cycle impact analysis of cadmium in CdTe PV production*. Renewable and Sustainable Energy Review 8, pp. 303-334.
j *First Solar*. Available at: URL: http://www.firstsolar.com/en/recycle_program.php. [Accessed 22/03/11].

removing the films using acid and hydrogen peroxide and separating the metal-rich liquid for further processing.[a] 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.[b] The recycling of CdTe solar cells is able to produce very high purity tellurium available for use within the production of new solar cells.[c]

7.3.5 Conclusions

There is a potential to recycle neodymium and dysprosium from pre-consumer magnets, although further R&D of the recycling technologies is required. As for post-consumer waste, the best opportunities lie within recycling the magnets contained within hard disc drives where the volumes arising in the waste stream are significant and consumer driven separation is occurring due to data security reasons. However in general, magnets are not expected to enter waste streams in large quantities for some time and to effectively recover them, collection and sorting systems would need to be developed. There are some technologies being developed to effectively recover/reuse magnets but further research in this area is still needed for full commercialisation.

Indium recovery of pre-consumer processing waste appears to have been optimised, although mainly located in Asia. Post-consumer waste can also be recovered if they are concentrated high enough to make it viable for the processors to extract. This would require the separation of flat panel displays from other types of WEEE, which would give opportunity to recover the very large portion of indium's use in FPDs and possibly also PV panels in the future. Some technologies are being developed for indium recovery from FPDs, although further R&D is required, which will need to be ready for implementation as significant volumes enter the waste stream in the coming years.

Recovery of gallium from pre-consumer waste appears to have been optimised, although recovery from post-consumer electronic scrap and thin-film PV panels is non-existent. Opportunities for recovery from post-consumer waste are much more limited due to the very small use in those products, as well as the small-volume recycling stream. Tellurium recovery is possible from electronic scraps and thin-film PV panels, but it is dissipated in its major use in the steel industry.

Capital costs are incurred in both pre-processing of WEEE for rare earths and in the recycling process for all of the metals considered. Although relatively few recycling plants are required, the individual capital costs will be high, and will depend upon attribution methodologies in the case of integrated facilities.

7.4 Substitution

Substituting the bottleneck metals can also provide an effective solution to mitigating the risk from future metal supply-chain bottlenecks to the deployment of SET-Plan technologies. Substitution can either aim at replacing bottleneck metals in the actual SET-Plan technology or aim at substituting the metal in rival applications that compete with SET-Plan applications for the supply of bottleneck metals. This can be achieved by developing alternative materials that can be used as a substitute to the bottleneck metal in these technologies. Alternatively, it can also consist of replacing the specific technology with another technology that is its functional equivalent, but by virtue of its design does not rely on the bottleneck metals. The following sections discuss the potential for such substitution for each of the 5 high-risk metals: neodymium, dysprosium, indium, tellurium and gallium.

7.4.1 Neodymium and Dysprosium[d]

Discovered in the early 1980s as cheaper alternatives to samarium cobalt-based magnets, NdFeB

a *First Solar*. Available at: http://www.firstsolar.com/en/recycling.php. [Accessed 22/03/11].
b Larsen, Kari, August 2009. *End-of-life PV: then what? - Recycling solar PV panels*. Available at: http://www.renewableenergyfocus.com/view/3005/endoflife-pv-then-what-recycling-solar-pv-panels/. [Accessed 04/05/11].
c 5N Plus, January 2010. *Presentation: Recycling valuable metals from thin film modules.* 1st International Conference on PV Recycling, January 2010.
d This section has been drawn largely on content previously published in Oakdene Hollins for DfT, 2010. *Lanthanide Resources And Alternatives.*

magnets rapidly developed to become the strongest permanent magnetic material known, leading to a plethora of new technologies and novel uses. To date, NdFeB-based materials remain the strongest permanent magnets discovered, by a large margin.

Internationally, a vast amount of research has been targeted at improving various aspects of the performance of this material. Gradual advances in synthesis, manufacturing and magnetisation techniques have led to a two-fold increase in their magnetic strength since the mid-1980s, and developments of coatings have improved their resistance to corrosion. However the fundamental composition of the material has remained the same.[a]

In addition to increasing magnetic strength, progress has also been made in tuning the performance of these magnets to suit different needs. One of the largest technical barriers faced with NdFeB magnets is their rapid loss in magnetism at temperatures in excess of 80^{O}C. This issue is currently resolved by replacing a small quantity of neodymium with dysprosium, which is the most commonly used element for this purpose (although other Rare Earths, such as terbium, have been shown to work, these are less well suited due to price or performance considerations).[b] Increasing the proportion of this doping improves the temperature performance, but also progressively decreases baseline magnetic strength. Therefore many different grades of magnet are available with different substitution levels.

Various strategies for the reduction or elimination of neodymium and dysprosium usage in EV motor magnets have been found. These fall into three broad categories as explored below:

1. **Reduction of neodymium and dysprosium usage in existing magnetic materials**

   Neodymium – Increasing the magnetic strength of neodymium-based magnets would allow a reduction in the size of these magnets and therefore the quantity of neodymium required. As stated above, significant advances were made soon after the discovery of this material, resulting in a doubling of magnetic strength. More recent improvements are generally in production techniques, such as the shift from bonding to sintering of magnets, or enhanced methods for magnetisation using powerful superconducting magnets. These developments have primarily arisen from research in Japan, China and the USA. Some further improvements may also arise from development in areas such as nanotechnology and materials chemistry. However, the magnetic strength of the most recent generation of magnets is believed to be close to fundamental and technical limits of this material. Some opportunities may exist to substitute a portion of the neodymium content with another rare earth element, praseodymium, but at the cost of a loss of performance. Therefore, advances in this area are unlikely to provide a significant reduction in rare earth usage in magnets.

   Dysprosium – Dysprosium will suffer a greater supply deficit than other rare earths, if current trends continue. This has been identified by various organisations and a considerable research effort is underway to reduce the quantity of dysprosium required to achieve the necessary performance over the motor's operating temperature. As observed with neodymium minimisation strategies, new production techniques are being developed that provide the same level of temperature resistance but using much lower levels of dysprosium doping. These focus on utilising dysprosium more effectively within the material's chemical structure, but are some way from commercial-scale operation (for example, grain boundary diffusion alloying); therefore it is difficult to predict the actual reduction these will generate. Japanese companies and research bodies appear to be at the forefront of this research and have heavily invested in it, in support of their large magnet manufacturing industry. The Japanese Government has also been quick to identify issues surrounding dysprosium usage: a large scale government-sponsored research effort targeting dysprosium minimisation or substitution is ongoing. Published or known research from other countries is lagging behind this effort.

a Inowa, Takehisa M., 2008. *Rare Earth Magnets: Conservation of Energy and the Environment*. Magnetic Materials Research Centre, Shin-Etsu Chemical.
b GWMG, 2009. Presentation. 5th International Rare Earths Conference, Hong Kong, November 2009.

No feasible dysprosium replacement strategies were identified. The most suitable alternative dopant known is with the rare earth element, terbium. However, this element is rarer and more expensive, so adoption on a large scale is unlikely. In the short term, alternative strategies such as minimisation through design may provide a more effective way to reduce the demand for dysprosium. An example would be motor design and cooling features which reduce the operational temperature range, lowering the grade of magnet required. Further advances in technology, for example in the nanotechnology field, may provide materials-based minimisation options in the future.

2. **New or alternative magnetic materials**

Currently, there is no evidence of any successful developments towards new materials which can compete or better the strength of neodymium-based magnets. Indeed, many experts believe that no such material exists. Overall progress in this area is limited, and in 2008 there was very little public research and development specifically targeting this goal,[a] although the situation may have changed somewhat since then, for example Ne-Fe-Nitride.

Of known magnetic materials, the closest to neodymium magnets in terms of performance are samarium cobalt magnets. These magnets have superior resistance to temperature and are used in niche areas such as high temperature applications. However, these magnets have around half the magnetic strength of neodymium-based magnets and are therefore far less suitable for use in EV motors. Research in this field is reasonably mature and it is unlikely that their performance will be increased significantly. Other known permanent magnetic materials, such as aluminium-nickel-cobalt (AlNiCo) or ferrite-based magnets, are simply not powerful enough to be used in efficient EV motors; the mass of magnet required would be prohibitively heavy.

High Temperature Superconductors (HTS) magnets potentially provide a solution in the longer term.[b] These materials are able to provide higher magnetic strengths than permanent magnetic materials, but currently require cooling to very low temperatures to operate. Due to the potential benefits of superconduction for a large number of applications, there are significant ongoing research efforts targeting new superconducting materials, particularly superconductors that operate at higher temperatures. These materials are most likely to find use in large scale, static applications such as wind turbines.

In short, the replacement of neodymium-based magnets with either known or 'yet-to-be-discovered' magnetic materials should not be relied upon. Research may provide a suitable material in the future, but the likelihood and timescales involved are unclear.

3. **Technology choice**

Technology choice can be another way of mitigating the possible bottleneck. Neodymium and dysprosium are primarily used in PMG turbines. These can change from low speed to medium and high varieties. There are however, gear-based wind turbines with and without permanent magnet use as well as HTS, which is still in development stages. Each of these has different requirements for permanent magnets. Deployment of these variant technologies can reduce the demand for neodymium and dysprosium. The analysis in Section 6.2 highlights this clearly.

7.4.2 Indium

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

Perhaps the most advanced work is in the use of zinc oxides, which have been developed to be suitably adhesive for coatings through the production of zinc oxide nanopowders.[c] These can replace ITO in LCDs

a Inowa, Takehisa M. 2008. *Rare Earth Magnets: Conservation of Energy and the Environment.* Magnetic Materials Research Centre, Shin-Etsu Chemical.
b Hill, John F. , 2010. *Wind Turbines – The Era of the PMG*. Converteam, UK Magnetics Society Workshop, December 2010.
c Dobson, P. *Presentation: Material Substitution*. Materials KTN, March 2011).

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

Elsewhere, indium phosphide can be substituted by gallium arsenide in solar cells and in many semiconductor applications. Hafnium can replace indium in nuclear reactor control rod alloys.[g] Gallium can replace indium in InAs but as both elements could be in short supply in the future, this is perhaps debatable.

7.4.3 Gallium

Substitutes are available or are being developed for gallium in a number of applications. However the complete replacement of GaAs in all semiconductor applications looks unlikely at present. For example, GaAs-based integrated circuits are used in many defence-related applications because of their unique properties and there are no effective substitutes for GaAs in these applications. Replacement by different materials is possible in certain cases, however this typically relies on other scarce material, such as the germanium-based materials in certain mobile phone applications and indium compounds as an alternative to GaAs-based infrared laser diodes. Silicon can replace gallium in certain applications and silicon germanium has been proposed as a replacement for GaAs but, as this is not widespread, it can be assumed that the performance is not so good.[h]

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

7.4.4 Tellurium

Selenium can replace tellurium in free-machining low-carbon steels as can bismuth, calcium, lead, phosphorus and sulphur.[i] 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.[j] However, the replacement of tellurium with selenium has 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.[k] Substitution has already been largely completed within the photoreceptors of copiers and printers. 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.

a Hecht J.S., J. Soc et al., 2011. *For Information Display*, 19(2), pp. 157-162.
b Kymakis, E. et al., 2011. *IEEE Transactions Electron Devices*, 58(3), pp.860-864.
c Schnorr, J.M. & Swager, T.M. ,2011. *Chemistry of Materials*, 23(3), pp.646-657.
d D.W.Lee et al., 2011. J.Mat. Chem., 21(10), pp.3438-3446.
e K. Jo et al. 2011. *Langmuir*, 27(5), pp.2014-2018.
f Y. Zhu et al., *Chemistry of Materials*, 23(4), pp.935-939.
g USGS, 2010. Mineral Commodity Summaries.
h Available at: http://www.minerals.usgs.gov/minerals/pub/commodity.
i Available at: http://www.ibm.gov.in/seleniumandtellurium2009pdf.
j Available at: http://www.ibm.gov.in/seleniumandtellurium2009pdf.
k USGS, 2010. 2009 Minerals Yearbook: *Selenium & Tellurium.*

7.4.5 Conclusions

There have been intense efforts to reduce and substitute the use of neodymium and dysprosium in permanent magnets, but no substantial success has been achieved in terms of providing similar performance levels to Nd-based permanent magnets. However, substitution at the systems level, i.e. to other types of electric motors that do not rely on rare earths, seems to be a viable option to mitigate potential bottlenecks.

With regard to other bottleneck metals, there appears to be very little effort to replace gallium, indium and tellurium with other elements. Most of the references concerning gallium, indium and tellurium are decades old and it seems that it is more attractive to replace these materials with a completely new material rather than an existing metal. An exception to this is for indium in indium tin oxide where there is considerable research being undertaken to use zinc oxides and its derivatives, carbon nanotubes or graphene in thin films. Further research and development into these alternative materials is recommended.

7.5 Environmental Impact

The trade-off between the environmental impact of mining, refining and processing these metals and the environmental benefits of using them in low-carbon energy generation technologies has been considered. The life-cycle inventory of a number of metals (around 30) was gathered as part of the Raw Materials Initiative.[a] However because of the different applications and functions of the different metals, it was not possible to use these “cradle-to-gate” data: their use as facilitators of green technologies meant that the use-phase of the product was critical to consideration and such data was not typically available. Despite the lack of data, the status of tellurium, gallium and indium as co-products alongside raw materials of much greater volume means that the environmental impact attributable to them will be low, although this is likely to vary depending upon the methodology used for attribution. The environmental impact attributable to the production phase of rare earths will be higher. However, research done for rare earths and electric vehicles (rather than for wind turbine generators) shows that the environmental benefits of using the rare earths in motors is much greater than the environmental impact of production, even if production is assumed to come from ore grades over a magnitude lower than the current grades.[b]

7.6 Conclusions

This Chapter has examined the options to mitigate the metal supply-chain risks associated with the implementation of SET-Plan technologies, focusing on five metals for which high bottleneck risks have been identified (in Chapter 5). In particular, options to expand European primary output, increase reuse and recycling, reduce waste and the ability to substitute the bottleneck metals have been explored. The results show that there is some scope for effective mitigation measures, although many of them would require additional research efforts and investments and would only begin to contribute substantially to reducing the risk for future supply-chain bottlenecks towards the middle of the present decade at the earliest.

For rare earths, quite a sophisticated technological and industrial basis exists, which potentially represents the building blocks for a rare earths supply chain in Europe; although it is noted that these are owned by different companies and would require collaboration. In particular, Europe still has well-developed separation capacities, which present perhaps the most challenging step in the rare earths supply chain, although the complexities of re-opening separation facilities and modifying to the

a Raw Materials Initiative, Report of the Adhoc Working Group, June 2010. Available at: http://www.ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf p 29-30. [Accessed 04/05/2010]
b Oakdene Hollins Ltd *Lanthanide Resources and Alternatives,* UK Department for Business, Innovation and Skills / UK Department for Transport May 2010. Available at: http://www.oakdenehollins.co.uk/metals-mining.php. [Accessed 04/05/2011]

specificities of different ore bodies could be high. A key problem for rare earths however is securing a reliable supply of virgin material. There is some potential for actual mine production in Europe, but the deposits that have been identified so far will need considerable further exploration to ascertain their commercial viability and hurdles to secure environmental permits would form a substantial obstacle.

There is also some potential to recycle rare earths, both for pre-consumer and post-consumer scrap. However, further research is needed to develop and commercialise recycling technologies. A key problem for post-consumer applications is that large quantities of permanent magnets (for example, from electric vehicles and wind turbines) will not enter the waste stream for many years to come. A more immediate opportunity exists in recycling the magnets contained within hard disc drives, where the volumes arising in the waste stream are more significant. To enable effective recycling from such post-consumer sources collection and sorting systems would need to be developed. Efforts to replace neodymium and dysprosium in permanent magnet applications have so far not met much success and system level substitution, i.e. replacing the technologies that use rare earths with alternative technologies not reliant on permanent magnets, appears to be a more promising route. Continuing investment in alternative technologies is therefore important.

For indium, the possibilities to increase the production of virgin material from European zinc refining are limited, not unless refiners could be convinced to switch to alternative (mostly South American) ore suppliers. The ores that European zinc refiners currently use are generally low in indium content and where possible, indium recovery is often already optimised. The same applies to recycling of processing waste. There is however some potential to recycle indium from post-consumer waste in flat panel displays. Although larger quantities are only now beginning to enter the waste stream, further research on recycling technologies, as well as the development of infrastructure to collect and separate flat panel displays from other WEEE, is needed. On substitution, significant effort has been made to find substitutes for indium tin oxides. Some possible alternatives have been identified, but additional research in this regard is needed.

For tellurium, there is still considerable room to expand the scope and increase extraction rates of recovery from European copper refiners. This is particularly attractive for tellurium because only relatively small investments would be needed. Further efforts are necessary to increase existing European recycling from electronic scrap and PV applications. Substitution of tellurium in several low-value applications is possible and should be promoted.

Similarly, there is still much potential to increase gallium recovery from European aluminium refiners, as currently, much gallium content in bauxite that is processed in Europe ends up in waste streams. Recycling of processing waste is quite optimised already today. For most gallium applications, there is little scope for recycling due to its dissipative use. The recovery of gallium from pre-consumer electronics waste appears to have been optimised. Substitution of the gallium contained in LEDs by organic-based LEDs is a possibility, which should be supported.

In summary, there are a range of potential options to mitigate risks for future supply-chain bottlenecks for the five metals identified in Chapter 5, although each metal has its own recommendations. It is recommended that the European Commission and EU Member States should actively engage in considering a broad array of mitigation measures, even if many of the solutions will only contribute to mitigating bottleneck risk in the medium to long term. Among the options suggested for consideration are to:

1. Collect more data and provide better information on the demand, supply and price trends for metals that are used in significant quantities in SET-Plan technologies. Bottleneck risks are reduced by a faster flow of information between decision-makers and market participants both in metal markets as well as in the consuming industries.
2. Support and sustain the existing rare earths supply chain in Europe, including efforts to ensure reliable supply of ore concentrates at competitive prices.

3. Support junior miners in fast-tracking the exploration of promising European rare earth deposits as well as the respective permitting processes.
4. Engage in an active dialogue with zinc, copper and aluminium refiners over by-product recovery. For tellurium and gallium in particular, there is scope to increase European recovery rates.
5. Create incentives to encourage by-product recovery in zinc, copper and aluminium refining in Europe.
6. Promote the further development of recycling technologies and especially increased end-of-life collection and processing for a number of particular components and products, notably permanent magnets in hard disc drives and flat panel displays.
7. Invest broadly in alternative technologies that can provide system-level substitutes to technologies that rely heavily on bottleneck metals such as electro-motors for wind-turbines.
8. Promote further R&D into substituting indium in indium tin oxides.
9. Encourage the substitution of tellurium use in low-value applications.

In the final Chapter on the overall conclusions and recommendations, suggestions for concrete policy actions for the above options are discussed.

8 Conclusions and Recommendations

This report has examined the use of metals in six SET-Plan technologies: nuclear, solar, wind, bioenergy, carbon capture and storage (CCS) and electricity grids, which were discussed in Chapter 3. Chapter 4 identified 14 metals that these technologies are likely to rely on over the coming two decades in significant quantities relative to their current world supply. Chapter 5 went on to examine the risk of future supply-chain bottlenecks over the coming decade for these 14 metals, by analysing in detail the likelihood of rapid future global demand growth, limitations to expanding supply in the short to medium term, the concentration of supply and the political risks associated with key suppliers for each of these metals. The results identify 5 of the 14 metals for which indicators show a high risk for future supply-chain bottlenecks, which are the rare earths, neodymium and dysprosium, as well as the by-products indium, tellurium and gallium.

In the six SET-Plan technologies, these five metals are mainly used in various wind and solar energy generation technologies. Chapter 6 examined the impact on the demand for the five bottleneck metals of variations in the assumed future technology uptake and in the technology mix in the wind and solar sector. It shows that depending on the precise technology mix, demand could vary significantly, indicating a considerable degree of uncertainty. Chapter 7 then explored from a European perspective, a set of potential mitigation strategies, ranging from expanding European output for these metals, increasing recycling and reuse to reducing waste and finding substitutes for these metals in their main applications. The results showed that there are a number of options available to mitigate risks for future bottlenecks, although the most promising solutions vary from metal to metal. A number of promising elements of a possible risk mitigation strategy are identified for each of these metals, with concrete policy options that can be considered by the European Commission and EU Member States. The following four sections examine the results of the various Chapters in greater detail.

8.1 SET-Plan Technologies rely on Various Metals to Different Extents

The analysis in Chapter 4 provides quantitative estimates for the metal requirements of each of the six SET-Plan Technologies in terms of:

- kilogram per megawatt that is generated for nuclear, wind and solar power
- kilogram per million tonnes of oil equivalent that is generated from bioenergy
- kilogram per megawatt of fossil fuel electricity generation capacity to which CCS is applied
- kilogram per kilometre of electricity grid cables that are laid.

This allows estimating and comparing the metal demand of the two scenarios for the deployment of the six SET-Plan technologies.

In Chapter 4, the demand for 60 different metals in the most optimistic scenario is calculated for the deployment of each technology and finds that metal requirements in this scenario are most demanding between 2020 and 2030. However, these *absolute* volumes are not a useful metric for comparison because global production volumes for different metals differ considerably ranging from tens of millions of tonnes for some metals to less than a hundred tonnes per annum for others. Instead, Chapter 4 compares the average annual demand between 2020 and 2030 for each metal in this scenario to the global production volume of this metal in 2010. This ratio (expressed as a percentage) allows comparing the *relative* stress of the deployment of SET-Plan technologies on the demand for different metals.

The results show that the deployment of different SET-Plan technologies in Europe creates very different challenges for different metals. For some, the average annual demand between 2020 and 2030 in Europe has a negligible impact on the global demand for that metal (less than a tenth of a percent) compared to others for which it will imply a major challenge for suppliers. For example, more than 50% of current global tellurium output per annum would be needed each year between 2020 and 2030 to satisfy the demand generated in Europe. Note that this does not include the demand from applications other than the six technologies or the demand from countries outside of Europe.

Chapter 4 finds that for the deployment of the six SET-Plan technologies in Europe, 14 metals will require 1% or more of current world supply per annum between 2020 and 2030. These are designated as metals for which there is a significant demand and are referred to as the group of significant metals for SET-Plan technologies. In the order of their relative demand on current world supply, the 14 metals are tellurium, indium, tin, hafnium, silver, dysprosium, gallium, neodymium, cadmium, nickel, molybdenum, vanadium, niobium and selenium. The deployment of these technologies also requires other metals, but these are needed in such small quantities compared to current world supply that their sourcing is extremely unlikely to constitute a significant problem. It is therefore noted that the deployment of SET-Plan technologies can create some pressure on the supply of many minor metals. However, as the current output of many base metals is so large, the additional pressure from the deployment of SET-Plan technologies is small.

8.2 Different Metals face Different Risks for Future Supply-Chain Bottlenecks

High demand for a metal does not necessarily constitute a problem as it stimulates increasing supply. Metal supply has expanded significantly in the past and there is no reason to assume *a priori* that rapid demand will necessarily constitute a problem. Nonetheless, there is potential for supply-chain bottlenecks to occur which could result in price rises and supply disruptions. This could slow the deployment of the SET-Plan technologies and endanger the achievement of the Europe 2020 targets. In Chapter 5, the risks for such future supply-chain bottlenecks to occur are evaluated for each of the fourteen metals for which the deployment of SET-Plan technologies creates significant demand.

Measuring such future risks is a complex challenge and is not an exact science. The present study improves on several existing studies by putting more emphasis on actual market dynamics and supply and demand forecasts, rather than aggregating individual contributing factors. It was the combination of market factors (the likelihood of rapid global demand growth and the limitations on expanding supply in the short to medium term), together with political factors (the cross-country concentration of supply and political risks associated with major producers), that were examined to assess the risk of future supply-chain bottlenecks occurring. In contrast to many earlier studies, the scoring of these factors abstains from using precise numeric risk measures and instead employs a simple low-medium-high scale, to emphasise the large margins of uncertainty associated with such assessments of future developments.

The results of Chapter 5 show that for five of these fourteen metals (cadmium, hafnium, molybdenum, nickel and silver), the likelihood of supply-chain bottlenecks occurring is found to be low. This is either the case because demand growth is expected to be relatively slow or because there are few serious obstacles on expanding output through bringing additional capacity into production. Political risks fail to change this assessment, either because production is relatively diversified or dominant producers are associated with low risks.

Moderate risks are found for four other metals (niobium, selenium, tin and vanadium). Demand for niobium, selenium and vanadium is expected to increase relatively rapidly. However, only moderate growth is expected for tin and there are few limitations to expand niobium and vanadium output. They are nonetheless assigned a medium risk score because of the presence of significant political risks. In the case of niobium, it is the very high supplier concentration that leads to concerns; for vanadium and tin, there are high political risk scores for all major producers. In the case of selenium, there are no major political risks, but strong demand and its by-product character result in a medium overall bottleneck score. For these four metals, there is no immediate concern over supply-chain bottlenecks. However, supply and demand developments could deteriorate in the future and lead to the formation of supply-chain bottlenecks. The markets for these metals should therefore be monitored regularly for signs of such deterioration.

Finally, there are five metals for which the screening finds high risks for supply-chain bottlenecks. These metals are:

1. dysprosium
2. neodymium
3. tellurium
4. gallium
5. indium

Over the coming decade a continuation of the rapid demand growth is expected to keep the supply side under pressure. In each case, there are also significant obstacles to expanding output in the short to medium term, resulting in high overall market risk. In the case of the rare earths neodymium and dysprosium, these difficulties are related to the commercial and technical challenges in bringing new rare earths mines to the market. For indium, tellurium and gallium, it is the by-product character that poses obstacles to the expansion of supply. These high-market risks are compounded in the rare earths case by high political risks due to the concentration of supply in China. Political risks are less prominent for indium, tellurium and gallium, as supply is less concentrated and in each case there is significant production which is associated with low political risks.

8.3 No Overall Bottlenecks for the SET-Plan, but Technology Mix Matters

Taken altogether, Chapters 4 and 5 demonstrate, using the most optimistic projections for technology uptake, very different vulnerabilities for different technologies, which are summarised below:

- PV uses three bottleneck metals: tellurium, indium and gallium, of which the annual demand between 2020 and 2030 of tellurium (50.4%) and indium (19.4%) represent very significant proportions of current world supply. Demand for gallium is estimated to be significantly less at 4%. PV also uses large quantities of some of the other 14 significant metals, notably tin (10%) and silver (5%), as well as cadmium and selenium.
- Wind uses two bottleneck metals: neodymium and dysprosium at around 4% of current world supply, as well as smaller quantities of two significant metals, nickel and molybdenum.
- Nuclear uses only one bottleneck metal which is indium, albeit in a relatively small proportion of world supply (1.4%). Hafnium is the most important among the group of significant metals required at an estimated 7%, with minor uses of seven other significant metals.
- CCS does not use any bottleneck metals, but uses four of the group of 14 significant metals, of which niobium and vanadium are required most in relative terms.
- Biofuels and Electricity Grids do not use any of the bottleneck or significant metals.

The solar (PV) and wind energy sector are thus at the highest risk of being negatively affected by future supply-chain bottlenecks, with other SET-Plan technologies being much less at risk. Chapter 6 therefore examined in greater detail the metal requirements from the PV and wind sectors on the basis of major uncertainties with regards firstly to the uptake of SET-Plan and secondly to variations in the mix of individual technologies that will be used in PV and wind energy sectors.

The results show that particularly in the PV sector, future demand will be highly sensitive to different uptake technology mixes. For example, depending on the specification, by 2020 the deployment of PV technology in Europe may require annually between 40 - 50% of current world supply in tellurium. Such sensitivities in demand would likely have very significant impacts on what are relatively small and volatile metals markets. For the wind sector, the results vary much less, with annual demand for neodymium and dysprosium not exceeding 4% of current world supply at any point in time, although the timing of demand did vary.

On the technology mix, for both PV and wind, numerous sub-technologies exist, each with different requirements for the bottleneck metals. For PV, CdTe has large metal requirements of tellurium and CIGS has high requirements for indium and gallium. However, the currently dominant c-Si technology does not require any of the bottleneck metals. As a consequence, a greater shift towards CdTe and CIGS thin film technologies for PV could considerably increase the SET-Plan demand for tellurium, indium and gallium by as much as 60, 200 and 250% respectively. For wind, the dominant technology of geared-turbine systems often does not use permanent magnets at all and therefore do not require any neodymium and dysprosium. However, many systems do employ permanent magnets, with the usage being particularly high in the low-speed systems. The effect of a shift away from electromagnetic systems towards permanent magnetic based direct drive systems would be to increase the SET-Plan demand for both neodymium and dysprosium.

An important conclusion that can be drawn from this analysis is that the existence of technology options implies that there are no unavoidable bottlenecks that could affect the implementation of the SET-Plan as a whole. If bottlenecks for particular technologies do materialise, then alternative technologies are in principle able to substitute potential bottleneck technologies and help to nonetheless achieve the SET-Plan targets. For companies who are committed to particular technologies, the implications of metal bottlenecks are likely to be much more serious. Consequently, it is recommended that in order to increase resilience, the SET-Plan avoids such technology “lock-in”, and does not attempt to “pick winners” by favouring particular technologies, for example, through highly-targeted research or subsidies. However, due to the high uncertainties related both to metal demand and the risks of bottlenecks, it is not suggested that technologies with potential metal bottlenecks should be discouraged, as they in many cases are able to deliver superior performance compared to other technologies that are less vulnerable to bottlenecks.

8.4 Numerous Risk Mitigation Options Exist

Chapter 7 explored a number of options that could form elements of a risk mitigation strategy that reduces the likelihood of supply-chain bottlenecks for the five metals for which high risks have been identified. This was based on an in-depth mapping of the supply chains for these metals and considering possible policy interventions at each stage, including:

- increasing European primary production and by-product separation
- encouraging reuse, recycling and waste reduction
- examining substitution potential.

The results show that there is some scope for effective mitigation measures, although many of them would require additional research efforts and investments, and would only begin to contribute substantially to reducing the risk for future supply-chain bottlenecks towards the middle of this decade at the earliest.

For rare earths, a quite sophisticated technological and industrial base exists in Europe, which potentially could form the building blocks for a future rare earths supply chain in Europe, although it is noted that these are owned by different companies and would require collaboration. A key problem for rare earth companies in Europe is securing a reliable supply of virgin material. There is some potential for actual mine production in Europe, but the deposits that have been identified so far, will need considerable further exploration to ascertain their commercial viability. Furthermore, hurdles to secure environmental permits would form a substantial obstacle to actual production. A new mine, concentration and separation facility with significant capacity relative to world demand is likely to cost in excess of €500m.

Therefore the utilisation and expansion of pre-existing assets is a preferred strategy to a green field facility.

There is also some potential to recycle rare earths, both for pre-consumer and post-consumer scrap. However, further research is needed to develop and commercialise recycling technologies. A key problem for post-consumer applications is that large quantities of permanent magnets will not enter the waste stream for many years. A more immediate opportunity exists within recycling the magnets contained within hard disc drives. To enable effective recycling from such post-consumer sources, collection and sorting systems would need to be developed. Costs are difficult to estimate but may be of the order of tens of millions of Euros for pre-processing and recycling. Efforts to replace neodymium and dysprosium in permanent magnet applications have so far not met with much success and system level substitution, i.e. replacing the technologies that use rare earths with alternative technologies that do not rely on permanent magnets, appears to be a more promising route. Continuing investments in alternative technologies is therefore important.

For indium, the possibilities to increase the production of virgin material from European zinc refining are limited, unless refiners could be convinced to switch to alternative (mostly South American) ore suppliers. The ores that European zinc refiners currently use are generally low in indium content and where possible, indium recovery is often already optimised. The same applies to recycling of processing waste. There is however some potential to recycle indium from post-consumer waste in flat panel displays, although further research of the recycling technologies, as well as the development of infrastructure to collect and separate flat panel displays from other WEEE would be necessary. Capital cost of indium separation plants at the primary stage are reportedly of the order of €50m and therefore comparatively, indium recycling should be attractive if sufficient material can be extracted from the recyclate.

For tellurium, there is still considerable room to expand the scope and increase extraction rates of recovery from European copper refiners. This is particularly attractive for tellurium because only relatively small investments would be needed compared to those required to extract speciality metals such as gallium and indium. Further efforts are necessary to increase existing European recycling from electronic scrap and PV applications. Substitution of tellurium in several low-value applications is possible and should be promoted.

Similarly, there is still much potential to increase gallium recovery from European aluminium refiners, as currently much of the gallium content in bauxite that is processed in Europe ends up in waste streams. Recycling of processing waste is quite optimised already today. For most gallium applications, there is little scope for recycling due to its dissipative use. The recovery of gallium from pre-consumer electronics waste appears to have been optimised. Substitution of the gallium contained in LEDs by organic-based LEDs is a possibility, which should be supported.

In summary, there are a range of potential options to mitigate risks for future supply bottlenecks for the five metals identified in Chapter 5. It is recommended that the European Commission and EU Member States should actively engage in considering a broad array of mitigation measures, even if many of the solutions will only contribute substantially to mitigating bottleneck risk in the medium to long term (5 to 15 years). Our recommendations are to:

1. Collect more data and provide better information on the demand, supply and price trends for metals that are used in significant quantities in SET-Plan technologies. Bottleneck risks are reduced by a faster flow of information between decision-makers and market participants both in metal markets, as well as in the consuming industries. This can be achieved by:
    i. ensuring that materials used in significant quantities are included in the Raw Materials Yearbook proposed by the Raw Materials Initiative *ad hoc* Working Group
    ii. the publication of regular studies on supply and demand for bottleneck metals

    iii. ensuring that any informational actions for the "critical" materials gallium, indium and the rare earths are also duplicated for tellurium, which falls outside this group.

2. Support and sustain the existing rare earths supply chain in Europe, including efforts to ensure reliable supply of ore concentrates at competitive prices through:
    i. feasibility studies on bringing back into use and updating existing assets
    ii. R&D and demonstration projects on new lower cost separation processes, particularly those from by-product or tailings containing rare earths
    iii. collaboration with other countries/regions with a shared agenda of risk reduction such as the USA and Japan in exchange of information on underpinning science or in pre-competitive research.
3. Support junior miners, possibly via EBRD co-funding of feasibility studies, in exploration of promising European rare earth deposits, as well as the respective permit processes.
4. Raise awareness and engage in an active dialogue with zinc, copper and aluminium refiners over by-product recovery. For tellurium and gallium in particular there is scope to increase European recovery rates. This can be achieved, for example, by funding workshops and networks via the appropriate metal industry study group or development association to identify risks, barriers and benefits to further investment.
5. Create incentives to encourage by-product recovery in zinc, copper and aluminium refining in Europe, possibly via funding of feasibility studies or loans by EBRD.
6. Promote the further development of recycling technologies and especially increased end-of-life collection and processing for a number of particular components and products, notably permanent magnets in hard disc drives and flat panel displays. Funding should be provided for demonstration projects in hard disc drive and flat panel display disassembly and recycling where this is proposed to recover high percentages of rare earths and indium, for recycling processes to recover the rare earths and indium and for innovative design that enables easier and quicker disassembly whilst retaining product integrity and functionality.
7. Measures for the implementation of the revised WEEE Directive should include encouragement for the recovery of such less common metals alongside the main metals that are usually targeted for mass-based recovery systems.
8. Invest broadly in alternative technologies that can provide system-level substitutes to technologies that rely heavily on bottleneck metals whilst retaining performance advantages. This includes alternative systems for wind turbines.
9. Funding of further R&D into substituting indium in indium tin oxides.
10. Encourage the substitution of tellurium use in low-value applications via innovation funding.

Lastly, it is proposed that future research should be carried out, within the scope of this study, to identify the metal requirements and associated bottlenecks from low-carbon technologies other than the six SET-Plan technologies. Important demand-side technologies such as electric vehicles, low-carbon lighting, electricity storage or fuel cell and hydrogen technologies, which are key to Europe's low-carbon energy transition and the attainment of the SET-Plan targets, should be examined for their metal use and associated risks for supply-chain bottlenecks. Such studies should be periodically updated on a timescale appropriate to the development of the technology, which is likely to be every 5-10 years.

Critical Metals in Strategic Energy Technologies

Appendices

Appendix 1: Energy Mix Projections

A.1.1 Projection of European Energy Mix

The following table and figure present information on the forecast energy mix of the EU-27 till 2030. These estimates are based upon assumptions made including macroeconomic performance, energy prices and the effect of national and European polices. Clear trends in the energy mix are:

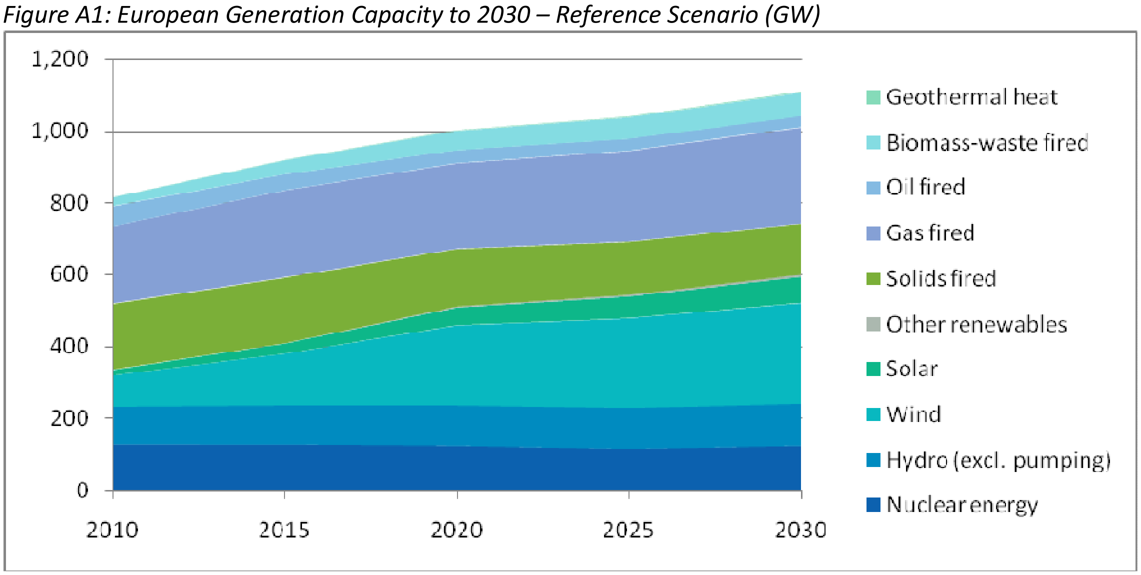
- Total capacity rising by 36% between 2010 and 2020
- Share of renewables rising from 26% to 43% of the electricity mix between 2010 and 2020, with large increases in solar and wind capacity
- Load factors falling due to increased reliance on intermittent sources of energy.

Table A1: European Generation Capacity to 2030 – Reference Scenario (GW)

Energy Source	2010	2015	2020	2025	2030
Nuclear energy	127	127	123	115	124
Hydro (excl. pumping)	107	111	114	115	118
Wind	86	144	222	248	280
Solar	15	28	49	60	72
Other renewables	0	1	4	5	7
Solids fired: conventional	183	182	161	148	142
Solids fired: CCS	0	0	5	6	6
Gas fired	216	243	238	254	268
Oil fired	56	44	37	34	31
Biomass-waste fired	24	40	55	60	66
Geothermal heat	1	1	1	2	3
Total	**815**	**921**	**1,009**	**1,047**	**1,117**
Load factor	**44.0%**	**41.8%**	**40.2%**	**41.1%**	**39.9%**

Source: EU energy trends to 2030 — Update 2009, EC (2010)

Figure A1: European Generation Capacity to 2030 – Reference Scenario (GW)



Source: EU energy trends to 2030 — Update 2009, DG Energy (2010)

A.1.2 Uptake of SET-Plan Technologies

The following tables provide details of scenarios for the uptake of SET-Plan technologies in Europe for 2020 and 2030. The two principal sources used were:

- Commission (2007), *A European Strategic Energy Technology Plan (SET-Plan): Technology Map*, Commission Staff Working Document, SEC (2007) 1510
- JRC-SETIS (2009), *2009 Technology Map of the European Strategic Energy Technology Plan (SET-Plan): Part – I: Technology Descriptions*, JRC-SETIS Work Group.

From these scenarios, the highest estimate was selected as providing the upper-bound scenario. This upper-bound scenario was used in Chapter 3 to identify the group of metals that are the most significant to the SET-Plan technologies. (These upper-bound estimates have been highlighted in the following tables with an asterisk.)

A.1.1.1 Wind

For wind energy, four scenarios were identified, three of which came from SET-Plan documentation (Table A2). The fourth came from the European Wind Energy Association (EWEA),[a] which was an updated industry estimate. This EWEA target was selected as the upper bound scenario.

Table A2: Wind Capacity (GWe)

Source	Scenario	2020	2030
Commission (2007)	Baseline	120	148
Commission (2007)	Potential penetration	180	300
JRC-SETIS (2009)	Industry target	230	350
***EWEA (2010)**	Short & medium term	230	400

A.1.1.2 Solar

For solar energy, three scenarios were identified for both photovoltaic (PV) and concentrated solar power (CSP), all of which can be found in SET-Plan documentation (Table A3 and Table A4). For PV, the solar expert at JRC-IE provided an estimate [JRC-IE (2010]] that was selected as the upper bound, on the basis that the EPIA scenario represented the industry's ambitions rather than a concrete target and also because an estimate was available for 2020 only. For CSP, the European Solar Industry Initiative target from 2009 was selected as the upper bound.

Table A3: Solar Photovoltaics Capacity (GWp)

Source	Scenario	2020	2030
Commission (2007)	Baseline[b]	9	16
Commission (2007)	Maximum potential penetration	125	665
JRC-SETIS (2009)	EPIA: Vision for 2020	390	-
***JRC-IE (2010)**	High scenario	360	630

a EWEA, 2010. The European Wind Initiative: Wind power research and development for the next ten years.
b This baseline figure was taken from the table rather than the text of the document.

Table A4: Concentrated Solar Capacity (GWe)

Source	Scenario	2020	2030
Commission (2007)	Baseline	0	0
Commission (2007)	Maximum potential penetration	1.8	4.6
***JRC-SETIS (2009)**	European Solar Industry Initiative	30	60

A.1.1.3 Nuclear

For nuclear fission, four scenarios were identified, two of which came from SET-Plan documentation (Table A5). Industry scenarios came from World Nuclear Association (WNA) modelling, with 2030 targets coming from WNA Nuclear Century Outlook Data. World Nuclear Power Reactor Data are used for 2020 estimates, comprising the sum of reactors operable, under construction and planned in the Low scenario; with reactors proposed included in the High scenario. The WNA High scenario was selected as the upper bound.

Table A5: Nuclear Fission Capacity (GWe)

Source	Scenario	2020	2030
Commission (2007)	Baseline	114	100
Commission (2007)	Maximum potential penetration	150	200
World Nuclear Association	Low	156	171
***World Nuclear Association**	High	198	297

A.1.1.4 Carbon capture and storage

For CCS, three scenarios were identified, all of which came from SET-Plan documentation (Table A6). On the basis that the Maximum potential penetration estimated in 2009 superseded that from 2007, this was selected as the upper bound, although the 2020 estimate was revised upwards to 7 GW to take account of the metals being used in demonstration plants.

Table A6: Zero Emission Fossil Fuel Power Plant Capacity (GWe)

Source	Scenario	2020	2030
Commission (2007)	Baseline	0	0
Commission (2007)	Maximum potential penetration	30	190
***JRC-SETIS (2009)**	Maximum potential penetration	0	80

A.1.1.5 Electricity Grids

For Electricity Grids, most scenarios were presented in terms of how much investment was required in infrastructure, rather than in terms of capacity itself. Only one scenario was identified that quantified the required length of cable for Electricity Grids, originating from ENTSO-E (Table A7). This estimate was for "Projects of European significance until 2020".[a] This was therefore selected as the upper bound scenario.

Table A7: Electricity Grids Development (km)

Source	Scenario	2020	2030
***ENTSO-E (2010)**	Projects of European significance	42,100	-

a ENTSO-E, 2010. Ten-Year Network Development Plan 2010-2020.

A.1.1.6 Biofuels

For biofuels, three scenarios were identified, estimated in terms of biofuel consumption as a percentage share of EU road transport petrol and diesel consumption, which came from SET-Plan documentation (Table A8).

These estimates can be calculated in absolute terms in Mtoe using the forecast Road Transport Petrol and Diesel Consumption listed in DG Energy's *EU energy trends to 2030 — Update 2009*. Under the reference scenario, 313 Mtoe and 301 Mtoe are forecast to be consumed in 2020 and 2030 respectively in public road transport, private cars and motorcycles and trucks. These estimates are shown in Table A9. The Maximum potential penetration scenario was selected as the upper bound.

Table A8: Biofuels Consumption in Road Transport (% of petrol and diesel consumption)

Source	Scenario	2020	2030
Commission (2007)	Baseline	7.5%	9.5%
Commission (2007)	Lower range potential penetration	10%	15%
***Commission (2007)**	Maximum potential penetration	14%	20%

Table A9: Biofuels Consumption in Road Transport (Mtoe)

Source	Scenario	2020	2030
Commission (2007)	Baseline	26.2	34.5
Commission (2007)	Lower range potential penetration	35.0	54.5
***Commission (2007)**	Maximum potential penetration	48.9	72.7

A.1.3 Scenario Modelling

In Chapter 6, impact assessments of the bottleneck metals were modelled against two different uptake scenarios of the SET-Plan. The details of the generation capacity mix behind these estimates are presented here. (Electricity grids and biofuels are not included in these scenarios because the metals required in their implementation were not found to have significant usage).

A.1.1.1 Low and High scenarios

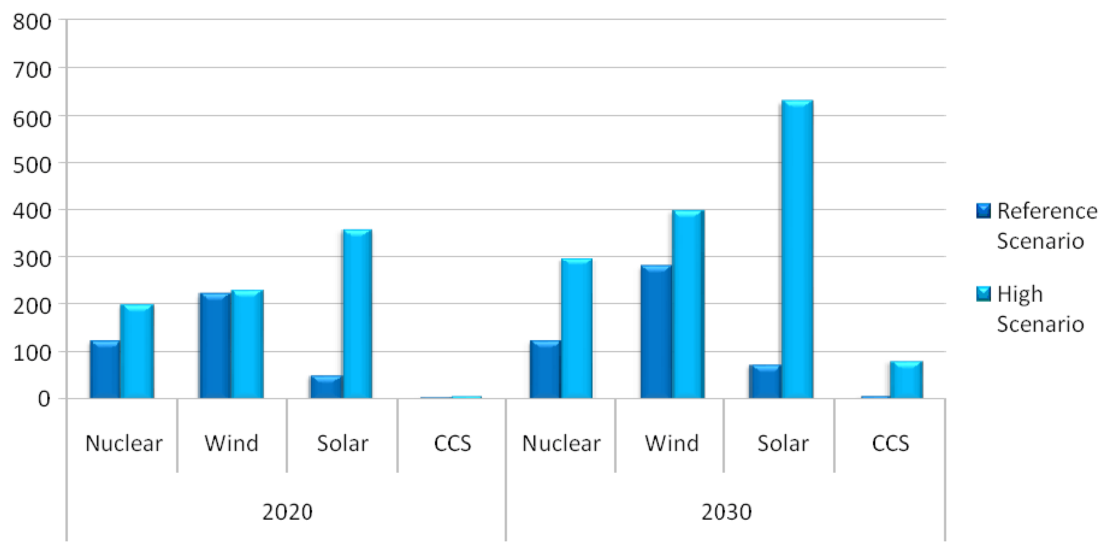
The Low uptake scenario is that given by the Reference scenario estimated by the EC and shown in Table A1 and Figure A1. The High uptake scenario is the combination of all of the upper-bound scenarios selected in the previous section, and used for the purpose of the significance screening.

It is interesting to compare the capacities indicated by the High scenario against those in the Low scenario (Table A10 and Figure A2). The striking feature that emerges is the difference between the relative optimism of the energy sources. The ratio between the High scenario and Low scenario is 8 times for solar and 13 times for CCS in 2030; whereas for nuclear and wind, it is between 1 and 3. Clearly additional policy support and/or a step change in the technology is required to meet the High scenario for solar and CCS.

Table A10: Comparison of Low (Reference) and High scenarios (GW)

Year	Energy Source	Low (Reference) Scenario	High scenario	Ratio of High to Reference
2020	Nuclear	123	198	1.61
	Wind	222	230	1.04
	Solar	49	360	7.35
	CCS	5	7	1.4
	Total	**399**	**795**	**1.99**
2030	Nuclear	124	297	2.40
	Wind	280	400	1.43
	Solar	72	630	8.75
	CCS	6	80	13.33
	Total	**482**	**1,407**	**2.92**

Figure A2: Comparison of Low (Reference) and High scenarios (GW)



Another result from this comparison is that in 2030, the total capacity from only the SET-Plan technologies in the High scenario exceeds that forecast from all energy sources from the Low scenario (Table A1). Three justifications might be given for this:

1. load factors will fall as renewables comprise a greater share of generation capacity
2. generation capacity from non-SET-Plan sources will decline
3. some of the targets listed in the High scenario represent ambitions that may not be fulfilled.

Appendix 2: Metal Composition of SET-Plan Technologies

A.2.1 Nuclear Energy

The assumptions for the different speciality metals involved in nuclear generation are given in Table A11. These were constructed as follows:

1. Reactors to be built in Europe were assumed to be either Westinghouse AP1000 or Areva EPR designs. Therefore wherever possible, material inventories were obtained from documents concerning these designs: www.areva.com, www.ukap1000application.com

2. Information on fuel requirements were obtained from the World Nuclear Association: www.world-nuclear.org

3. Information on steam generators and boilers for nuclear reactors was obtained from Doosan Babcock and Doosan Group: www.doosan.com

4. A variety of sources was used to locate the identity and composition of the various specialist alloys, such as:
   a. Presentations from Westinghouse AP1000 UK equipment supplier launch, October 2008
   b. *Supercritical water reactors: survey of materials experience and R&D needs to assess viability* Buongiorno J. et al US Dept of Energy contract DE-AC07-991D13727
   c. *Zirconium in the Nuclear Industry* 8th International Symposium, van Swan, Eucken (ed.s) ASTM STP 1023
   d. *Materials UK Energy Review 2008: The mapping of the materials supply chain in the UK's power generation sector*: http://www.matuk.co.uk/docs/Mapping_Materials_Supply%20locked.pdf

5. Where data on metals inventories were not available from these designs, sources of data on other designs were used, notably on a 1,175 MWe Trojan Nuclear Plant in Rainier, Oregon that has operated since 1975: *Scrap metal inventories at US nuclear power plants* Appendix A in *Technical support document: potential for recycling of scrap metal from nuclear facilities* Part 1, Volume 1. Available at www.epa.gov

Table A11: Speciality Metals for Nuclear Energy Generation

Metal	Application	Model System	tonnes / reactor	tonnes / MWe	Assumptions
Cd	Reactor control rod alloy 5%	AP1000	0.52	0.0005	Assumed that Ag alloys are used in PWR control rods in preference to Hf, which is a possible substitute
Cr	Alloying element in stainless steels for reactor components	AP1000	108.36	0.1084	Decommissioning study indicates total stainless steel in nuclear island to be maximum of 602t. Need to allow for stainless steel in generating area also. Max Cr content 18%
Cr	Alloying element in stainless steels for reactor components	Trojan	374	0.3183	Up to 18% Cr based on 2,080 s/steel in an 1,175 MWe in a PWR from USA EPA inventory on Trojan Nuclear Plant. AP1000 applications for high Cr alloys include turbine rotors (ASTM 470), inconel heat exchanger tubing
Co	Alloying element in Ni based superalloys for turbine generator				Limited use of superalloys in steam turbine generators
Cu	Electrical systems and as an alloying element	Trojan	70	0.0596	70t inventory based on figures from US EPA
Gd	Burnable absorber	AP1000	0		Gd replaced by boron in AP1000 - main use is in nuclear submarines
Hf	Advanced alloys			0.0005	Used 2007 data from NAMTEC, World Nuclear Assoc
In	Reactor control rod alloy 15%	AP1000	1.56	0.0016	Assumed that Ag alloys are used in PWR control rods in preference to Hf, which is a possible substitute
Pb	Shielding	Trojan	5	0.0043	No Generation IV reactors in use, where it could be a coolant
Mo	Alloying element in stainless steels for reactor components	Trojan	83.2	0.0708	Up to 4% Mo based on 2,080 s/steel
Ni	Superalloys in turbines and stainless steels	Trojan	300.2	0.2555	S/steel 14% + 12t inconel from EPA inventory
Nb	Alloying element for stabilised austenitic stainless steels	n/a	2	0.0020	Up to 5% Nb in superalloys, but these not widely used in nuclear generation. Most common s/steels used are 304 and 316 in nuclear installations, but these do not contain Nb. Assumed a nominal 2t for miscellaneous specialist alloy steel applications
Re	Alloying element for high temperature turbine and reactor materials				Re not required in steam turbine blades
Ag	Reactor control rod alloy 80%	AP1000	8.3	0.0083	Assumed that Ag alloys are used in PWR control rods in preference to Hf, which is a possible substitute
Sn	Alloying element for Zr metals 1.5%	AP1000	4.5675	0.0046	Zircaloy 4 composition

Metal	Application	Model System	tonnes / reactor	tonnes / MWe	Assumptions
Ti	Corrosion resistant tubing and alloying element in Ni superalloys	Doosan Babcock	1.5	0.0015	Limited use of Ni-based superalloys. 0.75% content of 409 s/steel, used in steam generators
W	Alloying element in Ni based superalloys and high strength steels	AP1000	5	0.0050	Limited use of Ni-based superalloys. Some W in high temp turbine blades (Cr-Mo-V-W steel). Nominal figure selected
U	Nuclear fuel 5 % enriched UO2 pellets		500	0.1744	Calculated using World Nuclear Data
V	Alloying element in high strength steel for turbine casing bolts	AP1000	0.6	0.0006	V content 0.1-0.5% typically in turbine rotors and similar low alloy steels. Estimated mass of rotors
Y	Alloying addition to steels for turbine blades and bolting applications	n/a	0.5	0.0005	Nominal 0.5t assumed for some specialist alloy applications
Zr	Fuel rod cladding + 50% allowance for use in grids, guide thimbles etc	AP1000	30.45	0.0305	8 grids per assembly of 264 fuel rods, mass not specified

A.2.2 Solar Energy

Solar energy technologies studied here are PV and CSP. PV technologies are divided into polycrystalline silicon (c-Si) and thin-film based technologies: amorphous silicon (a-Si), CdTe and copper indium gallium diselenide (CIGS). The following current market share is taken into account: 80% polycrystalline silicon, 10% amorphous silicon, 5% CdTe and 5% CIGS.

Metal requirements for a polycrystalline PV are shown in Table A12. Metal requirements change depending on the year the PV panel was manufactured. Our analysis is based on the 2007 figures. It is noted that manufacturers are continuing in their efforts to reduce the thickness of the materials used, notably for silicon. Metal losses during manufacturing are not taken into account.

For a-Si, calculations are based on a 100W/m^2 module, with a silicon layer of 5 micron. There is also a 100 nm transparent conductive oxide (TCO) layer, which is composed of indium oxide In_2O_3 (90%) and tin (10%), giving indium and tin requirements of 5.32 and 0.714 kg/MW respectively.

For CdTe thin-film PVs, the calculations were based on 100 W/m^2 panel. Currently the active CdTe thin-film layer is around 2.5-3 µm thick, with Te requirements of 93.3 kg/MW. Consultation with CdTe manufacturers has revealed that for the TCO layer, different materials are used. For some of the smaller manufacturers, tin-doped indium oxide is the TCO of choice with requirements of 15.9 and 21.4 kg/MW of indium and tin respectively. The main alternative TCO is tin oxide, which appears to be used by the largest CdTe manufacturer First Solar.

For CIGS-based thin films, calculations were based on 120 W/m^2 panel. The thin layer and conductive layer were 2µm and 1µm in thickness respectively. Metals requirements for each layer are shown in Table A13.

For concentrated solar power (CSP), the data used is from the EuroTrough ET 150 (2002)[a] and Solnova 1[b] projects, both in Spain, and takes into account only silver used as reflective coating. It was assumed that the silver coating is 100nm. Silver requirement is calculated to be 6.7 and 6.3 kg/MW respectively.

Table A12: Example for the Composition of a c-Si Standard Module (215Wp)

Component	Quantity (2003)[c] %	Quantity (2007)[d] %	kg/kWp
Glass	62.7	74.16	77.3
Frames (e.g. AlMgSi0,5)	22	10.3	10.7
EVA	7.5	6.55	6.8
Solar cells	4	3.48	3.6
Backing film (Tedlar)	2.5	3.6	3.8
Junction box	1.2	n/a	n/a
Adhesive, potting compound	n/a	1.16	1.2
Weight, kg/kWp	103.6		103.4
Metals			**kg/MWp**
Al			10593
Mg			53.5
Si			3653
Cu	0.37	0.57	2741
Ag	0.14	0.005	24
Sn	0.12	0.12	577
Pb	0.12	0.07	336

Table A13: Metal Requirement for CIGS Thin Film PV Panel

Component	Metals	kg/MW
Thin film	Cu	21.02
	In	18.99
	Ga	2.34
	Se	9.56
TCO	Sn	5.95
	In	44.29

A.2.3 Wind Energy

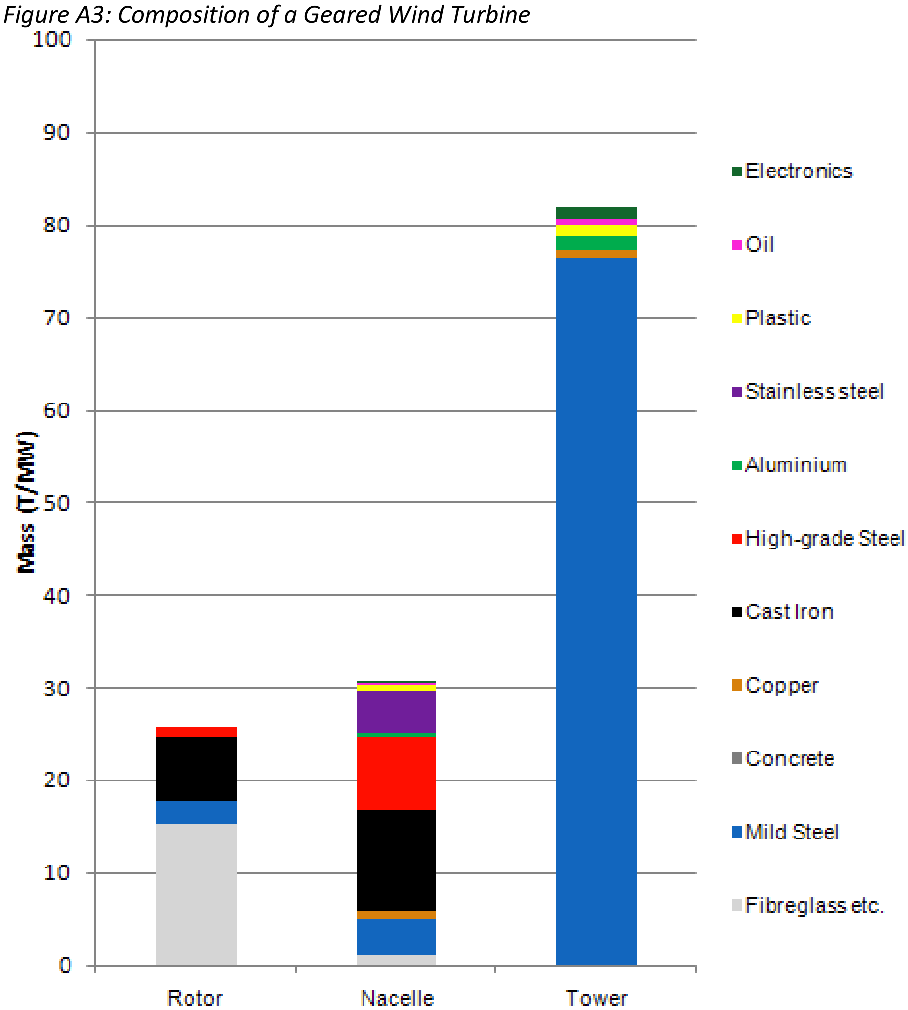
The components of wind energy, for at least the established technology of geared turbines with electromagnet generators (86 % of the market in 2009),[e] are well known and quantified. Figure A3 presents details of each of the types of materials used for a geared wind turbine per MW of generation capacity. Of potential interest for this project are the metals that might be used as alloys for the stainless and high-grade steels; and also the copper used.

a EuroTrough: Parabolic Trough Collector Family Developed and Qualified for Cost Efficient Solar Power Generation, Collaborative FP4 and FP5 Framework project, JOR3-JT98-0231 and ERK6-CT-1999-00018, respectively.
b Solnova 1: 50 MW Parabolic Trough Plant, Abengoa Solar, Spain.
c Ökopol and Institute for EnergeticsMaterial-related requirements on photovoltaic products and their disposal, Environmental research plan, FKZ 202 33 304, Federal Environment Agency, Referat III.2.5, Berlin 2004
d Study on the development of a take back and recovery system for photovoltaic products. Funded by BMU, Grant Number 03MAP092, November 2007

e Roberto Lacal Arántegui, Wind/PMG expert, JRC, Personal communication

Corus Speciality Steels, whose customers include Siemens and Vestas, report that a typical grade used for the high-grade applications (gears, bearings, shafts, locating pins, spindles and hydraulic manifolds) would be 18NiCrMo7.[a] For the stainless steel, Type 316 was selected as a typical grade. It has good corrosion resistance and is commonly used for exterior architectural components in marine coastal areas.[b] The chemical composition of these steels is shown in Table A14.

Figure A3: Composition of a Geared Wind Turbine



Source: Offshore Wind – Making a Material Difference, BVG Associates & UK Renewables

Table A14: Typical Grades of Steel used in Wind Energy

Type	Grade	Cr	Ni	Mo	Mn	Source
High Grade Steel	18NiCrMo7	1.65%	1.55%	0.30%	0.70%	Corus Speciality Steels
Stainless Steel	Type 316	17.00%	12.00%	2.50%	0.70%	All Stainless

Permanent magnet generators (PMGs) are the alternative technology to electromagnet generators. The magnets replace the copper windings normally in the rotor of the electromagnet generators. The specific mass (kg/MW) of magnets in a PMG is dependent on, among other things, the generator speed and then to its size.

Table A15 shows a range of estimates of low-speed PMGs, although these require significantly higher magnetic content than medium- and high-speed PMGs. Table A16 shows the chemical composition of the

a Corus Speciality Steels. Wind Power Generation Presentation. (Personal communication).
b All Stainless Ltd. Available at: http://www.allstainlessltd.co.uk/info_sheet_316.html. [Accessed 22/09/2010].

permanent magnets. Based upon the information from these sources, 0.7 tonnes of magnets per MW and 29% Nd and 2% Dy were selected as the middle estimates which would be used for the analysis.[a]

Table A15: Permanent Magnets used for Low-Speed PMG Wind Energy (tonnes per MW)

Source	Min	Max	Mid
General Electric[b]	0.5	0.75	0.625
Technology Metals Research[c]	0.67	0.67	0.67
Avalon Rare Metals[b]	0.6	1	0.8
Jack Lifton Report[d]	0.7	1	0.85

Table A16: Chemical Composition of Permanent Magnets

Source	Fe	Nd	Dy	B
Shin Etsu[e]	66%	29%	3%	1%
Great Western Minerals Group[f]	68%	31%		1%
Technology Metals Research[c]	69%	28%	2%	1%
Avalon Rare Metals[b]		30%		

An important aspect in the modelling, however, is the technology split that is assumed between permanent magnets and electromagnet generators and between geared and gearless transmission. In Oakdene Hollins' previous study on rare earth elements,[g] a survey of wind turbine companies, produced by an independent wind energy consultant, estimated that 20% of global wind turbine installations between 2015 and 2020 were likely to use permanent magnets, rising to 25% for 2021-2030. Subsequent data provided by the JRC Institute for Energy and the EWEA suggested that within Europe the penetration of permanent magnets is likely to be lower than for the world as a whole, due to in part the existence of a European manufacturer of direct drive using non-permanent magnet-based systems. In the light of this data, it is assumed a 15% permanent magnet share for 2020 and a 20% share for 2030.

As mentioned above, different speeds of the permanent magnet generator means that they have different specific mass of permanent magnets, e.g. 80 kg/MW for medium/high speed versus 700 kg/MW for low speed. However, very limited data is available on the likely market shares between these different types of generators, so it has been excluded from the main analysis. Nonetheless, these further technology sensitivities are discussed within Chapter 6.

A.2.4 Bioenergy

For bioenergy generation, the Fischer-Tropsch (F-T) type catalyst is taken into account, as syngas produced from biomass feed will be catalysed to produced bio-diesel or bio-gasoline. For this process, the well-known F-T catalyst is cobalt based with a ruthenium promoter, i.e. 98% Co and 2% Ru. The loading on the alumina substrate was 20% by mass. Fixed bed and slurry bed reactors produce different levels of product. An average use of 0.15 tonne/m^3 catalyst per hour is quoted in the literature. If the lifetime of a catalyst is around 10 years then 1m^3 of catalyst produces about 13,143 toe products in its lifetime. In 1m^3 catalyst, there is 776 kg cobalt and 16 kg ruthenium (20% metal loading only). Hence for every ktoe produced, 6 kg of cobalt and 0.12 kg ruthenium are required (or 5.61 tonnes of cobalt and 0.12 tonnes of ruthenium per Mtoe of product).

a These estimates were considered reasonable by the US industry association, REITA.
b Corporate Presentation, Avalon Rare Metals (2010). Available at: http://avalonraremetals.com/investors/presentations/. [Accessed 17/09/2010].
c Technology Metals Research, 2010. *The Green Revolution in China*.
d Lifton, Jack, 2009. *Report: The Rare Earth Crisis of 2009 - Part 1*.
e Etsu, Shin, November 2009. *Presentation: Nd Magnets and Their Applications*. 5th International Rare Earths Conference, Hong Kong.
f GWMG, November 2009. *Presentation: Rare Earth Magnets and their Raw Materials Supply*. 5th International Rare Earths Conference, Hong Kong.

g Oakdene Hollins for DfT, 2010. Lanthanide Resources and Alternatives.

A.2.5 Carbon Capture and Storage

The implementation of CCS infrastructure will be at the utility scale, which precludes the use of expensive metals in most of the stages. In terms of volume, the major use of materials is likely to be associated with steel for the capture plant, CO_2 transport pipes and associated changes to the generation system.

Over the next 10 years around 12 demonstration plants are expected to be built in the EU, with enough capacity to store CO_2 produced by the generation of 3,600 MW. Beyond 2020 and up to 2030, the target capacity is 80,000 MW, corresponding to around 89 commercial scale CCS plants (Table A17).

Table A17: CCS Capacity 2010 to 2030

		2010	2015	2020	2030
Total MW		0	600	20,000	83,600
Demonstration	MW	0	300	3,600	3,600
	No. of plants (based on 300 MW)	0	2	12	12
Commercial	MW	0	0	16,400	80,000
	No. of plants (based on 900 MW)	0	0	18	89

Little is known about the materials required to construct a capture plant, as the technology is not fully matured, and is at a too early stage to determine which of the three alternatives will be the most viable. It is commonly known that the scale of the capture plant is likely to be similar to the actual generation plant, therefore it was estimated that they were of a similar size.

A standard 200 MW generator weighs 4,500 tonnes, most of which is steel and some high specification alloys. It was assumed that half of this capacity would be upgraded or replaced with the implementation of CCS. It was estimated that a similar quantity of materials would be required for each CCS plant, though these would all be produced from scratch (Table A18).

Table A18: Cumulative Steel Requirement based on the SET Plan Projections

	MW Capacity	Generators		Capture Plants Steel (tonnes)	Total
		No	Steel (tonnes)		
2020	20,000	50	210,000	420,000	630,000
2030	83,600	209	890,000	1,780,000	2,670,000

Different lengths of pipeline are expected for different implementation stages. Demonstration sites have been chosen closer to potential storage sites, the average length of pipeline is expected to be 300 km. Once CCS is established commercially, longer pipelines will be required from less optimal sites, therefore the average pipeline will be further and expected to be on average, 500 km.[a] The estimated pipeline lengths for the planned implementation are shown in Table A19.

Specifications for the pipes are assumed to be 34" inch diameter (DN859) with a 19 mm wall thickness, (assumed to be the average gauge of existing pipelines). Combining all this data provides an overall figure of the amount of steel required for the implementation of CCS on this scale. The cumulative totals are 5.57 million tonnes and 21.5 million tonnes for 2020 and 2030 respectively.

a McKinsey, 2008. Carbon Capture and Storage – Assessing the Economics.

Table A19: Cumulative Steel Demand Arising from CCS Pipeline

	Demo Plants	Pipeline (km)	Commercial Plants	Pipeline (km)	Total Pipeline (km)	Steel (tonnes)
2020	12	3,600	18	9,000	12,600	4,939,200
2030	12	3,600	89	44,500	48,100	18,855,200

The steel grades which are expected to form most of this infrastructure are shown in Table A20. This was then used to synthesise the resource demand for CCS on a *per annum* basis.

Table A20: Predicted Steel Grades used in CCS Implementation

Steel Grade Composition	C	Mn	P	S	Si	Cr	Ni	Cu	V	Nb	Mo	Co
API X65	0.07	1.5	0.009	0.004	0.093	0.13	0.16	0.11	0.04	0.04	0.003	0.003
API X100	0.07	1.9	0.008	0.005	0.1	0	0.5	0.3	0	0	0	0

Table A21: Predicted Consumption (tonnes) per Year, Based on X65 Grade Steel

	Total Weight (tonnes)	C	Mn	P	S	Si	Cr	Ni	Cu	V	Nb	Mo	Co
2020	557,000	390	8,360	50	22	553	725	2,570	1,550	223	223	17	17
2030	1,595,000	1,120	23,900	144	64	1,580	2,070	7,280	4,400	638	638	48	48

A.2.6 Electricity Grids

This area covers all transmission and distribution grid development issues, including development of the 'Smart Electricity Grid', but also traditional grid investment.

Electricity Grid investments to 2020

A number of review documents were used to define any additional material needs of the Electricity Grid in addition to traditional grid investment. These included:

- *Distributed Power Generation in Europe: technical issues for further integration* Angelo L'Abbate, Gianluca Fulli, Fred Starr, Stathis D. Peteves. JRC Scientific and Technical Reports, 2007
- *ENTSO-E Research and Development Plan: European Grid Towards 2020 Challenges and Beyond* March 2010
- *ENTSO-E Ten Year Network Development Plan 2010-2020* June 2010.

These were supplemented by interviews with the power transmission industry (Siemens, Mr Nigel Platt), grid operators (National Grid, Mr Ian Welch) and academic researchers (Dr Keith Bell, University of Strathclyde).

This research confirmed that the materials requirements of those components required specifically for making the grid "smarter" were minimal and could be ignored within this study. These included large-scale semiconductors for power electronics, semiconducting materials for additional ICT equipment and silica in fibre-optic cables. The additional demand for materials over and above worldwide demand for silicon-based semiconductors and fibre-optic cable is believed to be insignificant.

Conventional grid investments to 2020

This included conventional cabling and transformer investments required by national grid companies, including connection to renewable energy generation sources (e.g. offshore wind) and also grid connections between countries. The transmission grid investments to 2020 were taken from ENTSO-E projections in their ten year development plan (Table A22).

Table A22: Length of New and Refurbished Power Lines until 2020 (Projects of European Significance)

Project technology	Total length (km)	Length of new connections (km)	Length of upgraded connections (km)
AC	32,500	25,700	6,900
of which >300kV	*29,600*	*23,200*	*6,400*
DC (mainly subsea)	9,600	9,600	0
TOTAL	42,100	35,300	6,900
of which in mid-term	*18,700*		

Source: ENTSO-E, 2010

It was assumed that all DC cabling was sub-sea cabling and comprised copper-cored cables. All other cabling was assumed to comprise aluminium-cored cabling. Penetration of superconducting cables up to 2020 is assumed to remain at a demonstration level only and its materials demands can be ignored.

Sub-sea cabling

This was assumed to be copper-cored and sheathed in lead, using typical cross sections used for 400 kV cabling. Most cabling will be at much lower power and material requirements, but an upper level was used in order to produce conservative assumptions.

Table A23: Maximum Areas of Copper Conductor in 400 kV Cable

Copper diameter (mm)	30	34.2	38.1
mm^2	707	918	1140
Density g/cm^3	8.9	8.9	8.9
mass/km (t)	6.3	8.2	10.1

Source: NKT Cables

Hence total mass of copper used in cabling = 8.2 x 9600
= 80,000 tonnes (approx) across Europe to 2020.

As a worst-case scenario, all submarine cables were assumed to be lead sheathed. Lead sheathing for HV submarine cables has a mass of 1.5-2.2 t/km (Source: Prysmian Cables).
Hence total mass of lead used in cabling = 2.0 x 9600
= 19,000 tonnes (approx) across Europe to 2020.

Overhead cabling

Overhead cabling was assumed to be aluminium conductor, steel supported (ACSS) or steel reinforced (ACSR). Some penetration of carbon-fibre composite supported cable is predicted before 2020, but this will displace steel, which in any event was not included in the calculation since additional volumes of steel compared to overall worldwide demand are insignificant.

Table A24: Maximum Areas of Aluminium in ACSR Cables

ACSR cables using three largest conductors			
Aluminium c/s mm^2	1,000	1,120	1,250
Density g/cm^3	2.7	2.7	2.7
mass/km (t)	2.7	3.0	3.4

Source: ECN / General Cables

Hence total mass of aluminium used in cabling = 3.0 x 32500
= 100,000 tonnes (approx) across Europe to 2020.

Appendix 3: Summaries of each of the 14 significant metals

A.3.1 Cadmium

A.3.1.1 Background

At room temperatures cadmium (Cd) is a soft, ductile and malleable metal with a white-bluish colour and shares many characteristics with zinc and mercury. It has a low melting point and is toxic; similar to mercury. The average concentration in the earth's crust is between 0.1 and 0.5 parts per million (ppm) and it is present in almost all zinc minerals.

A.3.1.2 Resources

The majority of the world's primary cadmium production takes place in Asia; China produces 5,600 tonnes followed by the Republic of Korea, Japan and Kazakhstan. In total, 22,000 tonnes of cadmium was produced in 2010 (Table A25). Global secondary production of cadmium accounted for approximately 20% of all cadmium metal production with most secondary metal being produced from nickel-cadmium (NiCd) battery recycling.[a] China and India hold around a third of all cadmium reserves worldwide, with total reserves accounting for 660,000 tonnes.

In 2008, the EU32[b] accounted for 11.3% of world production of cadmium (Figure A4), with Poland, Germany, the Netherlands and Bulgaria as main producers. Quantitative estimates of European reserves are only available for Poland, which holds an estimated 22,000 tonnes or 3.3% of the world's cadmium reserves (Table A25).

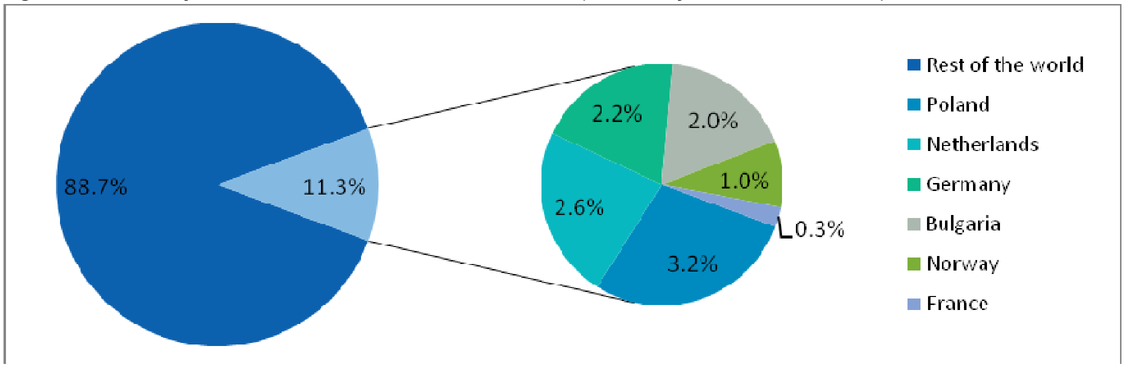
Table A25: World Cadmium Refinery Production and Reserves – 2010 (tonnes of cadmium content)

Country	Refinery Production (estimated)	Reserves
China	5,600	92,000
Korea, Republic of	3,200	—
Japan	1,900	—
Kazakhstan	1,700	51,000
Canada	1,500	18,000
Mexico	1,300	48,000
Russia	750	21,000
Poland	670	22,000
India	660	130,000
United States	650	39,000
Netherlands	600	—
Germany	440	—
Peru	400	45,000
Australia	360	61,000
Other countries	2,300	130,000
World total (rounded)	**22,000**	**660,000**

Source: USGS (2011), Mineral Commodity Summaries

a USGS, 2009. 2008 Minerals Yearbook: *Cadmium.*
b EU27, plus Iceland, Liechtenstein, Norway, Switzerland and Turkey.

Figure A4:EU32 of World Cadmium Production – 2008 (tonnes of cadmium content)



Source: British Geological Survey (2010), European Mineral Statistics 2004-2008

A.3.1.3 Dominant supplying countries and political risk

The Failed State Index of the Fund for Peace and the Worldwide Governance Indicator of the World Bank give an indication of the political stability of the four dominant supplying countries China, South Korea, Japan and Kazakhstan (Table A26 and Table A27). Political risk for European cadmium supply from the world's largest and fourth largest producers, China and Kazakhstan respectively, are relatively high. Together, the 4 dominant suppliers make up 56% of world cadmium production of world supply. These risks are however balanced by the relatively diversified structure of global output and a number of stable and reliable suppliers such as Japan and South Korea. The fact that there exists significant European production further lowers supply risks. The overall political supply risk is therefore considered as low.

Table A26: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3
South Korea	**153**	**41.6**	4.0	3.5	4.1	5.0	2.4	2.1	4.1	2.2	2.7	1.4	3.6	6.5
Japan	**164**	**31.2**	4.2	1.1	3.8	2.0	2.5	3.1	2.0	1.2	3.4	2.0	2.0	3.9
Kazakhstan	**105**	**72.5**	6.0	3.9	5.5	4.0	6.4	6.4	7.7	5.3	6.8	6.5	7.6	6.4

Source: Fund for Peace

low (0-40 / 0-3,3) **Medium (40-80 / 3,4 – 6,6)** **high (80-120 / 6,7 – 10)**

Table A27: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2
South Korea	**72.2**	68.2	52.4	83.3	75.2	82.5	71.4
Japan	**84.6**	81.0	83.5	86.7	81.0	88.2	87.1
Kazakhstan	**38.2**	19.0	69.8	48.1	38.6	34.9	19.0

Source: World Bank

low (100- 66.7 Percentile) **medium (66.6 - 33.4 Percentile)** **high (33.3 – 0 Percentile)**

A.3.1.4 Process routes

Cadmium is a minor component in most zinc ores and therefore is most often isolated as a by-product from mining, smelting and refining sulphidic ores of zinc; typically 0.2% to 0.3%.[a] The main processing steps are:

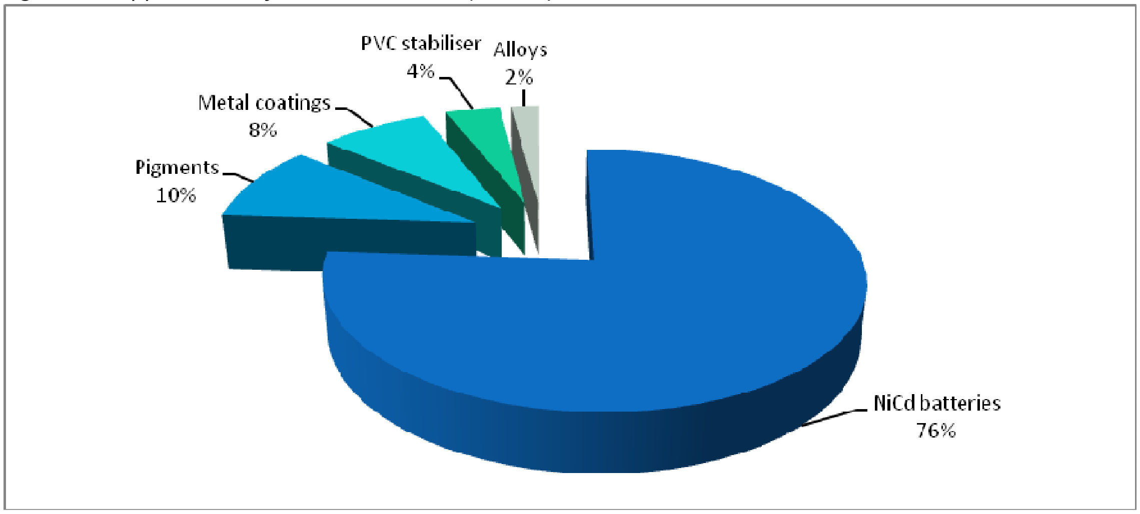
1. Crush and treat the ore using a differential floatation to remove the waste rock and create a high grade concentrate which is then converted to zinc oxide by roasting[b]
2. Purification using dilute sulphuric acid to dissolve both the zinc and cadmium
3. Recover cadmium by electro-winning to produce 99.99% pure cadmium cathode;[c] distillation can be used to obtain higher levels of purification if required.

To a lesser degree, cadmium is also recovered from lead and copper. Secondary cadmium is mainly produced from dust generated by recycling iron and steel scrap and also recovered from old NiCd batteries.

A.3.1.5 Applications

By far the largest application of cadmium is in NiCd batteries, with 76% of cadmium production used for this purpose (Figure A5). In the past cadmium was used a lot for metal coatings and pigments providing a range of colours from yellow and orange to red in plastics, glass and ceramics and as a stabiliser for plastics improving corrosion resistance. Over the last years more and more cadmium has been used for NiCd battery production whereas use in the other fields has gradually decreased, due to health and environmental concerns.

Figure A5: Applications of Cadmium – 2005 (tonnes)



Source: Hambleton A. (2010), Assessing Rare Metals as the Critical Supply Chain Bottleneck in Priority Energy Technologies, NAMTEC Ltd

A.3.1.6 Global demand and supply forecasts and expected price developments

Reliable quantitative forecasts for the development of the cadmium market do not exist due to unreliable production/consumption figures.[d] However, some important general observations can be made. Over the last decade global cadmium consumption experienced a slow but steady decline.[e] Both in the US and in the European Union, concerns over cadmium toxicity ushered in several rounds of increasingly restrictive regulations on cadmium use. The market share of NiCd batteries has also been

a USGS, 2008. Minerals Yearbook: *Cadmium*.

b Hambleton, A, 2010*. Assessing Rare Metals as the Critical Supply Chain Bottleneck in Priority Energy Technologies*. NAMTEC Ltd. (Personal communication)

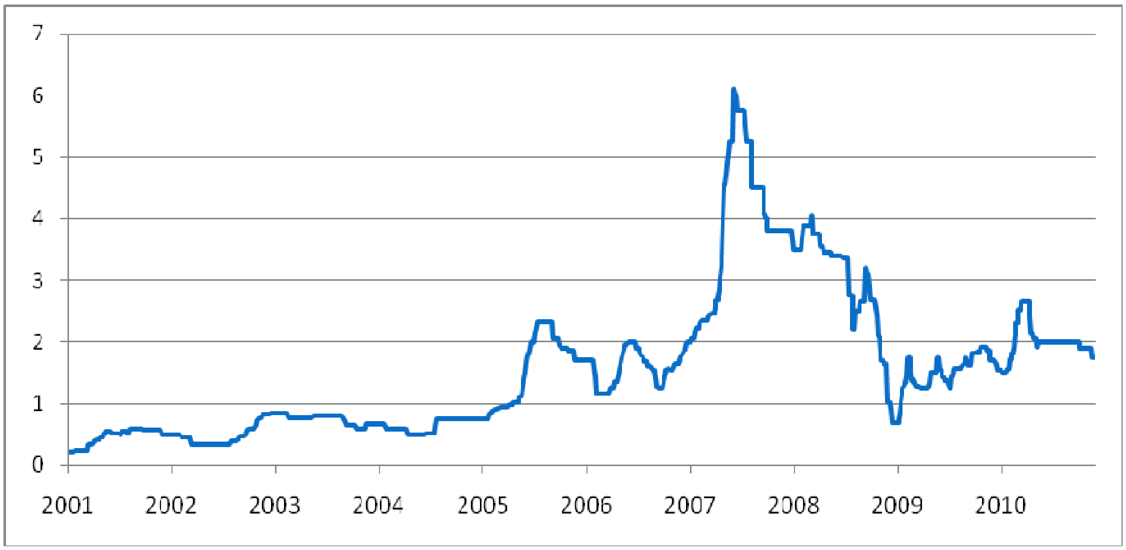
c *Metal Bulletin Monthly: Cadmium*, March 2006. Available at: http://www.mmta.co.uk/metals/Cd/. [Accessed 04/05/2011].

d de Metz, Patrick. Corporate Environmental and Governmental Affairs Director at Saft Batteries and Hugh Morrow, former President of the International Cadmium Association. (Personal communications)

e Based on the presentation: *Cadmium Market Report*, *October 2010.* (kindly provided by Hugh Morrow, former President of the International Cadmium Association).

visibly eroded by more advanced technologies, such as NiMH and Li-Ion batteries. However, a segment of NiCd batteries (15/20%) is likely to survive mainly in industrial applications due to their sturdiness, reliability and cost-effectiveness. Overall, industry experts expect the decline in demand for cadmium to continue.[a] Supply is expected to increase from secondary sources due to environmental legislation, possibly to the extent that primary production of cadmium from zinc refining may decline due to lower commercial incentives.[b]

Figure A6: Cadmium Metal Prices, min. 99.99% Purity (US$/lb)



Source: Metal Pages (to end 2010)

a de Metz, Patrick. Corporate Environmental and Governmental Affairs Director at *Saft Batteries.* (Personal communication)
b Ibid.

A.3.2 Dysprosium

A.3.2.1 Background

Dysprosium (Dy) is one of 15 rare earth elements also known as lanthanides and classed as a heavy rare earth element. Dysprosium is a very soft, lustrous, silvery metal but its physical appearance can be greatly affected even by small amounts of impurities and the pure metal rapidly corrodes. "It reacts with cold water and rapidly dissolves in acids".[a] It has high magnetic strengths especially at low temperatures and is used in high performance magnets. Dysprosium never occurs as a free element in nature but can be found in various minerals forming several brightly coloured salts.

A.3.2.2 Resources

Table A28 shows that China currently enjoys a virtual monopoly on the production of rare earth oxides, despite having just half of worldwide reserves. Further large reserves of rare earth elements can be found in the Commonwealth of Independent States (17%) and in the United States (12%). Within Europe, an estimated 1,000,000t of rare earth element reserves are known to be present in Norway at Kodal.[b] It is estimated that the total rare earth oxide reserves account for 110 million tonnes (Table A28).

An estimate of the world production of dysprosium for 2010 was 1,377 tonnes, representing around 1% of world rare earth oxide supply.[c] This equates to around 1,200 tonnes of dysprosium metal, which has been used as the main production estimate in the report. An alternative and higher estimate put dysprosium oxide new mine production at 2,000 tonnes for 2009.[d] Given the disproportionally high concentration of heavy rare earth elements in the lateritic ores of Southern China, the country's share of world dysprosium production must be estimated as even higher than its aggregate share in rare earth ore production.[e]

There is currently no dysprosium production in Europe and quantitative estimates for European dysprosium reserves are not available. However, it is reported that rare earth elements resources, i.e. reserves that are currently considered as uneconomic for extraction, are deposited in Greenland (4,890kt),[f] Sweden (~ 500kt)[g] and Finland (11,400t).[h]

A.3.2.3 Dominant supplying countries and political risk

China dominates the current world supply of dysprosium, with a share of ca. 97% in 2009. China has imposed export quotas on rare earth oxides (however not on the products made out of them) and have been tightening them progressively since 2004.[i] Further restrictions have been announced for the future. Given the total import dependence of Europe and the virtual supply-monopoly of China, political risks must be considered as extremely high.

A.3.2.4 Applications

The main use for dysprosium is in neodymium-iron-boron magnets for applications such as hard disc drives, automobiles and motors, as in wind energy generation (Figure A7). Typical dysprosium content of permanent magnets is 3% of their weight. High performance magnets for electric and hybrid vehicles make the magnets in electric motors lighter by 90%[j] and "give resistance to demagnetisation at high

a Emsley J. (2001), Nature's Building Blocks – An A-Z Guide to the Elements, Oxford University Press Inc., New York
b Cassard, Daniel. BRGM PROMINE database. (Personal communication).
c US Department of Energy (2010), *Critical Materials Strategy*.
d Lifton, Jack, 2010. Report: The Supply Issue for all metals, Volume 2, Issue 4. [Accessed 13/10/2010].
e Oakdene Hollins for DfT., 2010. *Lanthanide Resources and Alternatives.*
f USGS, 2010. *The Principal Rare Earth Deposits in the United States: A Summary of Domestic Deposits and a Global Perspective.*
g European Commission, 2010. *Critical raw materials for the EU, Annex V.*
h Based on a conversation with Eilu Pasi, Senior Geoscientist at GTK Finland.
i OECD Workshop on Raw Materials, October 2009. *Export restrictions on strategic raw material and their impact on trade and global supply.*
j Bradsher, K., 2009. Earth-Friendly Elements, Mined Destructively. *The New York Times.*

temperatures as the magnet reaches temperatures of 160ºC":[a] the dysprosium content for these applications is up to 10%.[b] Growth rates in the demand for rare earth elements in permanent magnets has been very strong, increasing from 5,500 tonnes rare earth oxide in 2003 to 10,400 tonnes in 2008[c] (annual growth of 13.6%); in 2015 IMCOA forecast that over 95% of dysprosium consumption for 2015 will be within permanent magnets.[d] Other applications for dysprosium are for control rods in nuclear reactors, in dosimeters for monitoring exposure to ionising radiation and, in combination with vanadium and other elements, also used in making laser materials.

Table A28: World Rare Earth Oxide (REO) Production and Reserves – 2010 (tonnes of REO content)

Country	Mine production (estimated)	Reserves (kt)
China	130,000	55,000
India	2,700	3,100
Brazil	550	48
Malaysia	350	30
Commonwealth of Independent States	n/a	19,000
United States	—	13,000
Australia	—	1,600
Other countries	n/a	22,000
World total (rounded)	**130,000**	**110,000**

Source: USGS (2011), Mineral Commodity Summaries

Table A29: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3

Source: Fund for Peace

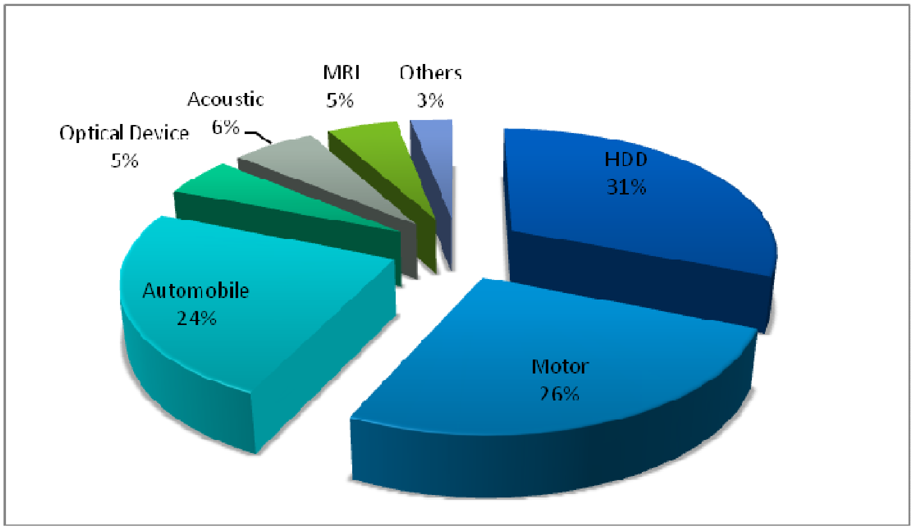
Table A30: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2

Source: World Bank

a MaximumEV, 2009. *Rare Earths and Neodymium*. Available at: http://maximumev.blogspot.com/2009/06/rare-earths-and-neodymium.html. [Accessed 04/05/2011].
b GWMG Presentation, November 2009. *Rare Earth Magnets and their Raw Materials Supply*. 5th International Rare Earths Conference, Hong Kong.
c Shin Etsu, 2009. *Presentation: Nd Magnet and Their Applications.* 5th International Rare Earths Conference, Hong Kong, 2009.
d IMCOA. (Personal communication).

Figure A7: Applications of Neodymium Magnets, 2009 (tonnes)



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

A.3.2.5 Global demand and supply forecasts and expected price developments

Dysprosium supply and demand are forecast to more than double over ten years (Figure A8). A significant supply shortage for dysprosium (23% of supply in 2020) is expected to open up over the coming decade. However, the severity of the dysprosium shortfall forecast here is much smaller than that forecast by Great Western Minerals Group, a junior rare earth miner, at 53% of supply in 2014.[a]

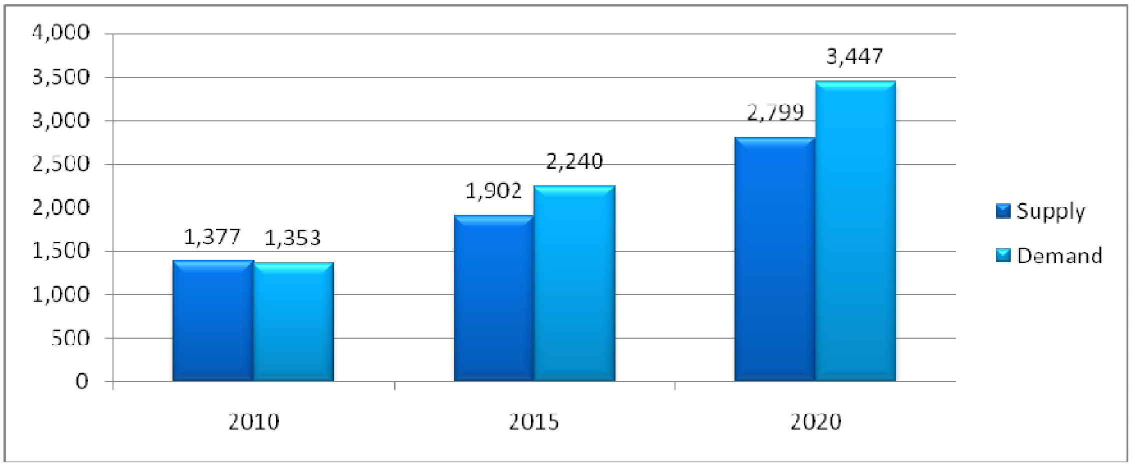
The assumptions underlying the supply and demand forecasts are:

- Global supply for dysprosium was 1,377 tonnes in 2010
- IMCOA[b] forecasts for demand and supply until 2014
- Dysprosium content remains constant at 0.9% of rare earth element supply, but demand represents 1.0%; as forecast for 2014 by IMCOA
- Longer term supply assumes growth slowing to 3% per year for Chinese supply, but remaining at 20% per year for supply in the rest of the world[c]
- Longer term demand assumes a 9% per year global growth rate, as modelled by Öko-Institut.[d]

Prices for dysprosium oxide have increased substantially over the past years and continue to escalate sharply (trebling in price in 2010 and rising by 400% in 2011 alone, from 100 $/kg to 1500 $/kg) on the back of strong demand, aggressive tightening of export restrictions in China and ongoing uncertainty about the further development of Chinese policy (Figures A9a and A9b). It should be noted that rare earth elements tend to represent a very small proportion of the final price of a product and are not readily substitutable. Despite several new projects outside of China that are due to come online over the coming years, expected strong demand growth is likely to sustain a supply deficit, resulting in continuing upward pressure over the coming decade.

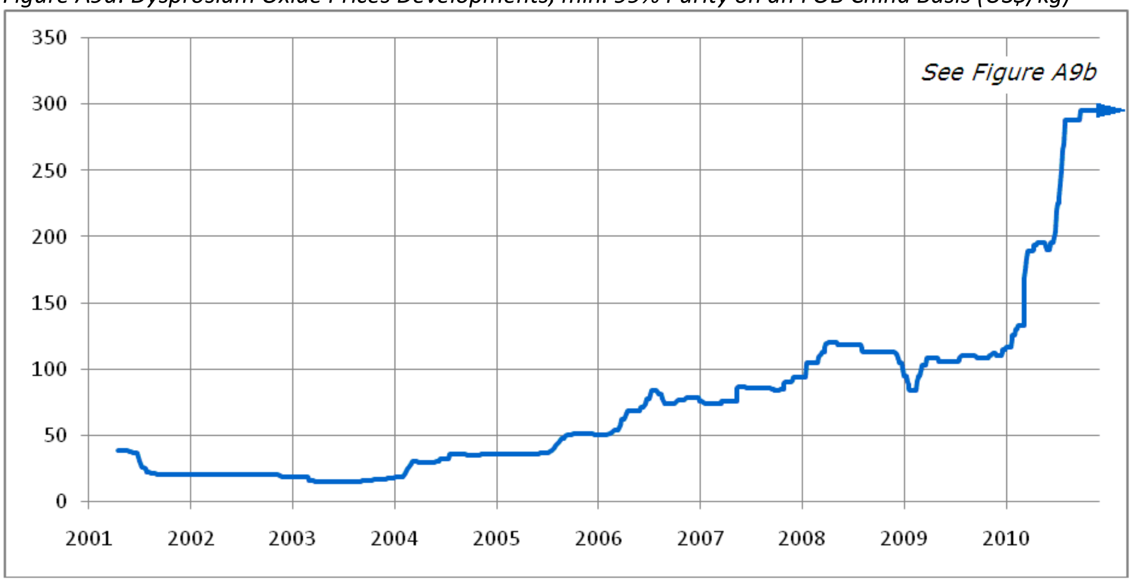
a GWMG, November 2009. *Presentation: Rare Earth Magnets and their Raw Materials Supply*. 5th International Rare Earths Conference, Hong Kong.
b IMCOA November 2009. *Presentation: Meeting Demand in 2014:The Critical Issues*. 5th International Rare Earths Conference, Hong Kong.
c Oakdene Hollins for DfT, 2010. *Lanthanide Resources and Alternatives – Scenario 2*.
d Öko-Institut for UNEP, 2009. *Critical Metals for Future Sustainable Technologies and their Recycling Potential.*

Figure A8: Dysprosium Oxide Supply and Demand Forecasts (kt)



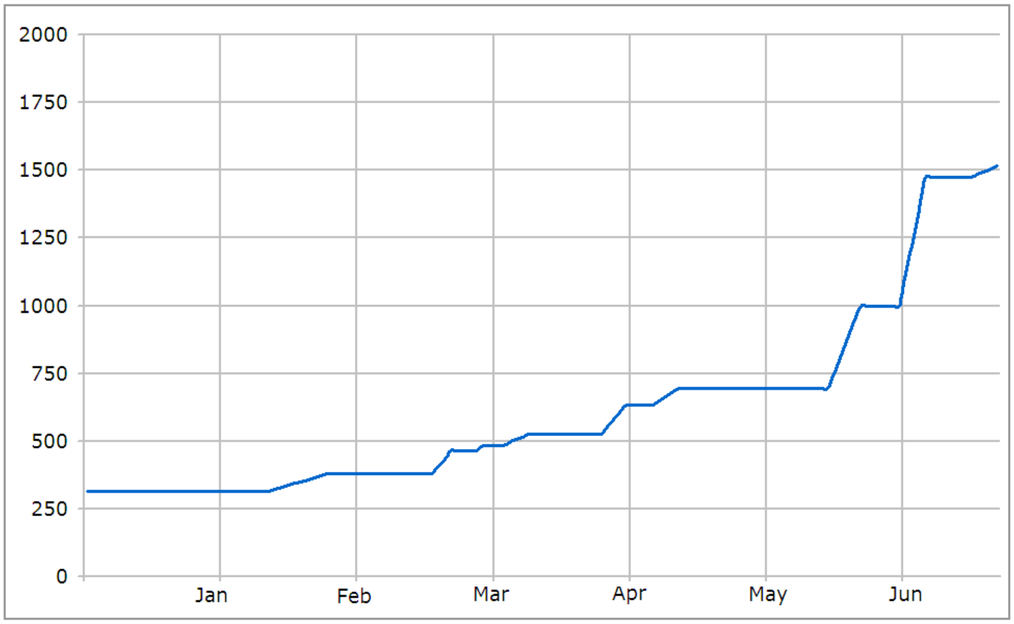
Sources: Own Calculations based on IMCOA, Öko-Institut

Figure A9a: Dysprosium Oxide Prices Developments, min. 99% Purity on an FOB China Basis (US$/kg)



Source: Metal Pages (to end 2010)

Figure A9b: Dysprosium Oxide Prices, min. 99% Purity on an FOB China Basis (US$/kg) - 2011



Source: Metal Pages (2011)

A.3.3 Gallium

A.3.3.1 Background

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

A.3.3.2 Resources

Estimating the world reserves of gallium is very difficult because it is produced as a by-product of treating bauxite, an aluminium ore, and to a lesser extent from zinc-processing residues. The US Geological Survey (USGS) estimates gallium's world resources in bauxite alone to be 1 billion kilograms. However, only parts of the very large global bauxite reserves are going to be mined over the next decades, so the gallium content of much of the bauxite reserves cannot be treated as recoverable in the near term.[b] In Table A32, an estimate is nonetheless provided of European gallium reserves based on European bauxite reserves. They were calculated by assuming an average content of 50ppm of gallium in bauxite and an average recovery rate of 40%.

There is considerable primary production capacity for gallium available globally, with China, Germany, Kazakhstan, Japan and Russia having the largest capacities (see Table A31). Additionally, gallium can be recycled from new scrap, with global recycling capacity, being estimated at 141 tonnes annually by the USGS, which is dominated by Germany, Japan, the UK and the US.[c] Actual production however is estimated to be considerably lower, estimated at 106 tonnes per year. Total output is estimated at 161 tonnes for 2010, which includes production from recycling processes.[d] Detailed outputs per country are not available, but China is considered to be the largest supplier of virgin material accounting for about half of global output. Concerning Europe, the BGR[e] reported that in 2006 Germany, Hungary and Slovakia refined 12, 5.5, and 0.5 tonnes of gallium from bauxite, respectively.

Table A31: World Primary Gallium Production Capacity – 2008 (tonnes of gallium content)

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

Source: USGS (2010), 2008 Mineral Yearbook: Gallium

A.3.3.3 Dominant supplying countries and political risk

Political risks for gallium supply to Europe are limited. The market is dominated by China, but other large producers such as Japan and the US are considered as reliable suppliers. Furthermore, Europe and

a Vulcan T. (2009), Gallium: A Slippery Metal, Hard Assets Investor
b USGS, 2010. Mineral Commodity Summaries.
c USGS, 2011. Mineral Commodity Summaries.
d Indium Corporation, April 2010. *Presentation: Indium, Gallium & Germanium, Supply and Outlook.* Rare Metals Symposium.
e Bundesanstalt für Geowissenschaften und Rohstoffe (German Geological Survey)

Germany in particular have significant primary production and recycling capacities and there are large reserves in bauxite ores available in Europe.

Table A32: European Gallium Reserves Based on Identified European Bauxite Deposits

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

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

A.3.3.4 Process routes

Even though gallium can be found in aluminium and zinc ores and to a very small extent in coal, diaspore and germanite, economic deposits of gallium rarely occur; therefore production is almost entirely as a by-product of alumina production. The concentration of gallium in bauxite ranges between 0.003% and 0.008%.[a] During the production of aluminium, gallium is extracted in an impure form from the crude aluminium hydroxide solution resulting from the Bayer process and is then further refined to high purity (>99.9999%) gallium.[b]

A.3.3.5 Applications

Almost the entire gallium production is used in semiconducting materials as a compound with arsenic as gallium arsenide (GaAs) and to a smaller extent as gallium nitride (GaN). GaAs is used in integrated (chips/microchips) circuits, laser diodes, photodetectors and solar cells, whereas GaN produces blue and violet LEDs and laser diodes used in Blue-ray DVD devices. Furthermore, gallium metal is used in high-temperature thermometers, to create high-quality mirrors, and in certain dental applications, often as a substitute for mercury.

A.3.3.6 Global demand, supply forecasts and expected price developments

Gallium supply and demand forecasts are given in Figure A11. Gallium is forecast to move from a small supply surplus indicated in 2010 to a substantial deficit representing over 50% of supply in 2020 due to strong growth in Solar PV. The demand forecast comes from Umicore;[c] although it is noted that it does not materially differ from the 10% per year growth rate, as modelled by Öko-Institut.[d]

The assumptions underlying the supply forecast are:

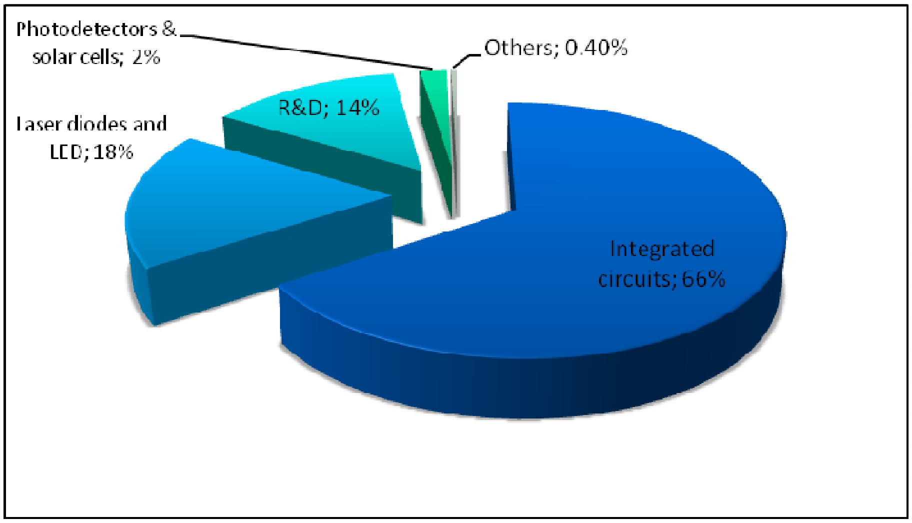
- Primary gallium production of 111 tonnes in 2008 and 78 tonnes in 2009; with secondary gallium production of 40 tonnes (both years); and 161 tonnes in total for 2010
- The parts per million of gallium extracted from bauxite remaining constant at 0.5 ppm modelled using supply forecasts for primary aluminium from the Economist Intelligence Unit (presented as forecasts for bauxite based on the long-run production relationship)
- Secondary production remains constant at 40 tonnes per year.

Prices for gallium peaked at over US$2,000/kg in 2001 and have subsequently remained below US$1,000/kg in the intervening period (Figure A12). Given sharply increasing demand, upward pressure

a European Commission, 2010. Critical raw materials for the EU, Annex V.
b Minor Metals Trade Association. Gallium. Available at: http://www.mmta.co.uk/metals/Ga/. [Accessed 01/02/2011]
c Umicore, 2010, in European Commission, 2010). Critical raw materials for the EU, Annex V.
d Öko-Institut for UNEP, 2009. Critical Metals for Future Sustainable Technologies and their Recycling Potential.

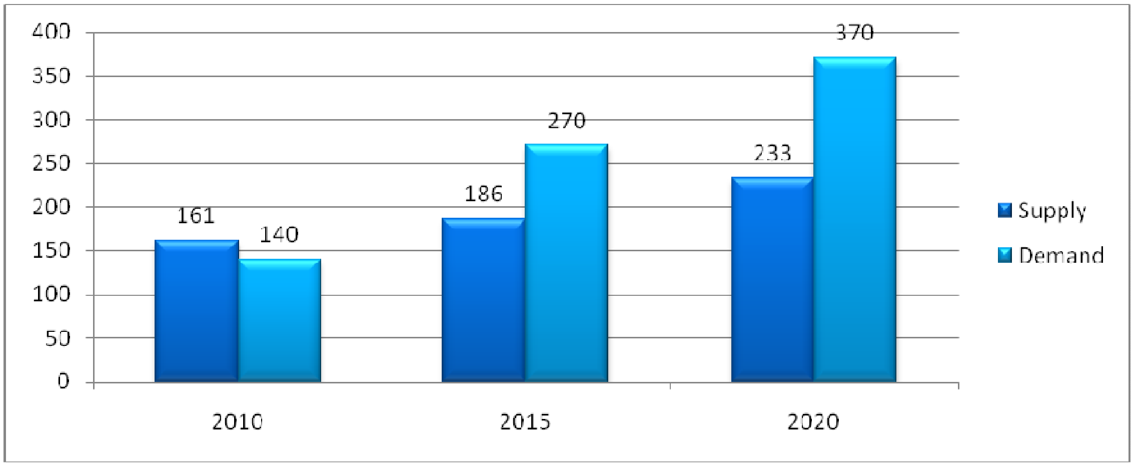
on prices is to be expected over the coming year and might induce additional capacity to come on stream.

Figure A10: Applications of Gallium (tonnes)



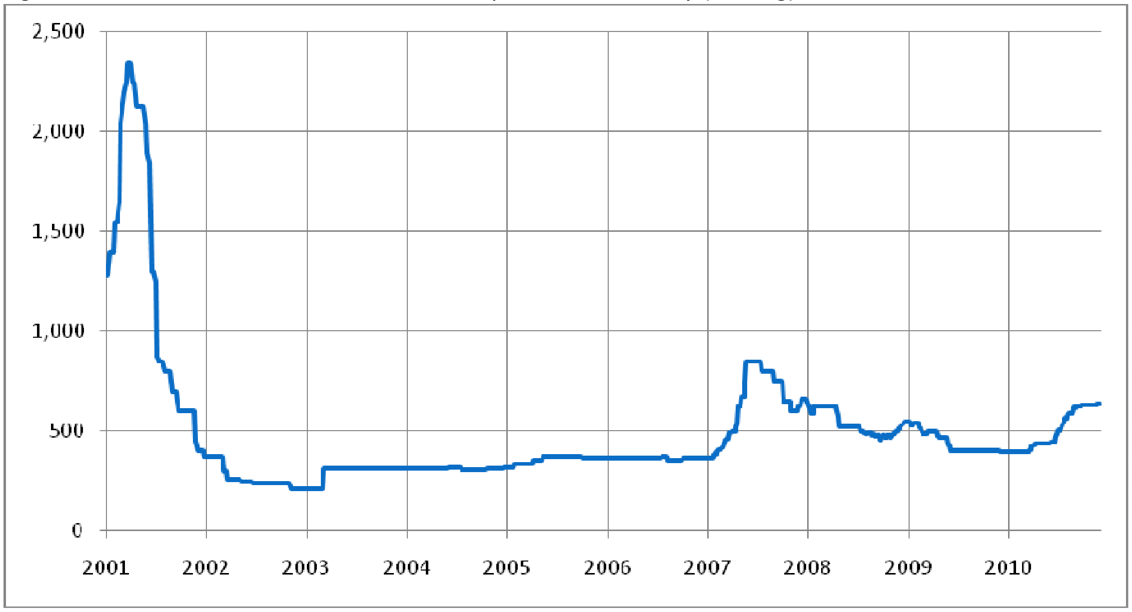
Source: European Commission (2010), Critical raw materials for the EU, Annex V

Figure A11: Gallium Supply and Demand Forecasts (tonnes)



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

Figure A12: Gallium Metal Prices, CIF Main Airport, 99.99% Purity (US$/kg)



Source: Metal Pages (to end 2010)

A.3.4 Hafnium

A.3.4.1 Background

Hafnium (Hf) is a ductile transition metal with a lustrous, silvery grey colour and is very similar to zirconium. As hafnium and zirconium have similar electronic configurations and their atoms are similarly sized, they are very difficult to separate. Some of hafnium's most valued characteristics are its corrosion resistance due to a tough, impenetrable oxide film on its surface leaving it unaffected by alkalis and most acids and its high melting point of 2,200 °C.[a] However they have very different neutron absorbing properties; hafnium absorbs neutrons making it suitable for control rods, whereas zirconium is transparent to neutrons. This necessitates the separation of hafnium from zirconium for nuclear applications of zirconium, and provides the main source of hafnium metal.

A.3.4.2 Resources

South Africa and Australia have the largest hafnium reserves with 280,000 tonnes and 230,000 tonnes respectively. Global hafnium reserves are estimated to be 660,000 tonnes (Table A33) and resources are said to exceed 1 million tonnes.[b] Annual production figures of hafnium are not recorded but are estimated to be less than 100 tonnes[c] with approximately 45 tonnes being produced in French power plants and another 45 tonnes coming from the United States.[d] An alternative estimate for hafnium supply can be calculated, bottom-up: 3-4,000 tonnes of zirconium were estimated to be used in nuclear applications in 2007,[e] of which the ratio of zirconium to hafnium is 50:1.[f] This puts hafnium production at around 75 tonnes. There are no available figures for European hafnium reserves and output: nevertheless, it is reported that *Cezus*, a company based in Jarrie, France, is the world leading producer of hafnium with a capacity of around 32 tonnes per annum.[g]

Table A33: World Hafnium Reserves – 2009 (tonnes of hafnium content)

Country	Reserves
South Africa	280,000
Australia	230,000
United States	68,000
Brazil	44,000
India	42,000
China	n/a
Indonesia	n/a
Ukraine	n/a
Other countries	n/a
World total (rounded)	**660,000**

Source: USGS (2010), Mineral Commodity Summaries

A.3.4.3 Dominant supplying countries and political risk

Given the dominant role of France and the US in the production of hafnium, and the concentration of more than two-thirds of zirconium reserves in South Africa and Australia, political risks for the supply of hafnium to Europe must be considered as low.

a Lenntech. *Hafnium*. Available at: http://www.lenntech.com/periodic/elements/hf.htm. [Accessed 01/02/2011].
b USGS, 2010. Mineral Commodity Summaries.
c Hambleton, A., 2010. *Assessing Rare Metals as the Critical Supply Chain Bottleneck in Priority Energy Technologies*. NAMTEC Ltd. (Personal communication).
d Minor Metals Trade Association. *Hafnium*. Available at: http://www.mmta.co.uk/metals/Hf/. [Accessed 01/02/2011].
e Roskill, 2007. *The Economics of Zirconium, 12th Edition*.
f USGS, 2010. Mineral Commodity Summaries.
g MBM, April 2007. *Hafnium*. Available at: http://www.mmta.co.uk/metals/Hf/. [Accessed 01/02/2011].

A.3.4.4 Process routes

Hafnium does not exist as a free element in nature, but can be found with zirconium in the mineral zircon and to a smaller amount in baddeleyite. Only two hafnium ores are known: alvite and hafnon. Hafnium's abundance in the Earth's crust is about 3 ppm making it the 45th most abundant element.[a]

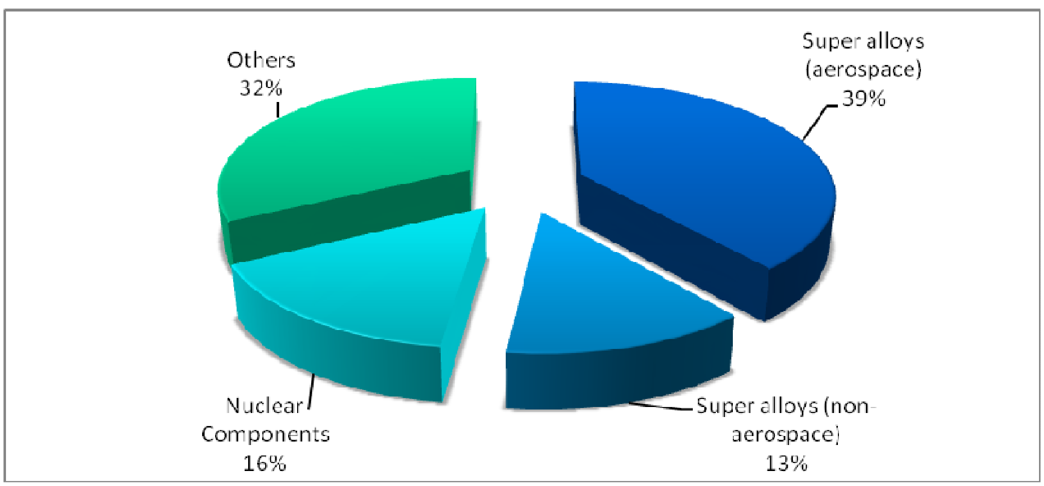
Commercial production of hafnium arose from the need to produce hafnium-free zirconium metal for use in nuclear reactors. As hafnium is so similar to zirconium, separating the two elements from each other is very difficult. Most zircon (and, therefore, hafnium) is mined from titanium-rich, heavy-mineral sand deposits.[b] The majority of hafnium comes from the hafnium-free zirconium production for nuclear-reactor applications.

Today, most of the hafnium is separated from zirconium through ion-exchange and solvent-extraction techniques. Separated as hafnium dioxide and zirconium dioxide, the hafnium compound is chlorinated to form hafnium tetrachloride, which is then sublimated before reduction with magnesium and distillation to produce a solid intermediate product. Once broken and crushed, the product is then refined in an iodide cell before electrode welding and vacuum-arc melting to produce metal ingots. Machining, forging, rolling and drawing produce a variety of wrought forms of the metal, including plate, sheet, wire and tube.

A.3.4.5 Applications

Today, the principal uses of hafnium are in the aerospace industry as an alloy additive in nickel-based super alloys and in the harsh environments of pressurised water reactors for nuclear control rods and submarines, where its properties of temperature and corrosion resistance and ability to absorb multiple neutrons are put to good use (Figure A13). However, hafnium can be substituted by silver-cadmium-indium control rods and is usually in the newer reactors.[c] Hafnium is also used in high-temperature ceramics, nozzles for plasma-arc metal cutting and in gas-filled and incandescent lamps. Some of the world's largest computer chip manufacturers have started to replace silicon with hafnium in semiconductors, as hafnium improves the performance of multi-core processors while at the same time consuming less power. In total, hafnium consumption was estimated at 77 tonnes for 2007.

Figure A13: Applications of Hafnium, 2007 (tonnes)



Source: Hambleton A. (2010), Assessing Rare Metals as the Critical Supply Chain Bottleneck in Priority Energy Technologies, NAMTEC Ltd

a Minor Metals Trade Association Website: *Hafnium*. Available at: http://www.mmta.co.uk/metals/Hf/. [Accessed 01/02/2011].
b Ibid.
c Lipmann, Anthony. Lipmann Walton & Co. (Personal Communication).

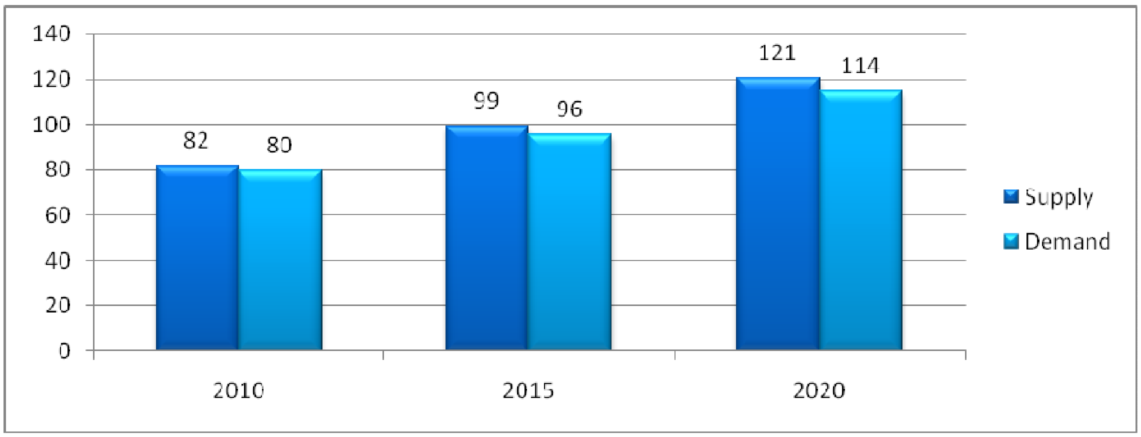
A.3.4.6 Global demand, supply forecasts and expected price developments

Hafnium supply and demand forecasts are given in Figure A14. A small surplus in hafnium metal production is forecast until 2020, driven by rapid expansion of zirconium use in nuclear applications, which necessitates the separation of the chemically-similar hafnium.[a]

The assumptions underlying the forecast are:

- Supply for hafnium is determined by the demand for zirconium nuclear alloy of 4,000 tonnes in 2009,[b] with a ratio of Zr:Hf of 50:1 (78 tonnes of hafnium)
- A growth rate in supply of hafnium of 4% a year (forecast for 'other' applications of zirconium by Roskill in their base forecast)
- Demand growth of 3.6% for super alloys in aerospace as forecast by the Federal Aviation Administration of the US Department of Transportation for International System Capacity[c]
- Demand growth of 5% for non-aerospace super alloys, comparable to rhenium[d]
- Demand growth of 4% for nuclear applications (as above) and 3% for the remaining applications.

Figure A14: Hafnium Supply and Demand Forecasts (tonnes)

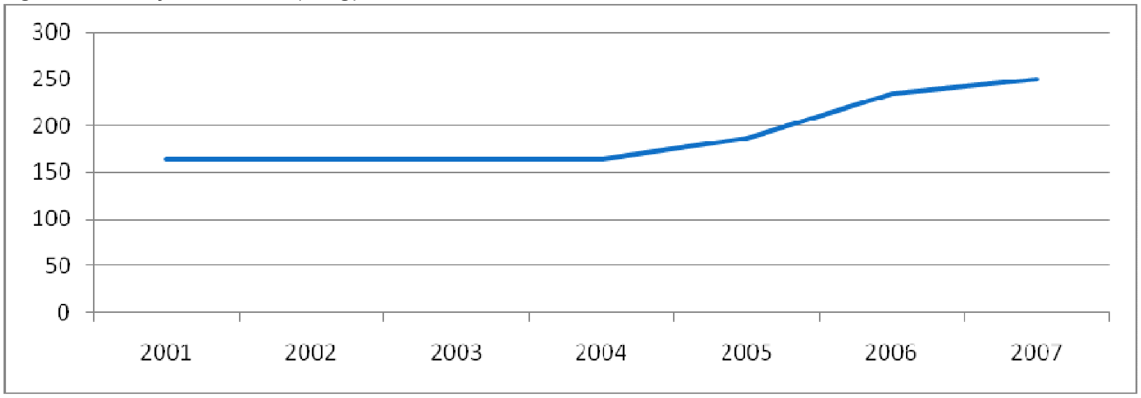


Sources: Own Calculations based on Roskill, USGS, US Dept. Transport

There is only limited price data available for hafnium. Metal Bulletin Monthly reports average prices of US$187/kg in 2005, rising to US$235/kg in 2006 (Figure A15) and in 2007 they climbed above US$250/kg. Current price levels for hafnium, 3% Zr impurity are at $450/kg, which represents a significant increase since 2007. For lower impurity levels, 1% and 0.2% Zr, prices are $900/kg and $1,200/kg respectively.[e] Given the significant surpluses forecast for hafnium over the coming decade, limited potential seems to exist for large price hikes.

a Roskill, 2007. The Economics of Zirconium, 12th Edition.
b Ibid
c US Department of Transportation, 2010. FAA Aerospace Forecast: Fiscal Years 2010-2030.
d Roskill, 2010. Rhenium: Market outlook to 2015, 8th edition.
e Lipmann, Anthony. Lipmann Walton & Co. (Personal Communication)

Figure A15: Hafnium Prices ($/kg) *Source: MBM (April 2007),Hafnium*



A.3.5 Indium

A.3.5.1 Background

Indium (In) is a very soft metal with a shiny silver colour and is mainly used in the production of flat screen monitors. Like some of the other strategic metals such as gallium, indium is solid at room temperature but has a relatively low melting point at 156.6 °C. Indium's abundance in the earth's crust is about three times more abundant than silver or mercury;[a] this is why it is most commonly recovered as a by-product of the processing of zinc sulphide.

A.3.5.2 Resources

As indium is extracted as a by-product of zinc refining, up-to-date figures for indium reserves are not readily available. However, in 2007 the US Geological Survey published their latest estimates on world indium reserves. According to USGS, 8,000 tonnes of economic indium deposits are located in China, with a world total of 11,000 tonnes. Additionally an estimated 16,000 tonnes of indium resources are identified in the USGS data worldwide. Newer estimates of resources are significantly higher, e.g. the Indium Corporation estimates 50,000 tonnes of indium resources worldwide, including a significant deposit in Neves Corvo, Portugal (ca. 4,700 tonnes) and smaller deposits in Germany.[b,c]

The majority of indium production occurs in Asia and is dominated by China, with a production of 300 metric tons in 2010, accounting for more than half of the world's total production of 574 tonnes of primary indium (Table A34). Belgium is reported by USGS as the only European country producing indium, refining it from imported lead and zinc. According to USGS, with a production of 30 tonnes out of the world total of 574 tonnes, Belgium represented 5% of the indium world supply in 2010. However Nyrstar's zinc facility in Auby (France) is also known to produce indium of about 30 to 40 tonnes p.a.[d] In addition to primary production, there is also a substantial capacity for recycling the metal, as approximately 70% of the indium contained in the main product, indium tin oxide (ITO), can be recovered and refined for re-use.[e] The recycling of indium, used in the form of ITO in liquid crystal display (LCD) flat-panel screens, takes place mainly in China, Japan and Korea. The Öko-Institut reported secondary production of 600 tonnes for 2009, against 786 reported by the Indium Corporation.[f] Despite the conflicting figures, there appears to be a consensus that indium recycling represents the gross of global supply today.

A.3.5.3 Dominant supplying countries and political risk

Political risks for Europe from top producing countries of indium are shown in Table A35 and Table A36. While South Korea, Japan and Canada do not give rise to concerns, the political risks for the world largest supplier, China, are higher. Given the relatively diversified structure of world supply and significant European production and recycling capacity, political risks to Europe are considered to be relatively low.

A.3.5.4 Process routes

Indium does not occur reclusively but as a minor metal in combination with other minerals. Commercially, "virgin" indium is extracted primarily as a by-product of ores of zinc, lead, copper and tin. Almost all indium is produced from residues collected from zinc refining and recycling of flue dusts and gases generated during the smelting of zinc. The remainder, if any, is derived from the smelting and refining of tin. The most widespread application to recover indium is during the zinc production process. Around 0.028 kg by-product indium can be recovered from 1 tonne of zinc ore.[g]

a USGS, 2004. Mineral Commodity Summaries.
b European Commission, 2010. *Critical raw materials for the EU, Annex V.*
c Cassard, Daniel. BRGM PROMINE database. (Personal communication).
d: Auby, Nyrstar. (Personal communication)
e Harrower M., 2005. *Indium, Mining Journal*, MMTA. Available at http://www.mmta.co.uk/metals/In/. [Accessed 07/05/11].
f Öko-Institut for UNEP, 2009. *Critical Metals for Future Sustainable Technologies and their Recycling Potential.*
g Öko-Institut for UNEP, 2009. *Critical Metals for Future Sustainable Technologies and their Recycling Potential.*

Table A34: World Primary Indium Refinery Production (2010), Reserves (2007) – (tonnes of indium content)

Country	Refinery production	Reserves
China	300	8,000
Korea, Republic of	80	—
Japan	70	—
Canada	35	150
Belgium	30	*
Peru	25	360
Brazil	5	—
Russia	4	80
United States	—	280
Other countries	25	1,800
World total (rounded)	**574**	**11,000**

**Reserves for this country are included with "Other countries." Note: Reserve estimates based on the indium content of zinc ores*
Source: USGS (2007, 2011), Mineral Commodity Summaries

Table A35: Failed States Index - 2009

Country	Rank	Total	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	**9.0**	**6.8**	**7.9**	**6.1**	**9.2**	**4.5**	**8.5**	**7.2**	**8.9**	**6.0**	**7.2**	**3.3**
South Korea	**153**	**41.6**	**4.0**	**3.5**	**4.1**	**5.0**	**2.4**	**2.1**	**4.1**	**2.2**	**2.7**	**1.4**	**3.6**	**6.5**
Japan	**164**	**31.2**	**4.2**	**1.1**	**3.8**	**2.0**	**2.5**	**3.1**	**2.0**	**1.2**	**3.4**	**2.0**	**2.0**	**3.9**
Canada	**166**	**27.7**	**3.3**	**2.4**	**3.0**	**2.1**	**4.7**	**2.0**	**1.7**	**1.2**	**2.1**	**1.1**	**2.4**	**1.7**

Source: Fund for Peace

Table A36: World Bank – Worldwide Governance Indicator2009

Country	Average	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2
South Korea	**72.2**	68.2	52.4	83.3	75.2	82.5	71.4
Japan	**84.5**	81.0	83.5	86.7	81.0	88.2	87.1
Canada	**94.5**	95.3	85.4	96.7	96.2	96.7	96.7

Source: World Bank

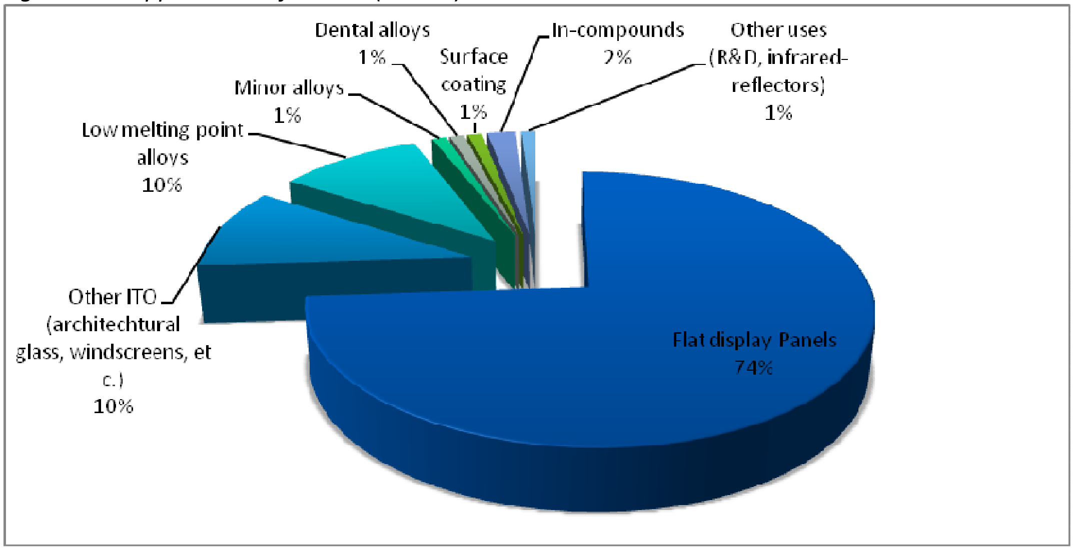
During the production of zinc, drosses and residues are created which are rich in copper, lead and tin. A flotation process is used to concentrate the copper, which is further processed by sintering and electrothermic reduction to produce a crude bullion. Electrolytic treatment of the bullion generates an anode slime containing up to 30% indium. Commercial-grade indium is produced once the slime has undergone a series of leaching, solvent extraction and electro-refining process steps.

The metal can reach purities of up to 99.999%. Indium can be refined in various forms, such as ingot, foil, powder, ribbon, shot and wire.

A.3.5.5 Applications

The most dominant application (74%) for indium is in the production of indium tin oxide (ITO), which is used as a coating on all types of flat panel displays. The remaining 25% is used for, for example, lead-free solders, batteries, SOX lamps, bearings, dental applications, nuclear reactor control rods, corrosion-inhibitors, semiconductors for laser diodes, architectural glass and windscreens, low melting-point alloys and/or as an element in cathodic protection systems.

Figure A16: Applications of Indium (tonnes)



Source: European Commission (2010), Critical raw materials for the EU, Annex V

A.3.5.6 Global demand, supply forecasts and expected price developments

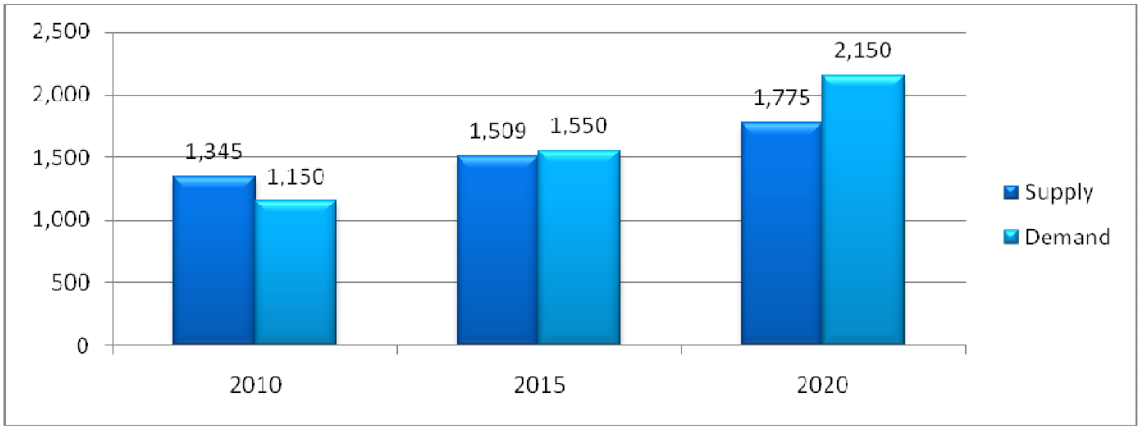
Future demand from the electronics industry will put severe pressure on supply. Indium supply and demand forecasts are given in Figure A17. The market is forecast to move from a small surplus in 2010 to a significant deficit in 2020, representing 21% of forecast supply because of strong growth in PV. The demand forecast comes from Umicore;[a] although it is noted that it does not substantially differ from the 5% per year growth rate, as modelled by Öko-Institut.[b] The assumptions underlying the supply forecast are:

- Primary and secondary indium production totalled 1,345 tonnes in 2010[c]
- The parts per million of indium extracted from zinc remaining constant at 50 ppm, modelled using supply forecasts for zinc from the Economist Intelligence Unit
- Secondary production matches primary production.

Prices for Indium hovered around US$1,000/kg during 2005 and 2006, and gradually fell back to around US$400/kg by 2010. An upward trend has since returned and potential for further price rises is expected particularly for the second half of the decade, when strong demand growth is likely to create significant pressure on prices.

a Umicore, 2009, in European Commission 2010. *Critical raw materials for the EU, Annex V.*
b Öko-Institut for UNEP, 2009. *Critical Metals for Future Sustainable Technologies and their Recycling Potential.*
c US Department of Energy, 2010. *Critical Materials Strategy.*

Figure A17: Indium Supply and Demand Forecasts (tonnes)



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

Figure A18: Indium Metal Prices, min. 99.99% Purity (US$/kg)

Source: Metal Pages (to end 2010)

A.3.6 Molybdenum

A.3.6.1 Background

Molybdenum (Mo) has a silver-white colour and has one of the highest melting points of all the elements and belongs to the elements with an estimated abundance of 1-1.5 ppm in the Earth's crust. Among its many favourable properties are its lightness, its high mechanical strength even at high temperatures, its resistance to corrosion and a low coefficient of thermal expansion. Due to its unique combination of properties, few metals can substitute molybdenum, especially as an alloying element in cast irons and steels. Molybdenum does not occur as a free metal in nature, but rather in various oxidation states in minerals.

A.3.6.2 Resources

The total world production of molybdenum in 2010 was 234,000 tonnes of which 81% came from China, USA and Chile (Table A37). Peru also plays an important role having produced 12,000 tonnes according to the USGS. Most reserves of molybdenum can also be found in China, USA and Chile (8.1 million tonnes) and the total reserves of the world are 9.8 million tonnes. Within Europe production is negligible but an estimated 600,000 tonnes of molybdenum reserves are reported to be present at Nordli in Norway.[a] Identified resources of molybdenum in the United States amount to about 5.4 million tonnes, and in the rest of the world about 14 million tonnes.[b] Resources of molybdenum are adequate to supply world needs for the foreseeable future.

Table A37: World Molybdenum Production and Reserves – 2010 (tonnes of molybdenum content)

Country	Mine production (t)	Reserves (kt)
China	94,000	4,300
United States	56,000	2,700
Chile	39,000	1,100
Peru	12,000	450
Canada	9,100	200
Mexico	8,000	130
Armenia	4,200	200
Russia	3,800	250
Iran	3,700	50
Mongolia	3,000	160
Uzbekistan	550	60
Kazakhstan	400	130
Kyrgyzstan	250	100
World total (rounded)	**234,000**	**9,800**

Source: USGS (2011), Mineral Commodity Summaries

A.3.6.3 Dominant supplying countries and political risk

China, United States and Chile are the leading producing countries for molybdenum, being together responsible for roughly 80% of world supply in 2009. Political risk for European supply of molybdenum stem mainly from its total import dependence and the concentrated nature of global supply, although

a Cassard, Daniel. BRGM PROMINE database. (Personal communication)
b USGS, 2010. Mineral Commodity Summaries.

these are somewhat lessened by the fact that with the USA, Canada and Chile, a number of larger and reliable suppliers exist. Overall, the supply risk is considered as medium.

Table A38: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3
United States	**159**	**34.0**	3.1	3.7	3.3	1.0	5.3	2.9	3.0	2.3	4.0	1.4	2.5	1.5
Chile	**155**	**37.5**	4.0	2.5	3.6	2.1	4.4	4.3	2.0	4.2	3.6	2.0	1.5	3.3

Source: Fund for Peace

Table A39: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2
United States	**83.4**	86.3	59.0	89.0	89.5	91.5	85.2
Chile	**83.5**	74.9	69.3	85.7	93.8	87.7	89.5

Source: World Bank

A.3.6.4 Process routes

Molybdenum occurs as the principal metal sulphide in large low-grade porphyry-molybdenum deposits and as an associated metal sulphide in low-grade porphyry-copper deposits. It is mined both as a primary product and as a by-product of copper mines. The most important molybdenum ore is molybdenite, which is commonly found with copper sulphides. Roasting plants then convert molybdenite concentrate to molybdic oxide, from which intermediate products, such as ferromolybdenum, metal powder and various chemicals, can be produced.

A.3.6.5 Applications

A wide range of high-technology products, including catalysts, jet engines, medical equipment and semi-conductors, rely on molybdenum metal and chemicals. Molybdenum's main use (82%) is as an alloying element in the steel, iron and super-alloy industry. The remaining molybdenum is used for catalysts, pigments, light-bulb filaments, gun barrels or as a lubricant. Molybdenum is also used in pipelines and motor vehicle components due to its high resistance to corrosion.

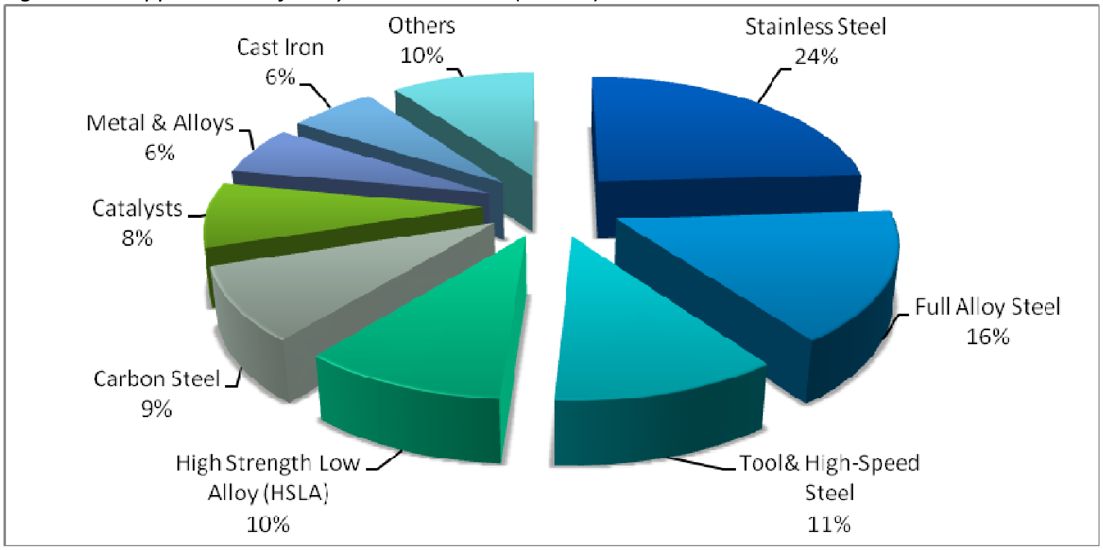
A.3.6.6 Global demand and supply forecasts and expected price developments

Molybdenum supply and demand forecasts are given in Figure A20.[a] Based on the existing mine

a *Mining Engineering*, October 2009. Molybdenum Supply Forecasting.

production, Roskill[a] and Mining Engineering[b] substantially agree that demand for molybdenum will start exceeding existing supply somewhere around the middle of the next decade. However, based on an estimated total future molybdenum production,[c] Mining Engineering foresees that the market surplus will last throughout the entire decade until 2020 when demand for molybdenum will start outstripping supply. This latter scenario is pictured in Figure A21.

Figure A19: Applications of Molybdenum – 2009(tonnes)



Source: Roskill (2010), Molybdenum Factsheet

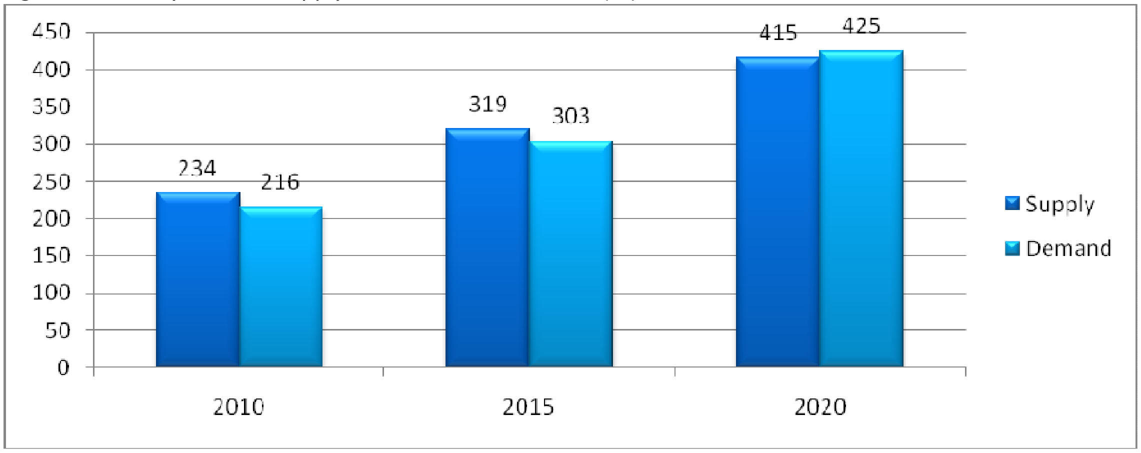
The assumptions underlying the forecast are:

- About 80% of molybdenum production is used as an alloying additive in steel
- A steady growth in molybdenum demand driven by higher steel consumption over the next decade (as forecast by Roskill)
- New mines opening around 2015 to meet growing molybdenum demand (as forecast by Mining Engineering).

Molybdenum prices have increased considerably over the past decade, even if the World Economic Crisis brought prices back to levels not seen since 2004. Given bullish demand projections, the current price recovery is expected to last through the first half of the coming decade, tough pressure is likely to ease in the second half as new capacity comes online.

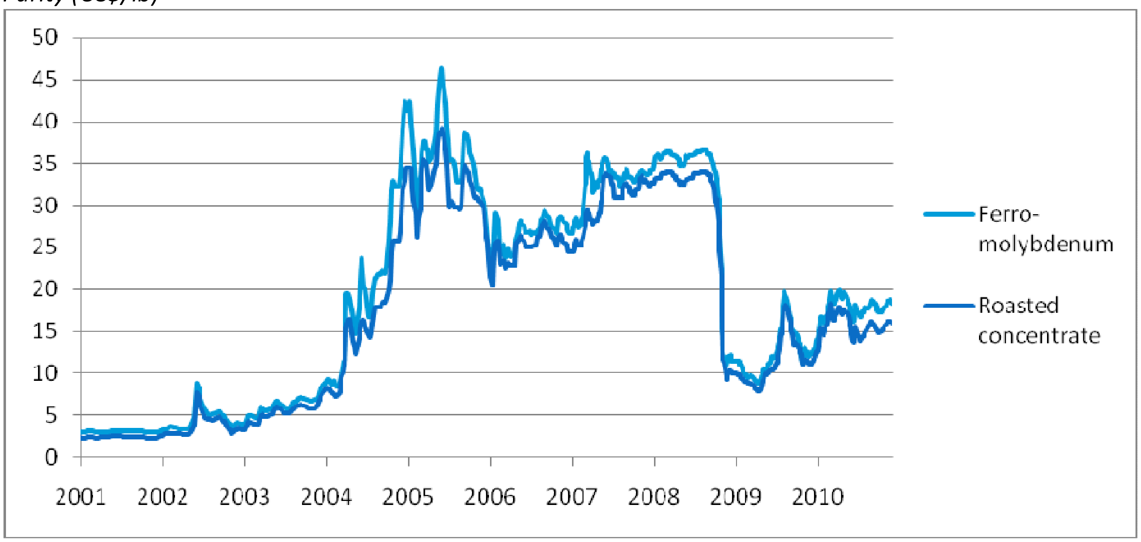
a Roskill, April 2010. Presentation: Global Molybdenum Market Outlook and Pricing. Minor Metals Conference.
b Mining Engineering, October 2009. Molybdenum Supply Forecasting.
c Which takes into account 30% and 70% of the potential output of possible and probable new mines respectively.

Figure A20: Molybdenum Supply and Demand Forecasts (kt)



Sources: Mining Engineering (October 2009), Molybdenum Supply Forecasting

Figure A21: Molybdenum Roasted Concentrate (Oxide) – 57% Purity & Ferro-molybdenum Prices – 65-70% Purity (US$/lb)



Source: Metal Pages (to end 2010)

A.3.7 Neodymium

A.3.7.1 Background

Neodymium (Nd) is the second most abundant rare earth metal in the earth's crust (after cerium) and is classed as a light rare earth element. It has a bright, silvery-white metallic lustre but quickly tarnishes in air and therefore must be either stored under oil or cast in plastic. If it stays exposed to the air, neodymium will quickly oxidize and the oxide layers will fall off exposing the metal to further oxidation. It has high magnetic strengths especially at low temperatures and is used in high performance magnets. Neodymium never occurs as a free element in nature but can be found in various minerals forming several brightly coloured salts.

A.3.7.2 Resources

Table A40 shows that China currently enjoys a virtual monopoly on the production of rare earth oxides, despite having just half of worldwide reserves. Further large reserves of rare earth elements can be found in the Commonwealth of Independent States (17%) and in the United States (12%). Within Europe, an estimated 1,000,000t of rare earth element reserves are known to be present in Norway at Kodal.[a] It is estimated that the total rare earth oxide reserves account for 110 million tonnes (Table A38).

An estimate of the world production of neodymium for 2010 was 21,307 tonnes, representing around 17% of world rare earth oxide supply.[b] This equates to around 18,260 tonnes of neodymium metal, which is the main production estimate used within the report. An alternative estimate put neodymium oxide new mine production at 19,096 tonnes for 2009.[c] Global reserves of neodymium are estimated to be 8 million tonnes.[d]

There is currently no neodymium production in Europe and quantitative estimates for European neodymium reserves are not available. However, it is reported that rare earth element resources, i.e. reserves that are currently considered as uneconomic for extraction, exist in Greenland (4.89 million tonnes),[e] Sweden (~500,000 tonnes)[f] and Finland (11,400 tonnes).[g]

Table A40: World Rare Earth Oxide (REO) Production and Reserves – 2010 (tonnes of REO content)

Country	Mine production (t)	Reserves (kt)
China	130,000	55,000
India	2,700	3,100
Brazil	550	48
Malaysia	350	30
Commonwealth of Independent States	n/a	19,000
United States	—	13,000
Australia	—	1,600
Other countries	n/a	22,000
World total (rounded)	**130,000**	**110,000**

Source: USGS (2011), Mineral Commodity Summaries

a Cassard, Daniel (BRGM)PROMINE database. (Personal communication)
b US Department of Energy, 2010. *Critical Materials Strategy*.
c Technology Metals Research, 2010. Annual Global Production of New Metal.
d Lenntech. *Neodymium*. Available at: http://www.lenntech.com/periodic/elements/nd.htm. [Accessed 01/02/2011].
e USGS, 2010. *The Principal Rare Earth Deposits in the United States: A Summary of Domestic Deposits and a Global Perspective.*
f European Commission, 2010. Critical raw materials for the EU, Annex V.
g Based on a conversation with Eilu Pasi, Senior Geoscientist at GTK Finland.

A.3.7.3 Dominant supplying countries and political risk

China dominates the current world supply of neodymium and other rare earth elements, with a share of 97% in 2009. China has imposed export restrictions on rare earth oxides (however not on the products made out of these oxides) and tightened export quotas progressively since 2004.[a] Further restrictions have been announced for the future. Given the total import dependence of Europe and the virtual supply-monopoly of China, political risks must be considered as extremely high.

Table A41: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3

Source: Fund for Peace

Table A42: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2

Source: World Bank

A.3.7.4 Process routes

Although neodymium is classed as a rare earth element it is widely distributed in the Earth's crust with an abundance of 38 ppm making it the 26th most abundant element.[b] It never appears naturally in its metallic form and is always accompanied by other rare earth elements and can be found in ore minerals such as monazite and bastnaesite with 10 to 18% of these mischmetals comprising of neodymium. Currently, most neodymium is extracted from bastnaesite, $(Ce,La,Nd,Pr)CO_3F$, and purified by solvent extraction. Ion-exchange purification is reserved for preparing the highest purities (typically >99.99 %).

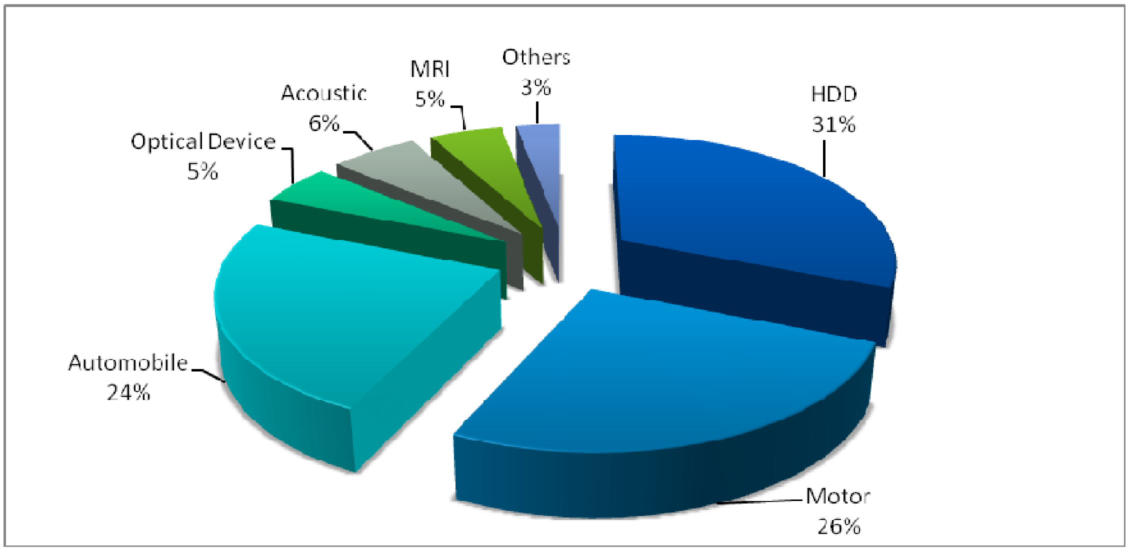
A.3.7.5 Applications

The main application for neodymium is as an alloy in high strength neodymium-iron-boron (NdFeB) magnets – the strongest permanent magnets currently available (typically containing 28% of neodymium by weight).[c] These magnets are used in generators, for example in wind turbines (included within "Motor" in Figure A22) or electric motors for hybrid cars; smaller magnets are used in computer hard discs, microphones, loudspeakers or in-ear headphones (Figure A22). Growth rates in the demand for rare earth elements in permanent magnets has been very strong, increasing from 5,500 tonnes in 2003

a OECD Workshop on Raw Materials , October 2009. Export restrictions on strategic raw material and their impact on trade and global supply.
b Emsley J., 2001. Nature's Building Blocks: An A-Z Guide to the Elements. New York: Oxford University Press Inc..
c Etsu, Shin, 2009. Presentation: Nd Magnet and Their Applications. 5th International Rare Earths Conference.

to 10,400 tonnes in 2008[a] (annual growth of 13.6%). In 2015, IMCOA forecast that over 90% of neodymium consumption for 2015 will be within permanent magnets.[b] Neodymium is also used in colour televisions, fluorescent lamps, energy-saving lamps and glasses. Adding neodymium to glass enables it to absorb the yellow sodium glare of flames and is therefore used in welding goggles. Neodymium-doped glass is also used in power lasers emitting infrared light. Similar to its use in glasses, neodymium salts are used as a colorant for enamels. "In the chemicals industry, neodymium oxide and nitrate are used as catalysts in the polymerisation of so-called dienes which are used in rubber manufacture."[c]

Figure A22: Applications of Neodymium Magnets, 2009 (%-tonnes)



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

A.3.7.6 Global demand and supply forecasts and expected price developments

Neodymium supply and demand forecasts (given in Figure A23) are both set to more than double over ten years. The significant supply shortage that currently exists for neodymium (9% of supply) is expected to continue, although the severity is forecast to lessen somewhat to around 3% of supply in 2013, before worsening to 12% by 2020.

The assumptions underlying these forecasts are:

- Global supply for neodymium was 21,300 tonnes in 2010
- IMCOA[d] forecasts for demand and supply until 2014
- Neodymium content remains constant at 16.2% of rare earth element supply, but demand represents 17.1% as forecast for 2014 by IMCOA
- Longer term supply assumes growth slowing to 3% per year for Chinese supply, but remaining at 20% per year for supply in the rest of the world[e]
- Longer term demand assumes a 9% per year growth rate, as modelled by Öko-Institut.[f]

Due to bullish demand, severe tightening of Chinese export quotas and continued uncertainty about China's future policy course, prices for neodymium oxide climbed considerably over the year 2010, reaching nearly US$90/kg by late 2010 (Figure A24a) and escalating rapidly by over 200% to $300/kg in the first half of 2011 alone (Figure A24b). Despite new production capacity being expected to come

a Ibid

b IMCOA. (Personal communication).

c Emsley J., 2001. *Nature's Building Blocks – An A-Z Guide to the Elements.* New York: Oxford University Press Inc..

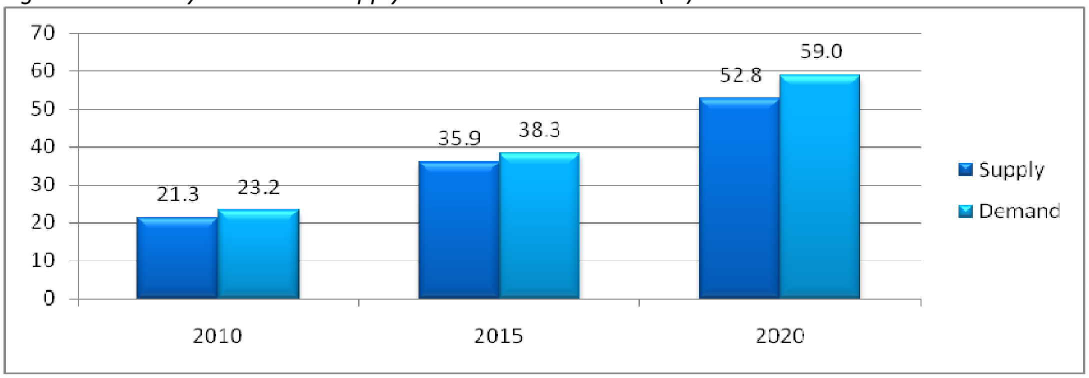
d IMCOA, 2009. *Presentation: Meeting Demand in 2014:The Critical Issues.* 5th International Rare Earths Conference, 2009.

e Oakdene Hollins for DfT, (2010). *Lanthanide Resources and Alternatives – Scenario 2.*

f Öko-Institut for UNEP ,2009. *Critical Metals for Future Sustainable Technologies and their Recycling Potential.*

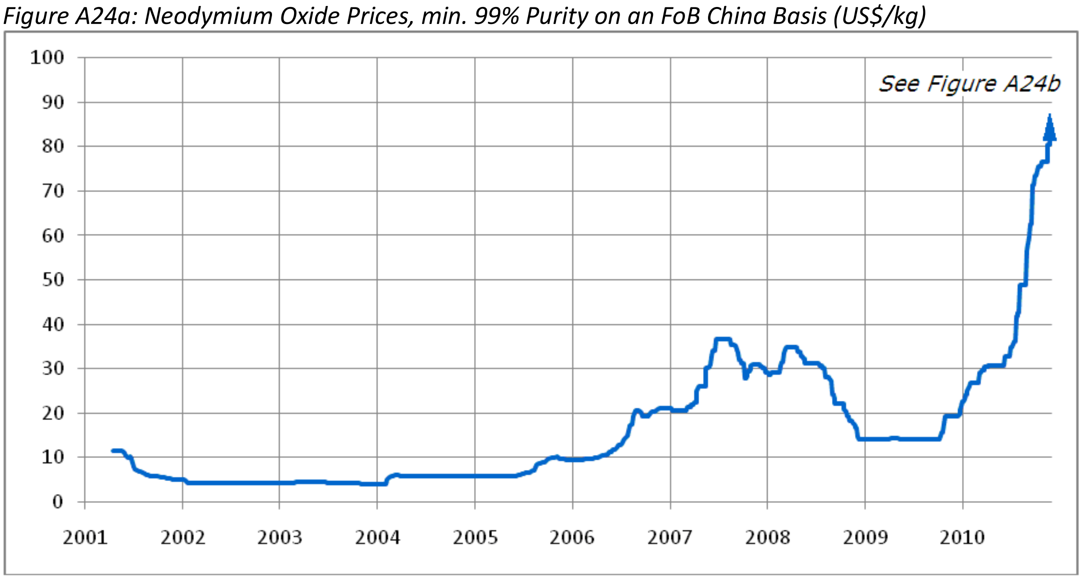
online outside of China over the coming years, pressure on prices is likely to remain due to high projected demand growth.

Figure A23: Neodymium Oxide Supply and Demand Forecasts (kt)



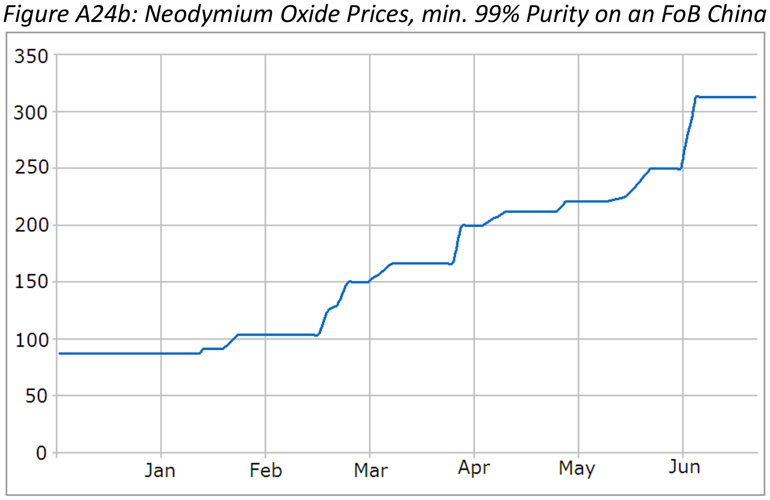
Sources: Own Calculations based on IMCOA, Öko-Institut

Figure A24a: Neodymium Oxide Prices, min. 99% Purity on an FoB China Basis (US$/kg)



Source: Metal Pages (to end 2010)

Figure A24b: Neodymium Oxide Prices, min. 99% Purity on an FoB China Basis (US$/kg) - 2011



Source: Metal Pages (2011)

A.3.8 Nickel

A.3.8.1 Background

Nickel (Ni) is a ferrous metal which is hard, ductile and malleable and has a high melting point. The metal has a silvery-white colour with a slight golden shade. Near room temperature, nickel is magnetic and has fairly low electrical and thermal conductivities. Some of the elements great qualities are its resistance to corrosion and oxidation and its strength at high temperatures. Nickel also has the ability to form alloys with many other metals.

A.3.8.2 Resources

In 2010, 1.55 million tonnes of nickel were produced. Russia, the world's largest supplier, produced 265,000 tonnes of nickel; followed by Indonesia, Philippines, Canada, Australia and New Caledonia. These six countries account together for 70% of world production. Nickel reserves were estimated to be 76 million tonnes, of which 24 million tonnes are located in Australia. Global nickel resources are estimated to be 130 million tonnes; 60% are in laterites and 40% are in magmatic sulphide deposits.[a] New Caledonia, a special collectivity of France, holds 9% of world nickel reserves. Small quantities of nickel reserves are found in Greece (0.7%), Spain (0.1%) and Finland.[b] In 2009, European mine output of nickel were estimated to be 9% of the world total, with the largest European producers being France (in New Caledonia) and Greece.[c]

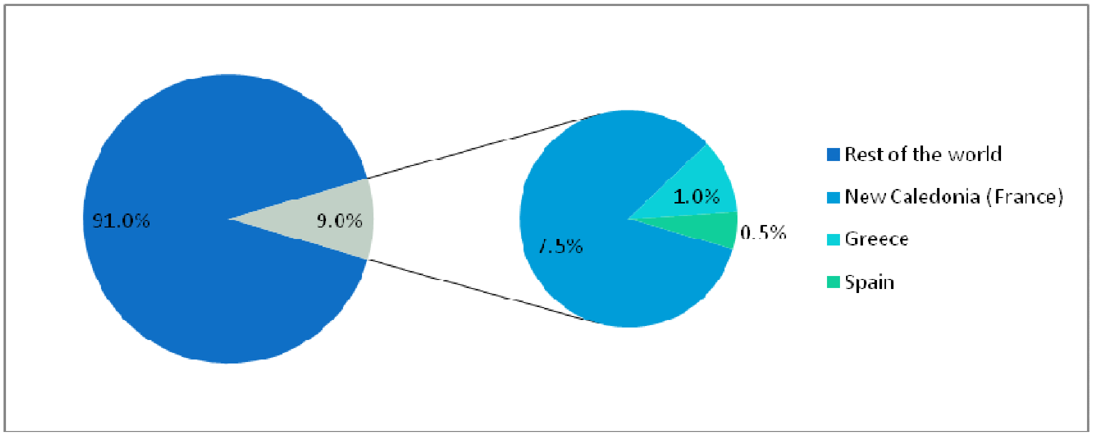
Table A43: World Nickel Production and Reserves – 2010 (tonnes of nickel content)

Country	Mine production (t)	Reserves (kt)
Russia	265,000	6,000
Indonesia	232,000	3,900
Philippines	156,000	1,100
Canada	155,000	3,800
Australia	139,000	24,000
New Caledonia	138,000	7,100
China	77,000	3,000
Cuba	74,000	5,500
Colombia	70,200	1,600
Brazil	66,200	8,700
South Africa	41,800	3,700
Botswana	32,400	490
Venezuela	14,300	490
Madagascar	7,500	1,300
Dominican Republic	3,100	960
Other countries	77,800	4,500
World total (rounded)	**1,550,000**	**76,000**

Source: USGS (2011), Mineral Commodity Summaries

a USGS, 2010. Mineral Commodity Summaries.
b Based on USGS, 2010. Mineral Commodity Summaries.
c Ibid

Figure A25: EU share of World Nickel Production – 2009 (tonnes of Nickel content)



Source: USGS (2010), Mineral Commodity Summaries

A.3.8.3 Dominant supplying countries and political risk

The substantial share of world nickel supply represented by Russia and Indonesia, which are together responsible for 32% of world nickel production, might pose risks on the long-term availability of nickel, as evidenced by their poor rankings in the tables below. Nonetheless, such risks are counterbalanced by a relatively diversified supply structure and significant production in Europe (9%).

Table A44: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
Russia	**71**	**80.8**	7.0	5.9	7.5	6.2	8.1	4.6	8.0	5.7	8.3	6.9	8.0	4.6
Indonesia	**62**	**84.1**	7.3	6.7	6.3	7.2	8.1	6.9	6.7	6.7	6.7	7.3	7.3	6.9
Philippines	**53**	**85.8**	7.2	6.3	7.5	7.2	7.6	6.0	8.5	6.1	7.0	7.7	7.9	6.8

Source: Fund for Peace

Table A45: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
Russia	**26.5**	22.3	21.7	44.8	35.2	23.6	11.4
Indonesia	**39.0**	48.3	24.1	46.7	42.9	34.4	28.1
Philippines	36.9	45.5	10.8	50.0	52.4	35.4	27.1

Source: World Bank

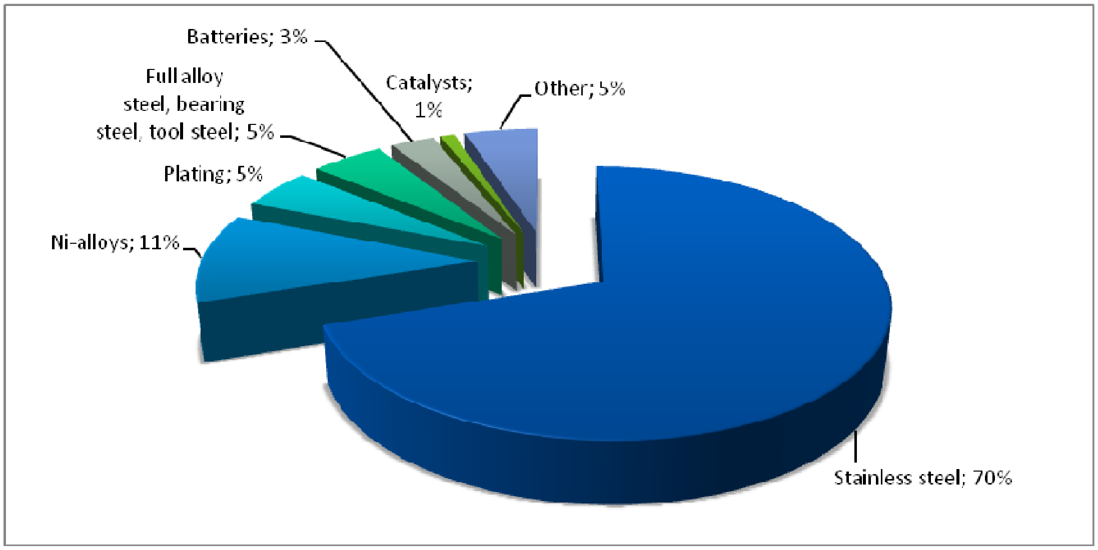
A.3.8.4 Process routes

Nickel's abundance in the earth's crust is 80-90 ppm but the largest deposits of the element are concentrated in the core, which makes it the fifth most common element on the planet. The majority of nickel is mined from two types of ore deposits – laterites and magmatic sulphides. Most known sulphide ores contain 0.2-2% of nickel but can also be as high as 8%. The average nickel content of nickel-bearing lateritic ores is 1-1.6%.[a] "Laterites currently account for around 70% of nickel contained in land-based deposits but contribute only 40% of world production".[b] In order to extract nickel from its ores, it needs to be conventionally roasted followed by multiple reduction processes – this yields a metal with a purity of 75% or more. A greater purification can be achieved through the Mond process resulting in a metal purity of 99.99%. Also, recycling nickel from scrap accounts for 41%.[c]

A.3.8.5 Applications

Due to nickel's corrosion-resistance and its ability as an alloy to increase strength, it is mainly used in the stainless steel production which accounts for 70%. About 11% of nickel is used as an alloy with non-ferrous metals and the remaining 19% are used in plating, especially in medical equipment and household cutlery, batteries, catalysts and other applications such as coins, magnets or electric guitar strings. It is also used as a green tint in glass.

Figure A26: Applications of Nickel – 2009 (tonnes)



Source: European Commission (2010), Critical raw materials for the EU, Annex V

A.3.8.6 Global demand, supply and price forecasts

Global demand and supply forecasts are available from MK Commodity Consulting (Figure A27). For 2010 the figures show a clear market surplus and, assuming that new nickel projects will come on stream as planned, market is projected to stay in surplus conditions until the middle of the decade. However, over the subsequent five year period (2015-2020), the nickel market is forecast to oscillate between small deficits and surpluses.

The assumptions underlying these forecasts are:

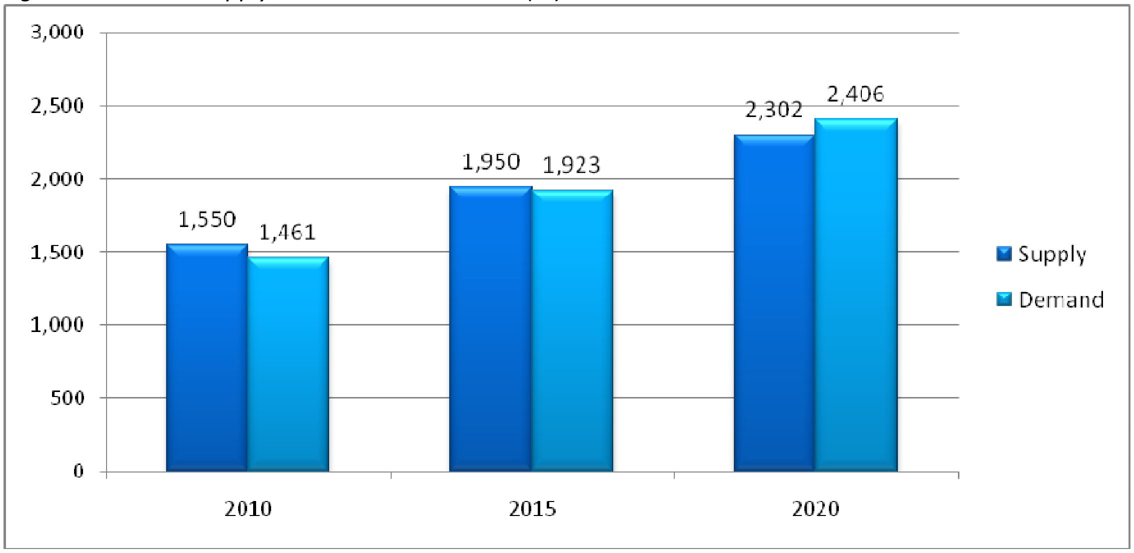
- 62% of nickel is used in stainless steel
- Stainless steel production growth in China has averaged 33% annually over the last ten years

a British Geological Survey, 2008. *Nickel.*
b Ibid
c European Commission, 2010. *Critical raw materials for the EU, Annex V.*

- China's nickel consumption is increasing rapidly driven by strong stainless steel demand (360,000 tonnes in 2008, 425,000 tonnes in 2009; 10-year CAGR of 25%)
- Domestic mines currently only supply about 20%
- New projects and extractions will reach the market.

The nickel price peaked in early 2007 and lost about 80% until the trough in early 2009 during the global recession. Prices have recovered considerably since and the upward trend is likely to continue early in the decade as small market deficits persist. Price pressure is then likely to ease towards the middle of the decade, before increasing again towards the end of the decade under the projected impact of rapid demand growth.

Figure A27: Nickel Supply and Demand Forecasts (kt)



Source: The Outlook for Nickel Dichotomies of the Fundamentals, Nov. 2010 by Marja Kirves/ MK Commodity Consulting

Figure A28: LME Nickel Cash Price (US$/tonne)

Source: Metal Pages (to end 2010)

A.3.9 Niobium (Columbium)

A.3.9.1 Background

Niobium (Nb), also called columbium, is the 41st element in the periodic table and can be described as ductile, grey, shiny and soft. It has many similarities to tantalum and both are often found in niobium minerals. Some of niobium's unique qualities are that it is superconductive, corrosion resistant and it is a very versatile additive used in alloys. Niobium is found in the minerals pyrochlore, the main commercial source for niobium, and columbite.

A.3.9.2 Resources

Brazil is by far the leading producer of niobium. In 2009, the two world's largest deposit of pyrochlore located in Araxá and Catalão, Brazil, produced 58,000 tonnes or 92% of the world's production, which the USGS puts at 63,000 tonnes. Most of the remaining 8% comes from the third biggest niobium mine located in Canada. Smaller quantities are being mined in Africa.[a]

The USGS estimates that Brazil's economic reserves of niobium stand at 2,900,000 tonnes and Canada's are 46,000 tonnes. However, according to the Tantalum-Niobium International Study Center, "the reserves [of niobium] are enough to supply current world demand for about 500 years; about 460 million tons".[b] Currently, there is no niobium production in Europe but an economic deposit of about 20,000 tonnes of niobium is known to exist in Norway.[c] Furthermore, large resources are known to exist in Finland.[d]

Table A46: World Niobium Production and Reserves – 2010 (tonnes of niobium content)

Country	Mine production	Reserves (kt)
Brazil	58,000	2,900
Canada	4,400	46
Other countries	600	n/a
World total (rounded)	**63,000**	**2,900**

Source: USGS (2011), Mineral Commodity Summaries

A.3.9.3 Dominant supplying countries and political risk

Although political risks for the dominant supplier (Brazil) are considered as moderate in both the Failed States Index and the Worldwide Governance Indicator (see Table A45 and Table A46), the political supply risk to Europe is rated here as high, given the extremely concentrated structure of global supply and Europe's total import dependence.

A.3.9.4 Process routes

Niobium's abundance in the Earth's crust is 20 ppm and it is primarily obtained from the mineral pyrochlore, but also from columbite and tantalum-bearing ores: however, only 10 to 15% of the niobium industry obtains its niobium from tantalum ores.[e] Niobium is also found in small quantities in slags resulting from smelting of some tin ores, tantalites, struverite and loparite. Niobium metal is either processed through converting niobium oxide into niobium ingots through aluminothermic reduction or by reduction in an electric arc furnace. The purified niobium is then converted into niobium hydroxide by the introduction of ammonia, followed by washing, filtration and calcining to the oxide. This separation process leads to purities exceeding 99.99% or more. Columbites are refined in the same way as tantalites

a The African producing countries are Democratic Republic of Congo, Ethiopia, Mozambique, Nigeria, Rwanda and Uganda.
b Vulcan, T., 2010. Niobium or Columbium? *Hard Assets Investor.*
c Cassard, Daniel. (BRGM)PROMINE database. (Personal communication)
d Ibid.
e Tantalum-Niobium International Study Center. *Niobium – Raw Materials and Processing*. Available at: http://tanb.org/niobium. [Accessed 01/02/2011].

but fluoride reduction is carried out with aluminium rather than sodium. "Niobium powders can be produced by the reduction of potassium niobium heptafluoride (K_2NbF_7) with sodium or by the reduction of niobium oxide with magnesium".[a]

Table A47: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimization of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
Brazil	**113**	**69.1**	6.4	3.9	6.4	5.0	8.9	4.1	6.4	6.0	5.6	6.9	5.1	4.4
Canada	**166**	**27.7**	3.3	2.4	3.0	2.1	4.7	2.0	1.7	1.2	2.1	1.1	2.4	1.7

Source: Fund for Peace

Table A48: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
Brazil	**55.8**	62.1	54.2	57.6	55.2	49.5	56.2
Canada	**94.5**	95.3	85.4	96.7	96.2	96.7	96.7

Source: World Bank

A.3.9.5 Applications

Due to niobium's characteristics it is mainly used in the steel industry (78%) as a superalloy in the form of ferro-niobium. High-strength, low-alloy steels containing niobium are used in automobiles, aeroplanes, and oil and gas pipelines. In addition, they are useful in structural purposes (22%), including bridges, buildings, nuclear reactors, railroad tracks and ship building. Superalloys which contain niobium are very heat resistant and are used in rocket and jet engines. In connection with titanium and tin, niobium is also used in superconducting magnets of MRI scanners. Niobium is also used in electronics, nuclear industry, optics and jewellery.

A.3.9.6 Global demand and supply forecasts and expected price developments

Niobium demand and supply forecasts are given in Figure A30. In the coming years niobium demand will be driven by the growing consumption of ferro-niobium (FeNb) in advanced metallurgical applications (High Strength Alloy Steel - HSLA). 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. Such expansion is forecast to reach its limit in 2012. However, increasing niobium prices will make new projects economical and from 2015, niobium production capacity is expected to start expanding again at the historical 1999-2010 CAGR of 8%. Under the above circumstances, niobium market will be in surplus conditions throughout the entire decade to 2020.

The assumptions underlying these forecasts are:

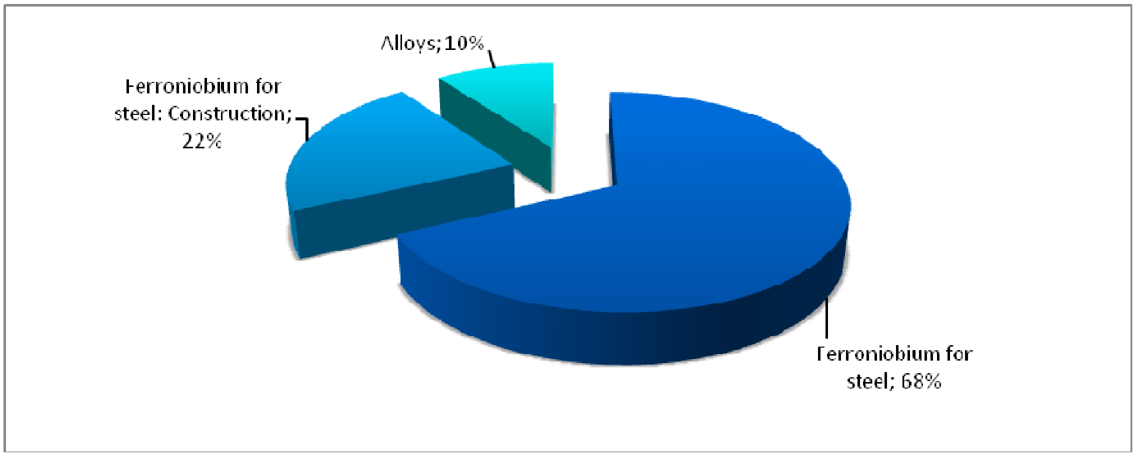
- About 90% of global niobium production is used as FeNb

a Tantalum-Niobium International Study Center. *Niobium – Raw Materials and Processing*. Available at: http://tanb.org/niobium. [Accessed 01/02/2011]

- Niobium demand will be driven by and follow the same growth rate of the demand for FeNb in the steel industry
- As forecast by IAMGOLD, FeNb demand is expected to grow at approximately 15% CAGR until 2014 supported by the recovery after the economic crisis[a]
- Over the period 2015-2020, a more conservative CAGR of 8% has been applied, based on projections for the HSLA market available from Byron Capital Market.[b]

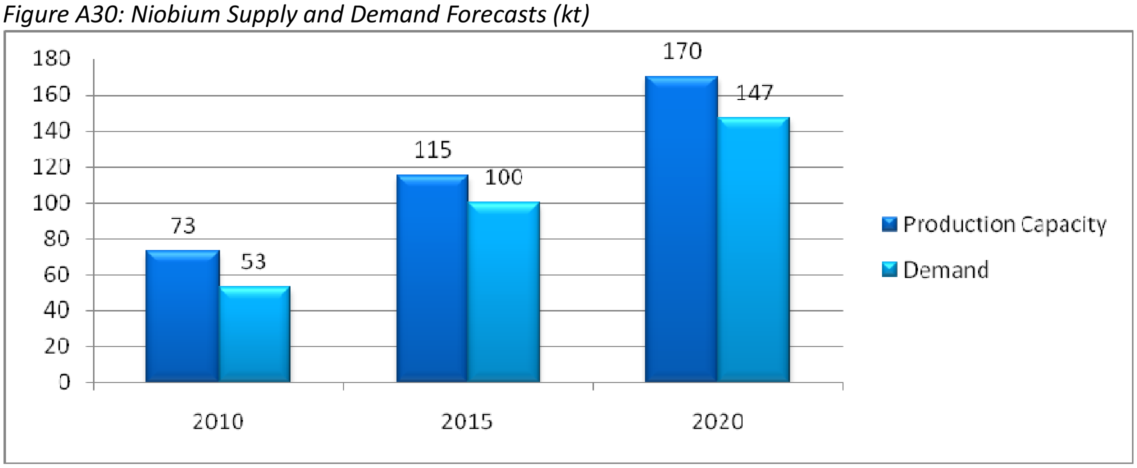
Prices for ferro-niobium have been stable over recent years at around $40/lb, having increased from $20/lb at the beginning of 2007 (Figure A30). Further price rises are likely over the coming decade in response to high growth rates in demand and the need for expensive investments to boost capacity.

Figure A29: Applications of Niobium (tonnes)



Source: European Commission (2010), Critical raw materials for the EU, Annex V

Figure A30: Niobium Supply and Demand Forecasts (kt)

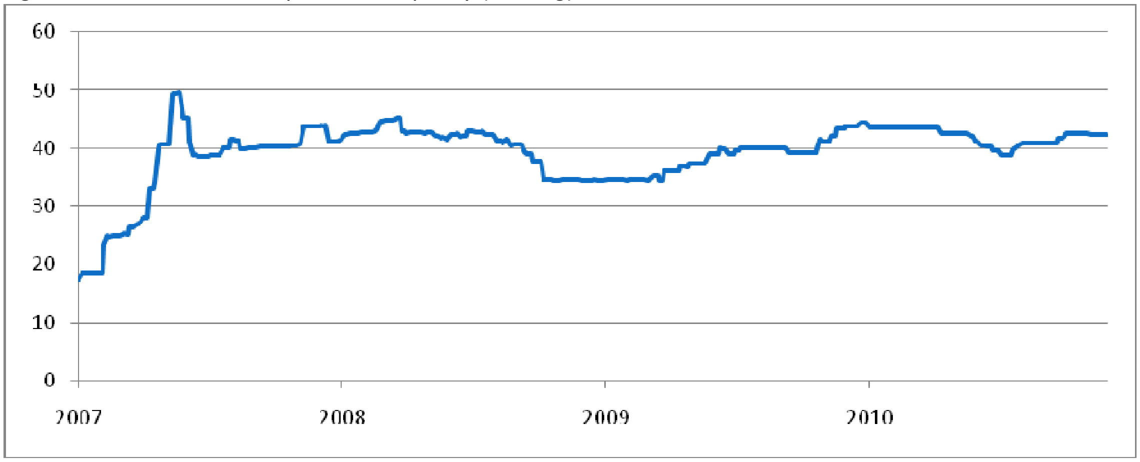


Sources: Iamgold Presentation and own calculations from Byron Capital Markets

a Byron Capital Markets, 2010. *Presentation: Lithium and Vanadium – The metals of the electric Revolution.* Objective Capital Rare Earths, Speciality and Minor Metals Investment Summit, March 2010.

b Iamgold Investor Presentation, June 2009. *Presentation: Niobec Tour*. Available at: http://www.iamgold.com/English/Investors/Presentations/default.aspx [Accessed 09/11/2010].

Figure A31: Ferro-niobium prices, 65% purity (US$/kg)



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

A.3.10 Selenium

A.3.10.1 Background

Selenium (Se) is a semi-conducting metalloid and shares many characteristics with sulphur and tellurium. Small amounts of selenium are considered to be beneficial for the human body but it can be toxic in larger quantities. The metal is the 69th most abundant element on Earth and it is rarely found in its pure state but often as a compound of other ores. Isolated selenium occurs in several different forms, of which a dense purplish-grey, semi-metal form is the most stable one. Selenium is well known for its conflicting attributes; it both adds and removes colour, oxidizes and deoxidizes and it can conduct electricity but it also non-conductive.

A.3.10.2 Resources

Table A47 presents global refinery production of selenium. The USGS estimates total world production of selenium of 3,000 to 3,500 tonnes, although the source of much of this production is not known.[a] In 2010, the largest known producer was Japan, followed by Germany, who together produced ca. 1,460 tonnes. Russia and Chile hold most of the global selenium reserves with 20,000 tonnes each of a total world reserve estimated to be 88,000 tonnes. In 2010, the EU27 accounted for at least 945 tonnes of selenium production, from Germany, Belgium and Finland. European selenium reserves are based on identified European copper deposits (Table A48). As for maximum availability, it is thought that copper anode slimes can provide an additional 4,600 tonnes of selenium.[b]

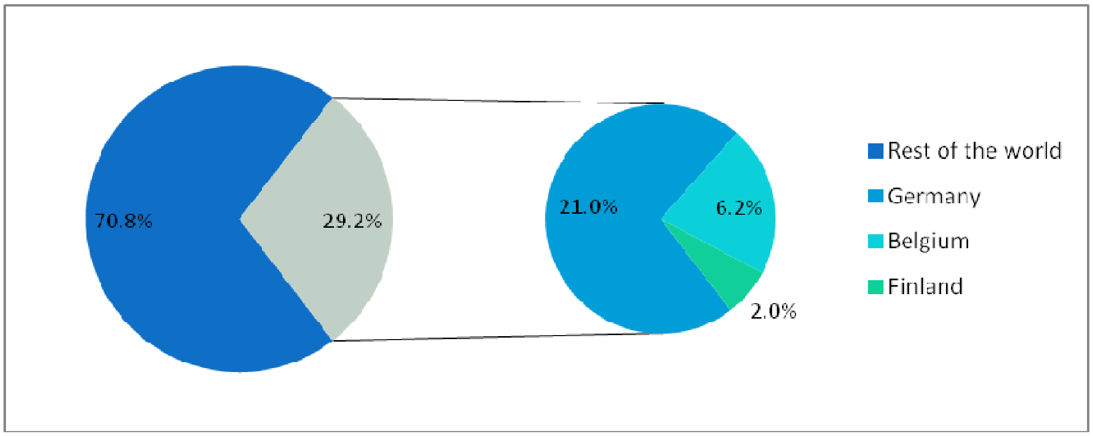
Table A49: World Selenium Refinery Production and Reserves in Selected Countries– 2010 (tonnes of selenium content)

Country	Refinery Production	Reserves
Japan	780	—
Germany	680	—
Belgium	200	—
Canada	170	6,000
Russia	140	20,000
Chile	70	20,000
Finland	65	—
Philippines	65	500
Peru	45	9,000
United States	W	10,000
Other countries	43	23,000
Unknown	992	—
World total (rounded)	**3,250**	**88,000**

W: Withheld to avoid disclosing company proprietary data
Source: USGS (2011), Mineral Commodity Summaries

a USGS, 2009. Minerals Yearbook: *Selenium and Tellurium*.
b Ibid

Figure A32: EU share of World Selenium Production – 2010



Source: USGS (2011), Mineral Commodity Summaries

Table A50: Estimates of European Selenium Reserves Based on Identified Copper Deposits

Country	European Copper Reserves (kt)	European Selenium Reserves (t)
Poland	26,000	6,500
Portugal	1,200	300
Spain	1,200	300
Sweden	900	225
Finland	200	50

Based on data obtained from Mr. Edelstein, copper expert at USGS

A.3.10.3 Dominant supplying countries and political risk

There are no significant political risks threatening the supply chain for selenium as production is relatively diversified and dominated by stable supplying countries (Table A49 and Table A50). Furthermore there exist considerable European reserves and sizable European production. Overall supply risk is therefore considered as low.

Table A51: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
Japan	**164**	**31.2**	4.2	1.1	3.8	2.0	2.5	3.1	2.0	1.2	3.4	2.0	2.0	3.9
Germany	**157**	**36.2**	3.5	3.9	4.9	2.8	4.9	3.2	2.3	1.9	2.5	2.1	1.8	2.4
Belgium	**162**	**33.5**	2.8	1.7	4.9	1.3	4.9	3.2	2.8	2.0	1.7	1.7	3.5	3.0

Source: Fund for Peace

Table A52: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
Japan	**84.6**	81.0	83.5	86.7	81.0	88.2	87.1
Germany	**90.1**	93.8	76.9	91.9	92.4	92.9	92.9
Belgium	**87.1**	94.8	74.1	90.5	86.7	88.7	91.0

Source: World Bank

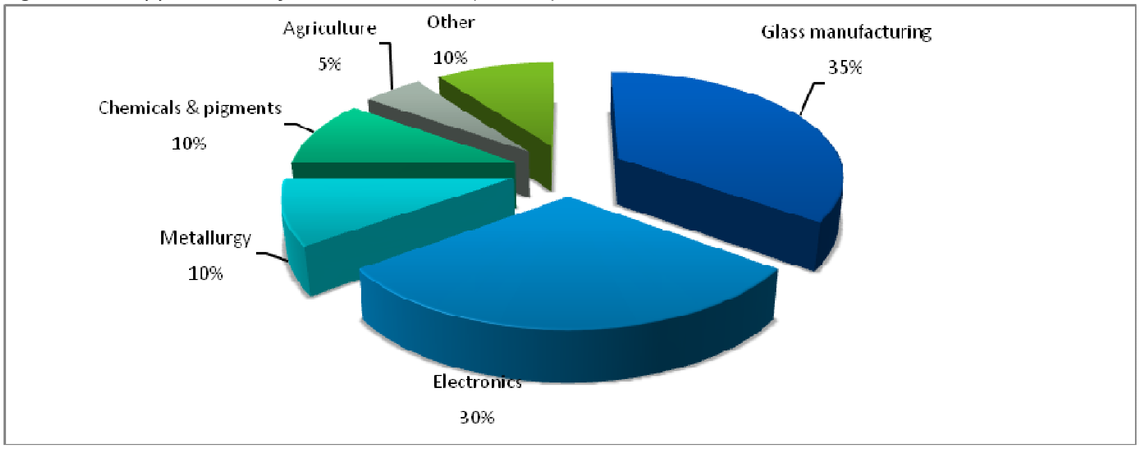
A.3.10.4 Process routes

Selenium is never found as a pure metal in nature and is widely distributed within the Earth's crust. Selenium's estimated overall abundance in the Earth's crust ranges from 0.03-0.08 ppm.[a] It most commonly occurs in sulphides of copper, iron and lead and is obtained as a by-product of their ores. About 90%[b] of primary selenium is recovered from anode slimes generated in the electrolytic refining of copper. "The selenium-containing slimes averaged 7% selenium by weight, with a few containing as much as 25% selenium".[c] Further treatment of the anode slimes leads to the extraction of elemental selenium. Coal also contains a relatively large amount of selenium (0.5 and 12 ppm)[d] but the recovery of selenium from coal does not appear likely in the foreseeable future.

A.3.10.5 Applications

Figures about the end-use of selenium vary but it can be said that the largest use of selenium worldwide is in glass manufacturing. According to the Selenium-Tellurium Development Association (STDA), 35% of selenium is being used in glass manufacturing mainly to decolorize the green tint caused by iron impurities in container glass. About 30% are used in electronics with a main focus on thin-film photovoltaic copper indium gallium diselenide (CIGS) solar cells and only some selenium is used on the replacement drums for older plain paper photocopiers. In metallurgy it is used, amongst others, as an additive to cast iron, copper, lead and steel alloys to improve machinability. Cadmium sulfoselenide pigments produce a ruby-red colour and are used in plastics, ceramics and glass. Selenium is also used as a fertiliser additive (5%) mainly in China and Australia to enrich selenium-poor soils.

Figure A33: Applications of Selenium - 2010 (tonnes)



Source: STDA Website, Sources of Selenium and Tellurium, available at URL: http://www.stda.org/se_te.html, [accessed 01/02/2011]

a Vulcan, T., 2010. Selenium: Contrary Stuff. *Hard Assets Investor*.
b Ibid
c USGS, 2010. 2009 Minerals Yearbook: *Selenium and Tellurium*
d USGS, 2010. Mineral Commodity Summaries.

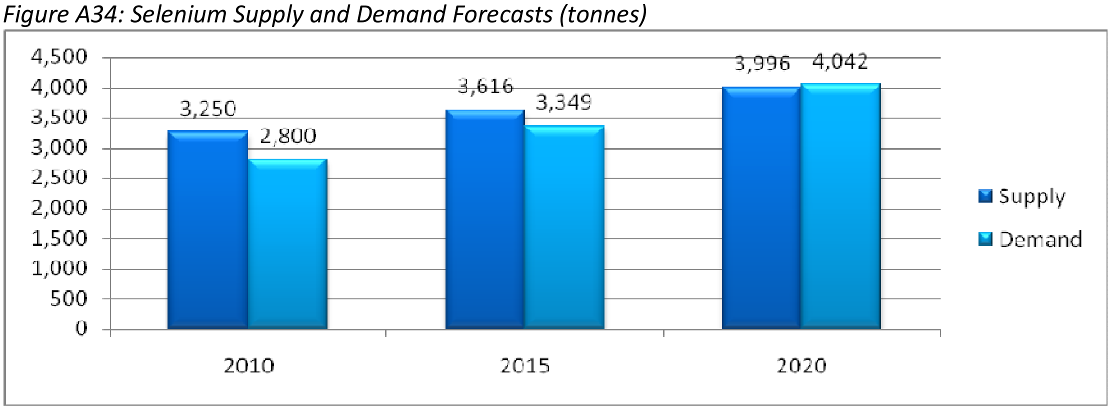
A.3.10.6 Global demand and supply forecasts and expected price developments

Selenium supply and demand forecasts are shown in Figure A34. Putting together USGS production estimates of 3,250 tonnes per year and current demand estimates from Global Industry Analysts of 2,800 tonnes per year;[a] then a surplus of selenium exists. This surplus is set to narrow over the next decade, moving the market into balance by 2020. Prices for selenium peaked above US$50/lb in 2005, although the general pattern of prices has been a range of US$15-50/lb over recent years (Figure A35). Prices have continued in this range, but recently in 2011, have increased further peaking at US$80/lb, and may increase further as supply to the market tightens.

The assumptions underlying the forecasts are:

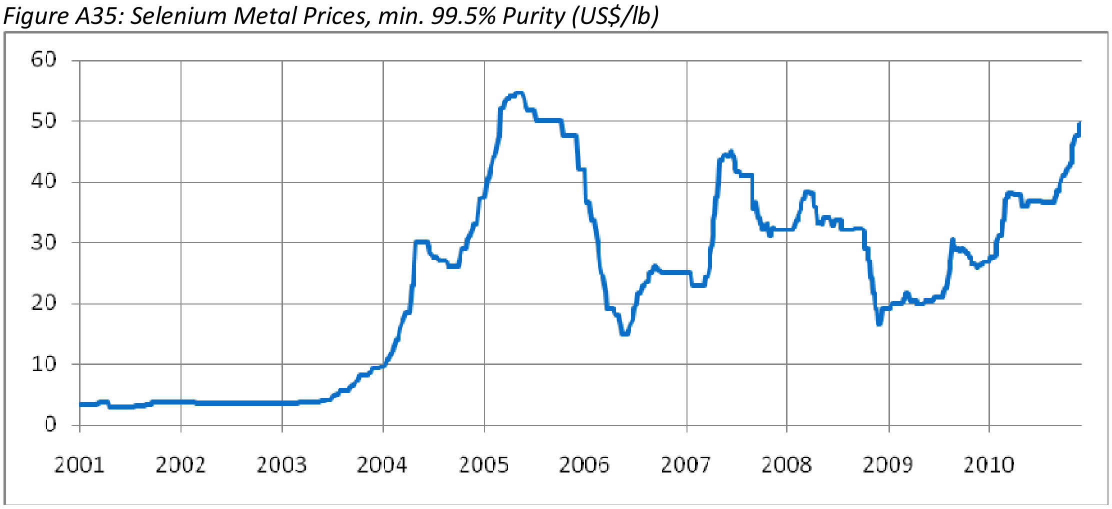
- Selenium supply from by-product copper sources tracks the trends in forecasted production for copper; with ppm of selenium extraction held constant (at around 173 ppm).
- Growth in the largest global market for selenium, glass manufacturing, is 3.6% p.a. as reported by Owens-Illinois, a major US container glass manufacturer for 2008-2013[b]
- For the solar fraction of electronics (11 tonnes in 2008),[c] a growth rate of 23% per year has been included, in line with the forecast for growth demand for gallium in the same solar cells
- Other electronics applications have been given a growth rate of 4% per year; with a 3% growth rate used for the remaining applications.

Figure A34: Selenium Supply and Demand Forecasts (tonnes)



Sources: Own Calculations based on USGS, Global Industry Analysts, Owens-Illinois, Umicore

Figure A35: Selenium Metal Prices, min. 99.5% Purity (US$/lb)



Source: Metal Pages (to end 2010)

a Global Industry Analysts in Metal Pages Research, 2008. *Selenium: Global Market Overview*.
b Owens-Illinois, November 2010. *Investor Presentation*. Available at: http://www.o-i.com/investor_relations_main.aspx. [Accessed 22/11/2011]
c Retorte, 2010. *Presentation Future usage of Se in CIGS*. Minor Metals Conference, April 2010.

A.3.11 Silver

A.3.11.1 Background

Like gold, silver (Ag) is soft, malleable and ductile; in fact, it is the most ductile of metals. Being one of the eight precious or noble metals, silver has the highest electrical and thermal conductivity of all metals. It has high photosensitivity to visible, X-ray and gamma-ray wavelengths in the electromagnetic spectrum and is chemically inert to oxygen. However, its use is restricted by its relatively high cost.

A.3.11.2 Resources

The total mine production of silver in 2010 was 22,200 tonnes worldwide with Peru, Mexico and China being the world's leading producers of silver, due to the fact that silver is mainly obtained as a by-product of copper and lead-zinc ores which are being mined in vast quantities in those countries. Between 1995 and 2008, world production of silver increased by 50% from 14,000 to 21,300 tonnes.[a]

Within Europe, Poland is a very important source of silver, providing 5% of the world mine production and over 40% percent of the EU's needs. Out of a total 510,000 tonnes of silver reserves worldwide, 64% can be found in Chile, Peru, Australia and Poland. In 2008, the EU32[b] were responsible for 8.5% of silver world production.[c] The USGS estimates silver reserves in Poland at 69,000t and does not provide any estimate for other European countries. The PROMINE project reports larger reserve figures for Poland, as well as relatively large reserves of silver in Spain and Sweden.[d] Quantitative estimates of reserves are not available for Sweden, Turkey and other European countries. Approximately one-fifth of the world silver market supply comes from recovering silver from scrap[e] but recycling rates vary significantly within the different usage sectors.

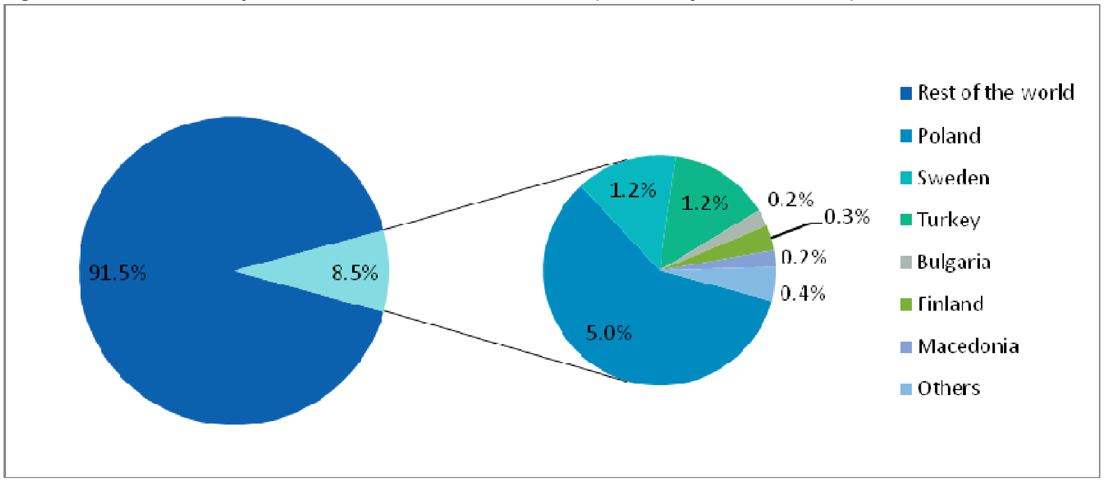
Table A53*: World Silver Production and Reserves – 2010 (tonnes of silver content)*

Country	Mine production	Reserves
Peru	4,000	120,000
Mexico	3,500	37,000
China	3,000	43,000
Australia	1,700	69,000
Chile	1,500	70,000
Russia	1,400	n/a
Bolivia	1,360	22,000
United States	1,280	25,000
Poland	1,200	69,000
Canada	700	7,000
Other countries	2,600	50,000
World total (rounded)	**22,200**	**510,000**

Source: USGS (2011), Mineral Commodity Summaries

a European Commission, 2010). Critical raw materials for the EU, Annex V.
b EU27, plus Iceland, Liechtenstein, Norway, Switzerland and Turkey.
c British Geological Survey, 2010. European Mineral Statistics 2004-2008.
d Cassard, Daniel. (BRGM)PROMINE database. (Personal communication)
e Butterman W.C. & Hilliard H.E., 2005. Mineral Commodity Profiles: Silver. USGS.

Figure A36: EU share of World Silver Production – 2009 (tonnes of silver content)



Source: British Geological Survey (2010), European Mineral Statistics 2004-2008

A.3.11.3 Dominant supplying countries and political risk

Silver production is fairly widespread throughout the world. Key suppliers such as Peru, China and Mexico (together controlling 47% of world silver supply) have relatively high political risks, but the diversified nature of global supply and the significant European production capacity still lead to an overall medium risk rating.

Table A54: Failed States Index - 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
Peru	**92**	**77.1**	6.6	4.5	6.4	7.3	8.2	5.6	6.9	6.3	5.5	7.2	6.9	5.7
Mexico	**98**	**75.4**	7.0	4.3	5.9	7.0	8.2	6.1	6.8	6.0	5.5	7.0	5.0	6.6
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3

Source: Fund for Peace

Table A55: World Bank – Worldwide Governance Indicator 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
Peru	**41.8**	50.2	17.9	43.3	63.8	30.2	45.2
Mexico	**46,8**	53.6	22.2	60.5	61.0	34.0	49.0
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2

Source: World Bank

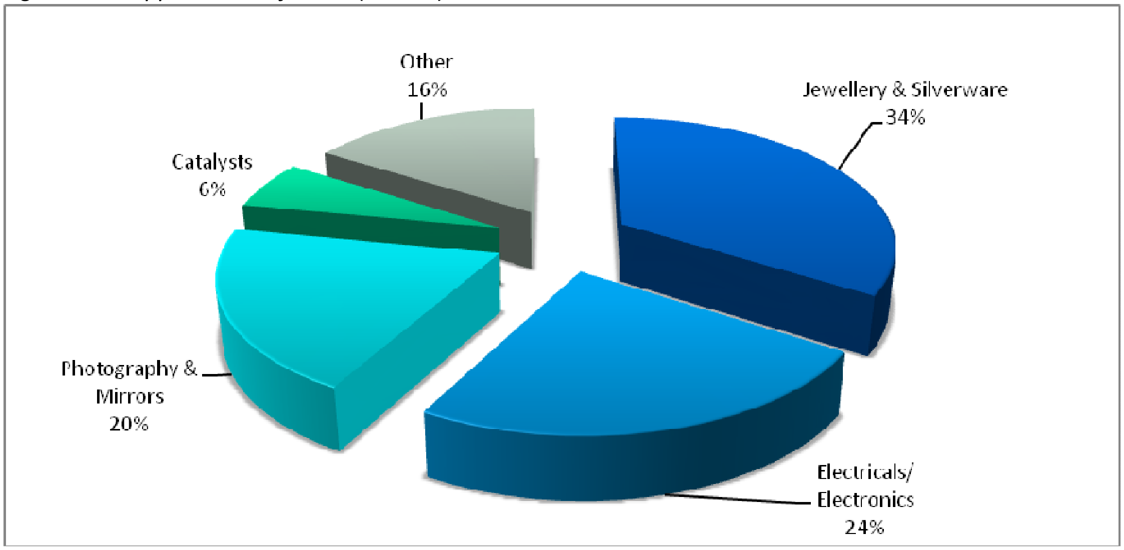
A.3.11.4 Process routes

The metal occurs naturally as an alloy with gold and other metals, and in minerals such as argentite and chlorargyrite. Only 30% of the processed silver comes from silver ores. The majority of the metal is being obtained as a by-product of lead and zinc ores (34%) and copper (23%). The remaining 12% are a by-product of gold ores.[a] In order to extract the silver from its ore it is crushed and then ground to free the sulphide ore minerals from the non-sulphide minerals. The two minerals are then separated by froth flotation. "In this process, the sulphide particles, which are hydrophobic, adhere preferentially to a froth of oily bubbles that floats to the surface of the flotation tank and is skimmed off and collected".[b] The purity of commercial-grade fine silver is at least 99.9% but higher purities are also available.

A.3.11.5 Applications

The largest amount of silver is used for non-industrial and decorative purposes, such as jewellery, silverware or coins accounting for more than one-third. Today, the industrial uses of silver (including photography), account for two-thirds of world silver consumption. About 24% of all silver is used in electrical and electronic equipment due to its high conductivity. Furthermore, 20% of silver is used in photography and mirrors and 6% in catalysis of chemical reactions. Solar energy (both photovoltaic and concentrated solar power) is included amongst "Other" (Figure A37).

Figure A37: Applications of Silver (tonnes)



Source: European Commission (2010), Critical raw materials for the EU, Annex V

A.3.11.6 Global demand and supply forecasts and expected price developments

Silver supply and demand forecasts are given in Figure A38. The market is forecast to remain roughly in balance until 2020, despite strong growth in new applications, such as solar, food hygiene and wound care because of the stability of demand in traditional applications.[c]

The assumptions underlying the supply forecast are:

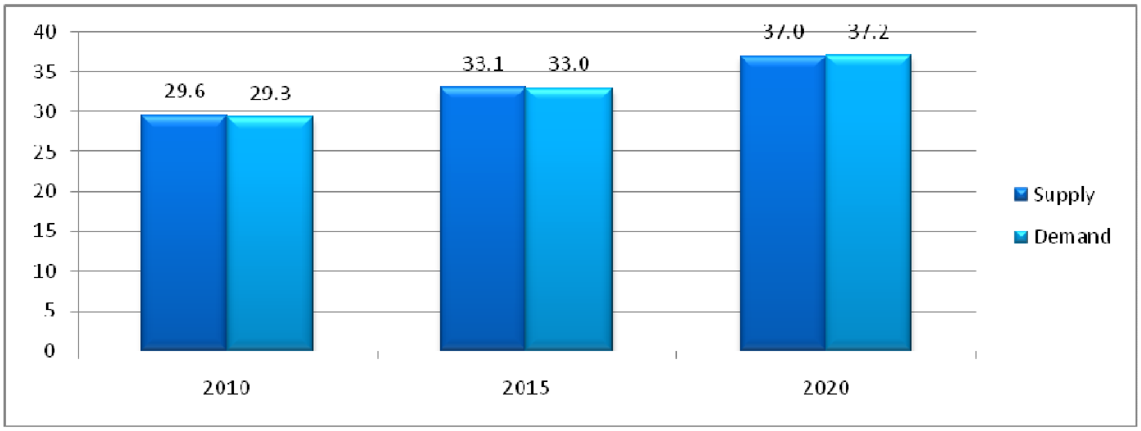
- Silver supply from co-product and by-product sources (gold, lead/zinc and copper) track the forecast production for these minerals, with ppm of silver extraction held constant
- Primary silver production grows at 3% per year
- Other sources of silver supply (scrap, government sources, etc.) are held constant.

Silver prices in recent years have mirrored the strong price increases seen in gold, with prices rising to US$30/ounce at the end of 2010 and rising significantly in 2011, as investors have sought security from currency risks amid the uncertainties associated with the Euro-zone sovereign debt crises. Prices have peaked at US$48/ounce, before falling back to US$35/ounce. Such speculative price moves due to silver's

a GFMS, 2010. World Silver Survey 2010.
b Butterman W.C. & Hilliard H.E., 2005. *Mineral Commodity Profiles: Silver*. USGS, Reston.
c Cross J., 2009. *Prospects for Silver Supply and Demand*, LBMA Precious Metals Conference.

role as a storage of value are likely to dominate the further development of prices, especially as underlying demand and supply fundamentals are roughly balanced.

Figure A38: Silver Supply and Demand Forecasts (kt)



Sources: Own Calculations based on Silver Institute, Economist Intelligence Unit, Silver Investor

Figure A39: Silver Metal Prices (US$/oz)

Source: Silver Price Website, available at URL: http://silverprice.org/silver-price-history.html, [accessed 5/12/10]

A.3.12 Tellurium

A.3.12.1 Background

Tellurium (Te) is a brittle, mildly toxic, silver-white metal which looks similar to tin. Tellurium, being 37 times rarer than platinum in the earth's crust, is closely associated with selenium, its periodic table neighbour, and the two metals are often found together. It is rarely found in its pure state but often found as a compound in ores of bismuth, copper, gold, lead, mercury, nickel, silver and zinc.

A.3.12.2 Resources

Due to secrecy, official data on the tellurium production are only available for a few states. In 2010, Japan, Russia, Canada and Peru produced 125 tonnes of tellurium and the estimated reserves of tellurium in copper deposits account to 22,000 tonnes with primary deposits known in China and Mexico. In 2009, experts estimated the global production of tellurium to be 450 to 500 tonnes,[a] explaining the large 'unknown' figure listed in Table A54. Here the higher estimate has been used, in line with that used by the US Department of Energy.[b] Estimates about the maximum theoretical global tellurium production, based on copper and lead production, vary between 1,630 and 1,700 and tonnes.[c] European tellurium reserves are based on identified European copper deposits (Table A55). Belgium, Germany and Finland are known to be significant European producers of tellurium, each of them accounting for approximately 20 tonnes of tellurium output annually.[d]

A.3.12.3 Dominant supplying countries and political risk

Ostensibly, the supply chain for tellurium seems not to be threatened by political risks. Despite the fact that precise figures for tellurium output and reserves are not available, it is clear that markets are relatively diversified and dominated by Western countries with relatively low political risks. Additionally, Europe produces significant amounts of tellurium.

Table A56*: World Tellurium Refinery Production and Reserves – 2010 (tonnes of tellurium content)*

Country	Refinery production	Reserves
Japan	40	—
Russia	35	n/a
Peru	30	2,300
Canada	20	700
United States	w[e]	3,000
Other countries	n/a	16,000
Unknown	375	—
World total (rounded)	**500**	**22,000**

w - Withheld to avoid disclosing company proprietary data.
Source: USGS (2011), Mineral Commodity Summaries

a USGS, 2010. 2009 Minerals Yearbook: Selenium and Tellurium & Öko-Institut for UNEP, 2009. Critical Metals for Future Sustainable Technologies and their Recycling Potential.
b US Department of Energy, 2010. Critical Materials Strategy.
c USGS, 2010. 2009 Minerals Yearbook: Selenium and Tellurium & Öko-Institut for UNEP, 2009. Critical Metals for Future Sustainable Technologies and their Recycling Potential.
d Hisshion, Daniel. Selenium-Tellurium Development Association. (Personal communication).
e For the US BGS report production of 50 tonnes for 2008. BGS, 2010. World Mineral Production 2004-2008.

Table A57: European Tellurium Reserves Based on Identified Copper Deposits

Country	European Copper Reserves (kt)	European Tellurium Reserves (t)
Poland	26,000	1,690
Portugal	1,200	78
Spain	1,200	78
Sweden	900	59
Finland	200	13

USGS 2010 – Based on a conversation with Mr. Edelstein, copper expert at USGS

Table A58: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
Japan	**164**	**31.2**	4.2	1.1	3.8	2.0	2.5	3.1	2.0	1.2	3.4	2.0	2.0	3.9
Russia	**71**	**80.8**	7.0	5.9	7.5	6.2	8.1	4.6	8.0	5.7	8.3	6.9	8.0	4.6
Peru	**92**	**77.1**	6.6	4.5	6.4	7.3	8.2	5.6	6.9	6.3	5.5	7.2	6.9	5.7
Canada	**166**	**27.7**	3.3	2.4	3.0	2.1	4.7	2.0	1.7	1.2	2.1	1.1	2.4	1.7

Source: Fund for Peace

Table A59: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
Japan	**84.6**	81.0	83.5	86.7	81.0	88.2	87.1
Russia	**26.5**	22.3	21.7	44.8	35.2	23.6	11.4
Peru	**41.8**	50.2	17.9	43.3	63.8	30.2	45.2
Canada	**94.5**	95.3	85.4	96.7	96.2	96.7	96.7

Source: World Bank

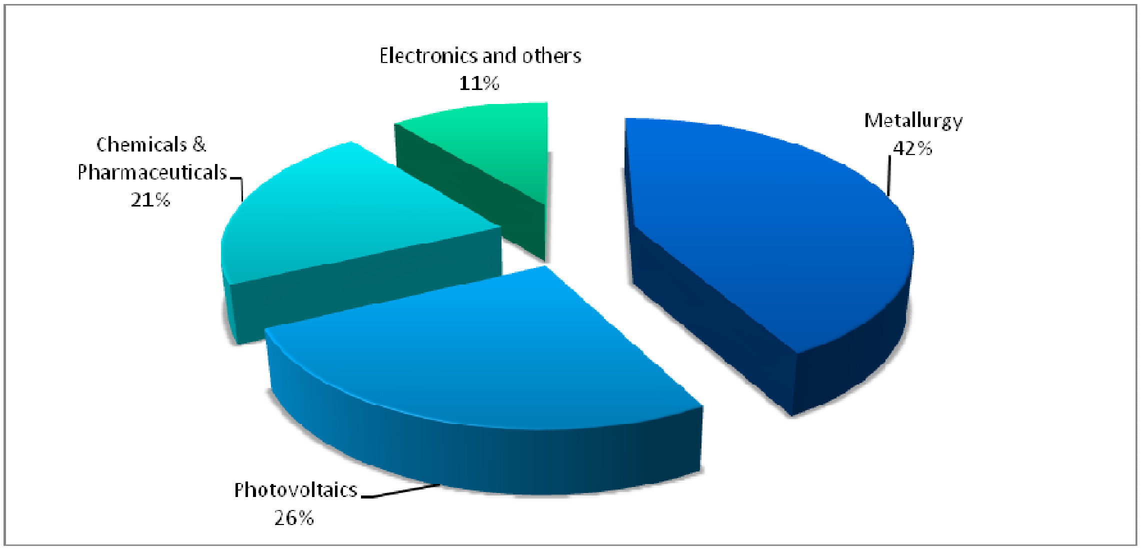
A.3.12.4 Process routes

Tellurium, an element widely distributed within the Earth's crust, does not occur in concentrations high enough to justify mining solely for its content. The element is mainly accumulated as a by-product during the copper refining process – but not all copper mines contain tellurium. More than 90% of tellurium is produced from anode slimes collected from electrolytic copper refining and 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.

A.3.12.5 Applications

Almost half of the total tellurium consumption is used as an alloying agent with steel and copper, where it improves machining characteristics. About 37% is used in photovoltaic and electronics for cadmium telluride (CdTe) solar panels, as well as in CDs, DVDs and 'phase change' memory chips. A further 21% of tellurium is used in chemicals and pharmaceuticals. Industrially, tellurium is used in catalysts and in the manufacture of synthetic fibres. A further important end-use of tellurium is in rubber manufacture, where it accelerates the vulcanising process.

Figure A40: Applications of Tellurium (tonnes)



Source: European Commission (2010), Critical raw materials for the EU, Annex V

A.3.12.6 Global demand and supply forecasts and expected price developments

Tellurium supply and demand forecasts are given in Figure A41. Tellurium is forecast to have a severe and worsening deficit – with demand predicted to be nearly three times larger than supply in 2020 due to strong growth in PV. The demand forecast is a growth of 10% per year and comes from Öko-Institut.[a]

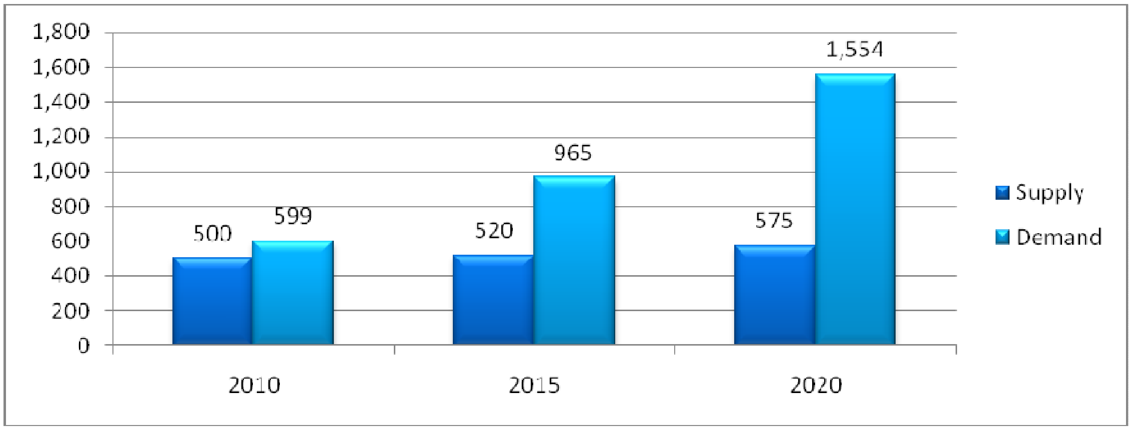
The assumptions underlying the supply forecast are:

- Primary tellurium production was 500 tonnes per year in 2010[b]
- The parts per million of tellurium extracted from copper remains constant at 25 ppm
- Tellurium supply tracks growth forecast for copper supply from the Economist Intelligence Unit.

Prices for tellurium almost doubled in 2010, rising from US$150/kg to near US$300/kg, and have increased significantly in 2011, peaking at US$425/ounce before falling back to below US$400/ounce. Given the extremely large demand deficits that are being projected for the coming decade, significant upward pressure on prices is to be expected.

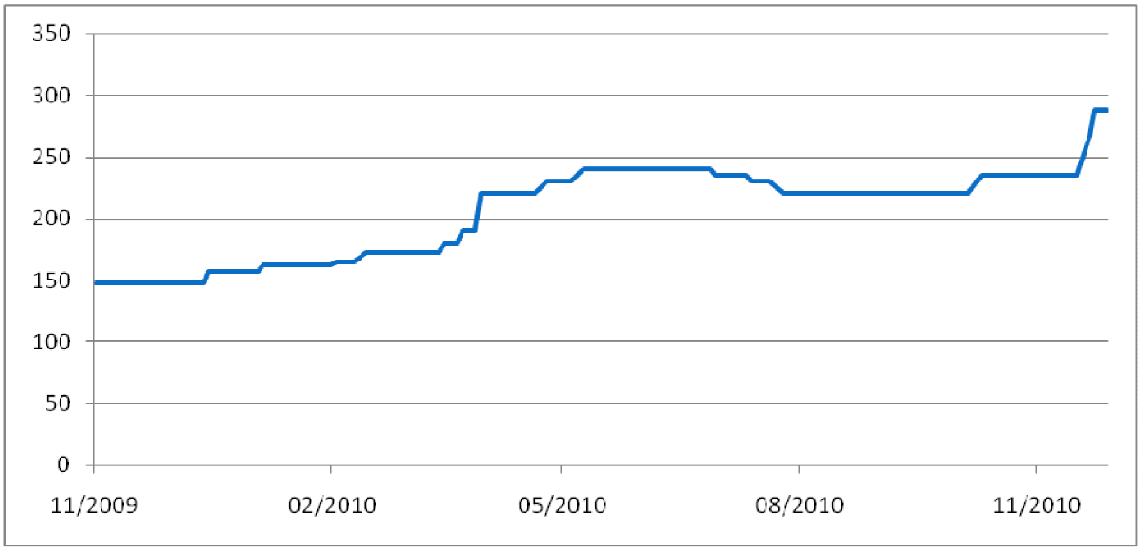
a Öko-Institut for UNEP, 2009. Critical Metals for Future Sustainable Technologies and their Recycling Potential.
b US Department of Energy, 2010). Critical Materials Strategy.

Figure A41: Tellurium Supply and Demand Forecasts (tonnes)



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

Figure A42: Tellurium Metal Prices, 99.99% Purity IWH Rotterdam (US$/kg)



Source: Metal Pages (to end 2010)

A.3.13 Tin

A.3.13.1 Background

Tin (Sn) shares many similarities with its neighbouring group elements germanium and lead. Tin has a silvery-white colour and is a malleable, ductile and a highly crystalline metal and resists corrosion. Tin exists in a metallic (β-tin) and non-metallic form (α-tin), also known as white and grey tin, depending on the temperature. Tin kept at room temperature or hotter is malleable (β-tin) but will turn brittle and lose all its metallic properties when cooled below 13.2 °C (α-tin).

A.3.13.2 Resources

China and Indonesia dominate the global tin production, accounting together for more than two-thirds of world production. There are several other large South American suppliers such as Peru, Bolivia and Brazil. World tin production in 2010 was estimated at 261,000 tonnes. Global reserves of tin are estimated to be 5.2 million tonnes and are sufficient to sustain recent annual production rates well into the future. Most of them are located in south-eastern Asia, Australia, Bolivia, Brazil, China and Russia. According to the ITRI, approximately 20% of tin world production comes from secondary tin representing an important source of the metal.[a] The recovery of tin through secondary production or recycling of scrap tin, is increasing rapidly.

Table A60*: World Tin Production and Reserves – 2010 (tonnes of tin content)*

Country	Mine production (t)	Reserves (kt)
China	115,000	1,500
Indonesia	60,000	800
Peru	38,000	710
Bolivia	16,000	400
Brazil	12,000	590
Congo (Kinshasa)	9,000	n/a
Vietnam	3,500	n/a
Australia	2,000	180
Malaysia	2,000	250
Russia	1,000	350
Portugal	100	70
Thailand	100	170
Other countries	2,000	180
World total (rounded)	**261,000**	**5,200**

Source: USGS (2011), Mineral Commodity Summaries

Portugal represents 1.3% of world tin reserves. USGS does not provide reserves estimates for any of the other EU32[b] countries.[c] Promine, however report the presence of tin reserves in Czech Republic, Spain and France.[d] In 2010, of the EU32 countries, only Portugal produced tin but only in very small quantities compared to the world total (100 out of 261,000 tonnes).

a USGS, 2010. 2008 Minerals Yearbook. *Tin.*
a EU27, plus Iceland, Liechtenstein, Norway, Switzerland and Turkey.
c Based on USGS, 2010. Mineral Commodity Summaries.
d Cassard, Daniel. BRGM PROMINE database. (Personal communication).

A.3.13.3 Dominant supplying countries and political risk

World tin production is fairly concentrated and takes place mainly in countries with high political risks, such as China, Indonesia and Peru, which together make up about 82% of world tin supply. Given that Europe is overwhelmingly dependent on imports, political risks for European tin supply are rated as high.

Table A61: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3
Indonesia	**62**	**84.1**	7.3	6.7	6.3	7.2	8.1	6.9	6.7	6.7	6.7	7.3	7.3	6.9
Peru	**92**	**77.1**	6.6	4.5	6.4	7.3	8.2	5.6	6.9	6.3	5.5	7.2	6.9	5.7

Source: Fund for Peace

Table A62: Worldwide Governance Indicator – 2009

Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2
Indonesia	**39.0**	48.3	24.1	46.7	42.9	34.4	28.1
Peru	**41.8**	50.2	17.9	43.3	63.8	30.2	45.2

Source: World Bank

A.3.13.4 Process routes

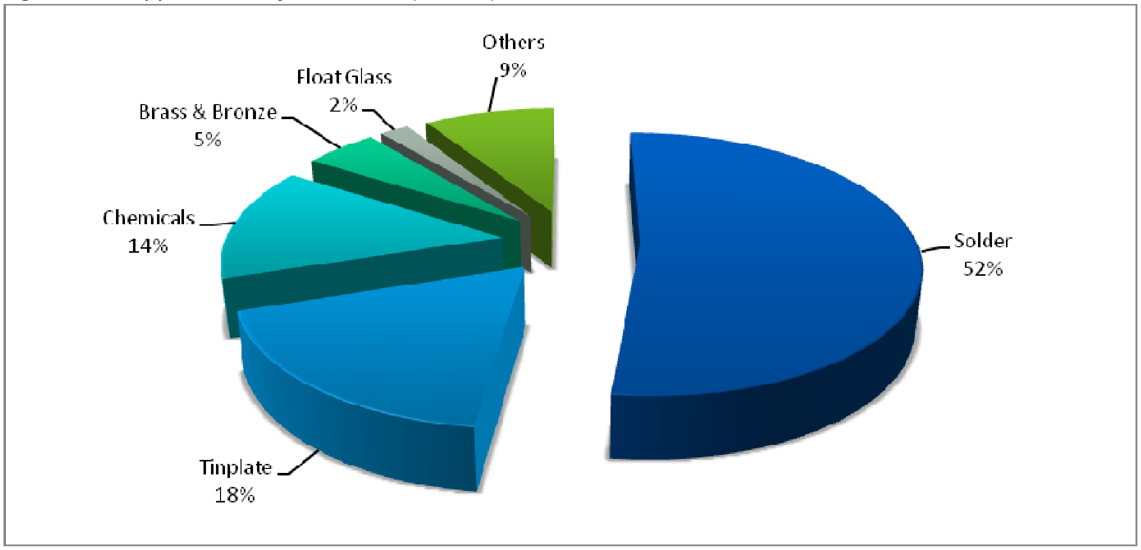
Tin's average concentration in the earth's crust is 2 ppm which makes it the 49th most abundant element. Tin does not occur naturally by itself but nine tin-bearing ores can be found in the Earth's crust of which only cassiterite is being mined excessively. Ores contain 0.015-1.0% tin by weight depending on the amount of impurities found in the ores and over 80% of the world's tin is found in these low-grade gravel deposits.[a]

A.3.13.5 Applications

According to ITRI, electronic solder accounted for 52% of all refined tin usage in 2009. Due to tin's corrosion resistance, it is often used as plating on steel sheets used for cans or food containers (18%). Another 14% are used in chemicals and the remaining 16% are in brass and bronze, as well as float glass production.

a How Products Are Made Website. Tin. Available at: http://www.madehow.com/Volume-4/Tin.html. [Accessed 01/02/2011].

Figure A43: Applications of Tin – 2009 (tonnes)



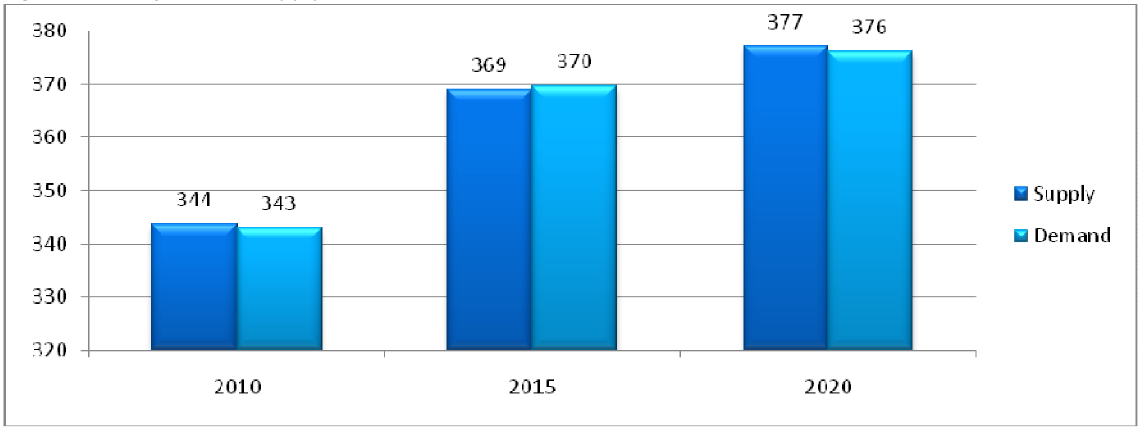
Source: ITRI Website, Data on Tin Use, available at URL: http://www.itri.co.uk/pooled/articles/BF_TECHART/view.asp?Q=BF_TECHART_318717, [accessed 01/02/2011]

A.3.13.6 Global demand and supply forecast and expected price developments

Tin supply and demand forecasts are given in Figure A44. The market is forecast to remain roughly in balance until 2020 based on the long-term growth indicated in the production and consumption of refined tin indicated in forecasts from the Economist Intelligence Unit.

Prices for tin peaked at around US$23,000/t in July 2008 and more recently in 2010 at around US$27,000/t, having fallen off to around US$10,000/t in the intervening period (Figure A45). Given the current tight markets, a further upward trend in prices is to be expected, which is likely to get reinforced towards the middle of the decade as the market moves increasingly towards a small deficit. Price pressures are only expected to ease towards the end of the decade.

Figure A44: Refined Tin Supply and Demand Forecasts (kt)



Source: Own Calculations based on Economist Intelligence Unit

Figure A45: LME Tin Cash Price (US$/t)

Source: Metal Pages (to end 2010)

A.3.14 Vanadium

A.3.14.1 Background

Vanadium (V) is a soft, silver-grey, ductile transition metal which is chemically similar to tantalum and niobium. Vanadium is the 17th most common element on earth and is used primarily as a steel hardener and strengthening agent imparting toughness and wear resistance. Adding small amounts of vanadium to steel leads to good castability, good rollability, reduced roll wear, relative insensitivity to finish rolling temperatures in structural steels and good weldability of structural steels. Furthermore, the formation of an oxide layer stabilizes the metal against oxidation.

A.3.14.2 Resources

Vanadium production is dominated by China, South Africa and Russia. Together they produced 98% of global vanadium supply in 2009. About 10 million tonnes of all vanadium reserves can be found in China and Russia and another 3.5 million tonnes in South Africa. With reserves adding up to a total of 13.6 million tonnes worldwide, the demand of vanadium can be met for at least another century at the present rate of consumption. There is no vanadium production in Europe,[a] but approximately 600,000t of vanadium reserves are known to be present in Norway while significant resources are reported for Finland.[b]

Table A63: World Vanadium Production and Reserves – 2010 (tonnes of vanadium content)

Country	Mine production (t)	Reserves (kt)
China	23,000	5,100
South Africa	18,000	3,500
Russia	14,000	5,000
United States	W	45
Other countries	1,000	n/a
World total (rounded)	**56,000**	**13,600**

Source: USGS (2011), Mineral Commodity Summaries

A.3.14.3 Dominant supplying countries and political risk

Table A62 and Table A63 display the political risks for the world's leading nations in vanadium production. As Europe is currently entirely import dependent and vanadium supply is controlled by three countries with relatively high political risks, overall political risks must be considered as high.

A.3.14.4 Process routes

Vanadium occurs in deposits of phosphate rock, titaniferous magnetite and uraniferous sandstone and siltstone. Significant amounts are also present in bauxite and carboniferous materials, such as coal, crude oil, oil shale and tar sands. Vanadium is usually recovered as a by- or co-product and can be recovered from catalysts, minerals and most importantly slags. Vanadium-bearing slags, generated from iron or uranium processing, can contain 10-25% vanadium pentoxide (V_2O_5). Vanadium recovered from slags is then either converted into ferro-vanadium or vanadates and vanadium oxides. About 56% of vanadium is obtained from slag processing. Another important source of vanadium is minerals, of which more than 60 contain vanadium. About 43% of vanadium production comes from minerals and only 1% is obtained from reprocessed catalysts.

a BGS, 2010. European Mineral Statistics 2004-2008.
b Cassard, Daniel. BRGM PROMINE database. (Personal communication)

Table A64: Failed States Index – 2009

Country	**Rank**	**Total**	Demographic Pressures	Refugees and IDPs	Group Grievance	Human Flight	Uneven Economic Development	Economic Decline	Delegitimisation of the State	Public Services	Human Rights	Security Apparatus	Factionalized Elites	External Intervention
China	**57**	**84.6**	9.0	6.8	7.9	6.1	9.2	4.5	8.5	7.2	8.9	6.0	7.2	3.3
South Africa	**122**	**67.4**	8.4	7.4	5.3	4.3	8.5	4.6	5.5	5.7	4.5	4.3	5.9	3.0
Russia	**71**	**80.8**	7.0	5.9	7.5	6.2	8.1	4.6	8.0	5.7	8.3	6.9	8.0	4.6

Source: Fund for Peace

Table A65: Worldwide Governance Indicator – 2009

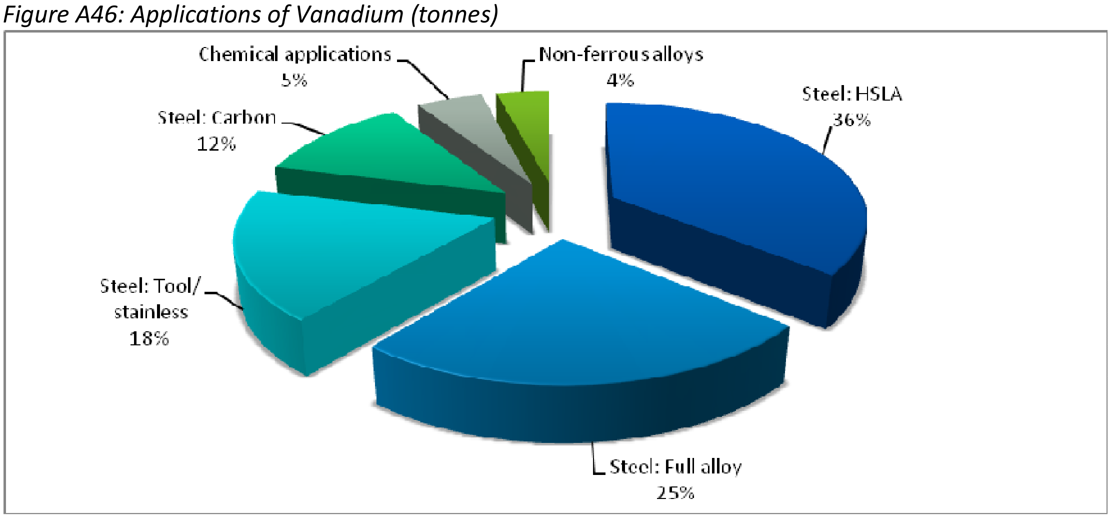
Country	**Average**	Voice & Accountability	Political Stability	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption
China	**36.8**	5.2	29.7	58.1	46.2	45.3	36.2
South Africa	**59.8**	66.4	44.3	67.6	64.3	56.1	60.5
Russia	**26.5**	22.3	21.7	44.8	35.2	23.6	11.4

Source: World Bank

A.3.14.5 Applications

Just over 90% of vanadium's current production is used as a hardening agent in steel and iron used for tools or automobiles adding strength and reliability to the material. Vanadium alloys enable steel to be used effectively at extremes of both high and low temperature. Titanium-aluminium-vanadium alloys are used in jet engines and high-speed airframes. The major non-metallurgical use is for catalysts sulphuric acid and maleic-anhydride production.

Figure A46: Applications of Vanadium (tonnes)



Source: European Commission (2010), Critical raw materials for the EU, Annex V

A.3.14.6 Global demand and supply forecast and expected price developments

A strong rise in vanadium demand will be only partly driven by a steady growth in steel demand (6% average annual growth for steel and 8% average annual growth for High steel).[a] New applications for vanadium have been recently discovered and non-metallurgical usage of vanadium is now rising at the same rate as GDP. The supply projections presented in Figure A47 must be considered as optimistic as they assume that all currently planned vanadium projects will come on stream to meet increasing demand. Under these conditions, the market would remain in considerable surplus throughout the whole 2010-2020 decade.[b]

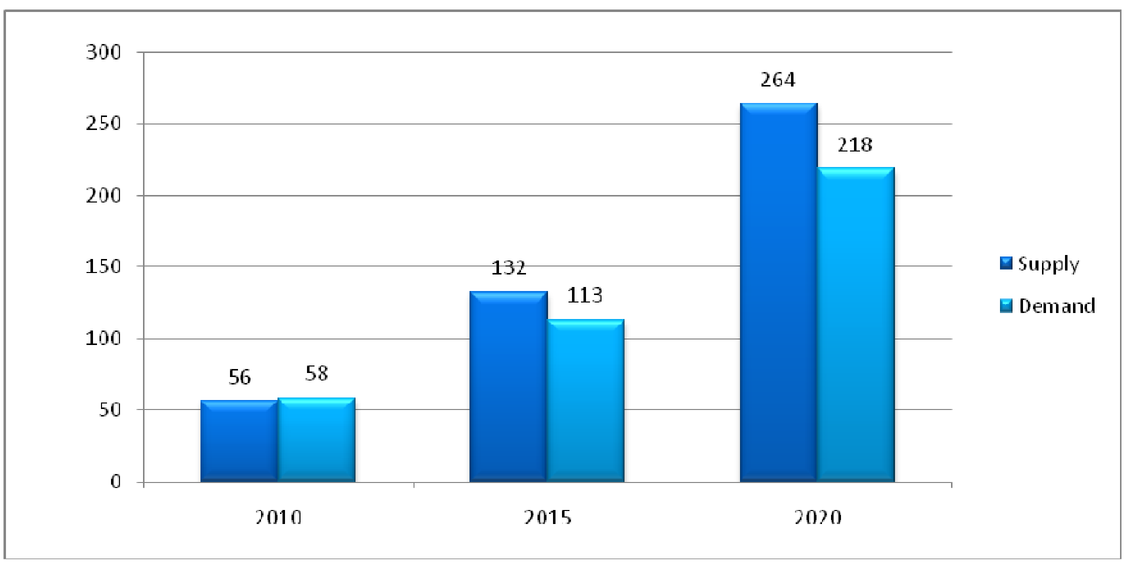
The assumptions of the forecast by Byron Capital Market are:

- Steel growth is rising rapidly; the World Steel Association estimates demand fell 8.6% in 2009, but is slated to rise 9.2% in 2010; Macquarie estimates steel demand will be up by nearly 6% per year thereafter, high grade steels by 8%
- Non-metallurgical usage rising at rates of GDP
- Li-ion battery use is a potential strong driver for new demand; $Li_3V_2(PO_4)_3$ is the highest voltage, highest energy cathode identified for Li-ion batteries
- Grid-level storage using vanadium redox flow batteries could grow to rival any other demand, but over time
- All projects and extractions reach the market.

From 2015 to 2020, it has been assumed that the average growth rate for 2010-2015 will continue for both supply and demand (respectively 14.8% and 14.1%).

Given the forecast for supply and demand presented above, the long-term downward trend of vanadium is likely to continue as over-production weighs on prices. Temporary spikes as witnessed in early 2005 and again in 2008 might nonetheless occur if the expansion of supply runs less smoothly than assumed in the forecast.

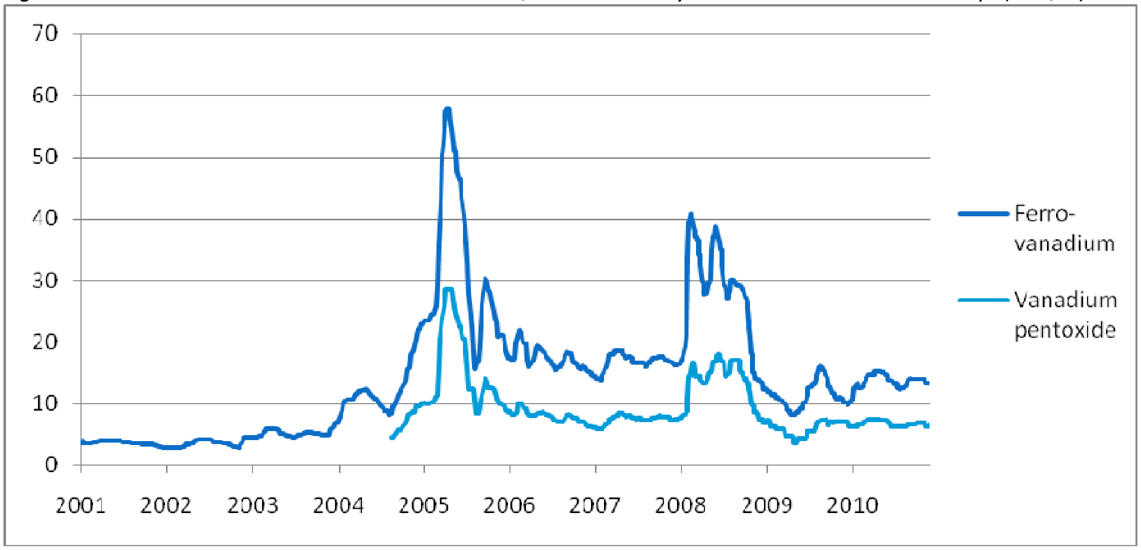
Figure A47: Vanadium Supply and Demand Forecasts (kt)



Source: Byron Capital Market (presentation)

a Macquarie, 2010. *Byron Capital Markets Presentation: Lithium and Vanadium – The metals of the electric Revolution.* Objective Capital Rare Earths, Speciality and Minor Metals Investment Summit, March 2010.
b Forecast based on Byron Capital Markets Presentation:*Lithium and Vanadium – The Metals Of The Electric Revolution.* Objective Capital Rare Earths, Speciality and Minor Metals Investment Summit, March 2010.

Figure A48: Vanadium Pentoxide Fused Flake Prices, min.98% Purity & Ferrovanadium 78-82% d.p. (US$/lb)



Source: Metal Pages (to end 2010)

European Commission

EUR 24884 EN – Joint Research Centre – Institute for Energy and Transport
Title: Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies
Author(s): R.L.Moss, E.Tzimas, H.Kara, P.Willis and J.Kooroshy
Luxembourg: Publications Office of the European Union
2011 – 162 pp. – 21.0 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-20698-6
doi: 10.2790/35600

Abstract

Due to the rapid growth in demand for certain materials, compounded by political risks associated with the geographical concentration of the supply of them, a shortage of these materials could be a potential bottleneck to the deployment of low-carbon energy technologies. In order to assess whether such shortages could jeopardise the objectives of the EU's Strategic Energy Technology Plan (SET-Plan), an improved understanding of these risks is vital. In particular, this report examines the use of metals in the six low-carbon energy technologies of SET-Plan, namely: nuclear, solar, wind, bioenergy, carbon capture and storage (CCS) and electricity grids. The study looks at the average annual demand for each metal for the deployment of the technologies in Europe between 2020 and 2030. The demand of each metal is compared to the respective global production volume in 2010. This ratio (expressed as a percentage) allows comparing the *relative* stress that the deployment of the six technologies in Europe is expected to create on the global supplies for these different metals. The study identifies 14 metals for which the deployment of the six technologies will require 1% or more (and in some cases, much more) of current world supply per annum between 2020 and 2030. These 14 metals, in order of decreasing demand, are tellurium, indium, tin, hafnium, silver, dysprosium, gallium, neodymium, cadmium, nickel, molybdenum, vanadium, niobium and selenium. The metals are examined further in terms of the risks of meeting the anticipated demand by analysing in detail the likelihood of rapid future global demand growth, limitations to expanding supply in the short to medium term, and the concentration of supply and political risks associated with key suppliers. The report pinpoints 5 of the 14 metals to be at high risk, namely: the rare earth metals neodymium and dysprosium, and the by-products (from the processing of other metals) indium, tellurium and gallium. The report explores a set of potential mitigation strategies, ranging from expanding European output, increasing recycling and reuse to reducing waste and finding substitutes for these metals in their main applications. A number of recommendations are provided which include:

- ensuring that materials used in significant quantities are included in the Raw Materials Yearbook proposed by the Raw Materials Initiative *ad hoc* Working Group,
- the publication of regular studies on supply and demand for critical metals,
- efforts to ensure reliable supply of ore concentrates at competitive prices,
- promoting R&D and demonstration projects on new lower cost separation processes, particularly those from by-product or tailings containing rare earths,
- collaborating with other countries/regions with a shared agenda of risk reduction,
- raising awareness and engaging in an active dialogue with zinc, copper and aluminium refiners over by-product recovery,
- creating incentives to encourage by-product recovery in zinc, copper and aluminium refining in Europe,
- promoting the further development of recycling technologies and increasing end-of-life collection,
- measures for the implementation of the revised WEEE Directive, and
- investing broadly in alternative technologies.

It is also recommended that a similar study should be carried out to identify the metal requirements and associated bottlenecks in other green technologies, such as electric vehicles, low-carbon lighting, electricity storage and fuel cells and hydrogen.

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LD-NA-24884-EN-C

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