EUROPEAN PARLIAMENT

DIRECTORATE-GENERAL FOR INTERNAL POLICIES

POLICY DEPARTMENT A
ECONOMIC AND SCIENTIFIC POLICY

Economic and Monetary Affairs

Employment and Social Affairs

Environment, Public Health and Food Safety

Industry, Research and Energy

Internal Market and Consumer Protection

Substitutionability of Critical Raw Materials

STUDY

EN

2012

Substitutionability of Critical Raw Materials

DIRECTORATE GENERAL FOR INTERNAL POLICIES

POLICY DEPARTMENT A: ECONOMIC AND SCIENTIFIC POLICY

Substitutionability of Critical Raw Materials

STUDY

Abstract

The European Parliament has adopted a resolution that proposes focusing Research and Development on the substitution of critical raw materials to support sustainable development and encourage growth in the European economy.

This study addresses the question of which measures could foster the substitution of critical raw materials in the European Union. The main conclusion of the study is that the substitution of critical raw materials needs consistent and multidisciplinary research and development action as well as further incentives.

IP/A/ITRE/ST/2011-15 October 2012

PE 492.448 EN

This document was requested by the European Parliament's Committee on Industry, Research and Energy (ITRE).

AUTHORS

Mr. Kimmo Halme, Ramboll Management Consulting
Dr. Kalle A. Piirainen, Ramboll Management Consulting
Dr. Georgios Vekinis, Institute of Materials Science, National Center for Scientific Research Demokritos
Mr. Ernst-Udo Sievers, i.Con Innovation
Mr. Kimmo Viljamaa, Ramboll Management Consulting

RESPONSIBLE ADMINISTRATOR

Ms. Dorthe Høst Sarup
Mr. Balazs Mellar
Policy Department A: Economic and Scientific Policy
European Parliament
B-1047 Brussels
E-mail: Poldep-Economy-Science@europarl.europa.eu

LINGUISTIC VERSION

Original: EN

ABOUT THE EDITOR

To contact the Policy Department or to subscribe to its monthly newsletter please write to: Poldep-Economy-Science@europarl.europa.eu

Manuscript completed in October 2012.

This document is available on the Internet at:
http://www.europarl.europa.eu/studies

CONTENTS

LIST OF ABBREVIATIONS 5

LIST OF TABLES 8

LIST OF FIGURES 8

EXECUTIVE SUMMARY 9

1. INTRODUCTION 11

1.1. Background of the study 11

1.2. Scope of the study 12

1.3. Methodology 14

1.4. Structure of the study 14

2. OVERVIEW OF CRITICAL RAW MATERIALS AND THEIR SUBSTITUTION 15

2.1. Analysis on the substitution of critical raw materials 15

2.2. Detailed overview of the critical raw materials 20

2.2.1. Antimony (Sb) 20

2.2.2. Beryllium (Be) 22

2.2.3. Cobalt (Co) 24

2.2.4. Fluorspar 25

2.2.5. Gallium (Ga) 27

2.2.6. Germanium (Ge) 28

2.2.7. Graphite (C) 29

2.2.8. Indium (In) 31

2.2.9. Magnesium (Mg) 32

2.2.10. Niobium (Nb) 33

2.2.11. Platinum Group Metals (PGM) 34

2.2.12. Rare Earth Elements (REE) 35

2.2.13. Tantalum (Ta) 38

2.2.14. Tungsten (W) 39

3. EXISTING POLICIES FOR THE SUBSTITUTION OF CRITICAL RAW MATERIALS 42

3.1. Policies, measures and policy targets for substitution in the EU and its Member States 42

3.1.1. EU level 42

3.1.2. The Member States 45

3.1.3. The Member States: Germany 46

3.1.4. The Member States: Finland 47
3.1.5. The Member States: The Netherlands 47
3.1.6. The Member States: Sweden 48
3.1.7. The Member States: UK 48
3.1.8. The Member States: France 48
3.1.9. Summary of European strategies 49
3.2. Policies, measures and policy targets for substitution in the US, Japan and South Korea 49
3.2.1. The United States of America 49
3.2.2. The Republic of Korea 50
3.2.3. Japan 51
3.2.4. Summary of the international situation 52

4. POLICY RECOMMENDATIONS 55

4.1. Possibilities for supporting further substitution efforts through EU RDI programmes 55
4.2. Possibilities for supporting further substitution efforts through collaboration with third countries 63
4.3. The potential for other policies and measures to strengthen the development of CRM substitution in the EU 64

REFERENCES 68

ANNEX 1: LIST OF CRITICAL RAW MATERIALS 81

ANNEX 2: INTERVIEW QUESTIONS AND INTERVIEWEES 82

ANNEX 3: SUMMARY OF POLICIES IN THE EU AND MEMBER STATES DIRECTED TOWARD SUBSTITUTION OF CRM 85

ANNEX 4: SUMMARY OF POLICIES DIRECTED TOWARD SUBSTITUTION OF CRM IN THE US, JAPAN AND KOREA 97

LIST OF ABBREVIATIONS

ABS	Anti blocking system
ARPA-E	Advanced Research Projects Agency – Energy, United States
Be	Beryllium
BMBF	German Federal Ministry of Education and Research
BMWi	German Federal Ministry of Economics and Technology
C	Carbon
CIP	Community Innovation Program
Co	Cobalt
CRM	Critical Raw Materials
DARPA	Defense Advanced Research Projects Agency, United States
DFG	Deutsche Forschungsgemeinschaft
(US) DOE	United States Department of Energy
DRC	Democratic Republic of Congo
EC	The European Commission
EIP	European Innovation Partnership
EIT	European Institute for Innovation and Technology
EP	The European Parliament
ERA	European Research Area
ERA-NET	European Research Area NETwork
ETP	European Technology Platform
ETP-SMR	European Technology Platform on Sustainable Minerals Resources
EU	The European Union
EUR	Euro (currency)
FP7	European Union 7th Framework Programme for Research and Development

Ga	Gallium
Ge	Germanium
GPS	Global positioning system
H2020	Horizon 2020 - The framework programme for Research and Innovation
HF	Hydrofluoric acid
HFC	Hydrofluorocarbon
IC	Integrated circuit
In	Indium
IPR	Intellectual property rights
ITO	Indium-tin-oxide
IR	Infrared
IUPAC	International Union for Pure and Applied Chemistry
JRC	Joint Research Centre under FP7
KET	Key Enabling Technology
KOMIS	Korea Mineral Resources Information Service
KORES	Korea Resources Corporation
KRW	Korean Won, currency
LCD	Liquid Crystal Display
LED	Light Emitting Diode
METI	Japanese Ministry of Economy, Trade and Industry
MEUR	Millions of Euros, currency
MEXT	Japanese Ministry of Education, Culture, Sports, and Science and Technology
Mg	Magnesium
Nb	Niobium
MUSD	Millions of United States Dollars, currency

NEDO New Energy and Industrial Technology Development Organisation

NIMS Japanese National Institute for Materials Science

NMP Sub-division Nanosciences, nanotechnologies, Materials and new Production technologies under FP7

PGM Platinum Group Metals

PET Polyethylene terephtalate

PEDOT Poly 3,4-ethylene dioxythiophene

PPP Public-private partnership

PVC Polyvinyl chloride

RDI Research and Development and Innovation

REE Rare Earth Elements

RFID Radio frequency identification

ROK Republic of Korea, South Korea

Sb Antimony

SME Small or medium-sized enterprise

Ta Tantalum

UK The United Kingdom

US The United States of America

USD United States Dollar, currency

USGS The United States Geological Survey

W Tungsten

WTO World Trade Organisation

LIST OF TABLES

Table 1: Summary of the CRM and their substitutionability 18

Table 2: Typical applications of REE 36

LIST OF FIGURES

Figure 1: Overview of the main suppliers of Critical Raw Materials as defined by the Ad-hoc Working Group on defining Critical Raw Materials 13

Figure 2: Workflow diagram of the study 14

EXECUTIVE SUMMARY

Background

Among other turbulences in economic life, the availability and price of certain important raw materials have, in recent years, been subject to increasing uncertainty. The issues around these so-called critical raw materials (CRM) include strong and growing demand from industry as well as limited and volatile supply. Uncertainty surrounding the supply of raw materials potentially constrains economic growth as rising prices make key industries less profitable. In the worst cases, severe shortages of CRM may also result in temporary production halts. In the longer term, the risk remains that the expertise to make use of the existing and to develop new advanced construction materials will be lost. This is something that could conceivably have significant negative repercussions for the competitiveness of European industry.

Aim

This study broadly relates to the EU2020 Strategy and in particular to its sustainable growth objective, as well as to the EU Raw Materials Initiative, both of which aim to support sustainable growth in the EU. Within this larger strategic framework, one action that is available is the committing of further resources to research, development and innovation activities with the aim of developing sustainable substitutes for these critical raw materials.

The objective of this study is to analyse current research, development and innovation policies in this area, which aim to substitute CRM with alternative materials or other solutions. The analysis is limited to the European Union, and primarily to selected Member States including Finland, France, The Netherlands, Sweden and The United Kingdom, and to selected international benchmarks including Japan, the Republic of Korea and the United States of America.

Findings

In the context of currently available technologies most of the CRM, especially the platinum group metals and rare earth elements, are hard to substitute without loss of performance or resource efficiency. **The majority of substitutes are currently in the research and development stage** and market-ready solutions are rarely available. The lead time from research idea to market is generally also very long with, when starting from basic research on the properties of the materials to be substituted to a new product with equivalent properties, 5-15 years being the likely timeframe. **Some CRM are already being recycled and improving process efficiency and recycling may offer the opportunity to alleviate some problems in the short term.**

The EU institutions have been active in creating a comprehensive policy framework to support the substitution of CRM. On the EU level, an emerging issue is the interplay between the new framework programme for research and innovation (Horizon 2020), the proposed European Innovation Partnership and the planned Knowledge and Innovation Centre, which may create duplicate instruments for substitution research. The structure of Horizon 2020 as currently proposed does however seem rather fragmented on the issue of RDI and the substitution of CRM.

The individual Member States analysed have been less active in developing national minerals strategies or programmes to support the substitution of CRM, with the notable exception of Germany's comprehensive and strong policy response that balances short and long term interests through different measures.

Outside the EU, the benchmark countries including the United States of America, Japan and the Republic of Korea each have their own policy response to raw materials issues. Japan has the most comprehensive set of RDI instruments specifically designed to support the substitution of CRM. In the United States the policy response is still taking shape though a strong initiative under the Department of Energy has already been developed. The Republic of Korea in its turn is aiming to develop policies to secure the supply of raw materials rather than substituting CRM.

Based on the findings, it seems that **the current policy framework on the EU level already addresses the issue of CRM to an extent where immediate action is not deemed necessary**. However, while the EU implements a comprehensive set of initiatives and policies supporting the substitution of CRM, **the ongoing and foreseeable changes may create a fragmentation in terms of funding from this specialised perspective**.

The substitution of CRM is a complex issue. Substitutes often come with a long lead time from research to market thus demanding a policy response that considers the long term impact on industry as well as one which sets sustainable incentives. **The recommended actions in terms of EU level RDI policy include maintaining up to date information and a research programme on the substitution of CRM, the focusing of RDI efforts and the avoidance of fragmentation, as well as ensuring that the whole RDI spectrum, from high science to new product development, is much more highly incentiv**ised than is currently the case.

On the global level joint initiatives in other policy areas are also ongoing. **The recommended actions here include using the existing *fora* of exchange to increase discussion and coordination of CRM policy, as well as emphasising the role RDI centres and programmes play in gathering and exchanging the latest knowledge on CRM substitution.** Other possible policy responses include mapping European minerals deposits and disseminating information about CRM throughout the EU, raising awareness of the pending challenges through education and creating additional demand side incentives for the development of CRM substitutes.

1. INTRODUCTION

KEY FINDINGS

- The European economy is the largest in the world, with a strong industry, while the mineral production within EU does not satisfy the demand.
- The issue of addressing challenges with the minerals supply, especially concerning certain critical raw materials (CRM), has arisen with recent market volatility that is partly a result of dependency on certain countries.
- This study examines the present policy framework for substitution of CRM in the EU, in selected Member States, and in key benchmark countries including the United States of America, Japan and Republic of Korea.
- Additional policies are recommended to further support substitution.

1.1. Background of the study

As the global economy continues to grow, there is an ever-increasing pressure on the Earth's resources. The European Union (EU) has the largest economy in the world, but it lacks the mineral wealth needed to sustain the growth. This is why the EU depends on imports of many critical raw materials[1].

The EU's supply of critical raw materials is further threatened by the fact that some emerging economies, in particular China, are limiting raw materials supply by means of export restrictions[2]. The potential supply difficulties with regard to industrial raw materials are also emphasised in the European Commission Communication on "Tackling the challenges in commodity markets and on raw materials".[3]

Due to these risks, the European Parliament (EP) has recently adopted a resolution on raw materials. In it, the European Parliament *"Regrets that substitution and re-use are not sufficiently addressed in the Communication; recalls that substitution, particularly for CRM [critical raw materials] and REE [rare earth elements], is of great relevance and can offer efficient solutions to supply and environmental risks when possible; calls on the Commission, therefore, to ramp up its work in this field by leveraging research and innovation [RDI] funding through the possible development of a substitution programme in the forthcoming research framework programme, supporting demo-plants; encourages the Commission and the Member States to consider setting substitution targets while taking into account relevant impact assessments; calls on the Commission to make full use of the existing REE competency within the EU"*.[4]

---

1 Critical raw materials: The Commission has identified a list of 14 economically important raw materials which are subject to a higher risk of supply interruption. There are a number of reasons for this heightened supply risk, one of which is the high concentration of the production of a raw material in a given non-EU country, see also EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/rawmaterials/critical/index_en.htm.

2 See WTO rulings WT/DS394/R, WT/DS395/R and WT/DS398/R "China- measures related to the exportation of various raw materials" of July 5th 2011 (11-3179) Available at: http://www.wto.org/english/tratop_e/dispu_e/394_395_398r_e.pdf (Accessed 24.2.2012).

3 EC, 2011. Tackling the challenges in commodity markets and on raw materials, COM(2011) 25 Final.

4 European Parliament resolution of 13 September 2011 on an effective raw materials strategy for Europe (2011/2056(INI)), see:

The ability to substitute raw materials may provide four advantages:

- Flexibility, which can insulate industry from the risk of sudden supply disruptions.
- Cost savings, which can allow industry to find more cost-efficient raw materials.
- Weaken monopoly power, in cases where a single supplier country controls the market for a given raw material.
- Environmental benefits, if the new substitute materials require less resource inputs to the production process and/or reduce emissions or resource consumption over the life-cycle of the product.[5]

This particular study is one effort to understand the state of the art in the EU and Member States in their efforts to address the issues of critical raw materials. Parallel to this study, the European Commission has commissioned a study entitled “Raw materials: Study on innovative technologies and possible pilot plants”[6] which will be a technical feasibility study for building pilot production facilities that can demonstrably increase materials efficiency over exiting production technologies, which will feed into establishing the European Innovation Partnership (EIP) platform associated with the implementation of the EU2020 strategy. In the research field, the current call for proposals for the 7th Framework programme for Research, Technological Development and Demonstration contains a call for a project for “Development of advanced magnetic materials without, or with reduced use of, critical raw materials” (NMP.2012.4.1-3) and a coordination and support action for “Substitution of critical raw materials: networking, specifying R&D needs and priorities” (NMP.2012.4.1-4), both under the EU 7th Framework Programme for Research and Technological Development (FP7)[7].

1.2. Scope of the study

In relation to the other, more technical efforts to address the issues around the use of Critical Raw Materials, the aim of this study is to survey the policies and instrument that support substitution of CRM on the levels of EU and the Member States. The main research question of the study is:

"Which (policy) measures could foster the substitution of critical raw materials (as defined by the European Commission) as well as other metals that are mined as by-products of other metals, including in particular rare earths?"

The study focuses on the existing and foreseeable technical solutions as well as the policies and strategies to substitute the CRM in the value chain. The particular focus is on the policies that can support substitution.

The geographical coverage includes the EU level and selected Member States, namely France, Germany, Finland, Sweden, the Netherlands and the United Kingdom (UK). The selection is based on the fact that strategically in the raw materials field these countries and regions are the most advanced. The analysis of the third countries is based on literature review as well as on brief contacts with key experts with knowledge of policies and initiatives in these countries.

---

http://www.europarl.europa.eu/oeil/FindByProcnum.do?lang=en&procnum=INI/2011/2056; EC, 2011. Tackling the challenges in commodity markets and on raw materials, COM(2011) 25 Final.

5 Stull, G. 2011. Raw materials: EU policy to secure access and improve use-efficiency, Library of the European parliament, Library Briefing 30/03/3011 Available: http://www.europarl.europa.eu/RegData/bibliotheque/briefing/2011/110150/LDM_BRI(2011)110150_REV1_EN.pdf (Accessed 26.5.2012).

6 EC DG-ENTR, Raw materials: Study on innovative technologies and possible pilot plants, Call for Tender No: 112/PP/ENT/CIP/11/C/N06S001, Tender Specifications, Available at: http://ec.europa.eu/enterprise/newsroom/cf/_getdocument.cfm?doc_id=6865 (Accessed 12.3.2012).

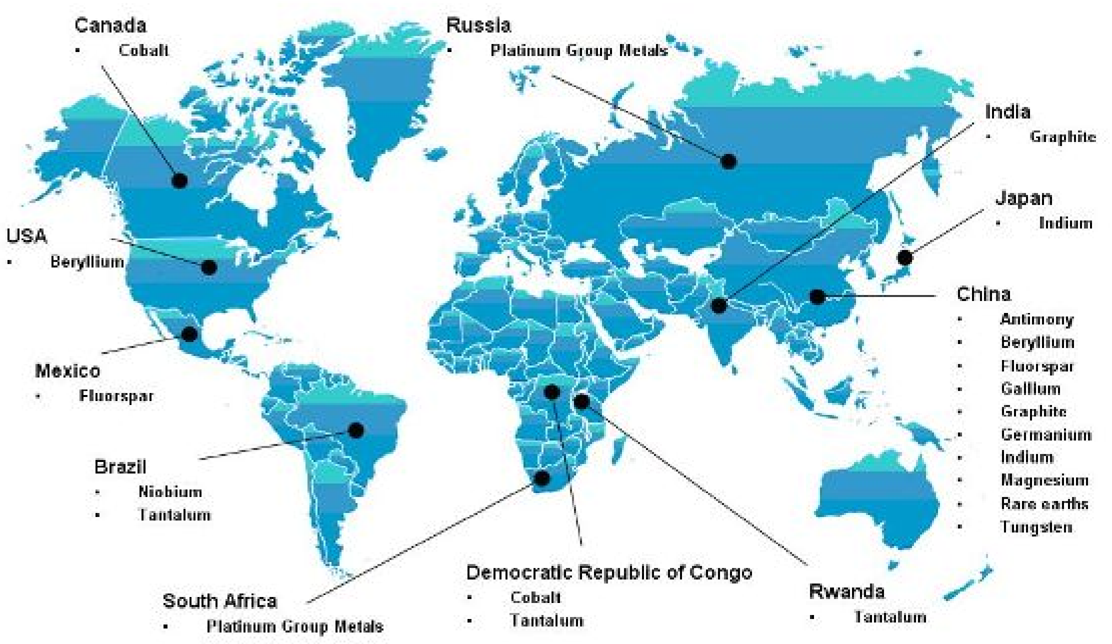
7 EC, FP7,Cooperation, Theme 4: Nanosciences, nanotechnologies, Materials and new Production technologies – NMP, Work Programme 2012, C(2011)5068.

In the context of this study Critical Raw Materials (CRM) including the Rare Earth Elements (REE), are chemical elements, more specifically metals, which are important for the development and sustainability of the EU industry. The list of CRM that are included in the scope of this study is established in a study commissioned by the European Commission (EC), Directorate-General Enterprise and Industry (DG-ENTR). The list includes 14 entries; altogether 35 metallic elements (12 elements, plus 6 elements called Platinum Group Metals [PGM] and the 17 REE) (see also Appendix 1).

The CRM, as defined by EC, are used extensively in semi conductors, (micro-) electronics, as well as vital ingredients in many a structural alloy, such as several steel and aluminium alloys employed in all walks of life from bridge building, bicycles and car manufacturing to aerospace and weapon systems. Many of the CRM are actually most important in the latter extreme applications, where high performance, i.e. maximum strengths and/or extremely light yet strong structures are sought after.

One common denominator between the CRM is that the existing value chain and the state of the art in technology is built on using the CRM, and they are difficult to substitute in their applications at least without loss of performance, while their supply is a monopoly or oligopoly, and often controlled by governments that can be at least in a certain light considered politically unfriendly or unstable, as illustrated in Figure 1. EU is notoriously lacking the CRM production and reserves, even though European industry is quite dependent on these materials.

Figure 1: Overview of the main suppliers of Critical Raw Materials as defined by the Ad-hoc Working Group on defining Critical Raw Materials[8]



Thus the substitution of the CRM in the European economy is of great economic interest as well as being a European and national security issue. Substitution is a process where one element, material or product is substituted directly by an equivalent element, material or product or an altogether different material or service. In the case of CRMs, the main aim is

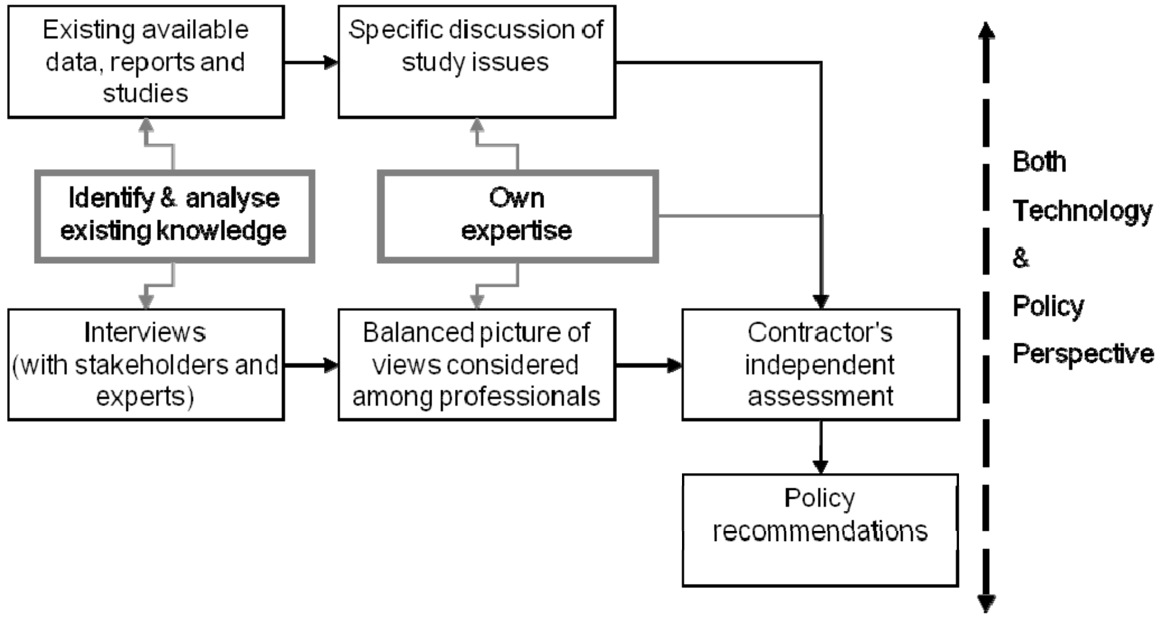
8 EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

to substitute them by either of these processes to lower the demand for CRMs altogether and to lessen (the) dependence on these materials.

1.3. Methodology

The approach aims to analyse the studies both in terms of technology and policy, and includes some key interviews in both directions. As illustrated in Figure 2, the study is based on the analysis of available policy and technical documents and supporting interviews, which are subsequently analysed by the authors who then compile the report on the state of the art in substitution of the CRM and the recommendations for action to support substitution.

Figure 2: Workflow diagram of the study



1.4. Structure of the study

This report is structured as follows: The introduction covers the background, scope, method of the study and structure of the report. The second chapter discusses the critical raw materials (CRM) and the technical challenges associated with their substitutions, as well as existing solutions. The third chapter surveys the policies directed for substitution of CRM, focusing specifically on policies that explicitly aim for substitution of CRM. Finally, the fourth chapter discusses the implications for policy, proposing further policies to support substitution of CRM.

2. OVERVIEW OF CRITICAL RAW MATERIALS AND THEIR SUBSTITUTION

KEY FINDINGS

- The issues concerning the CRM involve the strong and growing demand for the raw materials, as well as their geographic concentration and volatile supply.
- However, due to the ongoing evolution of industry, the criticality of raw materials is subject to change in the long term.
- With present technology, the CRM are hard to substitute without loss of performance or resource efficiency.
- The majority of substitutes are currently in the research and development stage, and market ready solutions are scarce.
- The lead time from research idea to market may be very long, 5-15 year starting from basic research on properties of materials to be substituted to a new product with equivalent properties.
- Some CRM are already recycled, but improving process efficiency and recycling may offer opportunities to alleviate the problem over the short term.

2.1. Analysis on the substitution of critical raw materials

The immediate challenges posed by extensive use of CRM are the constrained supply and geographically concentrated production. An often cited fact is that China as of 2011 held a market share of 97% of world REE production in 2011, which illustrates the concentration of supply. The drivers for growth in demand for CRM are general economic growth and demand for goods which contain CRM as raw materials or manufacturing of which use CRM. One of the most common examples is petro-chemical products, where platinum group metals play a key role in manufacturing. The global growth of consumer demand will project to demand for raw materials with some delay due to stockpiles in various parts of the value chain. However, the production of REE or other CRM does not scale up in the short run, as estimated lead time from a confirmed deposit to a working mine may be as long as ten years. The rise in price will increase competition in the supply of CRM and naturally direct funding for Research, Development and Innovation (RDI) to substitute present solutions.

During the interviews, the interviewees expressed the opinions that overall, the criticality of materials evolves and analyses of criticality tend to be snapshots. What is critical today may be abundant in a few years, depending on mining output, recycling rate or new technical developments (e.g. system replacements that are even developed without incentives: flash drives replace hard drives, etc.). Especially the supply side may produce unexpected variations in price as when the supply is low, e.g. due to export restrictions as was the case in 2011. During times of low supply and high prices there is an incentive to start new mining operations. However, when the new mines come on-line, probably several years later, the market situation may be completely different. When new supply enters the market it may drop the market price, as the demand has adjusted itself to the low supply and high market price or the supply may have increased due to new mining operations or regulatory changes over the ramp-up period of the production.

In many cases the actual criticality ranking is complicated (and varied) by the fact that some of the critical elements' availability depends on demand for and extraction of other materials, as the former are found mixed-in with the latter and it is not economically feasible to extract the critical elements on their own. This is particularly pertinent to gallium, germanium, indium and cobalt. Furthermore, as emphasised by the interviewees, the criticality ranking is also dependent on the relative ease (or difficulty) of increasing the rates of recycling of each element and any new recycling technologies. For example, platinum and palladium (the most important of the platinum group metals) are much more easily (and profitably) recycled than many of the other critical materials such as most of the REE and especially materials that are mostly used-up during their use.

From the 14 critical materials identified by the Raw Materials Initiative, REE and the Platinum Group Metals (PGM) were regarded as being the most critical at the moment. Indium, Germanium, Gallium and Lithium ranked second in criticality. Important application areas that depend on the supply of critical materials are electronics, lighting, displays, photovoltaics, e-mobility, batteries and catalysts for automobile and chemical industry. The majority of these applications are related to clean energy technologies.

Regarding the development of the situation, an interviewee noted that the market has a history of delivering when there is a shortage of material. In fact, there are signs that the market is already responding, but with a time lag that needs to be bridged. So a careful consideration of all parameters has to be taken into account before placing an emphasis on increased RDI on substitutes and to move such RDI efforts in the right direction. Especially for REE, it was noted in several interviews that the recent market price fluctuation is not so much a result of shortage of production quantities, but rather export restrictions from main suppliers, which mean that criticality is also politically driven. One interviewee stated that by 2016, a surplus of REE within the West is foreseeable with increased mining ambitions of *Molycorp Inc*.[9] and the opening of the *Lynas Corporation* mine in Mount Weld, Australia.[10]

The majority of substitutes are currently in basic or application-oriented research stage. Some substitutes have already been developed, e.g. new electric motors without REE have been developed and luminescent phosphors are replaced by LEDs. For automotive catalysts: palladium and platinum are mutually substitutable, and the choice of metal is based on the current price. The same applies for example for cathode materials for accumulators/storage batteries, which employ cobalt: the cathode material is developed with inherent flexibility to increase or decrease concentration of the metal. These are market ready examples. However, the industry has been trying to find replacements for PGMs for 30 years in catalysis, and has not achieved substitution with the same success. One of the reasons is the very high efficiency and ease of use of PGMs for most catalytic applications. The other is the apparent inability of the scientists to fully understand the actual micro mechanisms taking place during catalysis at the atomic level.[11]

Research on substitution is above all risky and lengthy endeavour taking anywhere from 5 – 15 years without any guarantee of success due to unforeseeable fluctuations in raw materials prices and at the same time customer demand as well as new products and services introduced by direct competitors and other companies. A person from industry

---

9 Molycorp, 2012. Molycorp To Launch Sequential Start-Up of New, State-of-the-Art Rare Earth Manufacturing Facility This Week, Press release 21.2.2012, Available: http://www.molycorp.com/molycorp-to-launch-sequential-start-up-of-new-state-of-the-art-rare-earth-manufacturing-facility-this-week/ (Accessed 26.3.2012).

10 Lynas Corporation Ltd. Lynas Corporate Brochure: Online in 2012, Delivering Rare Earths Globally, Available: http://www.lynascorp.com/content/upload/files/LYNAS_CORPORATE_BROCHURE.pdf (Accessed 24.3.1012).

11 Dr G. Xanthopoulou, NCSR Demokritos, Greece, interview 10.2.2012.

stated that true substitution research, meaning the discovery of disruptive and not incremental innovations, would have to try to fundamentally understand materials properties first (such as atomic-level catalysis) and answer why certain elements are needed and in what ratio to obtain those properties. The first step in substitution is to carry out research, and if successful, the RDI process will move to industrial applications. However, a prerequisite for obtaining and applying a substitute material are industrial incentives to do so. While such profound research and development approach is indeed a lengthy endeavour, it would potentially also enhance material efficiencies as an intermediate gain.

The other approach to substitution would be to replace the existing value network with altogether different products and/or services. For example, development and wide adoption of electric vehicles for consumer use together with a well functioning public transport would considerably lower the demand of PGMs for catalytic converters both upstream in petroleum refining as well as in the automotive industry. However, on the flipside, with the present technology this would increase dependency on REE considerably.

According to the interviews, replacements or substitutes for any critical material should start from the necessary functionality taking into account the availability of materials. This avoids the trap of replacing one CRM with another. Any research should thus look to replace CRM with abundant materials first. Initiatives exist where new e.g. semiconducting properties are obtained using iron through clever manipulation of micro- or nanostructures. Similarly, the very large specific surface area of nanoparticles and nanofibres allow very high reactive yields and good catalytic properties in many applications. Substitution efforts should focus on products where there is ‘dissipative’ use of CRM, i.e. applications that are not critical to the economy or do not demand the performance or properties that can be achieved only with CRM, and in fast-growing markets. In the longer time frame nanotechnology was seen as having the potential to discover materials with new properties, but solid-state chemistry, polymer science etc., should not be neglected when considering substitution research.

As can be summarised from the material-by-material analysis of recycling and substitution opportunities (below), many but not all materials can be recycled, and already are to some extent. However, the common challenge is that many of the applications use the CRM in an alloy with other metals often in very small concentration, which makes recycling economically challenging and requires development of processes as well as a sustainable value chain to exploit the opportunities. Regarding substitution, one observation is that CRM, especially PGM and REE are often to some extent interchangeable, and thus substitutable to a degree, but substitution with more abundantly available materials is more challenging in many cases.

Table 1: Summary of the CRM and their substitutionability

#	Material	Main and critical applications	Recyclability	Substitutionability	Recommendations
1	ANTIMONY	Storage batteries, fire retardant additive to plastics, micro-capacitors.	Already extensive recycling with strong possibility for expanding further.	Low-maintenance batteries have reduced need for lead additives. Substitutes exist for most of its applications with some commercial products available as fire-retardants.	**Support extension of recycling and research activities in Europe. Incentivise recycling and waste collection of batteries.**
2	BERYLLIUM	Military and consumer electronics, radar windows.	Easy recycling but at low rate because of very long lifetimes.	Many potential replacements exist for most applications but their current performance needs to be improved.	**Highly toxic material with long-term environmental and health impact. Reduce dependency by supporting research on improvements of properties of potential substitutes.**
3	COBALT	Alloying or binding additive for permanent magnets, superalloys, tools and catalysts.	Easy recycling from scrap and wastes. Extensive recycling already occurring and can increase.	Substitutes exist for superalloys, catalysts and permanent magnets. Potential substitutes for tooling (for bonding tungsten-carbide in "hard metals") not satisfactory.	**Support research for substitutes and replacements. Incentivise recycling of scrap and waste in Europe.**
4	FLUORSPAR	Main source of hydrofluoric acid (HF) used extensively in production of aluminium, steel, uranium, petroleum fuels, insulations and refrigerants.	Only very limited recycling possible as fluorspar is consumed during its use.	Substitutes exist but cost and performance are limited. Fluorosilisic acid may offer a source of HF but the technology needs further development.	**Increase in recycling rates (of scrap) can be marginal at best. Support extraction of new sources and further research on replacements in Europe.**
5	GALLIUM	Important component in LEDs used in optical displays and in new generation of solar cells. Some military applications.	Relatively easy recycling but only carried out when economic.	Substitutes exist for many applications, but difficult to substitute without loss of performance. New challenges from organic compounds for optical and energy applications.	**Incentivise recycling in Europe and development of new nano-technological replacements.**
6	GERMANIUM	PET catalyst, fibre optic fibres, infrared lenses.	Already extensively recycled to the extent of up to 30% of total production.	Can be substituted in most applications by silicon or other materials.	**Incentivise recycling in Europe, especially from used waste and encourage development of many promising replacements.**

#	Material	Main and critical applications	Recyclability	Substitutionability	Recommendations
7	GRAPHITE	Batteries, brake linings, aluminium and steel making.	Relatively easy to recycle but current recycling is limited due to sufficient global production	Synthetic graphite can be used instead of imported natural graphite in nearly all cases. For refractory uses a number of materials exist (especially advanced ceramics)	**Incentivise recycling, encourage more synthetic graphite production in Europe**
8	INDIUM	Mainly in flat panel liquid crystal displays (LCDs) and new generation of solar panels.	Large amounts recycled from manufacturing waste and from LCDs.	A number of new conductive, transparent materials have been announced.	**Incentivising recycling and good prospects for new replacement materials may reduce indium criticality with time.**
9	MAGNESIUM	Light-weight vehicles, refractories, production of steel.	Limited recycling due to low price and weak incentives.	Substitutes exist but do not offer equal performance.	**Large magnesite deposits exist in Europe but it is cheaper to import Magnesium metal or high purity magnesium oxide. Incentivising production of the metal will reduce criticality.**
10	NIOBIUM	Superalloys, steels.	Recycled together with its alloys as it is difficult to recycle alone.	Substitutes exist but with lower performance.	**Incentivise research and development of replacement materials.**
11	PLATINUM GROUP METALS	Catalysts for vehicles and chemicals, high temperature components.	Relatively easy to recycle. Recycling rate is increasing.	Difficult to substitute but some oxides have been reported as potential substitutes in vehicle exhaust catalytic converters.	**Support and push recycling further in Europe.**
12	RARE EARTH ELEMENTS	Permanent magnets for motors and generators, electronics and displays.	Very difficult to recycle.	Substituting is difficult but some replacements have been reported recently, especially from nanotechnology.	**Support further research on replacements, along the lines of major programmes in the United States of America and Japan.**
13	TANTALUM	Electronic equipment and mobile telephony.	Relatively easy and extensive recycling.	Most potential substitutes result in decreased performance.	**Support recycling further and extend to manufactured goods in Europe.**
14	TUNGSTEN	**Tools, anvils for diamond synthesis, projectiles.**	**Extensive recycling of manufacturing waste**	**Some substitutes exist but offer inferior performance.**	**Incentivise further recycling – search for European sources, although this will need cost support.**

Source: Authors' summary. Please refer to the appropriate footnotes presented below.

2.2. Detailed overview of the critical raw materials

2.2.1. Antimony (Sb)

Antimony is a shiny, medium-soft metal, most often occurring with sulphur, lead, copper or silver. There are many minerals that contain antimony but Stibnite (Sb_2S_3) is the predominant extraction ore. Antimony trioxide is the most industrially important of the antimony compounds and is primarily used in flame-retardant formulations (additive in many types of plastics, about 50% of total use in 2011[12]) which are used in children's clothing, toys, aircraft and automobile seat covers. It is also used as hardener for lead in storage batteries. In the metallic form, antimony is also used in various solders and other alloys, in the glass for television picture tubes and computer monitors (as antimony tin oxide), in pigments, in stabilisers and in catalysts for the manufacture of PET plastic (polyethylene terephthalate) which is used for drinks bottles and packaging. In some forms it is used in ammunitions in cable insulation and in friction bearings[13].

Antimony is also used in zinc-oxide varistors, as a clarifying agent in manufacturing certain types of glass and in the production of titanium dioxide pigments, as a component in the manufacture of complex inorganic coloured rutile pigments and as an opacifier in cast iron bath and sink enamelling. Finally, highly pure antimony (99.999%) is used in semiconductors and micro capacitors in the computer industry[14].

The main global producers are China (>85% in 2010), Russia, Bolivia and South Africa. New production projects are under development in Australia, The United States of America (US), Canada and Laos[15]. China restricted mining operations in 2010, ostensibly to reduce illegal mining and pollution[16], but this has led to instability of supply worldwide, increasing the price. On the other hand, this is thought to have been the impetus for the new explorations and drive for development of hitherto uneconomical reserves and also of more extensive recycling, especially of batteries.

Secondary (recycled) production of antimony is already quite extensive and apparently increasing, mainly as antimonial lead from storage batteries, however, recently antimony has been surpassed as an additive to some extent and the secondary production has been in decline[17].

Antimony is substitutable in many of its applications by a number of other elements[18]. It can be substituted with, for example, by chromium, tin, zinc, and titanium compounds in

---

12 USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

13 USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012); International Antimony Association, Available: http://www.antimony.be/ (Accessed on 12.3.2012); Sherman, L.M. 1994. Antimony oxide price spiral draws attention to alternatives, Plastics Technology, 1 September 1994, Available: http://www.thefreelibrary.com/Antimony+oxide+price+spiral+draws+attention+to+alternatives.-a016111319 (Accessed 15.3.2012).

14 Minor Metals Trade Association, Minor Metals in the Periodic Table: Antimony, Available: http://www.mmta.co.uk/metals/Sb/ (Accessed on 12.3.2012); EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

15 USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

16 USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

17 Carlin, J. F. Jr., Recycling of Antimony in the United States in 2000, U.S. Geological Survey Circular 1196–Q, USGS, Available at: http://pubs.usgs.gov/circ/c1196q/c1196q.pdf (Accessed 12.3.2012); USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

18 Minor Metals Trade Association, Minor Metals in the Periodic Table: Antimony, Available: http://www.mmta.co.uk/metals/Sb/ (Accessed on 12.3.2012).

the paint industry; by cadmium, sulphur, copper, and calcium to harden lead; and by a number of organic and inorganic (alumina trihydroxide, magnesium hydroxide) compounds in fire retardation[19]. The trend to low-maintenance batteries has recently reduced the consumption of antimony as an additive[20]. Calcium can also be used as an additive in batteries instead of antimony[21]. Replacements for antimony oxide for fire-retardation applications have appeared commercially. A web search carried out on March 12th 2012 showed that a number of industrial manufacturers are already marketing various new fire-retardant materials, containing for example various organic compounds or hydrated aluminium oxide. Zinc borate or molybdenum or tin compounds have also been reported as potential replacements of antimony oxide for fire retardation[22].

Main imports are from Bolivia (>75%), China and Peru[23]. The primary consumption of antimony (as oxide) within the EU is in flame-retardant plastic (both PVC and non-PVC) comprising 37% of the EU market[24]. Recycling offers about 10% of total production with an increasing trend[25]. The European Commission is funding a number of collaborative projects aimed at antimony substitution including project FUNFLUOS[26], project POLYCAT[27] and project DROPLET WELD[28].

Summary and recommendations: As mentioned above, a number of substitutes for antimony are known and more appear to be under development. Already, alternative fire retardant materials for use in plastics are commercially available. If the performance of these identified alternatives can be improved and industry is encouraged to adopt them, the criticality of supply of antimony may be decreased. Substitution of antimony will also reduce production work-place health risks due to the known toxicity of antimony (see e.g. ref. 16). Supplies of secondary antimony from recycling of the very large amount of waste in lead-based batteries appear to be able to cover an increasing percentage of European needs in the near and medium term. In the long term, however, this will probably decrease because of the current use of lead-free batteries.

[19] Minor Metals Trade Association, Minor Metals in the Periodic Table: Antimony, Available: http://www.mmta.co.uk/metals/Sb/ (Accessed on 12.3.2012); USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

[20] USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

[21] USGS, Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).

[22] Shen, K. K. 2001 Zinc Borates: 30 Years of Successful Development as Multifunctional Fire Retardants, Fire and Polymers, ACS.

[23] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[24] Sherman, L.M., 1994. Antimony oxide price spiral draws attention to alternatives, Plastics Technology, 1 September 1994, Available: http://www.thefreelibrary.com/Antimony+oxide+price+spiral+draws+attention+to+alternatives.-a016111319 (Accessed 15.3.2012).

[25] European Battery Recycling Association (EBRA), http://www.ebra-recycling.org/ (Accessed 15.3.2012)

[26] Project FUNFLUOS, Available at: http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=7524569 (Accessed 12.3.2012).

[27] Project POLYCAT, Available at: http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=11519466 (Accessed 12.3.2012).

[28] Project DROPLET, Available at: http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=4674898 (Accessed 12.3.2012).

2.2.2. Beryllium (Be)

Beryllium is a shiny white, soft, alkaline earth metal with low density and high melting point. It has a high strength to weight ratio, low coefficient of thermal expansion, good resistance to corrosion and good thermal and electrical conductive properties, all important properties for engineering. However, it is known to be highly toxic[29], a fact that has probably been responsible for its relatively low utilisation, except in critical applications.

According to the United States Geological Survey (USGS)[30], about 45% of beryllium use (in 2011) is estimated to be in consumer electronics and telecommunications products, 12% in defence-related applications, 11% in industrial components and commercial aerospace applications and the remainder in appliances, automotive electronics, nuclear energy, medical devices and other applications. Beryllium is also used in the manufacture of telecommunications infrastructure equipment, computers and cellular phones. Copper beryllium alloy is used for housings for undersea fibre optic cables and also medical tools, instruments, imagers, for automotive electronics, such as ABS (anti blocking system) - brakes, airbags and collision avoidance radars. In the defence industry, beryllium is used for making missile guidance windows and rocket parts.

Beryllium is considered to be critical to the Galileo multi satellite-based positioning system project[31] with a positional resolution much higher than the ubiquitous US-based GPS (Global Positioning System). According to the EC's Directorate General Enterprise & Industry: "Galileo will underpin many sectors of the European economy through its services and make Europe independent in a technology that is becoming critical, including for strategic areas such as electricity distribution and telecommunication networks."[32]

World resources in known deposits of beryllium are estimated to be between 80,000 and 400,000 tons with about 40-65% of these resources in the US. Approximately 10% of consumption is currently recycled in the US and Europe with the latter apparently in the lead with an increasing trend. Currently, China, US, Brazil, Nigeria, Madagascar and Mozambique are the main producers of beryllium[33]. No primary supply of beryllium exists in Europe, although Russia and Kazakhstan stopped production in 1999 but still hold large stockpiles[34]. Recently, new production facilities are being encouraged in the US with government support since beryllium is designated as a critical material in the US and the US's policy is to reduce dependence on imports[35].

The US has been concerned about beryllium supply for years and the 2007 report on "Minerals, Critical Minerals and the US economy"[36] recommended a strategic policy on beryllium for replacement in non-critical applications and increased production and

[29] US Agency for toxic substances and disease registry, Toxicological profile for Beryllium, Available: http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=185&tid=33 (Accessed 15.3.2012).
[30] USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012).
[31] Beryllium Science and Technology Association, http://beryllium.eu/ (Accessed 12.3.2012).
[32] EC, 2011. Enterprise and Industry Newsletter, May 23rd 2011, http://ec.europa.eu/enterprise/newsroom/cf/newsletterarchivedetail.cfm?nl_id=997, (Accessed on 12.3.2012).
[33] USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Beryllium, Available: http://www.mmta.co.uk/metals/Be/ (Accessed on 12.3.2012).
[34] USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012).
[35] USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012); National Research Council of the National Academies, 2007, Minerals, Critical Minerals and the US Economy, Available: http://www.nma.org/pdf/101606_nrc_study.pdf (Accessed 14 March 2012).
[36] National Research Council of the National Academies, 2007. Minerals, Critical Minerals and the US Economy, Available: http://www.nma.org/pdf/101606_nrc_study.pdf (Accessed 14 March 2012).

recycling where possible. In 2005, a US *Capabilities Report* concluded that while imports to the US were not considered a viable long-term option, private commercial investment was unlikely to be adequate. It thus suggested that the Department of Defense begin a multiyear cost-share programme with private industry, "possibly through the Defence Production Act, to support the design, construction and equipping of a new beryllium metal production facility"[37].

Europe is nearly 100% dependent on imports from the US, Canada, China and Brazil[38] but the US has been restricting exports due to Beryllium's identification as a strategic metal[39]. Generally beryllium and its alloys are relatively easily recyclable, both as components and as machining scrap, resulting in a significant cost and energy savings. Beryllium-based components used in engineering applications have very long lifetimes and cannot therefore be relied upon for secondary supply by recycling. In the case of defence or space applications, no recycling of beryllium is possible[40].

Because the cost of beryllium is high, it is mainly used in applications in which its properties are supposedly critically needed[41]. According to the US Geological Survey, in some applications, beryllium alloys can be replaced by metal matrix or organic composites, aluminium alloys, pyrolytic graphite, silicon carbide, or titanium. Also, aluminium nitride or boron nitride are studied for replacing beryllium oxide in some electronics applications. In many cases however the performance obtained may be inferior, at least until the potential substitutes have been improved[42].

Be that as it may, the expense, toxicity and supply instability of beryllium has led to various efforts to find commercial and strategic replacements. No published reports on actual commercial substitution were found in the literature, but a web search on March 10th 2012 showed a number of commercial replacements for beryllium for some applications, e.g. nickel silicon chromium copper which can match beryllium copper in electrical conductivity and mechanical properties, and thus substitute it for many applications[43].

Summary and recommendations: Beryllium can easily be recycled but its toxicity adds an additional incentive to find replacements for it in applications where humans or the environment might be exposed to beryllium fall out. A European policy of proactively encouraging the development of replacement materials for beryllium in parallel with a proactive programme of recycling beryllium and its alloys may offer relief to the criticality of beryllium supply.

[37] National Research Council of the National Academies, 2008. Managing Materials for a Twenty-first Century Military, Available: http://www.nap.edu/openbook.php?record_id=12028&page=174 (Accessed 10 March 2012).

[38] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm

[39] USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012).

[40] Beryllium Science and Technology Association, available: http://beryllium.eu/ (Accessed 12.3.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Beryllium, Available: http://www.mmta.co.uk/metals/Be/ (Accessed on 12.3.2012).

[41] see e.g. Missile Defense Agency (US) Technology Programme, Available: http://www.mdatechnology.net/techprofile.aspx?id=594 (Accessed 10 March 2012).

[42] USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012).

[43] Veitch, D.B., 2007. A Copper-Nickel-Silicon-Chromium Alloy for Mold Tooling, MoldMaking Technology, Available: http://www.moldmakingtechnology.com/articles/a-copper-nickel-silicon-chromium-alloy-for-mold-tooling (Accesses 23.5.2012).

2.2.3. Cobalt (Co)

Cobalt is a hard, brittle, silver-gray metal that is used in a wide variety of engineering and chemical applications, the most important being as an alloying additive to other metals and ceramics to improve their properties and also for its catalytic and ferromagnetic properties. Crucially, cobalt is used for bonding tungsten carbide particles to make the industrially important "hard metals" or "cermets" cutting tools, in tool steels as well as superalloys for jet engines. The last decades have also seen the development of cobalt-containing permanent magnets for motors and generators. In smaller quantities, cobalt is also used in various communications hardware, pigments, rechargeable batteries and catalysts. The biggest growth market currently is in the rechargeable "Lithium-Ion" batteries used in billions of electronic devices from cell phones to laptops to hybrid automobiles[44].

The main primary producing countries of cobalt are Congo, China, Zambia and Russia. Although the Democratic Republic of Congo (DRC) is the main primary extracting country, China is the world's leading producer of refined cobalt for all applications. Exploration of the ocean bottom has shown that large deposits of cobalt and minerals exist as deep-sea nodules and crusts in the Pacific Ocean with an estimated total amount of as much as 10 million tonnes of cobalt[45] which means that, together with confirmed land sources, there is enough primary cobalt for at least 300 years of use at current use rate[46]. A small fraction of global production exists in Europe, but the largest portion of consumption is covered by imports (mainly from Congo, Russia and Tanzania[47]) and recycling. Most European production is concentrated in Belgium, France, Norway and Spain. Congo's political instability has caused problems with long-term security of supply for Europe since the European production can only cover a small proportion of needs. Substitution rate is estimated at nearly zero at present[48].

According to the US Geological Survey 2012[49], the world availability of refined cobalt in 1st half of 2011 was about 12% higher than that of the first half of 2010. China showed the largest increase in production of refined cobalt whereas production in Canada, Finland, and Zambia also increased significantly. In the next few years, a global increase in supply is foreseeable both from existing producers and also new mining projects, which are likely to outpace increases in consumption. However, the unstable political situation in Congo will remain the main global primary supply bottle-neck. In addition, primary extraction itself is often constrained by the fact that nearly all of world cobalt production is a by-product of primary nickel and copper extraction in the Congo and elsewhere[50].

In 2010, cobalt recycled from manufacturing waste or discarded tooling estimated to be equivalent to about 24% of total cobalt consumption in the US and about 15% globally[51]. Potential substitutes for cobalt and its alloys include barium or strontium ferrites,

---

[44] The Cobalt Development Institute, Available: http://www.thecdi.com/about-cobalt (Accessed 10.3.2012); USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012)

[45] USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012).

[46] The Cobalt Development Institute, Available: http://www.thecdi.com/about-cobalt (Accessed 10.3.2012); USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012).

[47] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[48] The Cobalt Development Institute, http://www.thecdi.com/about-cobalt, (Accessed on 10.3.2012).

[49] USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012).

[50] USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012).

[51] USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012).

neodymium-iron-boron, or nickel-iron alloys for permanent magnets used in motors or electronics. Cerium, iron, lead, manganese, or vanadium as oxides have been used to substitute for the wide range of coloured pigments made of cobalt. In bonded diamond tools, cobalt-iron-copper or iron-copper alloys have been used with some success. In tungsten carbide ("widia")-based cutting and wear resistant tools nickel, iron-cobalt-nickel and similar alloys have been used to bond the carbide particles but with limited success. Ceramics and ceramic composites have also been used with good performance in niche applications. Iron-phosphorous, manganese, nickel-cobalt-aluminium, or nickel-cobalt-manganese alloys have been studied for use instead of cobalt in lithium-ion batteries. Nickel-based super-alloys or advanced ceramics are being developed for use in jet engine blades. Nickel and special alloys as well as some oxides have been reported for catalysts for petroleum cracking. Finally, rhodium has been reported as a potential replacement for cobalt in hydro-formulation catalysts[52].

Summary and recommendations: A number of replacement materials have been identified for cobalt and its alloys. However, in most cases, the present state of technology is that most of them are either less satisfactory or more expensive or both. For example, cobalt replacement has been studied for many years in cutting tools based on tungsten carbide but with very limited results, probably due to the almost unique solubility properties between the two materials in this crucial composite material. In other applications there are indications that replacements do have the potential for improved performance but there is little or no incentive for their further development.

It is therefore recommended that funding be made available for research on specific and promising replacement materials, targeted to critical applications. In addition, recycling rates of cobalt can increase to higher than current levels, but this will also require further incentives. This is expected to increase, since scrap recycling is relatively easy and cost effective from many wastes.

2.2.4. Fluorspar

Fluorspar is the commercial term for the mineral Calcium fluoride CaF_2 for both the metallurgical and the ceramic grades. It is the main source for Hydrofluoric acid (HF) and nearly all industrial fluorocarbon and fluorine compounds. Fluorspar is used directly or indirectly to manufacture products such as aluminium metal, petroleum products, insulating foams, refrigerants, steel, and uranium for fuel in nuclear reactors. Hydrofluoric acid is one of the main industrial chemicals. It is widely used in automotive and other transport applications, energy, defence, civil engineering, and medicine[53].

The Kyoto Protocol (and previous agreements) limits fluorocarbon production and consumption since it is one of the main greenhouse gases. In addition, to protect the ozone layer in the atmosphere, hydro fluorocarbon and other fluorocarbons are heavily regulated globally. The EU has established a more aggressive phase-out of hydro(chloro)fluorocarbons (HFC) than the US. HFCs have been banned in new refrigeration equipment after July 1st 2002 whereas, after 2010, virgin HFCs may not be used in any existing equipment.[54]

---

52 USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012); Vivet, S., Joubert, J.-M., Knosp, B., Percheron-Guégan, A., 2003. Effects of cobalt replacement by nickel, manganese, aluminium and iron on the crystallographic and electrochemical properties of AB -type alloys, Journal of Alloys and Compounds. 356–357 pp. 779–783.

53 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).

54 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012); British Geological Survey, www.bgs.ac.uk (Accessed 15.2.2012).

According to the USGS,[55] identified world fluorspar resources are approximately 500 million tons of contained fluorspar. However, the amount of extractable fluorine present in phosphate rock deposits worldwide is much higher. World reserves of phosphate rock are estimated to be 65 billion tons, which contain about 4.7 billion tons of 100% calcium fluoride equivalent[56]. China is the main producer (about 60% in 2011) followed by Mexico, Mongolia, Russia and South Africa. The US has recently re-started some production and in the EU only Spain has any significant production (about 2% of global production)[57]. India has made it clear it is aiming at becoming a major fluorspar producer in the coming years[58]. In Europe, there is very limited fluorspar production, mainly for economic reasons. Europe consumes about 25% of world production (the US consumes another 10%) but is heavily reliant on imports (about 70%) from China, South Africa and Mexico[59], which complements production in Spain and the UK. French and Italian production ceased in 2006[60]. Recently, because of the current higher price, two new production projects have been announced: one in Sweden where a new significant fluorspar deposit has been opened at Storuman[61] and another in Norway at Lassedalen[62].

Import restrictions from China in 2010 have resulted in shortages and increased prices for fluorspar, together with many other raw materials. The World Trade Organisation (WTO) has since ruled (as a result of complaints from the EU, Mexico and the US) that aspects of China's export policies on several important industrial raw materials (including fluorspar) are inconsistent with China's WTO obligations. The WTO panel did not accept China's argument that its export policies were justified on grounds of natural resource conservation. The panel recommended that China bring its policies into conformity with its WTO obligations, but China has since appealed the panel's ruling[63].

Since Fluorspar is actually consumed during use in most of its applications, especially as flux in smelting, only very minor, niche, possibilities for recycling exist. A few thousand tons per year of synthetic fluorspar is recovered primarily from uranium enrichment in the US, but also from petroleum alkylation and stainless steel pickling. Primary aluminium producers recycle hydrofluoric acid and fluorides from smelting operations and some are also recycled during the petroleum alkylation process[64].

USGS reports that olivine and/or dolomitic limestone have been used as substitutes for fluorspar in many processes. In aluminium smelting a number of fluxes have been used, including dross, borax, calcium chloride, iron oxides, feldspar, manganese ore, silica sand,

---

55 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).

56 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).

57 Hetherington, L., Bloodworth, A.W. Industrial minerals production in Europe – current situation and future trends, British Geological Survey, Available: http://nora.nerc.ac.uk/6092/1/Industrial_minerals_in_EU.pdf, (Accessed 14.2.2012).

58 Business Wire, 2011. China & India to Be World Leaders of Fluorspar Production According To Merchant Research & Consulting, Ltd., Available: http://www.businesswire.com/news/home/20110714005943/en/China-India-World-Leaders-Fluorspar-Production-Merchant (Accessed on 15.2.2012).

59 EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

60 Hetherington, L., Bloodworth, A.W. Industrial minerals production in Europe – current situation and future trends, British Geological Survey, Available: http://nora.nerc.ac.uk/6092/1/Industrial_minerals_in_EU.pdf, (Accessed 14.2.2012).

61 Tertiary minerals Plc., Projects, Sweden, Storuman. Available: http://www.tertiaryminerals.com/storuman.html (Accessed 15.3.2012).

62 Tertiary minerals Plc., Projects, Norway, Lassedalen, Available: http://www.tertiaryminerals.com/lassedalen-4.html (Accessed 15.3.2012).

63 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).

64 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).

and titanium dioxide, but the cost is generally higher. In aluminium fluoride production, fluorosilisic acid, a by-product of phosphoric acid production has been used as a substitute which is also being studied to determine its potential to be a substitute in HF production as well[65].

Summary and recommendations: Fluorspar gets used up during most of its applications so it is not feasible to attempt to rely on recycling or re-using. However, some alternatives have been tested successfully and may offer some solution for a number of applications if the suitable incentives are put into place.

2.2.5. Gallium (Ga)

Gallium is a soft metal with a melting point close to room temperature and occurs in very small concentrations within the ores of other metals. Some fly-ash from coal-burning power stations contains up to about 1.5% gallium[66], but currently commercial extraction operations from fly-ash exist. For economic reasons, most gallium is produced as a by-product of bauxite treatment during extraction of aluminium or from zinc-processing residues. This means that gallium production can be affected significantly by disturbances in aluminium or zinc production[67].

Gallium is alloyed with arsenic to produce gallium arsenide which is used for light-emitting diodes (LED) and laser diodes. Gallium nitride is used in integrated circuits (ICs) and optoelectronic devices such as laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells. The current very strong demand for “smart phones” in combination with continuing strong demand for military, lighting and energy applications has meant that gallium is experiencing very strong demand presently[68].

Global deposits of gallium within extractable minerals are in the tens of millions of tons, many times larger than current annual global needs. According to the USGS, in 2011, world primary gallium production was estimated to be about 216 tons with China, Germany, Kazakhstan and Ukraine being the leading producers. Lesser output came from Hungary, Japan, the Republic of Korea, and Russia. This primary production is supplemented by about 100 tons of secondary (recycled) production[69].

The US, and to a lesser extent Europe, are heavily dependent on imports of gallium, gallium arsenide and gallium nitride since recovery from existing local aluminium and zinc extraction operations are apparently uneconomic. A recent trend has been to import pure gallium and alloy it locally with arsenic or nitrogen for applications[70].

---

65 USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).

66 Wang, W.F. Qin, Y. Liu, X.H. Zhao, J.L., Wang, J.Y. Wu, G.D. Liu, J.T. 2011. Distribution, occurrence and enrichment causes of gallium in coals from the Jungar Coalfield, Inner Mongolia, SCIENCE CHINA Earth Sciences, Vol. 54, No.7, pp. 1053-1068, Available: http://www.springerlink.com/content/y5t0r55023522136/fulltext.pdf (Accessed 17.3.2012)

67 USGS, Statistics and Information, Mineral Commodity Summary: Gallium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2012-galli.pdf (Accessed 12.2.2012).

68 USGS, Statistics and Information, Mineral Commodity Summary: Gallium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2012-galli.pdf (Accessed 12.2.2012).

69 EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm; USGS, Statistics and Information, Mineral Commodity Summary: Gallium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2012-galli.pdf (Accessed 12.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Gallium, Available: http://www.mmta.co.uk/metals/Ga/ (Accessed on 12.2.2012)

70 MetalPages, 2012. Gallium a ‘sad’ market, nowhere to turn, Available: http://www.metal-pages.com/news/story/60256/gallium-a-sad-market-nowhere-to-turn/ (Accessed on 10.2.2012).

Gallium recycling is relatively easy and much secondary production from new production waste is already evident. During 2011 Gallium was recycled from new waste in Canada, Germany, Japan, the United Kingdom, and the United States[71].

Considering substitutes, some specific wavelength infrared laser diodes can be made with indium phosphide components while visible lasers can be made on the basis of helium-neon. No effective substitutes for gallium arsenide have yet appeared for defence-related ICs however, but gallium arsenide in heterojunction bipolar transistors are being challenged in some applications by silicon-germanium[72]. Amorphous silicon is still the main competitor of gallium arsenide for solar-cell applications and new nano-technological inventions are being studied for this purpose[73]. According to the USGS, liquid crystal displays and LEDs from organic compounds are already developed for use in TVs and computer or phone displays. Also new silicon-based potential replacement for gallium arsenide has been reported recently[74].

Summary and recommendations: Further development of the organic compounds will probably reduce gallium dependency, except for some *niche* applications. With sufficient recycling facilities a large fraction of future European demand may be met. Since gallium is found in bauxite, it may be possible to produce some from the large bauxite reserves (or even mine dumps).

2.2.6. Germanium (Ge)

Germanium is usually recovered from the leaching of zinc (or copper) residues or fly-ash from coal-fired power stations. As a result, its production is affected by the production of zinc and to a lesser extent, of copper and their extraction from zinc and lead-zinc-copper sulphide ores. Germanium's main current application is as a polymerisation catalyst for PET (polyethylene terephthalate), a commercially important plastic. It is also used in telecommunications fibre optics, in infrared night-vision devices and as a semiconductor and substrate in electronic circuitry and solar cells[75].

According to the USGS, the world's total production of germanium in 2010 was between 100 and 120 tons. This includes primary germanium production from zinc concentrates and fly ash as well as secondary production from recycled material which is currently about 30% of total. Worldwide, China is the main producer of germanium metal and compounds followed by Canada, Finland and Russia. Most European imports come from China or the USA. Recycling of germanium recovered from used materials, such as fibre-optic window blanks in decommissioned military vehicles or fibre-optic cables, has increased during the past decade with an increasing trend worldwide, including Europe.[76]

---

71 USGS, Statistics and Information, Mineral Commodity Summary: Gallium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2012-galli.pdf (Accessed 12.2.2012).

72 USGS, Statistics and Information, Mineral Commodity Summary: Gallium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2012-galli.pdf (Accessed 12.2.2012).

73 Bullis, K., 2007. Cheap solar cells: Carbon nanotubes could help make nanoparticle-based solar cells more efficient and practical, Technology Review, Massachusetts Institute of Technology, Available: http://www.technologyreview.com/energy/18259/ (Accessed 17.3.2012).

74 Imthurn, G.P., 2009. Silicon-on-Sapphire, a replacement for gallium arsenide?, 2009 IEEE International SOI Conference, 5-8 Oct. 2009, Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5318759 (Accessed 17.3.2012).

75 USGS, Statistics and Information, Germanium, Available: http://minerals.usgs.gov/minerals/pubs/commodity/germanium/ (Accessed 12.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Germanium, Available: http://www.mmta.co.uk/metals/Ge/ (Accessed on 12.2.2012).

76 USGS, Statistics and Information, Germanium, Available: http://minerals.usgs.gov/minerals/pubs/commodity/germanium/ (Accessed 12.2.2012).

According to USGS, "Silicon can be a less-expensive substitute for germanium in certain electronic applications. Some metallic compounds can be substituted in high-frequency electronics applications and in some light-emitting-diode applications. Zinc selenide and germanium glass substitute for germanium metal in infrared applications systems but often at the expense of performance. Titanium has the potential to be a substitute as a polymerisation catalyst."[77]

Summary and recommendations: Germanium can be substituted by a number of metal alloys, including Silicon for electronic and optical applications. Only in some niche areas is germanium's high performance considered to be difficult to emulate.

2.2.7. Graphite (C)

Graphite is one of the main types of carbon, the others being coal (mostly amorphous) and diamond. Recently, carbon nanotubes, fullerenes and grapheme have been added to the list. Graphite occurs naturally in metamorphic rocks. In addition to natural mined graphite, synthetic graphite is also available for specific applications, although its cost is higher at present. It is a soft, light mineral, flexible but not elastic and has a very high melting point of about 3,930°C. It has a layered atomic structure and cleaves, which make it almost ideal as a solid lubricant. It is also the most electrically and thermally conductive of the non-metals and is generally chemically inert.

Because of the above properties graphite is used in many industrial applications including brake linings, metal casting, lubricants and steelmaking all of which accounted for about 75% of natural graphite consumption in 2011. Storage batteries, electric motors, fuel cells and writing pencils are ubiquitous applications. Graphite's lubrication ability and high thermal conductivity makes it an excellent material for high-temperature mechanical applications because it provides effective lubrication at a friction interface while furnishing a thermally conductive matrix to remove heat from the same interface. The main market for high-purity synthetic graphite is as an alloying additive in iron to make steel. Other significant uses of all types of graphite are in the manufacture of catalyst supports in chemical engineering, fillers, rubber additive, lithium-ion batteries, solid carbon shapes and kiln furniture and seals. Graphite is also used for antistatic plastics, conductive plastics and rubbers, electromagnetic interference shielding, electrostatic paint and powder coatings, high-voltage power cable conductive shields, membrane switches and resistors, semi-conductive cable compounds, and electrostatic paint and powder coatings[78]. It was also used in the early nuclear power stations.

Large amorphous graphite deposits are found in China, India, Brazil, North Korea, Mexico and the United States. Flake or crystalline flake graphite is found in Austria, Brazil, Canada, China, Germany, and Madagascar. Vein or lump graphite, the highest quality type of natural graphite is mined in Sri Lanka. Synthetic graphite is now used more than natural graphite and accounts for a significant share of the graphite market, especially in North America[79]. World production of natural graphite decreased slightly in 2009 to an estimated

[77] USGS, Statistics and Information, Germanium, Available: http://minerals.usgs.gov/minerals/pubs/commodity/germanium/; Minor Metals Trade Association, Minor Metals in the Periodic Table: Germanium, Available: http://www.mmta.co.uk/metals/Ge/ (Accessed on 12.2.2012).

[78] USGS, Statistics and Information, Graphite, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/ (Accessed 12.2.2012); The European Carbon and Graphite Association, Available: http://www.ecga.net/ (Accessed 12.2.2012).

[79] USGS, Statistics and Information, Graphite, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/ (Accessed 12.2.2012).

1.09 million metric tons compared with 1.12 in 2008[80]. China is the leading producing nation with about 73% of the total. Romania, Sweden and Norway are the main (small) producers of mined amorphous graphite in Europe[81]. Europe is highly dependent on imports of graphite; up to 95% of consumption is imported mainly from China[82].

Due to for example the foreseen proliferation of hybrid and electric vehicles, the production of high-quality flake graphite would need to double from the present volume to satisfy the forecasted increase in lithium-ion battery demand. It is probable that much of this demand has to be satisfied with synthetic graphite. For example, carbon dioxide may be convertible to graphite and some studies show that this may offer a possibility in the near future, balancing industrial needs with environmental protection[83]. Generally, the technology for producing high quality synthetic graphite is available and is being applied further in Europe, but, generally, the market situation is not yet conducive to the necessary investments[84].

Recycling is limited at present since the current abundance of graphite in the world market inhibits increased recycling efforts[85]. The most common source of recycled graphite are refractory materials, such as heat shields, insulations and linings from e.g. furnaces. According to USGS, "Recycling high-quality flake graphite from steelmaking [and from aluminium smelting] is technically feasible, but not practiced widely at the present time. The market for recycled refractory graphite material is now growing, with material being recycled into products such as brake linings and thermal insulation"[86].

Synthetic graphite, clean, unused waste from discarded components and calcined petroleum coke are very good replacements for use in iron and steel production. Finely ground coke with olivine is a potential competitor in foundry facing applications. Molybdenum disulfide competes as a dry lubricant but is more sensitive to oxidising conditions[87].

Summary and recommendations: It does not appear necessary to develop alternative materials to graphite since the technology for the production of high quality synthetic graphite is available. However, better incentives for investments for graphite production facilities may offer the way to self-sufficiency in Europe.

80 USGS, Statistics and Information, Graphite, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/ (Accessed 12.2.2012).

81 The European Carbon and Graphite Association, Available: http://www.ecga.net/, (Accessed 12.2.2012).

82 EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

83 USGS, Statistics and Information, Graphite, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/ (Accessed 12.2.2012); The European Carbon and Graphite Association, Available: http://www.ecga.net/ (Accessed 12.2.2012).

84 The European Carbon and Graphite Association, Available: http://www.ecga.net/ (Accessed 12.2.2012).

85 British Geological Survey, Borrowdale - Lake District, Available: http://www.bgs.ac.uk/research/ukgeology/borrowdale.html (Accessed 13.3.2012); The European Carbon and Graphite Association, Available: http://www.ecga.net/, (Accessed 12.2.2012).

86 USGS, Statistics and Information, Mineral Commodity Summary: Graphite (natural) 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/mcs-2012-graph.pdf (Accessed 24.5.2012).

87 European Federation of Refractories Producers, Raw materials critical for the refractory industry, Available: http://www.pre.eu/en/raw-materials (Accessed 15.2.2012); USGS, Statistics and Information, Graphite, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/ (Accessed 12.2.2012).

2.2.8. Indium (In)

Indium is a very ductile metal, occurring as a liquid over a wide temperature range. It is mainly extracted from the zinc-sulphide ore mineral sphalerite and is not mined alone but recovered as a by-product of lead and zinc smelting, occurring in lead and zinc sulphide ores at about 1%. Many other metal ores contain indium but they are not economic to mine for indium. Vein stock work deposits of tin and tungsten host the highest known concentrations of indium. However, the indium from this type of deposit is also difficult to recover economically[88].

Indium is mainly used as indium-tin-oxide (ITO) for electrically conductive thin film coatings in a variety of flat-panel devices; most commonly liquid crystal displays (LCDs). Other uses are solders and alloys, new types of solar panels (major future growth area), electrical components and semiconductors, generally as indium arsenide and indium antimonide[89].

The world production of indium is approximately 75 tons per year including secondary production (recycling). Most ITO production is in Japan, China, the South Korea and Taiwan[90]. Europe is almost totally dependent on imports for indium[91].

A significant amount of indium is recycled, mainly from production processes such as ITO sputtering mainly in China, Japan and South Korea where most production and sputtering of ITO take place. If economically viable, indium is also recovered from scrap Liquid Crystal Display panels. Recent improvements to the process technology have made indium recovery from tailings viable when the price of indium is high[92].

"Indium's recent price volatility and various supply concerns associated with the metal have accelerated the development of ITO substitutes. Antimony tin oxide coatings, which are deposited by an ink-jetting process, have been developed as an alternative to ITO coatings in LCDs and have been successfully annealed to LCD glass. Carbon nanotube coatings, applied by wet-processing techniques, have been developed as an alternative to ITO coatings in flexible displays, solar cells, and touch screens. Poly(3,4-ethylene dioxythiophene) (PEDOT) has also been developed as a substitute for ITO in flexible displays and organic light-emitting diodes. PEDOT can be applied in a variety of ways, including spin coating, dip coating, and printing techniques. Graphene quantum dots have been developed to replace ITO electrodes in solar cells and also have been explored as a replacement for ITO in LCDs. Researchers have recently developed a more adhesive zinc oxide nanopowder to replace ITO in LCDs. The technology was estimated to be commercially available within the next 3 years. Gallium arsenide can substitute for indium phosphide in solar cells and in many semiconductor applications. Hafnium can replace indium in nuclear reactor control rod alloys."[93]

---

88 The Indium Corporation, Available: http://www.indium.com/ (Accessed 14.2.2012); USGS, Statistics and Information, Mineral Commodity Summary: Indium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf (Accessed 13.2.2012).

89 The Indium Corporation, Available: http://www.indium.com/ (Accessed 14.2.2012); USGS, Statistics and Information, Mineral Commodity Summary: Indium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf (Accessed 13.2.2012).

90 USGS, Statistics and Information, Mineral Commodity Summary: Indium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf (Accessed 13.2.2012).

91 EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

92 Minor Metals Trade Association, Minor Metals in the Periodic Table: Indium, Available: http://www.mmta.co.uk/metals/In/ (Accessed on 13.3.2012); USGS, Statistics and Information, Mineral Commodity Summary: Indium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf (Accessed 13.2.2012).

93 USGS, Statistics and Information, Mineral Commodity Summary: Indium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf (Accessed 13.2.2012); see

Summary and recommendations: New developments for flat-panel display technology show that a number of new technologies exist, most notably zinc oxide nanopowders and carbon nanotubes. The further development of such new materials will reduce European dependence on indium.

2.2.9. Magnesium (Mg)

Magnesium is a strong, silvery-white, light-weight metal which oxidises instantaneously in air forming a thin layer of protective oxide. Without this oxide layer magnesium metal in thin strips or powder can ignite. The two main magnesium-containing minerals are dolomite and magnesite from which most extraction takes place. The majority of magnesium metal is produced by electrolysis of molten magnesium chloride with a little being produced by the thermal reduction of magnesium oxide with ferro-silicon. Magnesium and its alloys are increasingly being used in the automotive sector as a structural material due to its good strength-to-weight ratio, which indirectly enables fuel savings by enabling building lighter vehicles. Magnesium oxide is used extensively as a very high refractory material (melting point nearly 3000^{o}C), as a supplement in cattle feed, additive in plastics as a bulking agent, producing heat resistant bricks, desulphurisation of iron and steel. Also magnesium (hydr-)oxide is used, e.g. in some medicines ("Milk of Magnesia").[94]

China, Russia, Turkey, US are the main producers of magnesium oxide from which magnesium metal is obtained. Others are North Korea, Israel, Brazil, Kazakhstan, Slovakia, Austria and Greece. Reserves of magnesite are estimated at over two billion tonnes as ores and more than a billion tones of magnesium is dissolved in the oceans[95].

Magnesium metal is imported to Europe but magnesium oxide is produced in large quantities in the EU in Slovakia, Austria and Greece with some prospects for further production. In general, large magnesite deposits exist in Europe but at the moment imported magnesium metal or high purity magnesium oxide are more economical. The potential increase in demand for magnesite is driven, amongst others, by an upsurge in interest in magnesium-based vehicles. These vehicles, being very light, would help reduce emissions, drawing closer to the EC emissions limits[96].

In 2011, about 21,000 tons of magnesium was recovered from old production waste in the US and a similar amount in the EU. Some magnesium-based refractories are recycled, either for reuse as refractory material or for use as construction aggregate[97].

Aluminium and zinc can substitute magnesium in castings and wrought products. Calcium carbide may be used instead of magnesium for iron and steel desulphurisation. Alumina, chromite and silica may be used instead of magnesia for many refractory applications.

also: Minor Metals Trade Association, Minor Metals in the Periodic Table: Indium, Available: http://www.mmta.co.uk/metals/In/ (Accessed on 13.3.2012); Suzuki, A. Transparent conductive zinc oxide film: New Light for Indium-free Solar Cells, ULVAC Group, ULVAC Corporate Center, Available: http://www.ulvac-uc.co.jp/pdf/prm_arc/056e/No56E-04.pdf (Accessed 17.3.2012).

94 Shand, M.A., 2006. The Chemistry and Technology of Magnesia, John Wiley & Sons, New York.

95 USGS, Statistics and Information, Mineral Commodity Summary: Magnesium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2012-mgcom.pdf (Accessed 16.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Magnesium, Available: http://www.mmta.co.uk/metals/Mg/ (Accessed 16.2.2012); European Federation of Refractories Producers, Raw materials critical for the refractory industry, Available: http://www.pre.eu/en/raw-materials (Accessed 16.2.2012).

96 Sillekens, W.H., Agnew, S.R., Neelammeggham, N.R., Mathaudhu, S.N. (eds.), 2011. Magnesium Technology, The Minerals, Metals & Materials Society, John Wiley and Sons.

97 USGS, Statistics and Information, Mineral Commodity Summary: Magnesium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2012-mgcom.pdf (Accessed 16.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Magnesium, Available: http://www.mmta.co.uk/metals/Mg/ (Accessed 16.2.2012).

Spinel (an oxide compound of aluminium and magnesium) can also be used instead of magnesium oxide at lower temperatures[98].

Summary and recommendations: Magnesite is wide spread in Europe with strong production of magnesium oxide in Europe. Further incentives should be found for conversion to magnesium metal production to reduce criticality of supply.

2.2.10. Niobium (Nb)

Sometimes called columbium, niobium is a soft, grey transition metal very often found together with tantalum. Niobium is sometimes produced as by-product of tin smelting. The major niobium engineering alloys produced are ferroniobium, nickel-niobium and niobium metal and oxide. Ferroniobium is used worldwide as an alloying component in steels for vehicles. High-purity ferroniobium and nickel niobium are used in nickel-, cobalt-, and iron-base superalloys for applications such as jet engine components, rocket subassemblies, and heat-resistant equipment[99].

Main producers of niobium are Brazil and Canada with about 90% of total production (about 60 000 tons in 2009). Smaller amounts are also produced in Mozambique, Saudi Arabia and Greenland. No shortage of Niobium is expected globally in the next few years. World resources of niobium are adequate to supply projected needs. Brazil alone has over 460 million tons of reserves[100]. Apart from a small amount produced in Greenland, Europe imports all the Niobium alloys needed[101].

Niobium is recycled when niobium-bearing steels and superalloys are recycled but waste recovery specifically for niobium content is generally negligible. Although the amount of niobium recycled is not clear, it may be as much as 20% of apparent consumption[102].

According to the US Geological Survey, the following materials can be substituted for niobium, but a performance or cost penalty may result: molybdenum and vanadium as alloying elements in high-strength low-alloy steels; tantalum and titanium, as alloying elements in stainless and high-strength steels; and ceramics, molybdenum, tantalum, and tungsten in high-temperature applications[103].

Summary and recommendations: As mentioned above, some replacement materials for niobium exist but in many cases, current technologies (and alternative alloys) appear to exact a performance penalty. The EC should encourage research on improving the effectiveness of these potential substitutes.

98 U.S. International Trade Commission, 2005. Magnesium From China and Russia, Investigations Nos. 731-TA-1071 and 1072, United States International Trade Commission Publication 3765, Washington, DC.

99 USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 21.2.2012); Minor Metals in the Periodic Table: Niobium, Available: http://www.mmta.co.uk/metals/Nb/ (Accessed 21.2.2012).

100 USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 21.2.2012); Minor Metals in the Periodic Table: Niobium, Available: http://www.mmta.co.uk/metals/Nb/ (Accessed 21.2.2012).

101 British Geological Survey, 2011. Niobium-tantalum, Available: http://www.bgs.ac.uk/downloads/start.cfm?id=2033 (Accessed 21.2.2012); EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

102 Tantalum-Niobium study centre, Available: http://tanb.org/ (Accessed 21.2.2012); USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 21.2.2012).

103 USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 21.2.2012).

2.2.11. Platinum Group Metals (PGM)

The six platinum group metals (PGM) are iridium, osmium, palladium, platinum, rhodium, and ruthenium. They are generally found together and are characterised by high melting points, corrosion resistance and good and stable electrical properties. The most important applications of the PGMs are as catalysts or as a material for catalytic converters for various applications. Platinum's wear and tarnish resistance characteristics are exploited in fine jewellery. Platinum, platinum alloys and iridium are used for refining of crude oil and for the growth of single crystals, especially oxides. Ruthenium dioxide is used as a coating on dimensionally stable titanium anodes utilised in the production of chlorine and caustic soda. Palladium can be used in a variety of products ranging from catalytic converters to fuel cells, which produce energy by converting hydrogen and oxygen to water[104]. A wide range of PGM alloy compositions is also used in electrical contacts, circuits, thermocouples and furnace components as well as various electrodes[105].

Since 1979, the automotive industry has emerged as the main consumer of palladium and platinum (as oxidation catalysts) and rhodium (as reduction catalyst) in catalytic converters to clean toxic automobile exhaust emissions containing carbon monoxide, nitrogen oxide and various aromatic hydrocarbons. Over half of the supply of palladium and platinum is used in catalytic converters, which convert up to 90% of harmful gases from auto exhaust into less-harmful substances (nitrogen, carbon dioxide and water vapour)[106].

The main producers of PGMs are South Africa (nearly 90% of global production of platinum and about 50% of palladium) and Russia. Recently the US and Canadian production has improved and more production projects are in the pipeline. Some production has also started in Colombia. Zimbabwean production has decreased sharply recently due to political instabilities[107]. World resources of PGMs in economic mineral concentrations are estimated to total more than 100 million kilograms. The largest reserves are in South Africa followed by Russia. The total global consumption of PGMs is about 245 tons (in 2010), increasing significantly over previous years[108]. Europe imports all its PGM needs from South Africa and Russia. No production exists in Europe, but recycling has increased over the last years[109].

Because the PGMs are usually little affected by use, over 95% recyclability is possible from most of their applications. However at present, the total recycling rate is still only about 15% although increasing. In 2011, in the US, an estimated 36,000 kilogram of PGM was recovered from new and old scrap in 2011 with a similar amount worldwide[110].

---

[104] Lewis R., 2009. Brown Chemists Create More Efficient Palladium Fuel Cell Catalysts, Brown University News and Events, Available: http://news.brown.edu/pressreleases/2009/03/palladium (Accessed 22.5.2012).

[105] USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012); Dr Galina Xanthopoulou, NCSR Demokritos, Greece, interview 10 February 2012.

[106] USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012); Dr Galina Xanthopoulou, NCSR Demokritos, Greece, interview 10 February 2012.

[107] International PGM Association, Available: http://www.ipa-news.com/en/ (Accessed 21.2.2012); USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012).

[108] USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012); International PGM Association, Available: http://www.ipa-news.com/en/ (Accessed 21.2.2012).

[109] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[110] National Research Council of the National Academies, 2007. Minerals, Critical Minerals and the US Economy, Available: http://www.nma.org/pdf/101606_nrc_study.pdf (Accessed 9.2.2012); USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012);

Recycling rates are now increasing globally, which is expected to alleviate supply shortages. In many countries recycling rates have increased sharply as the first and second generation catalytic converters used in vehicles are getting to the end of their usable life. In fact, the amount of palladium and platinum used in older catalytic converters was much larger than the amounts used in modern units, thus forming a large potential supply[111]. The new Waste Electrical and Electronic Equipment Directive (WEEE, passed by the European Parliament in January 2012) will plausibly have a major effect on increasing the recycling rate of all metals including PGMs[112].

Generally the PGMs are very efficient as catalysts and it is difficult to find materials that can substitute them. For some catalytic uses certain other PGMs (e.g. palladium) can substitute for platinum but this sometimes leads to losses in performance. Nevertheless, cerium, iron, manganese and nickel have been reported as viable substitutes, although each has its own limitations[113]. For oxidation of exhaust gases, a new type of catalyst based on chromium-copper oxides has been reported that may be able to substitute PGMs in vehicle exhausts but requires further development[114].

Summary and recommendations: PGMs are a very successful type of materials as catalysts and for other uses. Since their recyclability is very effective, the emphasis of future efforts should be placed on encouraging recycling and re-use. Some substitutes for PGMs have been identified but they are mainly other PGMs. Some new materials have appeared but need more support for further development.

2.2.12. Rare Earth Elements (REE)

The Rare Earth Elements (REE) include the 15 elements in the lanthanide group: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium as well as yttrium and scandium, a total of 17 elements. The elemental forms of rare earths are iron gray to silvery lustrous metals that are typically soft, malleable, and ductile and usually reactive, especially at elevated temperatures or when finely divided. The rare earths range in abundance from cerium, the most abundant, to thulium and lutetium, the least abundant.

Economically extractable concentrations of rare earths are less common than for most other ores. Globally, "bastnäsite deposits in China and the United States constitute the largest percentage of the world's rare-earth economic resources, while monazite deposits in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the United States constitute the second largest segment. Apatite, cheralite, eudialyte, loparite, phosphorites, rare-earth-bearing (ion adsorption) clays, secondary monazite, spent

[111] PGM Review, Available: http://www.platinummetalsreview.com/ (Accessed 21.2.2012); European Council, European Parliament, 2002. Directive 2002/96/EC on Waste Electrical and Electronic Equipment, Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:037:0024:0038:en:PDF (Accessed 21 February 2012); Hagelüken, C. 2012. Recycling the Platinum Group Metals: A European Perspective, PGM Review, Vol. 56, No.1, pp. 29-35.

[112] European Council, European Parliament, 2002. Directive 2002/96/EC on Waste Electrical and Electronic Equipment, Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:037:0024:0038:en:PDF (Accessed 21 February 2012).

[113] USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012).

[114] Xanthopoulou G., Vekinis G., 1998. Investigation of Catalytic Oxidation of CO over a Cu-Cr-oxide Catalyst made by Self-Propagating High-Temperature Synthesis, Applied Catalysis B: Environmental, Vol. 19, pp. 37-44.

uranium solutions, and xenotime make up most of the remaining resources. Undiscovered resources are thought to be very large relative to expected demand"[115].

Rare earths are now used extensively in some critical applications such as automotive catalytic converters, fluid cracking catalysts in petroleum refining, colour television and flat panel displays for cell phones, portable DVDs, and laptops, permanent magnets and rechargeable batteries for hybrid and electric vehicles and generators for wind turbines as well as numerous medical devices[116]. Especially the new rare-earth permanent magnets are much more efficient than usual cobalt- or ferrite-based magnets. More details on their applications are given in the table below[117].

Table 2: Typical applications of REE[118]

#	Rare Earth Element	Main Applications
1	Lanthanum	Hybrid automotive engines, metal alloys
2	Cerium	Auto catalyst, petrol refining, metal alloys
3	Praseodymium	Magnets
4	Neodymium	Auto catalyst, petroleum refining, high power/high flux magnets in e.g. computer hard drives, headphones, loudspeaker elements, electric motors including hybrid engines
5	Promethium	Niche uses, light source (with phosphor), atomic battery
6	Samarium	Magnets
7	Europium	Red colour for television and computer screens
8	Gadolinium	Magnets
9	Terbium	Phosphors, permanent magnets
10	Dysprosium	Permanent magnets, hybrid engines
11	Holmium	Glass colouring, lasers
12	Erbium	Phosphors
13	Thulium	Medical x-ray units
14	Ytterbium	Lasers, steel alloys
15	Lutetium	Catalysts in petroleum refining
16	Yttrium	Red colour, fluorescent lamps, tough ceramics, metal alloy agent
17	Scandium	Aluminium alloy strengthening, oxide fuel cells

[115] USGS, Statistics and Information, Mineral Commodity Summary: Rare Earths 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf (Accessed 19.2.2012).
[116] USGS, Statistics and Information, Mineral Commodity Summary: Rare Earths 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf (Accessed 19.2.2012).
[117] Humphreys, M. 2011. Rare Earth Elements: The Global Supply Chain, Congressional Research Service Report for Congress, R41347.
[118] USGS, Statistics and Information, Mineral Commodity Summary: Rare Earths 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf (Accessed 19.2.2012); Humphreys, M. 2011. Rare Earth Elements: The Global Supply Chain, Congressional Research Service Report for Congress, R41347.

The largest producer and supplier of REE is now China (99% of current supply, mainly due to low-cost operations and substantial own needs), US (re-starting operations in 2012) and Australia. The total global demand in 2011 was 136 000 metric tonnes, while production was 133 600 tonnes, the gap being filled with previously mined over-the-ground stock. While the production and use are quite balanced at the moment, the demand is projected to grow, reaching 185 000 tonnes per annum by 2015.[119] Because of China's decision to restrict exports in 2010, many countries have re-started explorations with varying success, such as Alaska's Bokan Mountain discovery[120]. No raw REE production is known in the EU. Permanent magnet manufacturing and other applications in the European Union are dependent on imported rare earth raw materials, nearly all of them from China[121].

Most rare earths are difficult to recycle since they are used in minute quantities in alloys and various compounds. Currently, only small quantities are recycled, mostly from permanent magnet manufacturing scrap. New recycling technologies are being tested in many countries but with limited success[122].

Substitute materials for many applications of REE exist, but generally there is a performance penalty. In fact, most alloys that contain REE were developed to replace previous technologies that were not satisfactory in demanding applications. For example, in permanent magnets, ferrite was used for decades until the superior neodymium-based and the samarium-cobalt alloys were discovered[123].

Lately, because of the instability of rare earth supply from China, the US and Japan have been supporting large research programmes searching for satisfactory substitutes for rare earths[124]. For example iron nitride appears to offer a potential replacement for a number of rare earth applications[125]. Nanotechnological materials also appear to be promising substitutes[126]. Various papers and reports proposing possible replacements for rare earths have appeared on the web and in scientific literature in the last years[127]. Japan has been supporting research on rare earth substitution for a number of years now under the "The

[119] Humphreys, M., 2011. Rare Earth Elements: The Global Supply Chain, Congressional Research Service Report for Congress, R41347.

[120] Grushkin, D., 2011. Alaska's Billion Dollar Mountain, Business Week, 27.10.2011, Available. http://www.businessweek.com/magazine/alaskas-billion-dollar-mountain-10272011.html. (Accessed 15.2.2012).

[121] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[122] EC Directive 2002/96/EC on Waste Electrical and Electronic Equipment, Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:037:0024:0038:en:PDF (Accessed 21 February 2012); USGS, Statistics and Information, Mineral Commodity Summary: Rare Earths 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf (Accessed 19.2.2012); Humphreys, M. 2011. Rare Earth Elements: The Global Supply Chain, Congressional Research Service Report for Congress, R41347.

[123] Dr D. Niarchos, NCSR Demokritos, Greece, interview 5.3.2012.

[124] Professor G. Hadjipanayis, University of Delaware, USA, interview, 29.2.2012; Erdem T., Volkan Demir, H., 2011. Semiconductor nanocrystals as rare earth alternatives, Nature Photonics, No. 5, p. 126, Available: http://www.nature.com/nphoton/journal/v5/n3/full/nphoton.2011.25.html (Accessed 19.3.2012).

[125] Tomioka, T, Monozukuri, N. 2011. Iron Nitride Powder Produced as Substitute for Rare Metal, Tech-On, Available: http://techon.nikkeibp.co.jp/english/NEWS_EN/20110307/190128/ (Accessed 18.3.2012).

[126] The Institute of Nanotechnology, 2011. Replacing Rare Earths With Silicon Chips, Available: http://www.nano.org.uk/news/1296/ (Accessed 18.3.2012).

[127] Erdem T., Volkan Demir, H. 2011. Semiconductor nanocrystals as rare earth alternatives, Nature Photonics, No. 5, p. 126, Available: http://www.nature.com/nphoton/journal/v5/n3/full/nphoton.2011.25.html (Accessed 19.3.2012); Beissman, T. 2012. Toyota finds alternatives to rare earth metals for hybrids: report, Car Advice, Available: http://www.caradvice.com.au/156331/toyota-finds-alternative-to-rare-earth-metals-for-hybrids-report/ (Accessed 19.3.2012); International Copper Association Ltd. Copper Presents an Effective Alternative to Rare Earth Magnets in Electric Vehicles, Available: http://copperalliance.org/wordpress/wp-content/uploads/downloads/2012/02/us_12apr_11.pdf (Accessed 19.3.2012).

New Energy and Industrial Technology Development Organisation" (NEDO)[128]. Japan is also planning to initiate a new, wide-ranging project to find substitutes for rare earths, as well as a number of other critical raw materials during 2012[129].

> *Summary and recommendations*: Since rare earths cannot be recycled easily and cost-effectively, supply needs to be assured to avoid serious problems in many sectors. Although a few promising substitutes have been identified already, there is a need for more research especially in the field of nanotechnology or for iron nitride.

2.2.13. Tantalum (Ta)

Tantalum is a hard but ductile metal which can be formed easily. Its outer layers oxidise readily, forming a protective oxide surface layer (similar to many other metals such as aluminium and magnesium), which makes it highly corrosion resistant, and resistant to most acids. It is also a good conductor of heat and electricity and has a high melting point. Its main minerals are tantalite, microlite, or wodginite and it is also produced as a by-product of cassiterite. It most often occurs with niobium.

Up to 60% of tantalum production has been used in capacitors for consumer electronics, while in 2010 the fraction was 24%. While tantalum can be substituted with aluminium, niobium, and multi-layer ceramics in many applications, due to miniaturisation and ensuing high operating temperatures, tantalum-capacitors remain optimum for various applications. Tantalum is also an important material in dielectric resonators, e.g. cellular base stations for mobile telephony. Other frequent use of tantalum include high-strength, low-alloy steels and so called superalloys for high-temperature, high-stress applications, refractory materials, as well as alloy metals in cutting tools and ceramics.[130]

The primary source for tantalum has been Australia. In fact, the main mines in Australia were shut down or have been on care and maintenance only for a period of time, but they have been restarting operations again recently. This has been the case in Canada as well. Other producing regions for raw tantalum include Brazil, Ethiopia, Central Africa (Rwanda), Nigeria, Mozambique and China. However, China is the main producer of tantalum products[131]. Generally, there is limited large-scale mining for tantalum and consequently much of the tantalum-bearing ore comes from small scale mining (60-70% of total supply in 2009)[132].

Identified resources of tantalum, most of which are in Australia and Brazil, are considered adequate to meet projected needs globally. Serious issues for the supply of tantalum include the conflicts around the Democratic Republic of Congo, Rwanda and Uganda, the

[128] New Energy and Industrial Technology Development Organisation (NEDO), Japan, Rare Earth Metal Substitute Materials Development Project, Available: http://www.nedo.go.jp/english/activities_nedoprojects_nano.html (Accessed 18.3.2012).

[129] Professor O. Odawara, Tokyo Institute of Technology, Japan, interview 23 February 2012; Sanford, J. 2011. Japan announces new rare earth policy, RareMetalBlog, Available: http://www.raremetalblog.com/2011/02/japanese-government-announces-new-rare-earth-policy-.html, (Accessed on 24.2.2012).

[130] USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 21.2.2012); British Geological Survey, 2011. Niobium-tantalum, Available: http://www.bgs.ac.uk/downloads/start.cfm?id=2033 (Accessed 21.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Tantalum, Available: http://www.mmta.co.uk/metals/Ta/ (Accessed 18.3.2012)

[131] Tantalum-Niobium Study Centre, Available: http://tanb.org/ (Accessed 7.2.2012); USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 6.2.2012).

[132] USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 6.2.2012).

new regulations covering low level natural radioactivity in ores and government export licences from the US and other countries[133]. No EU production exists, except secondary production as recycled material, which is currently expanding[134].

There is extensive recycling of tantalum which in fact constitutes a major secondary production source, with an increasing trend. There are two main types of secondary production, either old low-tantalum grade tin slags, primarily from South East Asia, China and Germany, or recycling of new production waste from tantalum-containing electronic components and from tantalum-containing cemented carbide and superalloys[135].

While substitutes for tantalum exist, they result in a loss of performance especially for mobile telephony. According to the US Geological Survey, the following materials can be substituted for tantalum: niobium in carbides; aluminium and ceramics in electronic capacitors; glass, niobium, platinum, titanium, and zirconium in corrosion-resistant equipment; and hafnium, iridium, molybdenum, niobium, rhenium, and tungsten in high-temperature applications.[136].

Summary and recommendations: The future supply situation for tantalum appears bright due to widespread and increasing trend in the use of tantalum recycling. The specific criticality for the supply of tantalum may be reduced significantly if recycling is further extended to manufacturing waste and discarded electronic consumer and military goods.

2.2.14. Tungsten (W)

Tungsten (or wolfram) is a hard, heavy transition metal. In its normal, non-purified form, it is brittle but if highly purified (excluding oxygen and carbon) it is plastic and malleable. It has the highest melting point (3422°C) of all elements except carbon and the highest of all non-alloyed metals. It also has the highest tensile strength at very high temperatures (>1650°C) and the lowest coefficient of expansion of any pure metal. The most important mined minerals are scheelite, wolframite and stolzite[137].

"Tungsten … is a metal with a wide range of uses, the largest of which is as tungsten carbide in cemented carbides. Cemented carbides (also called hardmetals) are wear-resistant materials used by the metalworking, mining, and construction industries. Tungsten metal wires, electrodes, and/or contacts are used in lighting, electronic, electrical, heating, and welding applications. Tungsten is also used to make heavy metal alloys for armaments, heat sinks, and high-density applications, such as weights and counterweights; superalloys for turbine blades; tool steels; and wear-resistant alloy parts and coatings. Tungsten composites are used as a substitute for lead in bullets and shot. Tungsten

[133] National Research Council of the National Academies, 2007. Minerals, Critical Minerals and the US Economy, Available: http://www.nma.org/pdf/101606_nrc_study.pdf (Accessed 9.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Tantalum, Available: http://www.mmta.co.uk/metals/Ta/ (Accessed 18.3.2012); USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 6.2.2012).

[134] Tantalum-Niobium International Study Centre, Critical raw materials for the EU - Report of the Ad-hoc Working Group on defining critical raw materials - response to the EU raw materials criticality report, Available: http://ec.europa.eu/enterprise/policies/raw-materials/files/pc-contributions/org-050-tantalum-niobium-international-study-center-tic_en.pdf (Accessed 7.2.2012); EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[135] USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 6.2.2012).

[136] USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available : http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 6.2.2012).

[137] Azom.com, Tungsten, an overview, Available: http://www.azom.com/article.aspx?ArticleID=1201 (Accessed 18.2.2012)

chemical compounds are used in catalysts, inorganic pigments, and high-temperature lubricants"[138].

The largest producer of tungsten is China (>80% of global total) followed by USA, Russia, Austria, Portugal, Bolivia, and Canada. According to USGS, "China's Government regulates its tungsten industry by limiting the number of exploration, mining, and export licenses; limiting or forbidding foreign investment; imposing constraints on mining and processing; establishing quotas on production and exports; adjusting export quotas to favour value-added downstream materials and products; and imposing export taxes on tungsten materials. ... To conserve its resources and meet increasing domestic demand, the Chinese Government was expected to continue to limit tungsten production and exports and increase tungsten imports"[139].

Europe is dependent on very high rates of imports for tungsten (about 73%)[140] but decreasing due to increased recycling. Although Europe used to be the world's main producer of tungsten carbide tools (Germany, UK, Austria) it is now lagging behind China. Main suppliers of Europe are Russia, Bolivia and Uganda. Portuguese and Austrian mines supply a small part of the total need in Europe. The Variscan Belt stretching from Austria, Germany and Czech Republic to North France, South East UK to Spain and Portugal has significant deposits of tungsten that may be extractable (under certain cost conditions) to reduce criticality[141].

There are very high recycling rates for tungsten and its carbides worldwide, especially from manufacturing waste from tungsten carbide tools and projectiles. Globally, total recycling rates are about 35% and increasing with similar rates for Europe. In 2011, the tungsten contained in new waste consumed by processors and end users represented approximately 55% of apparent consumption of tungsten in all forms[142].

According to USGS, "Potential substitutes for cemented tungsten carbides include cemented carbides based on molybdenum carbide and titanium carbide, ceramics, ceramic-metallic composites (cermets), and tool steels. Potential substitutes for other applications are as follows: molybdenum for certain tungsten mill products; molybdenum steels for tungsten steels; lighting based on carbon nanotube filaments, induction technology, and light-emitting diodes for lighting based on tungsten electrodes or filaments; depleted uranium or lead for tungsten or tungsten alloys in applications requiring high-density or the ability to shield radiation; and depleted uranium alloys or hardened steel for cemented tungsten carbides or tungsten alloys in armour-piercing projectiles. In some applications, substitution would result in increased cost or a loss in product performance"[143].

---

[138] USGS, Statistics and Information, Tungsten, Available: http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/ (Accessed 18.2.2012); British Geological Survey, Minerals UK, Available: http://www.bgs.ac.uk/mineralsuk/home.html (Accessed 18.2.2012); International Tungsten Industry Association, Available: http://www.itia.info/ (Accessed 19.2.2012).

[139] USGS, Statistics and Information, Mineral Commodity Survey: Tungsten 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/mcs-2012-tungs.pdf (Accessed 18.2.2012).

[140] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[141] Int. Tungsten Industry Association, Available: http://www.itia.info/ (Accessed 19.2.2012).

[142] British Geological Survey, 2011. Tungsten, Available: http://www.bgs.ac.uk/downloads/start.cfm?id=1981 (Accessed 21.2.2012); Azom.com, Tungsten, an overview, Available: http://www.azom.com/article.aspx?ArticleID=1201 (Accessed 18.2.2012); British Geological Survey, 2011. Tungsten – A hard metal to replace, Available: http://www.bgs.ac.uk/news/NEWS/Tungsten_Profile_press_release.pdf (Accessed 21.2.2012); Minor Metals Trade Association, Minor Metals in the Periodic Table: Tungsten, Available: http://www.mmta.co.uk/metals/W/ (Accessed 21.2.2012).

[143] USGS, Statistics and Information, Mineral Commodity Survey: Tungsten 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/mcs-2012-tungs.pdf (Accessed 18.2.2012).

Summary and recommendations: It appears that tungsten carbide is difficult to replace without losing performance. The high rate of recycling in Europe offers a way to decrease criticality of tungsten in Europe. However, new sources may need to be found to ensure obstacle-free supply.

3. EXISTING POLICIES FOR THE SUBSTITUTION OF CRITICAL RAW MATERIALS

KEY FINDINGS

- Within the EU, the EU institutions have been active in creating a comprehensive policy framework to support substitution of CRM.
- On the EU level, an emerging issue is the interplay between the new framework programme for research and innovation (Horizon 2020), the proposed European Innovation Partnership, the foreseen Knowledge and Innovation Centre, which may create duplicate instruments for substitution research.
- The structure of Horizon 2020 as presently proposed also seems fragmented from the specific point of view of RDI to substitute CRM.
- The analysed Member States individually have been less active in developing minerals strategies or programmes to support substitution of CRM, with the notable exception of Germany's comprehensive and strong policy response that balances short and long term interests through different measures.
- Outside the EU, the benchmark countries including the United States of America, Japan and the Republic of Korea each have their own policy response to raw materials issues.
- Japan has the most comprehensive set of RDI instruments specifically to support substitution of CRM.
- In the United States the policy response for CRM substitution is still taking its form apart from a RDI initiative under the Department of Energy.
- Korea in its turn is aiming to develop policies to secure supply of raw materials rather than substituting CRM.

3.1. Policies, measures and policy targets for substitution in the EU and its Member States

3.1.1. EU level

The EC Communication "Tackling the challenges in commodity markets and on raw materials"[144] voices a concern about supply security and prices of various raw materials. The communication describes price volatility which coincides with the economic boom ending with the financial crisis of 2008, economic recovery and the Chinese decision to enforce export duties on certain raw materials to ensure national supply security in 2009. The communication picks up where the earlier Raw materials initiative left in 2008 and is also closely linked with the EU2020 flagship initiative "A Resource-efficient Europe"[145], which sets the target to lay down a framework of policies to support creation of a resource-

[144] EC, 2011. Tackling the challenges in commodity markets and on raw materials, COM(2011) 25 Final.
[145] EC, 2011. A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy, COM(2011) 21 final.

efficient and low-carbon economy, including technological improvement and innovation, transition to new energy sources, industrial, agricultural and logistic systems as well as behaviour of consumers. To support the development, EC has drafted a roadmap for resource efficient growth[146].

The European materials policy has a principle aim of increasing self-sufficiency, sustainability and competitiveness of European industry and economy, by reducing dependency on third countries for raw materials and energy. The rationale is at least twofold: financial and security-oriented. The European economy cannot be competitive and grow to create welfare for everyone as projected in the general EU2020 Strategy if the industry is constrained by lack of resources necessary to keep on the path of sustainable and sustained growth. Besides constraining growth, serious shortage of resources could result in withering of the industries where the value chain depends on CRM, which in turn may turn into loss of vital know-how within EU. Furthermore, especially in times of crisis self-sufficiency is important as one cannot rely on outside sources for political and logistical reasons. Especially the Americans are quite aware and explicit about the fact that their defensive capability depends directly on REE and other CRM supplies[147]. One aspect of the larger scheme of things is substituting CRM, and especially REE, with different materials or altogether different solutions.

While EU institutions are active in policy making within the union, the EU also has engaged in a dialogue with US and Japan to discuss the options to lessen the demand for REE and increase efficiency of raw materials use.[148] The issues of CRM policy are intertwined with energy policy, not least because REE are vital ingredients in powerful permanent magnets utilised in high-performance electric motors and generators as well as in batteries, which in turn are the building blocks of e.g. wind turbines, hybrid and electric vehicles, not to mention their use in chemical catalytic converters for the petro-chemical industries[149].

Besides these strategic initiatives, the EU institutions and the Member States have set up a host of policies and instruments to support substitution of CRM. The European Commission has paid attention to the importance of uninterrupted supply of raw materials since "The raw materials initiative"[150] of 2008 when raw materials were seen primarily as an issue of growth and jobs. However, on the EU level the thrust for replacing/substituting CRM through innovation is a major theme since 2011, with a slightly altered agenda of sustaining the present level of use and present value chain until new solutions can be developed[151]. It seems that the current level of interest in CRM can be largely traced back to first the Chinese decision to mandate export duties for REE back in 2009[152], second to the simultaneous production and export limits in China (the provider of almost all of worlds REE as of today[153]) and third to the rise in demand for CRM, which have caused the raw

---

[146] EC, 2011. Roadmap to a Resource Efficient Europe, COM(2011) 571 final.

[147] See e.g. Grasso, V.B., 2011. Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress, Congressional Research Service Report for Congress, R41744; Gschneider, K.A., Jr., 2011. Rare Earth Metals: Supply, Demand, Recycling, and Substitutions, a presentation for The Council for Chemical Research, Dearborn, MI, May 3rd 2011.

[148] Reppert-Bismark, J. von, 2011. U.S., EU, Japan to discuss rare earths in October, Reuters News, Available at: http://www.reuters.com/article/2011/09/08/us-eu-rareearths-idUSTRE7876M320110908, (Accessed 6.2.2011).

[149] Moss, R.L., Tzimas, E., Kara, H., Willis, P., Kooroshy, J., 2011. Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies, Joint Research Centre - Institute for Energy and Transport.

[150] EC, 2008. The raw materials initiative: Meeting our critical needs for growth and jobs in Europe, COM(2008) 699 final.

[151] EC DG-ENTR, Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

[152] See WTO rulings, op.cit.

[153] See e.g. Miles, T., 2011. China rare earth prices explode as export volumes collapse, Reuters News Service, March 22nd 2011. Available at:

material prices to rise sharply during 2011. However, at the moment of writing, the idea of improving specifically CRM/REE supply security or substitution is relatively new, and the main focus in many countries' materials technology programmes seem to be general development of new technologies and solutions to existing technical and commercial programmes, rather than explicitly replacing the use of CRM.

Another route beside trade and industrial policy envisioned by the European Parliament and the European Commission to achieve substitution of CRM is intensive RDI effort, such as is proposed in the "Partnering in Research and Innovation Communication"[154]. The communication proposes building a critical mass of research and innovation through public-private partnerships (PPPs) and through engaging in joint agenda setting between public and private actors to ensure mutual benefits. One of such initiatives is the newly proposed European Innovation Partnership (EIP) on raw materials[155], which implements the EIP concept envisioned in the EU2020 flagship initiative "Innovation Union". The EIP is an initiative to support innovation along the whole value/production chain from prospecting and exploration through mining and processing to recycling, as well as substitution of CRM. The EIP targets to include partners from all relevant stakeholder groups and to network between existing networks, including European Technology Platforms and ERA-NETs.

On a more practical level, the objectives are also implemented down to the EU 7th Framework Programme for Research and Innovation (FP7). Especially the Specific Programme Cooperation includes several relevant funding themes, including environmental research and energy research. The FP7 environmental theme contains strands such as conservation, sustainable management and recycling of natural and human-made materials. Energy research aims to create new sustainable technologies, which have largely relied so far on CRM. The most relevant theme or sub-division seems to be however the Nano- and materials technology theme, as exhibited particularly in the 2012 Work Programme on Nanosciences, nanotechnologies, Materials and new Production technologies - NMP[156] of the EU FP7. The NMP 2012 call includes, among others, the following themes/calls: "Rational design of nano-catalysts for sustainable energy production...", "Innovative recycling technologies of key metals in high-tech applications" and "Development of advanced magnetic materials [completely] without [or with less CRM]". Besides the flagship RDI programme, the EC also commissions technical studies to research the feasibility of substitution of CRM[157].

The major emerging issue in EU RDI policy is the phase-out of FP7 and the emerging Horizon 2020 – The framework programme for Research and Innovation (H2020), and its interplay with the partially overlapping EIP on Sustainable materials resources and a possibly emerging KIC administrated by EIT. Starting 2014, H2020 supersedes FP7, while it is foreseeable that some of the themes found in the H2020 proposal might be introduced to FP7 during its last year.

The present FP7 is split into 7 specific programmes and altogether 25 subdivisions inside the specific programmes. The largest specific programmes are Cooperation for collaborative

http://www.reuters.com/article/2011/03/22/us-china-rareearth-idUSTRE72L10I20110322 (Accessed 9.2.2012).

154 EC, 2011. Partnering in Research and Innovation, COM(2011) 572 final.

155 EC DG-ENTR, 2012. European innovation partnership on raw materials, Available at: http://ec.europa.eu/enterprise/policies/raw-materials/innovation-partnership/index_en.htm; EC, 2012. Making raw materials available for Europe's future well-being: Proposal for a European Innovation Partnership on raw materials, SWD(2012) 27 final, available at: http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/communication_final_en.pdf.

156 EC, FP7,Cooperation, Theme 4: Nanosciences, nanotechnologies, Materials and new Production Technologies – NMP, Work Programme 2012, C(2011)5068.

157 EC DG-ENTR, 2011. Call for Tender Raw Materials: Study on innovative technologies and possible pilot plants, No: 112/PP/ENT/CIP11/CN06S001.

RDI projects, Ideas for top academic research, and People for international researcher mobility, and these specific programmes are split into subdivisions that concern different themes or aspects of RDI activities. Differing from FP7, H2020 is planned to have four pillars called 'Excellent science' (Pillar I), 'Industrial leadership' (Pillar II), 'Societal challenges' (Pillar III), as well as 'Non-nuclear direct actions of the Joint Research Centre (JRC)' (Pillar IV).[158] Comparing the structures of FP7 and H2020 proposal, within Pillar I the first specific objective of strengthening European research through the European Research Council is analogous to the FP7 specific programme 'Ideas' and the objective of strengthening skills, training and career development through Marie Sklodowska-Curie actions corresponds to the FP7 specific programme 'People'. The Pillar II and to some extent Pillar III then are rather close in content to the FP7 specific programme 'Cooperation'.

Looking at the relevance of the H2020 proposal to CRM substitution, the most relevant specific objective in Pillar I would be the 'Future Emerging Technologies' programme which is open to various thematic fields, while in the second pillar funding to RDI on 'Nanotechnologies', 'Advanced materials' as well as 'Advanced manufacturing and processing technologies' under the specific objective of boosting Europe's 'Industrial leadership' are the most relevant. The CRM issues are also being addressed under the third pillar by the specific objective of achieving a resource-efficient and climate change resilient economy and a sustainable supply of raw materials including recycling and resource efficiency. As an overall observation, however, it could be suggested that while there is potentially a substantial funding for CRM substitution, the structure seems rather dispersed with multiple and to some extent overlapping actions that all potentially address the CRM issues.

3.1.2. The Member States

Looking at the national level, the Member States at large have not been that active specifically on substitution of CRM. In a recent publication surveying raw materials and minerals strategies around the world it is confirmed that as of 2011 only three Member States have an explicit minerals strategy: Germany, France and Finland[159]. Two of the raw materials strategies mentioned above are publicly available, the German Raw Materials Strategy[160] and Finnish Minerals Strategy[161]. Especially the latter strategy aims to boost the traditional minerals sector, including mining and extraction, processing and refining and production of metals. One interpretation for the finding that there are relatively few explicit raw materials strategies, and that at least some are more concerned with developing minerals and mining industry than raw materials supply is that due to a period of liquid global minerals market, there has been relatively little concern over supply security until recently and the Member States have pursued a passive strategy toward minerals. The policy analysis is detailed in Annex III, while the general findings are discussed below.

[158] EC, 2011. Proposal for a Council Decision: establishing the Specific Programme Implementing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020), COM(2011) 811 final.

[159] Tiess, G., 2011. General and International Mineral Policy – Focus: Europe, Springer Verlag, Wien - New York.

[160] Federal Ministry of Economics and Technology (BMWi), 2010. The German Government's raw materials strategy- Safeguarding a sustainable supply of non-energy mineral resources for Germany, Federal Ministry of Economics and Technology (BMWi), Public relations division, Berlin.

[161] Finland's Minerals Strategy, 2010, Ministry of Employment and the Economy, Finnish Geological Survey. Available at: http://www.mineraalistrategia.fi/ (Accessed 7.2.2012).

3.1.3. The Member States: Germany

The German raw materials strategy is set on the principles that the government itself is not going to be commercially active, but it will provide framework conditions and incentives for the industry to develop sustainable solutions to the raw materials supply problem. The German approach is horizontal across conventional policy sectors, including economic and trade policy, foreign policy and development policy, as well as industrial and RDI policy. Across these sectors, the Federal Government is aiming to cater to the immediate needs by providing framework conditions to develop minerals production and lower trade barriers, while providing incentives to develop recycling, resource efficiency and technologies to substitute presently critical raw materials.[162]

The German strategy is accompanied with RDI programmes. On the federal level the Federal Ministry for Education and Research (BMBF) has established the Framework Program for Sustainable Development (*Rahmenprogramm Forschung für Nachhaltige Entwicklungen* - FONA II)[163], within which there is a programme r^3 – Innovative Technologies for Resource Efficiency (*Innovative Technologien für Ressourceneffizienz - Strategische Metalle und Mineralien)*, with a focus on strategic metals and minerals. It addresses cooperation projects of industry and R&D institutions aiming to increase resource efficiency, improve recycling and substitution of critical raw materials (2012-2015, 30 MEUR funding)[164]. Besides these programmes, BMBF has been active in establishing the Helmholtz Institute Freiberg for Resource Technology, a joint effort between the Helmholtz Association and Technische Universität Bergakademie Freiberg[165]. More indirect funding for materials science is available e.g. in the materials science programme WINGS (*Werkstoffinnovationen für Industrie und Gesellschaft* – WINGS)[166], which is aimed to raise innovation capability of German industry, particularly small and medium-sized enterprises (SMEs), and contribute to solving societal problems.

On the level of the German states (Ger. s. *Bundesland*, pl. *Bundesländer*) Bavaria and Hamburg have taken their own actions. Bavaria has established a Research programme for new materials (*Forschungsprogramm Neue Werkstoffe*)[167], which is aimed for RDI for new materials and products based on them, including metals for various applications, polymers, ceramics and nanomaterials, as well as basic research into materials science and materials production technologies. In Hamburg the focus is on resource conservation and efficiency in the Resource Conservation Project (*Unternehmen für Ressourcenschutz*), which engages the local industry and entrepreneurs to engage in the project to lower emissions, to raise

[162] Federal Ministry of Economics and Technology (BMWi), 2010. The German Government's raw materials strategy- Safeguarding a sustainable supply of non-energy mineral resources for Germany, Federal Ministry of Economics and Technology (BMWi), Public relations division, Berlin.

[163] Federal Ministry of Education and Research BMBF, 2009. Forschung für nachhaltige Entwicklungen: Rahmenprogramm des BMBF, Bundesministerium für Bildung und Forschung (BMBF) Referat 721 – Grundsatzfragen Kultur, Nachhaltigkeit, Umweltrecht, Berlin, Available at: http://www.ptj.de/lw_resource/datapool/_items/item_1578/forschung_nachhaltige_entwicklungen.pdf (Accessed: 9.2.2012).

[164] Federal Ministry of Education and Research BMBF, 2011. FONA Research on Sustainable Development – Resources and Sustainability – Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals, Available at: http://www.fona.de/en/9815 (Accessed 9.2.2012).

[165] Helmholtz Zentrum Dresden-Rossendorf – Press Release, June 14th 2011, available at: https://www.hzdr.de/db/Cms?pOid=33647&pNid=473; Federal Ministry of Education and Research BMBF, 2011. FONA Research on Sustainable Development – Resources and Sustainability – Innovative Technologies for Resource Efficiency – Helmholtz Institute Freiberg for Resource Efficiency, Available at: http://www.fona.de/en/9813.

[166] Federal Ministry of Education and Research BMBF, 2007. WING – Materials Innovations for Industry and Society, Available: http://www.bmbf.de/en/3780.php (Accessed 13.3.2012).

[167] Bavarian Ministry for Trade, Infrastructure, Transport and Technology, 2007. Bekanntmachung des Bayerischen Staatministeriums für Wirtshaft, Infrastructur, Verkehr und Technologie, Richtlinien Zum Forschungsprogramm "Neue Werkstoffe", Available at: http://www.ptj.de/lw_resource/datapool/_items/item_2487/2007-02-01-richtlinien_neue_werkstoffe.pdf.

efficiency in resource and raw materials use, while lowering operations cost and cleaning the environment and improving quality of life in Hamburg[168].

Overall the German Federal Government and also some of the states have been quite active in initiating RDI to support CRM substitution. The CRM agenda has been also interwoven in several RDI programmes, as exhibited by the theme emerging over a variety of programmes related to materials science, but also sustainable development and similar agendas.

3.1.4. The Member States: Finland

While the Finnish strategy is explicitly tied to the EU Raw Materials Initiative, the main thrust is in developing policy and means for large scale exploration and extraction of the known and discovered minerals deposits, albeit in an environmentally sustainable way and by respecting labour rights. The policy content supports the proposition that Finland has been more concerned about continuous economic growth and continuity of supply of raw materials, rather than substitution of CRM.[169]

In a manner, the strategy is in conflict with the initiative to substitute CRM; if the strategy is implemented as planned, it will sustain the present value chain instead of trying to build one based on substitute materials.

3.1.5. The Member States: The Netherlands

Also the Netherlands has a policy regarding raw materials, titled “Dutch Government Policy Document on Raw Materials”[170] published by the Ministry of Foreign Affairs as an answer to the Millennium Development Goal no. 7 “To ensure, by 2015, that more people are living in a sustainable environment.” and it marks the start of an integrated raw materials policy[171]. The policy includes all materials across the board and is concerned with supply security and sustainability of resources, as well as facilitating trade. However, the government has explicitly directed the responsibility for resource efficiency to the Ministry of Infrastructure and the Environment[172]. Thus, it seems that in the Netherlands, resources and their use are or have been seen primarily as an environmental and sustainability issue, and to a lesser extent as an issue that would be battled with RDI, but rather through conservation. However, the undated policy document clearly attaches the Netherlands to the European discussion on raw materials supply. The Netherlands welcomes a strong European policy aimed at promoting a liquid raw materials market and an open trading system. The Netherlands will, according to the strategy, also actively engage in policy making on EU level, as well as seek partnerships with other Member States to harmonise the various

[168] City of Hamburg, Citizens' Services - Environment – Environment Protection in Practice – Ressourcenschutz, Available at: http://www.hamburg.de/start-programm/ (Accessed 9.2.2012).

[169] Ministry of Employment and the Economy, Finnish Geological Survey, 2010. Finland's Minerals Strategy . Available at: http://www.mineraalistrategia.fi/ (Accessed 7.2.2012).

[170] Available: at : http://www.minbuza.nl/binaries/content/assets/minbuza/en/import/en/key_topics/development_cooperation/dutch_development_policy/millennium_development_goals_mdgs/dutch_aim_for_mdg_7/dutch_government_policy_document_on_raw_materials/dutch-government-policy-document-on-raw-materials/dutch-government-policy-document-on-raw-materials/hippogallery%3Aasset (Accessed 12.3.2012).

[171] Ministry of Foreign Affairs, Development Cooperation – Millennium Development Goals (MDGs) – Dutch Aim for MDG 7 - Dutch Government Policy Document on Raw Materials http://www.minbuza.nl/en/key-topics/development-cooperation/dutch-development-policy/millennium-development-goals-mdgs/dutch-aim-for-mdg-7/dutch-government-policy-document-on-raw-materials.html.

[172] See: The Government of Netherlands Environment – Resource Efficiency, Available at: http://www.government.nl/issues/environment/resource-efficiency and The Ministry of Infrastructure and the Environment, Topics – The Environment – International Policy Priorities, Available: http://english.verkeerenwaterstaat.nl/english/topics/the-environment/international_policy_priorities/#alinea2 (Accessed 12.3.2012).

national strategies. The Dutch government will further seek to encourage efficient, sustainable and innovative use and re-use of raw materials within its own public purchasing policy and operational management by e.g. introducing sustainability criteria to evaluation of tenders for government contracts, inviting the economic sector to indicate which materials should be considered critical, and encouraging development of among others substitutes for CRM. [173]

3.1.6. The Member States: Sweden

In Sweden the mining law is the main policy guiding use of raw materials. Based on public sources Sweden has not officially published a minerals strategy as of the time of the writing, which was also confirmed through the interviews. It has been further proposed that in Sweden the main attention is on exploitation of the national minerals and supporting the growth and development of the minerals industry[174].

3.1.7. The Member States: UK

In the UK the most relevant initiatives that are in force, are on the area of recycling and waste reduction[175]. However, at the time of the writing, the UK Parliament's House of Commons has commissioned studies similar to the US Congress to investigate issues surrounding strategically important metals[176].

3.1.8. The Member States: France

As far as information available at the time of writing, in France the CRM issues are tied to sustainable development as well as energy policy to some extent. The French National Strategy for Sustainable Development (NSDS) for the period 2010-2013[177] has been published by the Prime Minister's Office and adopted by the Interministerial Committee for Sustainable Development. The strategy aims to deal with 9 challenges regarding structure and sustainability of the economy, including sustainable consumption and production, conservation and sustainable management of the biodiversity and natural resources. Additionally the French Ministry of Industry has installed a Committee for Strategic Metals (*Comité des Métaux Stratégiques*, COMES) to investigate the CRM issue[178].

---

[173] The Government of Netherlands, Dutch Government Policy Document on Raw Materials, Available at: http://www.minbuza.nl/binaries/content/assets/minbuza/en/import/en/key_topics/development_cooperation/dutch_development_policy/millennium_development_goals_mdgs/dutch_aim_for_mdg_7/dutch_government_policy_document_on_raw_materials/dutch-government-policy-document-on-raw-materials/dutch-government-policy-document-on-raw-materials/hippogallery%3Aasset (Accessed 12.3.2012).

[174] Niemeläinen, E., Tuusjärvi, M., Niiranen, T., Vuori, S., and Kananoja, T. have analysed minerals strategies and policies around the world, including the following nations: India, China, South Africa, Brasilia, Chile, Canada, USA, Australia, Ireland, Sweden and Germany. (2010. Katsaus mineraalistrategioihin ja –politiikkoihin maailmalla [A review of minerals strategies and policies around the world], Geological Survey of Finland, Archive report M10/2010/27.

[175] see WRAP - Working together for a world without waste, 2011, Towards Resource Efficiency: WRAP Business Plan: 2008-2011, A Report on Impact, Available: http://www.wrap.org.uk/downloads/WRAP_Business_Plan_Review.73273d02.11459.pdf; WRAP - Working together for a world without waste, 2011, Business Plan: 2011-2015, Available at : http://www.wrap.org.uk/downloads/Bus_Plan_2011_Final_WEB_22.13e2f880.10869.pdf; Environment Agency, Corporate Plan 2011-15, GEHO0211BTKV-E-E, Available at: http://publications.environment-agency.gov.uk/PDF/GEHO0211BTKV-E-E.pdf;EPOW Web Page, Available at: http://www.environment-agency.gov.uk/aboutus/wfo/epow/123624.aspx (Accessed: 9.2.2012).

[176] House of Commons, Science and Technology Committee, 2011, Strategically important metals, Fifth Report of Sessions 2010-12, Volume I, HC 726, Available at: http://www.publications.parliament.uk/pa/cm201012/cmselect/cmsctech/726/726.pdf (Accessed 22.2.2012).

[177] Republic of France, Prime Minister's Office, National Sustainable Development Strategy 2010-2013: Towards a green and fair economy.

[178] Ministry of Industry, 2011. Création du Comité pour les métaux stratégiques (COMES), Available: http://www.economie.gouv.fr/economie/creation-comite-pour-metaux-strategiques-comes; Decree no. 2011-100 of January 24th 2011, Creation of the Committee for Strategic Metals, Décret n° 2011-100 du 24 janvier

3.1.9. Summary of European strategies

As is apparent from the analysis presented above, and from the more detailed overview of the relevant strategies and programmes in Annex III, the EU has been very proactive both in creating a strategy to tackle issues in raw materials supply as well as operationalising the strategy to its RDI instruments.

On the national level there is considerably more variation on the implementation of the EU strategy and the government role in raw materials. For example, in Finland, the raw materials strategy was created in response to the EU strategy, while in Germany the Federal government has been active in making raw materials strategy since 2007 and has implemented a host of policies to support the strategy and secure raw materials for the nation, whereas e.g. in The Netherlands the Government has apparently chosen a relatively *laissez faire* approach, in the sense that the Government positions itself as a facilitator for the private sector and markets. In UK and France, the policy making concerning raw materials supply is in its infancy, as both countries have recently set committees to investigate implications of CRM situation in national policy, but neither have explicit raw materials policy.

Further, most of the national strategies address only the two of the three main points of EU Raw materials initiative, namely they support freedom of movement in global markets and also reinforce supply of raw materials, but considerably less has been said about lowering the use of primary raw materials. The analysed strategies do not in general set tangible quantitative targets, with the partial exception of the EU Raw Materials Roadmap.

3.2. Policies, measures and policy targets for substitution in the US, Japan and South Korea

3.2.1. The United States of America

The United States of America (US) does not have an explicit Federal minerals strategy or policy such as the EU or Germany have developed and published. Nevertheless, as exhibited by recent studies inspired by the same developments as the EU Raw Materials Initiative, also the Federal authorities have apparently been in a state of heightened interest toward economic and security implications of shortcomings in supply of critical raw materials, particularly REE[179]. The US Government has historically been active in studying the raw materials supply issue[180], but the efforts have not materialised in an explicit policy, apart from the US Department of Energy (DOE) Critical Materials Strategy[181] which is aligned with the three pillars of DOE strategy: diversifying supply, developing substitutes and improving recycling. The strategy proposes and has resulted in actions to bring experts around the world to work on issues surrounding substitution of REE, as well as instruments to fund priority research on developing REE-free technologies in key technology areas.

2011 portant création du comité pour les métaux stratégiques (COMES), NOR: INDI1032803D, Available at: http://www.legifrance.gouv.fr/affichTexte.do;jsessionid=931360064F1082ABE36F9EBB721C365F.tpdjo02v_2?cidTexte=JORFTEXT000023474859&categorieLien=id# (Accessed 22.2.2012).

179 See e.g. Grasso, 2011; Humphreys, 2011 op.cit.

180 See e.g. The President's Materials Policy Commission, 1952. Resources for freedom: a Report to the President by the President's Materials Policy Commission; Congressional Budget Office, 1976. U.S. Raw Materials Policy: Problems and Possible Solutions, Background Paper No. 16, December 28, 1976, Congress of the United States, Congressional Budget Office.

181 US DOE, 2011. Critical Materials Strategy.

What is more, there has been a discussion in the US on the CRM issue, which has resulted in the following proposals, similar to other countries' strategies discussed above[182]:

- Survey private, government and defence sectors to understand the need and criticality of raw materials
- Collect, analyse and distribute data on strategically important critical minerals
- Stockpile REE and other CRM
- Promote prospecting and extracting CRM across the world
- Increase international cooperation and dialogue, make CRM producers a priority in diplomacy and development cooperation
- File WTO disputes against market distorting activities
- Encourage RDI and develop substitutes for REE
- Develop new technologies to raise the efficiency of recycling and use of REE
- Establish straw person buyers[183] to acquire resources.

On the practical level, DOE has launched the Advanced Research Projects Agency – Energy[184] (ARPA-E, a simile to the Defense Advanced Research Projects Agency, DARPA) which conducts out-of-the-box, high-risk, transformative research on energy technologies, including substitution of REE[185] with a total budget of 400 MUSD to spend over the period of two years to fund basic and applied research on energy technologies. As of programme audit April 20th, 2011, ARPA-E had issued 12 funding opportunity announcements and made 122 awards valued at approximately 369 MUSD to advance battery technology, explore alternative fuels, and improve building efficiencies, among other areas[186]. Besides ARPA-E, DOE supports the network of a total of 17 National Laboratories, which conduct basic and applied research on physics and technologies related to energy production. The Ames National Laboratory in Ames, Iowa, specialises in materials technology, including research on substitution of REE.

3.2.2. The Republic of Korea

In the Republic of Korea (South Korea, ROK) the policy implementation is mandated to Korea Resources Corporation (KORES), which is a governmental corporation with a mandate to secure raw materials supply in the Republic of Korea. KORES is overseen by the Ministry of Knowledge Economy[187]. KORES vision is to become a Global top 20 mining corporation through decisive expansion of overseas mining operations, innovative management, attaining world's best resource technology, while fulfilling social

[182] See e.g. Coppel, E., 2011. Rare Earth Metals and U.S. National Security, Briefing, American Security Project; Butts, K.H., Bankus, B., Norris, A. 2011. Strategic Minerals: Is China's Consumption a Threat to United States Security?, United States Army War College, Center for Strategic Leadership, Issue Paper, July 2011, Vol. 7-11.

[183] Straw person buyer is a defunct or empty 'dummy' corporation, incorporated to act as a front or cover for one or more real enterprises, e.g. to subterfuge the real buyer's identity. Straw persons, or dummy corporations, were successfully used, for example, by the US Central Intelligence Agency for covert acquisition of CRM from Soviet Union through Titanium Metals Corporation (TIMET) European subsidiaries and various other third parties for Project OXCART which later became the Lockheed A-12/SR-71 reconnaissance aircraft, see e.g. McIninch, T.P., 1996. The Oxcart Story, Studies in Intelligence, Vol. 15, Issue 1.; Rich, E.R., 1996. Skunk Works: A Personal Memoir of My Years of Lockheed, Back Bay Books.

[184] See Advanced Research Projects Agency – Energy (ARPA-E), Available: http://arpa-e.energy.gov/.

[185] DiGiovanni, 2009. Advanced Research Projects Agency Energy – ARPA-E, presentation at the DOE Business Opportunity Session, Dec. 17th 2009, Available at: http://energy.gov/sites/prod/files/ED2/business/documents/Digiovanni_Dec_17.pdf .

[186] DOE Office of Inspector General, Office of Audits and Inspections, Audit Report: The Advanced Research Projects Agency – Energy, OAS-RA-11-11, Available at: http://energy.gov/sites/prod/files/OAS-RA-11-11.pdf (Accessed 8.2.2012).

[187] Korea Resources Corporation Act (English translation) Act No. 9182, Dec. 26, 2008, Available at: http://eng.kores.or.kr:8080/gpms/eng/gpms/resources/down/eng_law1.pdf.

responsibilities[188]. The Korea Mineral Resources Information Service (KOMIS), run by KORES, explains that as South Korea lack mineral resources, its dependency on imports is likely to be ever higher. To alleviate this dependency the government has established KORES to develop and support Korean mining operations domestically and overseas[189]. The main businesses of KORES are mineral resources development domestically through support on prospecting and mining as well as RDI both economically and technically, as well as out of Korea by stoking information of resources available and conducting investment feasibility surveys and granting capital loans. The KORES portfolio includes also minerals research in the form of developing research targets and roadmaps, commissioning research and providing information for the industry and operating KOMIS which provides the service platform for KORES key services. The KORES paid-in capital was 790 Billion Korean Won (KRW) as of end of 2010, equivalent of roughly 537 MEUR[190], and the book value of the corporation was 2,396,313 million KRW or 1.6 Billion EUR, with holdings in minerals industry with a book value of approximately 855 Billion KRW, or 581 MEUR.

In general the ROK is active in pursuing supply security through investment in overseas materials and energy resources development to gain influence and certain degree of supply security, as development of domestic resource use cannot satisfy the demand[191]. While the strategy is organised through KORES, the content is quite similar to the strategies reviewed above. At the same time however, it has to be observed that the ROK is not deeply engaged in substituting REE or other CRM as much as securing their supply and sustaining the growth and development of the economy.

3.2.3. Japan

In Japan the Ministry of Economy, Trade and Industry (METI) has compiled a "Strategy for Ensuring Stable Supplies of Rare Metals. The four pillars are 1) securing overseas resources, 2) recycling, 3) development of alternative materials, and 4) stockpiling[192]. Thus the Japanese strategy is quite similar to the EU initiative on this area. The strategy is implemented through at least two national programmes which aim to support both basic research on materials technology to substitute CRM completely, and applied research and technology development to lower the consumption of CRM considerably (up to 30-80%). The programmes are called respectively "An elemental strategy project" implemented by Ministry of Education, Culture, Sports, and Science and Technology (MEXT), and the "Rare metal substitution material project" run by (METI) Science and technology Programme. Besides these initiatives, the Japanese Government has been running the National Institute for Materials Science (NIMS) since 2001, with the objective of conducting fundamental and innovative research on materials science, promotion of use of research results, providing shared research facilities and training researchers in the field of materials science. NIMS have a turnover of 25.6 Billion Yen, or 254 MEUR, and employ a total of 1500 persons where the research staff counts for 517 persons.[193] A technologist interviewee[194] stressed

---

188 Korea Resources Corporation – About KORES – Vision, Available at: http://eng.kores.or.kr:8080/gpms/user.tdf?a=common.HtmlApp&c=2001&page=/english/cor/cor_02.html&mc=ENG_COR_020 (Accessed 7.2.2011).

189 Korea Mineral Resources Information Service – Mining Information – Policy – Long Term Policy, Available at: http://www.kores.net/englishKomis/mining/e_policy_long.jsp#Goal (Accessed 7.2.2011).

190 Rate 1 EUR = approx 1470 KRW.

191 Kwon, O.Y., 2010. South Korea's approach to energy and resource security, Australian Strategic Policy Institute, Strategic Policy Forums: Australian and Asian perspectives on resources diplomacy. Available at: http://www.aspi.org.au/research/spf_article.aspx?aid=84 (Accessed 7.2.2012).

192 Ministry of Economy, Trade and Industry, 2009, http://www.meti.go.jp/english/press/data/20090728_01.html

193 Kishi, T., 2011 Overview of Japanese Research Activity on Critical Raw Materials – Elemental Strategy Project, Presentation at Japan-EU Workshop, Nov. 21st 2011, Available at: http://www.jst.go.jp/sicp/ws2011_eu/presentation/presentation_01.pdf; NIMS, Settlement and Workforce Report, Available at: http://www.nims.go.jp/eng/nims/settlement_workforce.html (Accessed, 8.2.2011).

194 Professor O. Odawara, Tokyo Institute of Technology, Japan, interview 23 February 2012.

that Japan has already been aware for some years of the potential for restricted supplies of many critical raw materials and already in 2007 started a long-term programme entitled ”Elements Science and Technology Project - Designing Materials Functions through Fundamental Research on Elements' Roles”[195]. In fact this project has very recently been boosted (February 5th, 2012) by the announcement of support for further projects on “Critical Elements”[196] details of which will become available later.

3.2.4. Summary of the international situation

In summary, the strategies in the US, Japan and South Korea are broadly similar to the approach in the EU, in that they aim to balance short and long term interests by minding the supply security of the raw materials most important to each respective nation in immediate term, while encouraging efforts to develop recycling techniques and substituting CRM in the industry through product and component innovation, new products and services. Both Japan and USA have implemented policies and programmes for substitution of raw materials. Japan especially has been working on the issue quite strongly and for a relatively long time already, and programmes to support substitution research have been operating since 2007. The US programme on advanced research on energy technology has been running since 2009, but substitution of CRM has been raised as a topic on interest only later in the more recent Critical Materials Strategy.

The difference in response might have something to do with different governance structures, as the US House of Representatives (Congress) is interested in raw materials security, but the Federal Government does not have a track record of similar interventions for RDI as the EU. That is, the US Government has not historically been as active as the EU in installing policy instruments such as RDI funding programmes or other measures to correct market failures. Differing from the USA and Japan, the ROK is approaching the raw materials issue by supporting the expansion of Korean minerals sector to secure supply. For details, see Annex IV.

Besides national programmes, international efforts on strategic metals have been initiated through the G8 research councils on multilateral research funding, one of which is the interdisciplinary programme on material efficiency and sustainable use of materials. This joint funding initiative is aimed at supporting excellent research on topics of global relevance best tackled through a multinational approach, recognising that global challenges need global solutions. Funding should support researchers to cooperate in consortia consisting of partners from at least three of the participating countries. Participating countries are Canada, France, Germany, Japan, Russia, United Kingdom and the US (out of established G8 countries, Italy is not participating).[197]

At the moment, as far as can be deduced from public sources, substituting CRM is under discussion in many countries. Nevertheless some efforts have already been launched particularly in Japan and in the USA. Out of the examined countries Japan has undertaken the strongest efforts to substitute CRM across industries, while in the US the main public effort is confined in the energy sector. In Japan programmes to support substitution of REE have been running since 2007 and a national research institute for materials science has been founded 2001, which has started a new strand of research called ‘Elements science

---

[195] Kishi, T., 2011. Overview of Japanese Research Activity on Critical Raw Materials – Elemental Strategy Project, Presentation at Japan-EU Workshop, Nov. 21st 2011, Available at: http://www.jst.go.jp/sicp/ws2011_eu/presentation/presentation_01.pdf; Kojima, A., 2011. Japan proposes an ”Elements strategy”, JapanEchoWeb, Editor’s Blog, Available http://www.japanechoweb.jp/editors-blog/jewb030 (Accessed 20.2.2012).

[196] Professor O. Odawara, Tokyo Institute of Technology, Japan, interview 23 February 2012.

[197] Japan Society for the Promotion of Sciences, The G8 Research Councils Initiative on Multilateral Research Funding, Available: http://www.jsps.go.jp/j-bottom/g8-initiative.html (Accessed 13.3.2012).

and Technology Center' where a large component of research is related to substitution of CRM[198]. One presumable driver behind these different policy responses is industry structure. For example, presumably the economy and infrastructure in the ROK is structured differently and may be in different stage of development, and the industry is more dependent on mineral imports, e.g. Korean steel industry that supports its burgeoning shipbuilding and machinery industries has to import practically all raw materials, not only CRM. This need is also mirrored in Korean raw materials policy, which aims to broaden the base of raw materials supply rather than conserve materials.

Also others have probed existing minerals strategies and policies across countries[199], including some of the world's foremost mineral producers and also EU Member States. Their review supports the finding that EU Member States have not, by and large, been active in making minerals policy. While in the 1980s governmental regulation and interventions were commonplace, liberalisation of markets became standard practice in the 1990s also in the minerals sector and this thrust is mirrored in most analysed policies. Niemeläinen et al.[200] (see ref. 199) summarise these policies, revealing that mining laws and raw materials policies have been revised in the 1990s in many countries, and thus the content and objectives are in many cases from that era, with the exception of recent policies from Germany (2007-2011), India (2008), China (2003) and South Africa (1998). The common themes over many strategies are primarily:

- Subsidising or supporting exploration/prospecting and mining
- Sustainable development of mining and minerals sectors
- Ensuring transparency and liquidity of global commodities/raw materials markets

And secondarily:

- RDI for prospecting, extraction and mining and refining minerals
- Attracting domestic and foreign investments
- Creating a regulatory framework for minerals sector
- Development of institutions and international collaboration.

Analysing the strategies, three groups of countries arise; (large) minerals exporters, (large) minerals importers, and the rest. Each group has their own response, which could be hypothesised to be dictated by the relationship of each country's mineral demand versus their domestic supply and vulnerability of their industry and raw materials supply.

In the first group each country is apparently anxious to boost exports and create jobs in the minerals sector. Particularly the large minerals exporters, e.g. China, India or South Africa, have little incentive to attempt to change the value chain from existing, as they are in the possession of the valued resources and they have also *de facto* monopoly or oligopoly power over the market price, which may be a considerable economic benefit as well as a diplomatic leverage. These countries in fact benefit from the *status quo* where demand of minerals exceeds the present production capacity, as this disparity is directly reflected positively in their trade balance as well as their international importance, while the domestic production keeps the industry in relatively good supply despite international market difficulties. To some extent this applies also to Finland and Sweden, which are

[198] Hono, K. Research Trends on Rare Earth and Critical Elements in Japan, Available: http://energy.gov/sites/prod/files/Session_A7_Hono_NIMS.pdf (Accessed 13.3.2012).

[199] The following have analysed minerals strategies and policies around the world, including the following nations: India, China, South Africa, Brasilia, Chile, Canada, USA, Australia, Ireland, Sweden and Germany. Geological Survey of Finland, Archive report M10/2010/27; Department for Environment, Food and Rural Affairs, 2012. Review of National Resource Strategies and Research, PB 13722, Available: http://www.defra.gov.uk/publications/files/pb13722-national-resource-strategies-review.pdf (Accessed27.3.2012)

[200] Niemeläinen, E., Tuusjärvi, M., Niiranen, T., Vuori, S., and Kananoja, T., 2010. Katsaus mineraalistrategioihin ja –politiikkoihin maailmalla [A review of minerals strategies and policies around the world].

countries with relatively good minerals resources, and which in Finland have been hitherto relatively little prospected.

In contrast, countries which are large net importers of raw materials and have relatively small minerals resources compared to demand, such as the EU countries in general and Germany in particular, seem considerably more anxious to find alternative supplies or substitutes for CRM. This finding arises from the comparison between the strategies of the large minerals producers like China and India, and also a smaller producers such as Finland or Sweden, which are mostly focused on developing the mining industry, and e.g. Germany, which is considerably more geared toward multi-faceted action to secure present and future supply of resources that keep the industry in production.

The German strategy could be said to be most comprehensive and advanced on the level of the Member States. The German strategy embraces the EU objectives to increase market transparency and knowledge about minerals resources, as well as increasing sustainability of resource use. Differing from the EU initiatives, the strategy also includes a component which could be called up-stream integration in value chain, that is, establishing bridge head position in overseas mineral deposits and securing supply of minerals by domestic suppliers (see also the Raw materials alliance and *Deutsche Rohstoff AG* above), developing foreign minerals deposits, and the complementing element of securing bilateral agreements with selected countries together with integration with development policy. This strategy is actually quite similar to the one adopted by the Republic of Korea, which puts extensive efforts to create a mining industry that is active in explorations and mining overseas to supplement the relatively few domestic resources.

4. POLICY RECOMMENDATIONS

KEY FINDINGS

- On the EU level, a comprehensive set of policies and initiatives are in place and in preparation to support CRM substitution. In the short term, current policies are able to address the most burning CRM issues sufficiently. Thus, there is no immediate need for new policy interventions. However, in the medium and long run, several concerns related to CRM substitution will need to be addressed in policy terms.

- Ongoing and foreseeable changes in EU RDI policy are, however, likely to fragment the funding base for CRM substitution. It would thus be advisable to consider the cross-cutting nature of CRM substitution in designing RDI incentives for the next programming period.

- CRM substitution is a time-consuming and complex process requiring visionary policy responses that are able to anticipate the different aspects of, and the far-reaching impacts on, research, industry, markets, etc.

- Policies to support CRM substitution should in particular encourage the creation of new value chains and ecosystems that are less dependent on CRM availability.

- To support apt policy planning, comprehensive and up to date information on the various efforts in respect of CRM substitution, covering the whole spectrum from research to market-related actions should be kept on the EU level.

- The instrumental role of CRM-related RDI centres, units and programmes should be recognised in generating, gathering and exchanging the latest information and knowledge on CRM substitution.

- On the global level, existing information exchange *fora*, including the OECD and the G8, should also be utilised to strengthen the dialogue and coordination of CRM policies.

- Other conceivable policy responses include better mapping of European mineral deposits, raising awareness of the challenges related to CRM and creating additional demand side incentives for the development of CRM substitutes.

4.1. Possibilities for supporting further substitution efforts through EU RDI programmes

The EU, and in particular the European Commission, has been very active as regards the raw materials initiative in recent years. Indeed, the Commission spearheaded a strong strategy tasked with securing the supply of raw materials. The EU has also integrated its raw materials strategy into the existing funding programmes, e.g. FP7, as well as ERA-NET (European Research Area Network) for materials and the emerging European Innovation Partnership (EIP).

Reviewing the current situation, none of the interviewees expressed a need for an immediate increase in substitution initiatives. Research and industry representatives alike thought that sufficient funding (from national and EU FP7 funding programmes) for research on resource efficiency, recycling, and substitution is available. National variations however exist in raw material access and RDI policy. At least in Germany, funding from BMBF (German Federal Ministry of Education and Research) or DFG (*Deutsche Forschungsgemeinschaft* eng. German Research Foundation) was preferred (due, reportedly, to its less bureaucratic nature and its less onerous requirements in terms of time-intensive reporting). Industry representatives also emphasised that they were looking forward to the European Innovation Partnership (EIP) on raw materials, and further expressed interest in the funding for pilot plants envisioned in the EIP proposal, primarily with a view to testing new production or recycling methods in small-scale facilities.

In the RDI policy field, the EU is already consolidating RDI instruments; the proposal for the RDI instrument Horizon 2020 – The Framework Programme for Research and Innovation will proposedly integrate the current FP7 with parts of the Competitiveness and Innovation Framework Programme (CIP) and the European Institute of Innovation and Technology (EIT), as well as the sector specific Information Communication Technologies Policy Support Programme and Intelligent Energy Europe Programme.[201] H2020 is likely however to continue to implement EU policy objectives in general and specific objectives, such as CRM substitution, in particular.

While consolidation potentially simplifies RDI policy, the internal structure of H2020 may present a number of challenges to the RDI consortia seeking funding for their efforts in respect of CRM substitution. The immediate question that arises when looking at the proposal for H2020 from the CRM substitution point of view is that the potential sources of funding are quite fragmented across the three pillars and also across the specific objectives within the second pillar, 'Industrial leadership'. Research relevant to CRM substitution could potentially fall under each of the pillars. For example: Under Pillar I CRM substitution could be a Future and Emerging Technology project or even a flagship project, as substitution can be positioned as a "grand interdisciplinary science and technology challenge"[202]. Under Pillar II one of the general themes is "[a]n integrated approach to Key Enabling Technologies" (KETs) with "the development of materials and methods to reduce energy and resource consumption" being one of the main implementation aspects[203]. However, looking at the specific objectives under the pillar, there are three or four separate relevant research themes; Nanotechnology, Advanced materials, Advanced Manufacturing and Processing, and to some extent also, Biotechnology. All of these fields can contribute to CRM substitution in their own right, but there is little incentive for multidisciplinary research to develop integrated solutions as the research fields have different silos in the programme. Finally, under Pillar III one of the main themes is "Climate action, resource efficiency and raw materials", which includes the sub-themes "Sustainably managing natural resources and ecosystems" and "Ensuring the sustainable supply of non-energy and non-agricultural raw materials"[204]. The themes under the third pillar are, at least in the proposal stage, parallel with those of the second pillar, but supposedly can envelop a multidisciplinary approach.

In sum, from the perspective of an RDI consortium looking to develop CRM substitutes, the structure of H2020 is in fact more fragmented from this specialised perspective than FP7, where most of the RDI specifically for CRM substitution falls under one or two sub-divisions of one specific programme, namely NMP for technology development and Environment for

[201] EC, 2011. Commission Staff Working Paper – Impact Assessment: Accompanying the Communication from the Commission 'Horizon 20202 – The Framework Programme for Research and Innovation', SEC(2011) 1427 final.
[202] EC, 2011. Proposal for a Council Decision: establishing the Specific Programme Implementing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020), COM(2011) 811 final p. 29.
[203] EC, 2011. Proposal for a Council Decision: establishing the Specific Programme Implementing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020), COM(2011) 811 final p. 37-38.
[204] EC, 2011. Proposal for a Council Decision: establishing the Specific Programme Implementing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020), COM(2011) 811 final p. 69-72.

research on recycling under specific programme Cooperation. It is foreseeable that positioning multi-disciplinary efforts to substitute CRM may present challenges for funding applicants, starting from choosing between pillars, and also within a pillar positioning the proposal between the specific actions. For example, comparing NMP sub-divisions under the FP7 specific programme Cooperation, one finds most if not all relevant calls for proposals to develop new materials to substitute CRM under one sub-division.

Another issue that arises even after the consolidation of instruments is the division of roles between EIT and its Knowledge and Innovation Communities (KICs), the EIP and H2020. The KIC concept is designed to offer a collaboration platform for at least three partners who commit to innovation collaboration over a long time horizon, up to 7-15 years. The KICs are independent international organisations with a dedicated general and RDI management as well as a 'co-location centre' which means a central hub or office that can bring the geographically distributed partners together. The KICs are effectively independent corporations. The target for operating turnover for the activities is 50-100 MEUR per year once fully operational and the EIT can fund up to 25% of the expenditures[205]. The proposed EIP is also a platform for collaboration, which is in many respects broadly similar to EIT/KIC. The major difference is that EIP is a project or programme funded by the EU rather than a centre, and it has sharply defined objectives to be reached by the end of the programme. Looking at the programmes more closely there is, potentially, significant overlap between the envisioned KIC on raw materials, the EIP, and the existing ERA-NET on Sustainable Materials Resources. Together with the H2020 all of these instruments have parallel and overlapping aims, although the individual approach of each is somewhat different.

Potentially, this fragmentation can create further confusion in the field and in some cases create challenges for potential participants in terms of choosing the right forum for their needs. The risk here is that the efforts taken at the European level are spread relatively thinly as the interested key actors will, to some extent, be divided between collaboration platforms, or will divide their limited time between platforms and initiatives instead of being wholly involved in any one effort. Additionally, coordination and networking between the initiatives creates significant overhead both for the EU and the participants. Nevertheless, as such these initiatives do not necessarily compete with H2020 or FP7, as the KICs in particular are not so much an RDI funding instrument as a networking action. These networks which bring relevant actors together to set up collaborative ventures may in fact facilitate participation in FP7 and H2020 as consortium building in respect of future proposals is achieved more easily between partners.

On another level, while the interviewees agreed that current EU level policy in this area is comprehensive, there nevertheless remains a significant need for better coordination and interlocking between EU and national programmes. Each Member State currently retains its own approach in respect of CRM, as discussed above. This results in the needless duplication of programmes and funding opportunities nationally and on the EU level.

A more fundamental issue is that the interviewees expressed, quite unilaterally, an opinion that substitution is seen as *one* of many tools to alleviate CRM shortages. It was pointed out that an integrated approach is needed to tackle criticality issues, and that a thorough analysis and risk assessment would have to be carried out for each critical material and its applications. An example of such an integrated approach can be found in a recent

[205] EIT – Innovation Communities – Overview – Knowledge and Innovation Communities: overview, Available: http://eit.europa.eu/kics1/knowledge-and-innovation-communities/overview.html; EIT 2009. Cal for Proposals EIT-KICKS-2009 Knowledge and Innovation Communities, Available: http://eit.europa.eu/fileadmin/Content/Downloads/PDF/kics/KICS_call_2009_04_02.pdf (Accessed 27.3.2012).

publication in Nature Materials[206]. Here, material scientists, resource strategists, and economists worked together and showed that even at an early stage of material development, scientific, ecological and economic aspects should all be considered together in tandem in order to develop the best material or substitute. Depending on the material and application, it may be easier to increase efficiency or promote recycling, while at other times substitution might be the better approach. According to industry sources the more resource-efficient use of materials should be the primary focus (effectively the low hanging fruit), secondary to this is recycling and only then should substitution be considered.

One important point worth considering in respect of RDI programming is that examples do exist of fields and applications where CRM substitution has proven to be extremely challenging. Despite the best efforts of those concerned, a decided inability to develop solutions to substitute CRM without loss of performance in certain technical areas remains. For example catalytic converters for both industrial and consumer applications have been extensively researched over a long period of time, but there has been little success in superseding CRM-dependent designs. An industry expert in the field of catalysis interviewed for this study stated that "one has been trying to find replacements for PGMs in catalysis for the last 30 years, and has not achieved catalysts with the same efficiency[207]". It has to be questioned what the return on RDI investment in this particular field would be, and would the resources used be better spent for example on developing more efficient or better recycling solutions for the materials already in use. The industry view is that to avoid harmful escalation of commitment a sensible strategy that takes into consideration the economic, ecological, and scientific factors together, would have to be developed and periodically re-adjusted with updated information for *each* CRM. The challenge here is that setting a focus on the RDI for CRM substitution needs to be well thought out and that substitution initiatives need to take into account entire value chains, i.e. developing innovative new products or services to solve the clients' problems that can substitute the existing product or service whose value chain currently depends on CRM.

From an industry standpoint, research-driven materials substitution in general is both a very risky and a lengthy endeavour. An interviewee from industry stated that true substitution research, meaning the discovery of disruptive and not incremental innovations, would have to try to fundamentally understand materials' properties and answer the question why certain elements are needed for certain applications; what is the physical and/or chemical mechanism behind the desired function. This research resembles pharmacological research in scale and scope rather than conventional new product development. The commercial new product development cycle is well under 5 years in many industries, from 1-2 in fast moving industries. In pharmacological product development researchers test thousands of chemical compounds for any marketable molecule, often without guaranteed success. The timescale is from the initiation of the research effort to a commercial application or a product anywhere from 10 – 15 years, and the investment is in the order of hundreds (even thousands) of millions of Euros, which is an order of magnitude larger than RDI programmes in other industries. According to the interviews, due to the timeframe and volume of the effort, publically funded basic research on materials substitution should, in the main, be directed toward broad-based and generic technological solutions, for instance battery technologies in general.

The interviewees also voiced a general opinion that to support CRM substitution, funding programmes should focus equally on basic, applied and industrial demonstration research, but that applied research should involve the key market players in consortia. Collaborative

[206] Krohns, S., Lunkenheimer, P., Meissner, S., Reller, A., Gleich, B., Rathgeber, A., Gaugler, T., Buhl, H. U., Sinclair D. C., Loidl A., 2011. The route to resource-efficient novel materials, Nature Materials 10, 899, Available: http://www.nature.com/nmat/journal/v10/n12/full/nmat3180.html.

[207] Hagelücken, private communication.

projects (in general, not necessarily in the context of FP7), which involve universities, research institutes and industry usually go only as far as prototype development. However, as soon as the projects become very application-oriented, large enterprises prefer to work on those projects within small industrial consortia. Accordingly, interviewees had serious doubts as to whether large international consortia, such as required in FP7, represent a feasible approach to solving CRM issues. Another concern was that intellectual property issues should be handled proactively and transparently from the start of funding programmes. This is particularly true for technologies that would grant large advantages in commercial production due to the improvements they generate either in performance or process efficiency. Large and resource-intensive industrial firms may favour internal development instead of public-private collaboration with universities due to the advantages gained in respect of information and intellectual property security and knowledge retention.

One individual application which has something of a keystone status is substitution of indium tin oxide (ITO). ITO is a state of the art material for conductive and optically transparent membranes, including touch screens and a variety of other display and lighting technologies. Finding an economical substitution for ITO would proffer significant market advantage. Thus it is highly unlikely that the manufacturers who possess the resources to develop commercial substitutes will want to take the risk of such information leaking to competitors by engaging in research collaboration. These opinions highlight the trend that enterprises welcome research partnerships on the generic level, but when the project moves towards the commercial event horizon, enterprises, especially large and well resourced ones, prefer proprietary research as the results grant them a degree of monopoly power over their rivals if the commercialisation of research succeeds.

This example highlights the fact that established enterprises are also, on occasion, prone to resist transformative change. This resistance to change is quite natural and is a product of the so-called path dependency created by ones' historical path, current knowledge base and past investments. In cases where radical changes are made to the dominant design, large investments in intellectual and physical capital and production technologies may be rendered obsolete relatively quickly, and this shift may cost a company its position in the market, if not its very existence. To illustrate the complex feedbacks/incentives further, we may examine a news piece with direct relevance from early 2012, where one manufacturer of hybrid vehicles broadcast that it was two years away from commercialising a REE-free hybrid vehicle, provided REE prices did not fall from mid-to late 2011 prices.[208] In this example, the notable fact is that CRM substitution in that particular application is technically feasible, if not yet commercially viable, but the manufacturer does not have sufficient incentive to commercialise the new technology.

An apt analogy for thinking about the magnitude of changes CRM substitution might bring to many industries may be the digital revolution in photography, where the well-established value chain based on analogue technology has been replaced with digital technology. The established value chain in, say, the 1980s consisted of companies from the chemical industry which supplied film and solutions for developing film, e.g. *Kodak*, *AGFA*, *Fuji*; and electromechanical equipment manufacturers which produced cameras and lenses, e.g. *Leica*, *Pentax*, *Nikon*, *Canon*; through distributors who also offered the service of developing the exposed film and making up printed copies of photos for the end users, e.g. local photography retailers. Most casual photographers in the western world however now take photographs digitally with cameras and integrated devices, which are increasingly produced by consumer electronics manufacturers instead of electromechanical

[208] Reuters, 2012. Toyota finds way to avoid using rare earth: report, January 23rd 2012. Available at: http://www.reuters.com/article/2012/01/23/us-toyota-rare-earth-idUSTRE80M0JK20120123 (accessed 26.1.2012)

manufacturers who excelled in making film cameras. Digital photography has effectively replaced film, and now many print their own photos with home printers, or order digital prints. The major film manufacturers have basically been pushed out of the digital value chains, while traditional manufacturers of photographic equipment are losing market share to e.g. mobile phones and/or tablet computers in the casual photography sector. The winners are companies like *Samsung*, *Apple Computer*, and *Nokia* along with camera manufacturers like *Canon* who also offer printing technologies. This example shows how a practical problem can be addressed with almost completely different value chains, with very different technologies and different knowledge. This change also illustrates how sometimes quite unforeseen changes in value chains can occur in a relatively short timeframe and how relatively small changes may have great consequences for entire industries.

Bearing these viewpoints in mind, it is notable that many of the policies discussed above, in section 3, are directed towards sustaining the current value chain in the industry through short or medium term measures aimed to sustain the supply of REE and other CRM, e.g. through stockpiling, building new supply capacity that builds on the existing ecosystem instead of altering it to create independence from these materials. Thus policy making, if the aim is to substitute CRM, should be focused on enabling the emergence of *new* ecosystems that may solve the problems presented by the clients in novel ways with new solutions. The following recommendations are directed primarily toward EU institutions, although they are also relevant to the Member States.

Maintaining up-to-date information about raw materials resources and their criticality

The EU has taken a considerable interest in raising awareness of the CRM issue and in implementing policies that will kick-start substitution. However, as pointed out in the interviews, the availability and importance of any individual raw material in the CRM list or outside it may become, or cease to be, critical as a result of e.g. the development of new technologies, materials and products; extensive substitution; through changes in customer preferences; or the finding of unforeseen new deposits.

The EU can create an important resource for substitution by maintaining up to date information on the current situation of various minerals resources, the global trade situation and the criticality of different raw materials. Further, information could be disseminated on the current use of CRM and the structure of value chains, highlighting the risk associated with the use of CRM and the potential economic and/or technical benefits of substitution.

Creating an RDI roadmap for substitution

While the raw materials strategy provides a clear direction in respect of where European industry should, in general, be headed, substitution efforts could be aided by a more specific roadmap for research on substitution. Side by side with the previous recommendation, the research roadmap should look at interdependence between materials efficiency, the recycling of end-of-life products and materials and the substitution of each critical material and application separately and in conjunction with each other. Another crucial point worthy of further analysis is whether substituting materials with currently non-critical ones creates negative externalities, e.g. by making currently abundant materials critical in cases where the existing production of the substitute material cannot satisfy the demand for the new application, or by creating environmental hazards in the event that recycling the substitute material or product is not feasible.

Ideally, CRM should be replaced by abundant materials and minerals. For example, initiatives exist where new semiconducting properties are obtained in iron through clever manipulation of micro- or nanostructures[209], potentially replacing silicon and germanium in some applications. However, managing funding on this level of detail requires a thorough socio-economic as well as a technical analysis in order to decide which CRM and applications to focus on.

To develop such a roadmap, economists, raw materials-, mining- and recycling experts, and materials scientist need to work together to determine which materials are the most fruitful targets for substitution RDI within a timeframe of e.g. 10 years. Such a roadmap would have to be updated on a periodic basis, to accommodate recent developments. In fact, these two recommendations, disseminating information and creating a roadmap for RDI, are potentially addressed by the proposed EIP initiative that aims to increase coordination between national geological surveys and set a roadmap for substitution.

Bringing focus to RDI efforts to avoid fragmentation

As discussed previously, the EU is already consolidating its RDI funding instruments under the Horizon 2020 programme. In addition to the integration of programmes, the substitution of CRM could also be integrated into the appropriate sectoral sub-programmes. In FP7 the main substitution themes have been proposed under the NMP programme and resource efficiency and recycling under the Environment programme, while in H2020 research aiming to find substitutes can fall under any one of six themes or specific actions across all three pillars. If an integrated approach to CRM is viewed as a key issue for European Industrial Leadership, CRM or CRM substitution could be e.g. raised to the level of a more important theme either under the specific action Advanced materials in the Industrial Leadership pillar, or even further, the different materials science and process technology actions could be merged to one action, possibly also including actions for supporting waste retrieval, processing and other recycling-related technologies to support the creation of an ecosystem that covers the full value chain. Another approach could also be to set up a more integrated theme on materials RDI in the Societal challenges pillar e.g. under the theme “Climate action, resource efficiency and raw materials“. No matter which of these options is implemented, the need for a more integrated approach on materials RDI and CRM supply and on efficient use and recycling in particular should be met by H2020.

A particular question of note here is whether Horizon 2020 will consolidate FP7 with parts of the CIP and EIT/KICs and, if so, whether it will envelop the gamut of RDI activity from basic research to new product and service development. If a new KIC is introduced in 2014 as proposed[210] and it maintains a similar organisation as, and aims analogous to, the current KICs, it may again result in further duplication of funding *fora* especially with the newly proposed EIP, at least in the area of coordination and support actions, unless the task division and roles between the KIC and EIP are not sufficiently differentiated.

The interviewees called for additional focus to be placed not only on the EU level but also for more interlocking and exchange among national and EU initiatives. The Member States are of course in a position to decide on their own funding schemes, but coordination with the European framework would help applicants to spot and apply for the appropriate funding in general and reduce duplicate funding, enabling the Member States to focus their resources on the nationally important aspects of RDI. This kind of exchange could be achieved by EU institutions, for example through the process of creating an RDI roadmap for CRM substitution, and by including the Member States and other major stakeholders in the process. Again the EIP and/or KIC are actions that are planned to address this issue at

[209] See e.g. Milosavljevic, M. Shao, G., Bibic, N., McKinty, N., Jaynes, C. Homewood, K.P., 2001. Amorphous-iron disilicide: A promising semiconductor, Applied Physics Letters, Vol. 79, No. 10.

[210] EC, 2011.Proposal for a Decision of the European Parliament and of the Council on the Strategic Innovation Agenda of the European Institute of Innovation and Technology (EIT): the contribution of the EIT to a more innovative Europe, COM(2011) 822 final.

least partially. Increased exchange and collaboration can also be supported through the ERA-NETs[211] and Coordination and/or Support Actions as a part of other RDI funding.

Recognising the different dimensions of substitution

As illustrated in "[The] guide to substitution" developed by the UK Chemicals stakeholder forum[212], the substitution of any material is a multidimensional issue and the various possible perspectives to substitution should be recognised when developing further policy and instruments for CRM substitution. Stereotypically, the goal is to find abundant materials and processing technologies that offer the same efficiency and the same essential properties as materials that include CRMs. However, that is only one angle to substitution; substitution can include innovation on all fronts besides developing direct material-for-material substitutes, including process-for-process, substance-for-substance, mechanism-for-mechanism, product-for-product and service-for-product solutions in addition to the most obvious[213]. The plethora of potentially available substitutes was illustrated by the example of digital versus film photography outlined above, illustrating product-for-product substitution in equipment and service-for-service substitution in printing.

Thinking broadly about the problem may help in structuring effective policy responses to the issue and especially in developing RDI programmes and their project evaluation criteria. Regarding the areas of research that can develop substitutes, interviewees indicated that nanotechnology may have the potential to discover materials with new properties, but solid-state chemistry, polymer science etc., should not be neglected when considering substitution research.

One additional aspect in respect of substitution proposed by the interviewees is that substitution efforts should focus first and foremost on products where dissipative CRM use occurs, which is to say, that substitution should focus on applications where CRMs cannot be recovered and precious resources are wasted as by-products. For example, (multi-) coloured Light Emitting Diodes (LEDs) are commonly used in toys and vanity products that are not easily recognised as electronics and end up in landfills with household refuse. However, they contain REEs in amounts that are insignificant when looking at individual products and the low concentration prohibits economical recycling, but when looking at the total waste material flow it is apparent that a significant amount of CRM are lost to landfills on a day-by-day basis.

Encompassing the entire RDI process with policy actions

In relation to the general question of CRM substitution it is important to speed up the development of commercial applications and, as such, application-oriented RDI funding may be particularly beneficial. The newly announced EIP on raw materials goes even further in aiming to support pilot production and recycling facilities in addition to the development of commercial applications, which is a step yet further in the direction of commercialising innovation to alleviate CRM issues.

However, the closer to commercial application the RDI work is, the more important it becomes to recognise contractual and intellectual property rights (IPR). Here EU and national institutions are in the position to negotiate a solid contractual platform that facilitates participation and fair play between partners in programmes, and reduces the risk

---

[211] EC, Community Research and Development Service – Coordination of Research Activities ERA-NET Scheme, Available: http://cordis.europa.eu/coordination/era-net.htm (Accessed 13.3.2012).

[212] UK Stakeholder Forum, 2010. A Guide to Substitution, August 2010, Available: http://archive.defra.gov.uk/environment/quality/chemicals/csf/documents/forum-guide-substitution.pdf.

[213] Examples of successful substitutions from the chemical industry are described in the UK Stakeholder Forum, 2010. A Guide to Substitution, August 2010, Available: http://archive.defra.gov.uk/environment/quality/chemicals/csf/documents/forum-guide-substitution.pdf.

of legal battle over results. As a national example, when the Finnish national funding agency for technology and innovation - TEKES - was winding up the major Strategic Centres for Science, Technology and Innovation, special attention was paid to negotiating a unilaterally accepted basic contract that includes clear clauses on ownership of IPR in respect of the knowledge the partners bring to the table, and to the knowledge, patents and products that are developed under the grant.[214]

Strengthening mechanisms to bring the EU to the forefront of materials science

Bringing the EU and the European Research Area (ERA) to the forefront of science is an overarching EU policy objective. CRM substitution not only provides an important economic challenge; it is also entails a large multidisciplinary scientific effort. To support substitution-oriented research, establishing strong materials science centres and programmes may be in order. Looking at the international benchmarks, for example, in Japan the National institute for Materials Science has been running since 2001. In the US, the policy response has thus far not been that strong with some US scientists arguing publicly that the intellectual infrastructure and knowledge base requires strengthening to enable successful CRM substitution[215]. The existing and foreseen European funding instruments, including FP7, the emerging H2020 and EIP on raw materials already represent an extensive effort, but additional specialised research may be called for in order to bring European research to the cutting edge and to avoid loss of competence in various fields around materials science and CRM through 'brain drain'.

One way to organise such an effort and to ensure a critical mass of researchers could be by mimicking the Japanese NIMS set up, the Helmholtz Institute for Resource Technology in Freiberg, Germany, or the Energy technologies institute in the UK. Such an institute could be organised as a Joint Research Centre (JRC) under Pillar IV in H2020, or under Pillar I as research infrastructure, or through other means, and would act as a nexus of materials science research within the EU as well as a meeting point for top materials scientists around the world. The institute could cover a broad range of RDI activities from basic to applied research and ideally also demonstration, with a focus on broadly used technologies and applications.

4.2. Possibilities for supporting further substitution efforts through collaboration with third countries

The general recommendations given to issues concerning the supply of raw materials fall into categories such as foreign policy and diplomacy (creating understanding between nations, creating preferred trade relationships etc.); development cooperation (helping selected developing countries develop their minerals sector); trade policy (negotiating supply, duties and filing disputes in the WTO); as well as industrial and RDI policy (collecting information about minerals resources, supporting RDI and supporting the minerals sector). These policy responses are however aimed primarily at sustaining the existing ecosystem which is built around the use of CRM, rather than CRM substitution. Thus additional policy responses are needed specifically on the issue of substitution.

Based on the analysis of minerals strategies, it was noted that large mineral suppliers elicit slightly different responses and respond to different incentives than mineral users. Most importantly, those countries that have precious minerals resources have less incentive to

[214] See e.g. Terms and Conditions, TEKES - Strategic Centres for Science, Technology and Innovation Available: http://www.tekes.fi/en/community/Strategic0Centres0for0Science_0Technology0and0Innovation/360/Strategic0Centres0for0Science_0Technology0and0Innovation/1296 (Accessed 14.3.2012).

[215] Coppel, 2011., op.cit; Gschneinder, K.A., The Rare Earth Crisis – The Lack of Intellectual Infrastructure, The Ames National Laboratory, Available at: https://www.ameslab.gov/files/RE_Crisis_Intell_Infrastruc_12.9.10.pdf (Accessed 8.2.2012).

substitute the existing value chain or seek new technical solutions, as the minerals trade brings direct benefits to their national economies. Thus the recommendations made here are most likely to be beneficial to those countries which adopt similar positions in respect of CRM as the EU and its Member States. The following recommendations can, moreover, be applied both on the EU level and by the individual Member States.

Using existing *fora* to exchange information and to discuss strategies to deal with the CRM issue

The EU as well as various individual Member States are active in international *fora* where various policy issues are discussed and coordinated. These forums can be used to discuss the European roadmap to sustainable resource use, as well as national issues to keep the roadmap up to date in terms of the international situation. For example the Group of 8 (G8) and the Organisation for Economic Development and Cooperation (OECD) are platforms for policy coordination and exchange where several Member States are represented and active. In addition to gathering information, these organisations can also act as a platform to spark high level interest in more specific forms of collaboration that can lead to more tangible results.

Emphasising the role of research centres in generating, gathering and exchanging knowledge

The most important platforms for international collaboration on CRM substitution are the existing and foreseeable research centres and RDI programmes. It is proposed that most of the worlds RDI capability on REE and their use and application is in China[216]. In addition, Japan already has strong RDI programmes in materials science and a long standing dedicated research centre. Integrating these knowledge resources across the EU and at the national level could proceed by extending the funding for RDI on materials science and engineering available also for foreign, e.g. Japanese and Chinese partners, especially if the research aims at CRM substitution.

Further support for the exchange of personnel between leading materials science research programmes and institutions would undoubtedly represent a beneficial exchange, e.g. such exchanges could be envisaged between the newly founded Helmholtz Institute for Resource Technology and the Japanese NIMS mentioned above. Another option to consider here is the founding of dedicated international programmes such as the initiative set up by the G8 research council. However, setting up completely new programmes may be administratively and economically burdensome compared to simply integrating new initiatives into existing programmes. The most costly option would be establishing an EU funded research institute to act as a network engine in materials science research and personnel exchange, as proposed above.

4.3. The potential for other policies and measures to strengthen the development of CRM substitution in the EU

The preceding sections dealt primarily with RDI policy on the EU and national level. The recommendations in this section fall into the domain of industrial and trade policy. It should, moreover, also be recognised that, as discussed previously, CRM substitution may, depending on the application, actually be technically quite difficult while the new product development cycle may take as long as 5-15 years. Thus the industry's incentive structure generally points to sustaining the existing value chain through either partial substitution,

[216] Coppel, 2011, op.cit; Gscheinder, K.A. The Rare Earth Crisis – The Lack of Intellectual Infrastructure, The Ames National Laboratory, Available at: https://www.ameslab.gov/files/RE_Crisis_Intell_Infrastruc_12.9.10.pdf (Accessed 8.2.2012).

recycling or various other measures that do not require the development of altogether new products, services or materials.

The decision to develop a certain technology involves a significant investment in RDI, machinery, creating a value network and partnering. Thus the barrier to migrating to another technology is high as it will not only involve developing a new technology and assuming a new knowledge base, but will also significantly alter the value network which involves seeking new partners. Large incumbent enterprises that have developed a well functioning value network, which is generally profitable and grants them a favourable distortion in the market in the form of economic rents, are particularly prone to resisting transformative change, be it from competition or legislation. Thus it is foreseeable that CRM substitution may encounter significant resistance to change from industry players that are either not prepared or do not recognise the issue as important. One such example of this was highlighted above where a manufacturer developed technologies for producing equipment without or with significantly less REE, but is planning to introduce them to markets only if REE prices will not drop from their current peak[217].

Another fundamental challenge for CRM substitution in a market economy is that private and public buyers alike, on average, seek the best perceived ratio between performance in a given application and price paid for the product and service. For a new product or service to be successful it has to supersede the previous design in at least one of these aspects if not both, which puts large pressure on RDI to develop economical but technically superior solutions without CRM.

Accordingly, the interviewees proposed actions that are directed first and foremost towards enhancing the market conditions for raw materials. The proposed actions include improving market transparency, exploring for new deposits in previously unexplored areas overseas while also prospecting to a greater depth than previously. All of these actions serve to alleviate the supply issues of the indentified CRM in the short to medium term context but if the EP wants to specifically favour CRM substitution, specific additional actions are required. Firstly, there is a need to raise awareness on the issue and its possible impacts and secondly to create additional incentives for substitution.

Considering the argument on resistance to change in industry and those in relation to the challenges faced in developing commercial solutions it is foreseeable that unless measures are taken to change the short and long term incentive structures across the board with regard to substitution fundamental changes in value chains may not be realised until the situation is already very critical. Positive incentives for RDI directed to substitution may not suffice to accelerate this. As such, other policy measures, including 'negative incentives' may be needed to make substitution an economically interesting solution for industry. These negative incentives may have additional leverage to transform the value chain as, if enforced; they will make the existing value network less profitable and will provide strong incentives to develop radically new solutions to practical problems previously solved with the help of CRM. Indeed, one of the interviewees suggested negative incentives were required to drive CRM substitution in applications that are not critical in terms of performance functionality.

The last resorts, so to speak, are trade and industrial policies to make CRM artificially less lucrative and/or substitutes seem more economical. The simplest negative incentive would be a mirror image of some of the producer nations' own regulations; to raise import duties on CRM and/or products containing CRM, or taxes on the use of CRM and sales of products based on CRM-content. The toughest incentive would be to restrict use of CRM in products

[217] Reuters, 2012. Toyota finds way to avoid using rare earth: report, January 23rd 2012. Available at: http://www.reuters.com/article/2012/01/23/us-toyota-rare-earth-idUSTRE80M0JK20120123 (accessed 26.1.2012).

marketed in the EU, in a manner resembling the Restriction of Hazardous Substances Directive[218], something which would probably introduce quite rapid transformative changes possibly on a worldwide level.

However, these policies also have several foreseeable negative externalities, some of which include temporary loss of profitability in the existing industries before the new ecosystem is built. This would, in turn, likely generate a short-term loss of employment and international competitiveness for European industry, depending on how much time the industry has to adapt before the hypothetical directive is passed. A study on the economic impacts of the Restriction of Hazardous Substances Directive[219] indicates that the directive had negative effects on the industry in the short term in the form of compliance costs including administrative burden and education and with regard to the level of technical costs accrued in relation to the phasing out of technologies. The estimated total compliance cost for past and future measures was estimated to be, on average, around 4.2% of turnover for Small and Medium-sized enterprises and 1% for large multinational enterprises as calculated in 2008[220], which gives an estimate on the scale of the effect. Nevertheless, the directive also had benefits especially in the form of positive externalities, including increased patenting activity following the passing of the directive, which may indicate a positive impact in respect of innovation.

Besides these more controversial measures, the following actions can be implemented on the EU level and nationally, before the more drastic measures:

Maintaining and disseminating up-to-date information on CRM

The issue of maintaining an RDI roadmap for CRM substitution and the gathering of intellectual capital within the EU and globally to undertake the necessary RDI was already discussed above. The industry and the general public can however also benefit from information on the issues relating to raw materials supply, as precise up-to-date information enables businesses, public bodies and consumers to make informed choices. For example, one of the interviewees indicated that enterprises are not necessarily aware of where and how much CRM is used in their products, as many of today's products were designed when CRM availability was not an issue.

Another audience who need the information are the officials, civil servants and politicians, both at the EU level and in the Member States, that plan, prepare, write and decide on legislation and regulation involving CRM. The information issue concerns both the EU and the Member States. While the EU would be in the best position to coordinate the effort, the Member States could share the task of collecting information on the national level and disseminating this information further. As CRM substitution is essentially a sustainability issue for the European economy, and thus is linked to waste handling and recycling, the information delivery on CRM could be partially bundled with environmental sustainability messages especially when directed toward the general public.

Another special topic is the perceived lack of interest in materials science and the consequent shortage in terms of competent workers. At least one of the interviewees noted that materials science is not an interesting study topic and that more students are needed to enable sustainable development. The faculty of educational institutions and students, especially in engineering and science, would be an important audience for CRM information.

[218] European Parliament, European Council, 2003. Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment, Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0095:EN:HTML (Accessed 14.3.2012)

[219] Bogaert, S. Acoleyen M. van, Tomme, I. van, Smet, L. De, Fleet, D., Salado, R., 2008. Study on the RoHS and WEEE Directives, Final Report, No 30-CE-0095296/00-09, EC DG-ENTR 06/11925/AL.

[220] Bogaert, S. et.al., Ibid.

Introducing the issue in an educational context would plausibly heighten the students' interest in the sustainability impact of design choices. Further, CRM could again be bundled with (other) sustainability issues, understanding sustainability broadly as an issue that concerns the whole life cycle of any given product from design to disposal.

The EU and the Member States can make substitution and recycling more effective and approachable by maintaining an up-to-date list of CRM and also other raw materials, their availability, and current virgin resources and recyclable resources. For example, EuroGeoSurveys, an association for European Geological Surveys, would be in a good position to maintain a publicly available map of European minerals resources that is updated periodically. Alternatively, action could also be taken through other initiatives, such as was proposed in the emerging EIP.

Further action could be taken to gather and analyse information on the materials used in different products and industries, to map value chains and production processes and explore landfills and other dump sites that may contain secondary minerals deposits that can be recycled. An initial approach here would be to map the use of CRM and their content in various products and in their value chains to highlight where CRM are used and what the most critical applications are as well as the most fruitful for substitution both in terms of solutions available and tolerance for loss of performance. This information should be gathered on an EU-wide level, updated periodically e.g. every 1-2 years, and delivered to Member States especially when states are updating minerals, raw materials or RDI policies. Periodic updates on CRM also ensure that efforts to substitute CRM are directed towards the right materials as industries and products evolve. This kind of information gathering system would also serve to create an RDI roadmap for substitution as discussed above.

Creating a market for CRM substitutes through public procurement

Again as discussed above, for natural reasons business enterprises may be initially averse to developing CRM substitutes, while consumers may be to a large extent unaware that such an issue even exists. The EU and the Member States are in a position to create a vast market for CRM substitutes as a part of their everyday operations through pre-commercial public procurement (PCP). Public procurement represents a substantial market, in Germany alone the total turnover figure in relation to public procurement is in the order of 250 Billion EUR per year[221] while on the EU level public procurement comprises 3.5% of GDP[222].

Thus following the example of The Netherlands (as discussed above) and including e.g. low CRM content, design for end-of-life recyclability or the high level of recycled raw materials in evaluation criteria for procured products, as well as the building of strong confidential relationships with several suppliers who are ready to work on substitution; all of these could act as significant incentives to drive innovation for substitution of CRM and provide a forum where products could be developed and piloted before being introduced to the market. Public procurement would potentially have a twofold advantage, it would offer an arena to develop CRM-free products that match or supersede existing design specifications and it would draw attention to the issue and possibly create an expanding private market to match. The EU can act to shape procurement legislation but it is the Member States themselves who are in the best position to take immediate action should they see fit.

[221] Bundesministerium für Wirtschaft und Technologie (BMWi), Bundesverband für Materialwirtschaft, Einkauf and Logistik .e.V (BME) 2010. Impulse für Innovationen im öffentlichen, Series Beschaffungswesen, Innovationpolitik, Infomationsgesellschaft, Telekommunikation, BMWi Öffentlichsarbait, Berlin, Available: http://www.bmwi.de/BMWi/Navigation/Service/publikationen,did=331868.html (Accessed 14.3.2012).

[222] Strand, I., Ramada, P., Canton, E., 2011. Public procurement in Europe: Cost and effectiveness, Available: http://ec.europa.eu/internal_market/publicprocurement/docs/modernising_rules/cost-effectiveness_en.pdf (Accessed 14.3.2012).

REFERENCES

- Advanced Research Projects Agency – Energy, Programs & Projects – Projects list, Available: http://arpa-e.energy.gov/ProgramsProjects/ViewAllProjects.aspx (Accessed: 13.3.2012).
- Agency for Toxic Substances and Disease Registry, 1992. Toxicological profile for antimony and compounds, U.S. Public Health Service, Available: http://www.atsdr.cdc.gov/toxprofiles/tp23.pdf(Accessed on 15.3.2012).
- Azom.com, Tungsten, an overview, Available: http://www.azom.com/article.aspx?ArticleID=1201(Accessed 18.2.2012).
- Bavarian ministry for Trade, Infrastructure, Transport and Technology, 2007. Bekanntmachung des Bayerischen Staatministeriums für Wirtshaft, Infrastructur, Verkehr und Technologie, Richtlinien Zum Forschungsprogramme "Neue Werkstoffe", Available at: http://www.ptj.de/lw_resource/datapool/_items/item_2487/2007-02-01-richtlinien_neue_werkstoffe.pdf.
- Beissman, T. 2012. Toyota finds alternatives to rare earth metals for hybrids: report, Car Advice, Available: http://www.caradvice.com.au/156331/toyota-finds-alternative-to-rare-earth-metals-for-hybrids-report/ (Accessed 19.3.2012).
- Beryllium Science and Technology Association, http://beryllium.eu/, accessed on 12 March 2012.
- Bogaert, S. Acoleyen M. van, Tomme, I. van, Smet, L. De, Fleet, D., Salado, R., 2008. Sudy on the RoHD and WEEE Directives, Final Report, No 30-CE-0095296/00-09, EC DG-ENTR 06/11925/AL.
- Bullis, K., 2007. Cheap solar cells: Carbon nanotubes could help make nanoparticle-based solar cells more efficient and practical, Technology Review, Massachusetts Institute of Technology, Available: http://www.technologyreview.com/energy/18259/ (Accessed 17.3.2012).
- Bundesverban de Deutshen Industrie, Presscenter – Pressemittelungen, Aufbau der Allianz zur Rohstoffsicherung beginnt, 20.1.2012, Available: http://www.bdi.eu/Pressemitteilungen_Pressemitteilung_Allianz_zur_Rohstoffsicherung_30_01_2012.htm (Accessed 13.3.2012).
- British Geological Survey, Borrowdale - Lake District, Available: http://www.bgs.ac.uk/research/ukgeology/borrowdale.html (Accessed 13.3.2012).
- British Geological Survey, 2011. Niobium-tantalum, Available: http://www.bgs.ac.uk/downloads/start.cfm?id=2033 (Accessed 21.2.2012).
- British Geological Survey, 2011. Tungsten, Available: http://www.bgs.ac.uk/downloads/start.cfm?id=1981 (Accessed 21.2.2012).
- British Geological Survey, 2011. Tungsten – A hard metal to replace, Available: http://www.bgs.ac.uk/news/NEWS/Tungsten_Profile_press_release.pdf (Accessed 21.2.2012).

- Bullis, K., 2007. Cheap solar cells: Carbon nanotubes could help make nanoparticle-based solar cells more efficient and practical, Technology Review, Massachusetts Institute of Technology, Available: http://www.technologyreview.com/energy/18259/ (Accessed 17.3.2012).

- Butts, K.H., Bankus, B., Norris, A., 2011. Strategic Minerals: Is China's Consumption a Threat to United States Security?, United States Army War College, Center for Strategic Leadership, Issue Paper, July 2011, Vol. 7-11.
- Business Wire, 2011. China & India to Be World Leaders of Fluorspar Production According To Merchant Research & Consulting, Ltd., Available: http://www.businesswire.com/news/home/20110714005943/en/China-India-World-Leaders-Fluorspar-Production-Merchant (Accessed on 15.2.2012).
- Centre national de la recherche scientifique, November 8th 2011, CNRS to coordinate European ERA-MIN project on non-energy mineral resources, Available: http://www2.cnrs.fr/en/1930.htm; ERA-MIN - Project introduction, Available: http://www.labo21.dsi.cnrs.fr/ (Accessed 13.3.2012).
- Carlin, J. F., Jr., Recycling of Antimony in the United States in 2000, U.S. Geological Survey Circular 1196–Q, USGS, Available at: http://pubs.usgs.gov/circ/c1196q/c1196q.pdf, (Accessed 12 March 2012).
- City of Hamburg - Citizens' Services - Environment – Environment Protection in Practice – Ressourcenschutz, Available at: http://www.hamburg.de/start-programm/ (Accessed 9.2.2012).
- The Cobalt Development Institute, Available: http://www.thecdi.com/about-cobalt (Accessed 10.3.2012).
- Cobalt Innovations, Available: http://www.cobaltinnovations.co.uk/managed_recycling/ (Accessed 10.3.2012).
- Congressional Budget Office, 1976. U.S. Raw Materials Policy: Problems and Possible Solutions, Background Paper No. 16, December 28, 1976, Congress of the United States, Congressional Budget Office.
- Coppel, E., 2011. Rare Earth Metals and U.S. National Security, Briefing, American Security Project.
- Department for Environment, Food and Rural Affairs, 2012. Review of National Resource Strategies and Research, PB 13722, Available: http://www.defra.gov.uk/publications/files/pb13722-national-resource-strategies-review.pdf (Accessed 27.3.2012).
- Department for Environment, Food and Rural Affairs, 2010. UK Stakeholder Forum for Chemical Industry, A Guide to Substitution, August 2010, Available: http://archive.defra.gov.uk/environment/quality/chemicals/csf/documents/forum-guide-substitution.pdf.
- Deutsche Rohstoff AG, Available: http://www.rohstoff.de/unternehmen-rohstoffe-deutschland-rohstoff-deutsch/?lang=en (Accessed 13.3.2012).
- Deutsche Rohstoff AG, Divisions – High-Tech Metals – Seltenerden Storkwitz AG, Available: http://www.rohstoff.de/geschaftsbereiche/hightech-metalle-seltene-erden-zinn-wolfram/storkwitz/?lang=en (Accessed 13.3.2012).
- Deutsche Rohstoff AG, 2012. Wolfram Camp Mining ships first concentrate, Available: http://www.rohstoff.de/2012/03/06/deutsche-rohstoff-ag-wolfram-camp-mine-liefert-erstes-konzentrat/?lang=en (Accessed 13.3.2012).
- Deutsche Rohstoff AG, Divisions – Gold and Silver, Available: http://www.rohstoff.de/geschaftsbereiche/gold-silber/?lang=en (Accessed 13.3.2012).

- US DOE Office of Inspector General, Office of Audits and Inspections, Audit Report: The Advanced Research Projects Agency – Energy, OAS-RA-11-11, Available at: http://energy.gov/sites/prod/files/OAS-RA-11-11.pdf (Accessed 8.2.2012).
- US DOE, Critical Materials Strategy, December 2011.
- US DOE, Office of Policy and International Affairs, 2011. Critical Materials Strategy, Available: http://energy.gov/pi/office-policy-and-international-affairs/downloads/2011-critical-materials-strategy (Accessed 13.3.2012); workshop documentation also available.
- DiGiovanni, 2009. Advanced Research Projects Agency Energy – ARPA-E, presentation at the DOE Business Opportunity Session, Dec. 17th 2009, Available at: http://energy.gov/sites/prod/files/ED2/business/documents/Digiovanni_Dec_17.pdf.
- The European Carbon and Graphite Association, Available: http://www.ecga.net/, (Accessed 12.2.2012).
- EC, Community Research and Development Service – Coordination of Research Activities ERA-NET Scheme, Available: http://cordis.europa.eu/coordination/era-net.htm (Accessed 13.3.2012).
- EC, FP7, Cooperation, Theme 4: Nanosciences, nanotechnologies, Materials and new Production Technologies – NMP, Work Programme 2012, C(2011)5068.
- EC 2011. A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy, COM(2011) 21 final.
- EC, 2011. Commission Staff Working Paper – Impact Assessment: Accompanying the Communication from the Commission 'Horizon 20202 – The Framework Programme for Research and Innovation', SEC(2011) 1427 final.
- EC, 2011. Proposal for a Council Decision: establishing the Specific Programme Implementing Horizon 2020 – the Framework Programme for Research and Innovation (2014-2020), COM(2011) 811 final.
- EC, 2011. Roadmap to a Resource Efficient Europe, COM(2011) 571 final.
- EC, 2011. Partnering in Research and Innovation, COM(2011) 572 final.
- EC, 2011. Tackling the challenges in commodity markets and on raw materials, COM(2011) 25 Final.
- EC, 2011. Decision of the European Parliament and of the Council on the Strategic Innovation Agenda of the European Institute of Innovation and Technology (EIT): the contribution of the EIT to a more innovative Europe, COM(2011) 822 final.
- EC, 2008. The raw materials initiative: Meeting our critical needs for growth and jobs in Europe, COM(2008) 699 final.
- EC, 2012. Making raw materials available for Europe's future well-being: Proposal for a European Innovation Partnership on raw materials, SWD(2012) 27 final, available at: http://ec.europa.eu/enterprise/policies/rawmaterials/files/docs/communication_final_en.pdf.
- EC, 2012. Making raw materials available for Europe's future wellbeing: Proposal for a European innovation partnership on raw materials, COM(2012) 82 final; EC DG-ENTR, European Innovation Partnership on raw materials, Available: http://ec.europa.eu/enterprise/policies/raw-materials/innovation-partnership/index_en.htm (Accessed, 12.3.2012).

- EC DG-ENTR, 2010. Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials, Version 30 July 2010. Available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.
- EC DG-ENTR, 2011. Call for Tender Raw Materials: Study on innovative technologies and possible pilot plants, No: 112/PP/ENT/CIP11/CN06S001.
- EC DG-ENTR, 2012, European innovation partnership on raw materials, Available at: http://ec.europa.eu/enterprise/policies/raw-materials/innovation-partnership/index_en.htm.
- EIT – Innovation Communities – Overview – Knowlegde and Innovation Communities: overview, Available: http://eit.europa.eu/kics1/knowledge-and-innovation-communities/overview.html.
- EIT, 2009. Cal for Proposals EIT-KICKS-2009 Knowledge and Innovation Communities, Available:http://eit.europa.eu/fileadmin/Content/Downloads/PDF/kics/KICS_call_2009_04_02.pdf (Accessed 27.3.2012).
- Environment Agency UK, Corporate Plan 2011-15, GEHO0211BTKV-E-E, Available at: http://publications.environment-agency.gov.uk/PDF/GEHO0211BTKV-E-E.pdf.
- Environment Agency UK, European Pathway to Zero Waste (EPOW), Available: http://www.environment-agency.gov.uk/aboutus/wfo/epow/123624.aspx (Accessed 13.2.2012).
- Environment Agency UK, European Pathway to Zero Waste (EPOW) – Projects, Available: http://www.environment-agency.gov.uk/aboutus/wfo/epow/123915.aspx (Accessed 13.2.2012).
- Erdem T., Volkan Demir, H., 2011. Semiconductor nanocrystals as rare earth alternatives, Nature Photonics, No. 5, p. 126, Available: http://www.nature.com/nphoton/journal/v5/n3/full/nphoton.2011.25.html (Accessed 19.3.2012).
- European Federation of Refractories Producers, Raw materials critical for the refractory industry, Available: http://www.pre.eu/en/raw-materials (Accessed 16.2.2012).
- European Environment Agency, 2011. 2011 Survey of resource efficiency policies in EEA member and cooperating countries, Country profile: France, Available: http://www.eea.europa.eu/themes/economy/resource-efficiency/resource-efficiency-policies-country-profiles (Accessed 13.3.2012).
- European Parliament resolution of 13 September 2011 on an effective raw materials strategy for Europe (2011/2056(INI)), see: http://www.europarl.europa.eu/oeil/FindByProcnum.do?lang=en&procnum=INI/2011/2056.
- European Parliament, European Council, Directive 2002/96/EC on Waste Electrical and Electronic Equipment, Available: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:037:0024:0038:en:PDF (Accessed 21 February 2012)
- European Parliament, European Council, 2003. Directive 2002/95/EC on the restriction of the use of certain hazardous substances in electrical and electronic equipment, Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0095:EN:HTML (Accessed 14.3.2012).

- ETP-SMR - Who are We? – History, Available: http://www.etpsmr.org/index.php?option=com_content&view=article&id=6&Itemid=4 (Accessed 13.3.2012).
- Federal Ministry of Economics and Technology (BMWi), 2010. The German Government's raw materials strategy- Safeguarding a sustainable supply of non-energy mineral resources for Germany, Federal Ministry of Economics and Technology (BMWi), Public relations division, Berlin.
- Federal Ministry of Economics and Technology (BMWi), Bundesverband für Materialwirtschaft, Einkauf and Logistik .e.V (BME) 2010. Impulse für Innovationen im öffentlichen, Series Beschaffungswesen, Innovationpolitik, Infomationsgesellschaft, Telekommunikation, BMWi Öffentlichsarbait, Berlin, Available: http://www.bmwi.de/BMWi/Navigation/Service/publikationen,did=331868.html (Accessed 14.3.2012).
- Federal Ministry of Economics and Technology (BMWi), 2010. The German Government's raw materials strategy- Safeguarding a sustainable supply of non-energy mineral resources for Germany, Federal Ministry of Economics and Technology (BMWi), Public relations division, Berlin.
- Federal Ministry of Education and Research (BMBF), 2011. FONA Research on Sustainable Development – Resources and Sustainability – Innovative Technologies for Resource Efficiency – Helmholz Institute Freiberg for Resource Efficiency, Available at: http://www.fona.de/en/9813.
- Federal Ministry of Education and Research (BMBF), 2011. FONA Research on Sustainable Development – Resources and Sustainability – Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals, Available at: http://www.fona.de/en/9815 (Accessed 9.2.2012).
- Federal Ministry of Education and Research (BMBF), Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals (r^3), Available: http://www.fona.de/en/9815 (Accessed 13.3.2012).
- Federal Ministry of Education and Research (BMBF), r^2 – Innovative Technologies for Resource Efficiency – Resource-intensive production processes – Joint Projects Available: http://www.r-zwei-innovation.de/en/510.php (Accessed 12.3.2012).
- Federal Ministry of Education and Research BMBF, 2007. WING – Materials Innovations for Industry and Society, Available: http://www.bmbf.de/en/3780.php (Accessed 13.3.2012).
- Federal Ministry of Education and Research BMBF, 2009. Forschung für nachhaltige Entwicklungen: Rahmenprogramm des BMBF, Bundesministerium für Bildung und Forschung (BMBF) Referat 721 – Grundsatzfragen Kultur, Nachhaltigkeit, Umweltrecht, Berlin, Available at: http://www.ptj.de/lw_resource/datapool/_items/item_1578/forschung_nachhaltige_entwicklungen.pdf (Accessed: 9.2.2012).
- Federal Ministry of Education and Research (BMBF), 2012. Internationale Partnerschaften für nachhaltige Klimaschutz- und Umwelttechnologien und -dienstleistungen (CLIENT), Available http://www.fona.de/de/9862 (Accessed 24.3.2012).
- Ministry of Employment and the Economy, Finnish Geological Survey, 2010. Finland's Minerals Strategy. Available at: http://www.mineraalistrategia.fi/ (Accessed 7.2.2012).

- The Finnish Funding Agency for Technology and Innovation – TEKES, Terms and Conditions, TEKES - Strategic Centres for Science, Technology and Innovation Available: http://www.tekes.fi/en/community/Strategic0Centres0for0Science_0Technology0and0Innovation/360/Strategic0Centres0for0Science_0Technology0and0Innovation/1296 (Accessed 14.3.2012).
- The Finnish Funding Agency for Technology and Innovation – TEKES, Functional materials – Projects, Available: http://www.tekes.fi/programmes/Materiaalit/Projects (Accessed 13.3.2012).
- The Finnish Funding Agency for Technology and Innovation – TEKES, Functional Materials: Application driven materials R&D Tekes programme 2007-2013, Available: http://www.tekes.fi/fi/gateway/PTARGS_0_201_403_994_2095_43/http%3B/tekes-ali1%3B7087/publishedcontent/publish/programmes/materiaalit/documents/uutisia/fmesitepainoon_pdf.pdf (Accsessed 13.3.2012).
- French Environment and Energy Management Agency, About ADEME –Strategic Directions, Available at: http://www2.ademe.fr/servlet/KBaseShow?sort=-1&cid=96&m=3&catid=17550 (Accessed 13.3.2012).
- The G8 Research Councils Initiative on Multilateral Research Funding, Second Call for Proposals from an initiative between Research Councils from Canada, France, Germany, Japan, Russia, the UK, and the USA, Available at: http://www.jsps.go.jp/j-bottom/g8-initiative.html (Accsessed 24.2.2012).
- Grushkin, D., 2011. Alaska's Billion Dollar Mountain, Business Week, 27.10.2011, Available. http://www.businessweek.com/magazine/alaskas-billion-dollar-mountain-10272011.html (Accessed 15.2.2012).
- Gschneider, K.A., Jr., 2011. Rare Earth Metals: Supply, Demand, Recycling, and Substitutions, a presentation for The Council for Chemical Research, Dearborn, MI, May 3rd 2011.
- Gscheinder, K.A., The Rare Earth Crisis – The Lack of Intellectual Infrastructure, The Ames National Laboratory, Available at: https://www.ameslab.gov/files/RE_Crisis_Intell_Infrastruc_12.9.10.pdf (Accessed 8.2.2012).
- The Government of Netherlands, Dutch Government Policy Document on Raw Materials, Available at: http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/mss-netherlands_en.pdf (Accessed 12.3.2012).
- The Government of Netherlands, Environment – Resource Efficiency, Available at: http://www.government.nl/issues/environment/resource-efficiency and The Ministry of Infrastructure and the Environment, Topics – The Environment – International Policy Priorities, Available: http://english.verkeerenwaterstaat.nl/english/topics/the-environment/international_policy_priorities/#alinea2 (Accesses 12.3.2012).
- Grasso, V.B., 2011. Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress, Congressional Research Service Report for Congress, R41744.
- Hagelüken, C. 2012. Recycling the Platinum Group Metals: A European Perspective, PGM Review, Vol. 56, No.1, pp. 29-35.

- Helmholtz Zentrum Dresden-Rossendorf – Press Release, June 14th 2011, Available at: https://www.hzdr.de/db/Cms?pOid=33647&pNid=473.
- Hetherington, L., Bloodworth, A.W., Industrial minerals production in Europe – current situation and future trends, British Geological Survey, Available: http://nora.nerc.ac.uk/6092/1/Industrial_minerals_in_EU.pdf, (Accessed 14.2.2012).
- Hono, K., Research Trends on Rare Earth and Critical Elements in Japan, Available: http://energy.gov/sites/prod/files/Session_A7_Hono_NIMS.pdf (Accessed 13.3.2012).
- House of Commons, Science and Technology Committee, 2011. Strategically important metals, Fifth Report of Sessions 2010-12, Volume I, HC 726, Available at: http://www.publications.parliament.uk/pa/cm201012/cmselect/cmsctech/726/726.pdf (Accessed 22.2.2012).
- Humphreys, M., 2011. Rare Earth Elements: The Global Supply Chain, Congressional Research Service Report for Congress, R41347.
- Imthurn, G.P., 2009. Silicon-on-Sapphire, a replacement for gallium arsenide?, 2009 IEEE International SOI Conference, 5-8 Oct. 2009, Available: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5318759 (Accessed 17.3.2012).
- The Indium Corporation, Available: http://www.indium.com/ (Accessed 14.2.2012).
- The Institute of Nanotechnology, 2011. Replacing Rare Earths With Silicon Chips, Available: http://www.nano.org.uk/news/1296/ (Accessed 18.3.2012).
- International Antimony Association, Available: http://www.antimony.be/ (Accessed on 12.3.2012).
- International Copper Association Ltd. Copper Presents an Effective Alternative to Rare Earth Magnets in Electric Vehicles, Available: http://copperalliance.org/wordpress/wp-content/uploads/downloads/2012/02/us_12apr_11.pdf (Accessed 19.3.2012).
- International PGM Association, Available: http://www.ipa-news.com/en/ (Accessed 21.2.2012).
- Int. Tungsten Industry Association, Available: http://www.itia.info/ (Accessed 19.2.2012).
- Japan Society for the Promotion of Sciences, The G8 Research Councils Initiative on Multilateral Research Funding, Available at: http://www.jsps.go.jp/j-bottom/g8-initiative.html (Accessed 13.3.2012).
- Kishi, T., 2011. Overview of Japanese Research Activity on Critical Raw Materials – Elemental Strategy Project, Presentation at Japan-EU Workshop, Nov. 21st 2011, Available at: http://www.jst.go.jp/sicp/ws2011_eu/presentation/presentation_01.pdf.
- Kojima, A., 2011. Japan proposes an "Elements strategy", JapanEchoWeb, Editor's Blog, Available at: http://www.japanechoweb.jp/editors-blog/jewb030 (Accessed 20.2.2012).
- Korea Resources Corporation Act (English translation) Act No. 9182, Dec. 26, 2008, Available at: http://eng.kores.or.kr:8080/gpms/eng/gpms/resources/down/eng_law1.pdf.
- Korea Resources Corporation – About KORES – Vision, Available at: http://eng.kores.or.kr:8080/gpms/user.tdf?a=common.HtmlApp&c=2001&page=/english/cor/cor_02.html&mc=ENG_COR_020 (Accessed 7.2.2011).

- Korea Resources Corporation – About KORES – Vision, Available at: http://eng.kores.or.kr:8080/gpms/user.tdf?a=common.HtmlApp&c=2001&page=/english/cor/cor_02.html&mc=ENG_COR_020 (Accessed 7.2.2011); Korea Resources Corporation Act (English translation) Act No. 9182, Dec. 26, 2008, Available at: http://eng.kores.or.kr:8080/gpms/eng/gpms/resources/down/eng_law1.pdf.
- Korea Mineral Resources Information Service – Mining Information – Policy – Long Term Policy, Available at: http://www.kores.net/englishKomis/mining/e_policy_long.jsp (Accessed 7.2.2011).
- Krohns, S., Lunkenheimer, P., Meissner, S., Reller, A., Gleich, B., Rathgeber, A., Gaugler, T., Buhl, H. U., Sinclair D. C., Loidl A., 2011. The route to resource-efficient novel materials, Nature Materials 10, 899, Available: http://www.nature.com/nmat/journal/v10/n12/full/nmat3180.html.
- Kwon, O.Y., 2010- South Korea's approach to energy and resource security, Australian Strategic Policy Institute, Strategic Policy Forums: Australian and Asian perspectives on resources diplomacy. Available at: http://www.aspi.org.au/research/spf_article.aspx?aid=84 (Accsessed 7.2.2012).
- Lewis R., 2009. Brown Chemists Create More Efficient Palladium Fuel Cell Catalysts, Brown University News and Events, Available: http://news.brown.edu/pressreleases/2009/03/palladium (Accsessed 22.5.2012).
- Linde, D, van de, 2012, Recycling Cobalt, The Gold Report on Co recycling, Available: http://www.theaureport.com/pub/na/10044 (Accessed on 10.3.2012).
- Lupi, C., Pasquali, M., Dell'era, A., 2005. Nickel and cobalt recycling from lithium-ion batteries by electrochemical processes", Waste Management, Vol. 25, No. 2, pp. 215-220. Available: http://www.ncbi.nlm.nih.gov/pubmed/15737721 (Accessed on 10.3.2012).
- Lynas Corporation Ltd., Lynas Corporate Brochure: Online in 2012, Delivering Rare Earths Globally, Available: http://www.lynascorp.com/content/upload/files/LYNAS_CORPORATE_BROCHURE.pdf (Accessed 24.3.1012).
- McIninch, T.P., 1996. The Oxcart Story, Studies in Intelligence, Vol. 15, Issue 1.
- MetalPages, 2012. Gallium a 'sad' market, nowhere to turn, Available: http://www.metal-pages.com/news/story/60256/gallium-a-sad-market-nowhere-to-turn/ (Accessed on 10.2.2012).
- Miles, T., 22.3.2011. China rare earth prices explode as export volumes collapse, Reuters News Service, Available at: http://www.reuters.com/article/2011/03/22/us-china-rareearth-idUSTRE72L10I20110322 (accessed 9.2.2012).
- Milosavljevic, M. Shao, G., Bibic, N., McKinty, N., Jaynes, C. Homewood, K.P., 2001. Amorphous-iron disilicide: A promising semiconductor, Applied Physics Letters, Vol. 79, No. 10.
- Ministry of Economy, Trade and Industry, 2009. http://www.meti.go.jp/english/press/data/20090728_01.html.
- Ministry of Foreign Affairs – Development Cooperation – Millennium Development Goals (MDGs) – Dutch Aim for MDG 7 - Dutch Government Policy Document on Raw Materials http://www.minbuza.nl/en/key-topics/development-cooperation/dutch-development-policy/millennium-development-goals-mdgs/dutch-aim-for-mdg-7/dutch-government-policy-document-on-raw-materials.html.

- Ministry of Industry, 2011. Création du Comité pour les métaux stratégiques (COMES), Available: http://www.economie.gouv.fr/economie/creation-comite-pour-metaux-strategiques-comes; Decree no.2011-100 of January 24th 2011,Creation of the Committee for Strategic Metals, Décret n° 2011-100 du 24 janvier 2011 portant création du comité pour les métaux stratégiques (COMES),NOR: INDI1032803D, Available at: http://www.legifrance.gouv.fr/affichTexte.do;jsessionid=931360064F1082ABE36F9EBB721C365F.tpdjo02v_2?cidTexte=JORFTEXT000023474859&categorieLien=id# (Accessed 22.2.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Antimony, Available: http://www.mmta.co.uk/metals/Sb/ (Accessed on 12.3.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Beryllium, Available: http://www.mmta.co.uk/metals/Be/ (Accessed on 12.3.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Gallium, Available: http://www.mmta.co.uk/metals/Ga/ (Accessed on 12.2.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Germanium, Available: http://www.mmta.co.uk/metals/Ge/ (Accessed on 12.2.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Indium, Available: http://www.mmta.co.uk/metals/In/ (Accessed on 13.3.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Magnesium, Available: http://www.mmta.co.uk/metals/Mg/ (Accessed 16.2.2012).
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Tungsten, Available: http://www.mmta.co.uk/metals/W/ (Accessed 21.2.2012)
- Minor Metals Trade Association, Minor Metals in the Periodic Table: Tantalum, Available: http://www.mmta.co.uk/metals/Ta/ (Accessed 18.3.2012).
- Missile Defense Agency (US) Technology Programme, Available: http://www.mdatechnology.net/techprofile.aspx?id=594,(Accessed 10 March 2012).
- Molycorp, 2012. Molycorp To Launch Sequential Start-Up of New, State-of-the-Art Rare Earth Manufacturing Facility This Week, Press release 21.2.2012, Available: http://www.molycorp.com/molycorp-to-launch-sequential-start-up-of-new-state-of-the-art-rare-earth-manufacturing-facility-this-week/ (Accessed 26.3.2012).
- Moss, R.L., Tzimas, E., Kara, H., Willis, P., Kooroshy, J., 2011. Critical Metals in Strategic Energy Technologies: Assessing Rare Metals as Supply-Chain Bottlenecks in Low-Carbon Energy Technologies, Joint Research Centre - Institute for Energy and Transport.
- National Research Council of the National Academies, 2007. Minerals, Critical Minerals and the US Economy, Available: http://www.nma.org/pdf/101606_nrc_study.pdf (Accessed 9.2.2012).
- National Research Council of the National Academies, 2008. Managing Materials for a Twenty-first Century Military, Available: http://www.nap.edu/openbook.php?record_id=12028&page=174 (Accessed 10 March 2012).
- Niemeläinen, E., Tuusjärvi, M., Niiranen, T., Vuori, S., and Kananoja, T., 2010. Katsaus mineraalistrategioihin ja –politiikkoihin maailmalla [A review of minerals strategies and policies around the world], Geological Survey of Finland, Archive report M10/2010/27.

- New Energy and Industrial Technology Development Organisation (NEDO), Japan, Rare Earth Metal Substitute Materials Development Project, Available: http://www.nedo.go.jp/english/activities_nedoprojects_nano.html (Accessed 18.3.2012).
- NIMS, Settlement and Workforce Report, Available at: http://www.nims.go.jp/eng/nims/settlement_workforce.html (Accessed, 8.2.2011).
- PGM Review, Available: http://www.platinummetalsreview.com/ (Accessed 21.2.2012).
- The President's Materials Policy Commission, 1952. Resources for freedom: a Report to the President by the President's Materials Policy Commission.
- Project Agency Jülich, Materialien für eine ressourceneffiziente Industrie und Gesellschaft – MatRessource, Available: http://www.ptj.de/matressource (Accessed 13.3.2012).
- Project Agency Jülich, KMU-innovativ: Ressourcen- und Energieeffizienz, Available: http://www.ptj.de/kmu_innovativ (Accessed 13.3.2012).
- Reppert-Bismark, J.von, 2011. U.S., EU, Japan to discuss rare earths in October, Reuters News, Available at: http://www.reuters.com/article/2011/09/08/us-eu-rareearths-idUSTRE7876M320110908, (Accessed 6.2.2011).
- Republic of France, Prime Minister's Office National Sustainable Development Strategy 2010-2013: Towards a green and fair economy.
- Reuters, 2012. Toyota finds way to avoid using rare earth: report, January 23rd 2012.Available at: http://www.reuters.com/article/2012/01/23/us-toyota-rare-earth-idUSTRE80M0JK20120123 (accessed 26.1.2012).
- Rich, E.R., 1996. Skunk Works: A Personal Memoir of My Years of Lockheed, Back Bay Books.
- RWTH – Aachen - University News, "Siemens Research Center" Starting at RWTH, Available: http://www.rwthaachen.de/cms/main/root/Die_RWTH/Aktuell/Pressemitteilungen/~xgn/Siemens_Forschungsbereich_an_der_RWTH_Aachen_s/?lidx=1 .
- Sanford, J. 2011. Japan announces new rare earth policy, RareMetalBlog, Available: http://www.raremetalblog.com/2011/02/japanese-government-announces-new-rare-earth-policy-.html, accessed on 24 February 2012.
- Shand, M.A., 2006. The Chemistry And Technology of Magnesia, John Wiley & Sons, New York.
- Shen, K. K., 2001. Zinc Borates: 30 Years of Successful Development as Multifunctional Fire Retardants, Fire and Polymers, ACS.
- Sherman, L.M., 1994. Antimony oxide price spiral draws attention to alternatives, Plastics Technology, Available: http://www.thefreelibrary.com/Antimony+oxide+price+spiral+draws+attention+to+alternatives.-a016111319 (Accessed 15.3.2012).
- Siemens - Innovation – Recycling Electric Motors as Source of Raw Materials, Available: http://www.siemens.com/innovation/en/news/2011/e_inno_1137_2.htm (Accessed 13.3.2012).
- Siemens Center of Knowledge Interchange RWTH Aachen, Available: http://www.cki.rwth-aachen.de/ (Accessed 13.3.2012).

- Sillekens, W.H., Agnew, S.R., Neelammeggham, N.R., Mathaudhu, S.N. (eds.), 2011. Magnesium Technology, The Minerals, Metals & Materials Society, John Wiley and Sons.
- Strand, I., Ramada, P., Canton, E., 2011. Public procurement in Europe: Cost and effectiveness, Available: http://ec.europa.eu/internal_market/publicprocurement/docs/modernising_rules/cost-effectiveness_en.pdf (Accessed 14.3.2012).
- Stull, G., 2011. Raw materials: EU policy to secure access and improve use-efficiency, Library of the European parliament, Library Briefing 30/03/3011 Available: http://www.europarl.europa.eu/RegData/bibliotheque/briefing/2011/110150/LDM_BRI(2011)110150_REV1_EN.pdf (Accessed 26.5.2012).
- Suzuki, A., Transparent conductive zinc oxide film: New Light for Indium-free Solar Cells, ULVAC Group, ULVAC Corporate Center, Available: http://www.ulvac-uc.co.jp/pdf/prm_arc/056e/No56E-04.pdf (Accessed 17.3.2012).
- Tantalum-Niobium Study Centre, Available: http://tanb.org/ (Accessed 7.2.2012).
- Tantalum-Niobium International Study Centre, Critical raw materials for the EU - Report of the Ad-hoc Working Group on defining critical raw materials - response to the EU raw materials criticality report, Available: http://ec.europa.eu/enterprise/policies/raw-materials/files/pc-contributions/org-050-tantalum-niobium-international-study-center-tic_en.pdf (Accessed 7.2.2012).
- Tiess, G., 2011. General and International Mineral Policy – Focus: Europe, Springer Verlag, Wien - New York.
- Tertiary minerals Plc., Projects, Sweden, Storuman. Available: http://www.tertiaryminerals.com/storuman.html (Accessed 15.3.2012).
- Tomioka, T, Monozukuri, N., 2011. Iron Nitride Powder Produced as Substitute for Rare Metal, Tech-On, Available: http://techon.nikkeibp.co.jp/english/NEWS_EN/20110307/190128/ (Accessed 18.3.2012).
- Tse, P.-K., 2011. China's Rare Earth Industry, Open–File Report 2011–1042, USGS, Available: http://files.eesi.org/usgs_china_030011.pdf, (Accessed 10.2.2012).
- UK Stakeholder Forum, 2010. A Guide to Substitution, August 2010, Available: http://archive.defra.gov.uk/environment/quality/chemicals/csf/documents/forum-guide-substitution.pdf.
- US Agency for toxic substances and disease registry, Toxicological profile for Beryllium, Available: http://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=185&tid=33 (Accessed 15.3.2012).
- USGS, Antimony Statistics and Information, Mineral Commodity Summary: Antimony 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2012-antim.pdf (Accessed 12.3.2012).
- USGS, Beryllium Statistics and Information, Mineral Commodity Summary: Beryllium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/mcs-2012-beryl.pdf (Accessed 15.3.2012).
- USGS, Cobalt Statistics and Information, Mineral Commodity Summary: Cobalt 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2012-cobal.pdf, (Accessed 10.3.2012).

- USGS, Fluorspar Statistics and Information, Available: http://minerals.usgs.gov/minerals/pubs/commodity/fluorspar/ (Accessed 15.2.2012).
- USGS, Statistics and Information, Mineral Commodity Summary: Gallium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/gallium/mcs-2012-galli.pdf (Accessed 12.2.2012).
- USGS, Statistics and Information, Germanium, Available: http://minerals.usgs.gov/minerals/pubs/commodity/germanium/ (Accessed 12.2.2012).
- USGS, Statistics and Information, Graphite, Available: http://minerals.usgs.gov/minerals/pubs/commodity/graphite/ (Accessed 12.2.2012).
- USGS, Statistics and Information, Mineral Commodity Summary: Indium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/indium/mcs-2012-indiu.pdf (Accessed 13.2.2012)
- USGS, Statistics and Information, Mineral Commodity Summary: Magnesium 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2012-mgcom.pdf (Accessed 16.2.2012).
- USGS, Statistics and Information, Niobium (Columbium) and Tantalum, Available: http://minerals.usgs.gov/minerals/pubs/commodity/niobium/ (Accessed 6.2.2012).
- USGS, Statistics and Information, Platinum-Group Metals, Available: http://minerals.usgs.gov/minerals/pubs/commodity/platinum/ (Accessed 21.2.2012).
- USGS, Statistics and Information, Mineral Commodity Summary: Rare Earths 2012, Available: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/mcs-2012-raree.pdf (Accessed 19.2.2012).
- USGS, Statistics and Information, Tungsten, Available: http://minerals.usgs.gov/minerals/pubs/commodity/tungsten/ (Accessed 18.2.2012); British Geological Survey, Minerals UK, Available: http://www.bgs.ac.uk/mineralsuk/home.html (Accessed 18.2.2012).
- U.S. International Trade Commission, 2005. Magnesium From China and Russia, Investigations Nos. 731-TA-1071 and 1072, United States International Trade Commission Publication 3765, Washington, DC.
- Veitch, D.B., 2007. A Copper-Nickel-Silicon-Chromium Alloy for Mold Tooling, MoldMaking Technology, Available: http://www.moldmakingtechnology.com/articles/a-copper-nickel-silicon-chromium-alloy-for-mold-tooling (Accesses 23.5.2012).
- Vivet, S., Joubert, J.-M., Knosp, B., Percheron-Guégan, A., 2003. Effects of cobalt replacement by nickel, manganese, aluminium and iron on the crystallographic and electrochemical properties of AB -type alloys, Journal of Alloys and Compounds. 356–357 pp. 779–783.
- Wang, W.F. Qin, Y. Liu, X.H. Zhao, J.L., Wang, J.Y. Wu, G.D. Liu, J.T., 2011. Distribution, occurrence and enrichment causes of gallium in coals from the Jungar Coalfield, Inner Mongolia", SCIENCE CHINA Earth Sciences, Vol. 54, No.7, pp. 1053-1068, Available http://www.springerlink.com/content/y5t0r55023522136/fulltext.pdf (Accessed 17.3.2012).

- WRAP - Working together for a world without waste, 2011. Towards Resource Efficiency: WRAP Business Plan: 2008-2011, A Report on Impact, Available: http://www.wrap.org.uk/downloads/WRAP_Business_Plan_Review.73273d02.11459.pdf
- WRAP - Working together for a world without waste, 2011. Business Plan: 2011-2015, Available at: http://www.wrap.org.uk/downloads/Bus_Plan_2011_Final_WEB_22.13e2f880.10869.pdf (Accessed 9.2.2012).
- Xanthopoulou G., Vekinis G., 1998. Investigation of Catalytic Oxidation of CO over a Cu-Cr-oxide Catalyst made by Self-Propagating High-Temperature Synthesis, Applied Catalysis B: Environmental, Vol. 19, pp. 37-44.

ANNEX 1: LIST OF CRITICAL RAW MATERIALS

Critical Raw Materials defined by the *Ad-hoc* Working Group on defining critical raw materials (op.cit.):

1. Antimony
2. Beryllium
3. Cobalt
4. Fluorspar
5. Gallium
6. Germanium
7. Graphite
8. Indium
9. Magnesium
10. Niobium

11.-16. PGMs (Platinum Group Metals), comprising platinum, palladium, iridium, rhodium, ruthenium and osmium

17.-33. Rare Earth Elements including yttrium, scandium, and the so-called lanthanides: lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium

11. Tantalum

12. Tungsten

Additional raw materials Considered in the WTO Dispute filed by the United States of America, Mexico and the European Union against China:

13. Bauxite,

14. Coke,

15. Fluorspar

16. Magnesium

17. Manganese,

18. Silicon carbide / silicon metal,

19. Yellow Phosphorus and

20. Zinc.

ANNEX 2: INTERVIEW QUESTIONS AND INTERVIEWEES

Interview template

1. The European Commission has launched the Raw Materials' initiative which has identified a group of 14 critical materials. Are you aware of the initiative and of similar national initiatives?

2. Your organisation is involved in the development of future technologies.
   a. For which technologies are you dependent on critical materials? Will specific applications be affected more than others?
   b. Which resources are the most critical to your organisation? For which materials and applications do you see substitution as the only option?
   c. What is the time frame for these materials?

3. Does the limitation of certain critical materials influence your innovation strategy?
   a. To what degree?
   b. And in which way mainly?

4. Are you already involved in initiatives / projects that target the substitution of critical materials?
   a. Which substitutes exist already for your research / business area of interest?
   b. What is the technology readiness level of those substitutes? (R&D stage, prototype stage, market readiness…)?

5. If you did not start any measures, what would be a trigger for you to scout for or develop alternative technologies / substitutes for new product developments?
   a. Are those targeting new technologies (e.g. conductive polymers replacing indium) or one element replacing the other (Pd for Pt)?
   b. How are they funded?
   c. Are those collaborative projects /initiatives?

6. Has there already been a strategy for the substitution of critical materials implemented?
   a. If yes, what is the strategy? Or else, is it in the planning stage and when will it become effective?
   b. From your perspective, which strategies for critical materials substitution are the most relevant? (technical / functional substitution, efficiency improvement or recycling)

7. What should new funding programmes entail to support the development of substitutes for critical raw materials with the goal of commercialising these new discoveries?

8. Do you think that there are technologies that have the potential to contribute significantly (more than others) to finding substitutes for critical raw materials?

9. Which application areas should primarily be targeted to find substitutes in the near term and midterm?

10. What initiatives, such as clusters, research programmes, funding programmes, are you aware of that focus on the substitution of critical raw materials?
    a. In addition to already existing programmes and initiatives such as innovation clusters, funding programmes, etc. would you welcome any additional initiatives?
    b. Rather at the national level, EU level or international level?
    c. Do you know of any international initiatives that already exist especially in JP and the US?
    d. Are you aware of initiatives that have already been successfully implemented elsewhere and might be beneficial if they were adopted?

11. What goals should be aimed at with funding programmes? Where should be the focus (basic / applied research, prototype development, industrial demonstration)?

12. What would be successful projects and how can success be monitored or even measured?
    a. What other policies/measures / policy targets could strengthen development / availability of substitutions in the EU? (e. g. R&D output targets, cost mechanisms, tax incentives)?

13. What sources of information are relevant to obtain updates / information on critical raw materials in terms of availability, pricing, substitution, recycling etc.?
    a. Which information sources do you consult?

List of interviewees

Patrice Christmann, PhD, MBA
Deputy Director, Corporate Strategy Directorate
Manager
BRGM mineral resources strategy

Derk Bol
Program Manager
Materials innovation institute (M2i)

Maria Pilar Aguar Fernandez
G3. Deputy Head of Unit
DG Research & Innovation
European Commission

Thomas Geelhaar, Dr.
Chief Technology Officer Chemicals
Senior Vice President
Merck KGaA

George Hadjipanayis, Prof, PhD
Professor and Chair
Department of Physics and Astronomy
University of Delaware

Christian Hagelüken, Dr
Director EU Government Affairs
Umicore

Liane Horst
Bundesministerium für Bildung und Forschung (BMBF)
Neue Werkstoffe, Nanotechnologie

Alois Loidl, Prof
Institute for Materials Research Management (IMRM)
Universität Augsburg

Nick Morley
Oakdene Hollins Ltd.

Dimitrios Niarchos, Dr
Chief Researcher and Head of the Magnetic Materials Laboratory
Institute of Materials Science
NCSR Demokritos

Osamu Odawara, Prof.
Interdisciplinary Graduate School of Science and Engineering
Tokyo Institute of Technology

Ari E. Oikarinen
Manager, Supplier Capability & Landscape
Merkets, Mechanics Sourcing
Nokia Corporation

Åsa Persson
Chief Mine Inspector
Mining Inspectorate of Sweden

Shahin Rahimifard, PhD, CEng, FIMechE, FHEA
Professor of Sustainable Engineering
Head of Competitive Sustainable Manufacturing Research Group
Director of Centre for Sustainable Manufacturing And Reuse/Recycling Technologies (SMART)
Wolfson School of Mechanical and Manufacturing Engineering

Michael Stelter, Prof
Direktor of the Institut für Nichteisen-Metallurgie und Reinststoffe
TU Bergakademie Freiberg
Prorektor of Research and Partner
Helmholtz-Institut Freiberg

Galina Xanthopoulou, PhD, Dr
Senior Researcher
Institute of Materials Science
NCSR Demokritos.

ANNEX 3: SUMMARY OF POLICIES IN THE EU AND MEMBER STATES DIRECTED TOWARD SUBSTITUTION OF CRM

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
European Union				
Raw Materials Roadmap	European Commission	EU	*Policy objectives/milestones by 2020 (directly relevant to CRM):* [223] • Citizen and decision makers have incentives to choose most resource efficient products • Market and policy incentives reward business investments in efficiency • Waste is managed as a resource. Waste generated per capita is in absolute decline. • Scientific breakthroughs and sustained innovation efforts have dramatically improved how we understand, manage, reduce the use, reuse, recycle, substitute and safeguard and value resources. *Means:* • Enhancing dialogues • Investing transition • Developing indicators	
EU-FP7 Specific programme on Nanosciences, nanotechnologies, Materials and new Production Technologies (NMP)	European Commission	EU	*Goals include* [224] • Development of catalysts based on nanotechnologies • Technologies for recycling REE and other key metals • Replacing REE in key technical applications	Calls for Proposals still open
EU-FP7 NMP 2012.4.1-3: Development of advanced magnetic materials without, or with reduced use of critical raw materials	European Commission	EU	*Goals include:* [225] • Development of catalysts based on nanotechnologies • Technologies for recycling REE and other key metals • Replacing REE in key technical applications	Calls for Proposals still open

[223] EC, 2011. Roadmap to a Resource Efficient Europe, COM(2011) 571 final.
[224] EC, FP7,Cooperation, Theme 4: Nanosciences, nanotechnologies, Materials and new Production Technologies – NMP, Work Programme 2012, C(2011)5068.
[225] EC, FP7,Cooperation, Theme 4: Nanosciences, nanotechnologies, Materials and new Production Technologies – NMP, Work Programme 2012, C(2011)5068.

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
EU FP7 NMP.2012.4.1-4: Substitution of critical raw materials: networking, specifying R&D needs and priorities; including substitutions for CRM (PGM, REE), NMP-2.2-4	European Commission	EU	*Goals include:*[226] • Substitution of 14 CRM from Raw Materials Initiative • Create competence cluster in CRM substitution area • Draft Roadmap with Activities, actors, timing, selection and networking of existing national activities/centres	Calls for Proposals still open
European Technology Platform on Sustainable Mineral Resources (ETP-SMR	The Geological Surveys of Europe (EuroGeoSurveys), European Commission	EU	*Goals:* [227] To modernise and reshape European extraction and processing sector of energy and non-energy minerals, including: • Providing RTD strategy and maintaining a research base • Focusing public and private investment • Contributing to resource efficiency, supply and reduction of materials use	Major projects Launched under FP7 (undisclosed)[228]
European Innovation Partnership on Raw Materials (EIP)	EC, DG-ENTR	EU	The partnership aims to bring together Member States and other stakeholders (companies, NGOs, researchers etc) at EU, national and regional level to tackle the big challenges by the following means: • Developing joint strategies • Pulling together capital and human resources • Ensuring the implementation and dissemination of innovative solutions Goals by 2020*:* • 10 pilot plants • Secured raw material supplies • International cooperation, substitution of critical materials • Improve infrastructure and know how basis on raw materials[229]	Starting 2012

[226] EC, FP7,Cooperation, Theme 4: Nanosciences, nanotechnologies, Materials and new Production Technologies – NMP, Work Programme 2012, C(2011)5068.
[227] ETP-SMR - Who are We? – History, Available: http://www.etpsmr.org/index.php?option=com_content&view=article&id=6&Itemid=4 (Accessed 13.3.2012).
[228] ETP-SMR - Who are We? – History, Available: http://www.etpsmr.org/index.php?option=com_content&view=article&id=6&Itemid=4 (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
ERA-MIN (Nov 2011)	Coordinated by: CNRS 11 partners from 9 countries: France (CNRS), Germany (BMBF, Jülich), Sweden (VINNOVA, SGU), The Netherlands (M2i), Finland (TEKES), Spain (CDTI), Portugal (FCT), Poland (NCBiR), and Hungary (MBFH). Number of partners is set to increase over the project's lifetime, with a view to establishing a European network	EU	ERA-NET on non-energy mineral resources, also known as 'strategic' or 'critical' metals. New consortium was officially launched on 8 November 2011 in Brussels and will form the basis of a major European network for the mineral raw materials community called ENERC (European non-energy mineral raw materials research community) *Aims:* • Step up coordination of R&D programmes in the field of industrial production and supply of raw materials • Benchmark national programmes and establish joint R&D programme • Collaborate with industry especially with European platform on sustainable mineral resources, also road mapping and networking activities[230]	

[229] EC, 2012, Making raw materials available for Europe's future wellbeing: Proposal for a European innovation partnership on raw materials, COM(2012) 82 final; EC DG-ENTR, European Innovation Partnership on raw materials, Available: http://ec.europa.eu/enterprise/policies/raw-materials/innovation-partnership/index_en.htm (Accessed, 12.3.2012).

[230] Centre national de la recherche scientifique, November 8th 2011, CNRS to coordinate European ERA-MIN project on non-energy mineral resources, Available: http://www2.cnrs.fr/en/1930.htm; ERA-MIN - Project introduction, Available: http://www.labo21.dsi.cnrs.fr/ (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
Member States				
Finland's Mineral Strategy	Ministry of Employment and the Economy, Finnish Geological Survey	FI	*Vision:* By 2050 Finland is a world leader in sustainable use of mineral resources and the minerals sector is one of the pillars of the economy *Action proposals:* • Creating a strong and coherent minerals policy • Securing the supply of raw materials • Reducing environmental impact of minerals sector while increasing productivity • Strengthening R&D capabilities and expertise[231]	
Functional Materials Programme	Finnish Funding Agency for Technology and Innovation - TEKES	FI	*Goals include:* • Develop new applications/products through materials technology, and to • Raise competitiveness of Finnish industry[232]	Funded projects include[233]: • New electrode materials for Lithium Ion batteries • Development of the recycling process for alkaline batteries
German Government's raw materials strategy	Federal government/ BMWi	DE	*Aims:* [234] • Reducing trade barriers and distortion of competition • Diversifying supply • Raising materials efficiency • Developing conditions and technologies for recycling • Bilateral partnerships with selected countries • Research into substitution of existing materials	

[231] Finland's Minerals Strategy, 2010, Ministry of Employment and the Economy, Finnish Geological Survey. Available at: http://www.mineraalistrategia.fi/ (Accessed 7.2.2012).

[232] TEKES, Functional Materials: Application driven materials R&D Tekes programme 2007-2013, Available: http://www.tekes.fi/fi/gateway/PTARGS_0_201_403_994_2095_43/http%3B/tekesali1%3B7087/publishedcontent/publish/programmes/materiaalit/documents/uutisia/fmesitepainoon_pdf (Accessed 13.3.2012).

[233] TEKES, Functional materials – Projects, Available: http://www.tekes.fi/programmes/Materiaalit/Projects (Accessed 13.3.2012).

[234] Federal Ministry of Economics and Technology (BMWi) 2010. The German Government's raw materials strategy- Safeguarding a sustainable supply of non-energy mineral resources for Germany, Federal Ministry of Economics and Technology (BMWi), Public relations division, Berlin.

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
			• Creating framework conditions for extraction • Integrating with European policy *Instruments:* • RDI funding instruments • Joint approach through trade, economic, foreign and development policy	
r^2 – Innovative Technologies for Resource Efficiency – Resource-intensive production processes	BMBF	DE	*Aims:* • Intelligent and efficient use of raw materials • Process improvement • Over 100 single projects will be bundled in 22 networks and funded with about 36,5 MEUR[235]	• Efficiency increase for chlorine production; catalysis • Reduction or substitution of Ruthenium (small amounts)[236]
KMU-innovativ: Ressourcen- und Energieeffizienz	BMBF, Project agency Jülich	DE	Additional support to SMEs participating in r^2 [237]	
r^3 – Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals	Federal government/ BMBF, Project agency Jülich	DE	*General aims:* • Collaborative research between academia and industry • Cooperation with developing countries • Cutting edge research in SMEs *Specific aims* • Increase efficiency of use of raw materials • Recycling technologies • Substitution of CRM Aims to link to ERA-Net EcoInnovera and other EU related technology platforms[238]	First projects will be granted funding spring 2012 Projects need to demonstrate that they can develop application oriented solutions, or show ways to transfer the results to products or services.
Helmholtz Institute Freiberg for Resource Technology	Federal Government/ BMBF, Helmholz Zentrum Dresden-Rossberg and TU Bergakademie Freiberg	DE	*Aims:* Examines the entire value-added chain of mineral raw materials from exploration to recycling.[239]	

[235] BMBF, r^2 – Innovative Technologies for Resource Efficiency – Resource-intensive production processes – Joint Projects Available: http://www.r-zwei-innovation.de/en/510.php (Accessed 12.3.2012).
[236] BMBF, Ibid.
[237] Project Agency Jülich, KMU-innovativ: Ressourcen- und Energieeffizienz, Available: http://www.ptj.de/kmu_innovativ (Accessed 13.3.2012).
[238] BMBF, Innovative Technologies for Resource Efficiency – Strategic Metals and Minerals (r^3), Available: http://www.fona.de/en/9815 (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
Materials Innovations for Industry and Society WING	Federal Government/ BMBF, Project agency Jülich	DE	*Program level aims:* • Strengthening the companies' innovative capabilities • Consideration of society's needs • Using RDI for sustainable development *Project level aims:* • Developing new products and processes • Building industry-academia cooperation structure involving SMEs • Contributing to societal problems, especially aging • Linking RDI with education and training • Contribute to establishing the ERA through greater participation in FP7 • Building bilateral collaboration between countries such as China, Korea, and Israel *Topics include:* • Nanotechnology materials concepts • Resource-efficient materials • Electromagnetic functional materials[240]	
MatRessource (part of WING Framework Program)	BMBF, Project agency Jülich	DE	*Aims:* • Substitution and material efficiency, reduction of rare earths in magnets, phosphors • Substitution of critical metals in catalysts, recycling of nanomaterials • Reduction of dependency on strategic metals and increase in material yield • Improved catalysts and process optimisation, improved materials for corrosion protection[241]	Call ended in February 2012 Funding aimed for of application oriented RDI close to industry, especially innovative, risky industrial collaborative projects, including multidisciplinary collaboration of enterprises with Universities & institutes, covering whole value chain. High participation of SMEs in collaborative projects is sought after[242]

[239] Helmholtz Zentrum Dresden-Rossendorf – Press Release, June 14th 2011, available at: https://www.hzdr.de/db/Cms?pOid=33647&pNid=473; Federal Ministry of Education and Research BMBF, 9.9.2011, FONA Research on Sustainable Development – Resources and Sustainability – Innovative Technologies for Resource Efficiency – Helmholz Institute Freiberg for Resource Efficiency, Available at: http://www.fona.de/en/9813.

[240] BMBF, 2007, WING – Materials Innovations for Industry and Society, Available: http://www.bmbf.de/en/3780.php (Accessed 13.3.2012).

[241] Project Agency Jülich, Materialien für eine ressourceneffiziente Industrie und Gesellschaft – MatRessource, Available at: http://www.ptj.de/matressource (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
CLIENT – innovative environmental technologies	BMBF; Project Agency DLR	DE	*Aims include:* • Resource use: Resource efficiency, raw materials' substitution, recycling • Includes development of prototypes or pilot-like applications • Focus on cooperation with partners in Brazil, Russia, India, China, South Africa and Vietnam[243]	
Research programme for new materials	Bavarian ministry for Trade, Infrastructure, Transport and Technology, Project Agency Jülich	DE	*Aims:* New Materials in the following fields: • Metals, including light alloys, alloys for high temperature, pulverised metal alloys • Polymers including high-strength thermo-mechanical compounds, functional polymers • Ceramics • Nanomaterials and –coatings • Materials science and production technologies Program volume 50 MEUR per year for Bavarian institutes[244]	
Raw materials alliance (der Allianz zur Rohstoffsicherung, Rohstoffallianz)	Industry partners	DE	Alliance of 12 industrial players to secure raw materials supplies Partners include: Aurubis, BASF, Bayer, BMW, Chemetall, Daimler, Evonik Industries, Georgsmarienhütte Holding, Bosch, Stahl-Holding-Saar, Thyssen-Krupp und Wacker Chemie Basic investment 0,3 MEUR per partner[245]	

[242] Project Agency Jülich, Materialien für eine ressourceneffiziente Industrie und Gesellschaft – MatRessource, Available at: http://www.ptj.de/matressource (Accessed 13.3.2012).

[243] BMBF 2012 Internationale Partnerschaften für nachhaltige Klimaschutz- und Umwelttechnologien und -dienstleistungen (CLIENT), Available http://www.fona.de/de/9862 (Accessed 24.3.2012).

[244] Bavarian ministry for Trade, Infrastructure, Transport and Technology 2007., op.cit.

[245] Bundesverban de Deutshen Industrie, Presscenter – Pressemittelungen, Aufbau der Allianz zur Rohstoffsicherung beginnt, 20.1.2012, Available at: http://www.bdi.eu/Pressemitteilungen_Pressemitteilung_Allianz_zur_Rohstoffsicherung_30_01_2012.htm (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
Deutsche Rohstoff AG	Public company	DE	*Aims to* Secure CRM and REE supply	• Shareholding in an Australian goldmine started production in January 2011[246] • Wolfram Camp Mining ships first tungsten concentrate in March 2012[247] • Daughter spin off Seltenerden Storkwitz AG founded Nov. 2011 to develop "the only known REE deposit on Western Europe"[248] esp. Yittrium in an old Saxony mine[249]
Siemens Center of Knowledge Interchange at Nord-Rhein-Westfahlen Technical Institute (RWTH) Aachen	Siemens, RTWH Aachen	DE	*Goal for research:* • Improved recovery and recycling of rare earths • Long term, fundamental research; SFB from DFG was role model[250]	Start January 2012 for 4 years with 6 MEUR budget. At least 9 doctoral students are expected to graduate during the programme life time.[251]
MORE (MOtor REcycling); "Key Technologies for Electric Mobility" (STROM)	BMBF/ Siemens, Daimler, Umicore, Vacuumschmelze, U Erlangen, Clausthal U of Technology, Oeko-Institut Darmstadt, and Fraunhofer Institute for Systems and Innovation Research ISI	DE	Co-operative for recycling of permanent magnets with a rare earth metals content of 30 % -compatible motor design, as well as ecological efficiency analyses and models for material cycles; whole value chain[252]	

246 Deutsche Rohstoff AG, Divisions – Gold and Silver, Available: http://www.rohstoff.de/geschaftsbereiche/gold-silber/?lang=en (Accessed 13.3.2012).
247 Deutsche Rohstoff AG, 2012, Wolfram Camp Mining ships first concentrate, Available at: http://www.rohstoff.de/2012/03/06/deutsche-rohstoff-ag-wolfram-camp-mine-liefert-erstes-konzentrat/?lang=en (Accessed 13.3.2012).
248 Deutsche Rohstoff AG, Divisions – High-Tech Metals – Seltenerden Storkwitz AG, Available at: http://www.rohstoff.de/geschaftsbereiche/hightech-metalle-seltene-erden-zinn-wolfram/storkwitz/?lang=en (Accessed 13.3.2012).
249 Deutsche Rohstoff AG, Available at: http://www.rohstoff.de/unternehmen-rohstoffe-deutschland-rohstoff-deutsch/?lang=en (Accessed 13.3.2012).
250 Siemens Center of Knowledge Interchange RWTH Aachen, Available: http://www.cki.rwth-aachen.de/ (Accessed 13.3.2012).
251 RWTH – Aachen - University News, "Siemens Research Center" Starting at RWTH, Available: http://www.rwth-aachen.de/aw/main/english/Themes/news/list_of_news/2011/~bkjn/_Siemens_Research_Center_starting_at_RW/; Siemens Center of Knowledge Interchange RWTH Aachen, Available: http://www.cki.rwth-aachen.de/ (Accessed 13.3.2012).
252 Siemens - Innovation – Recycling Electric Motors as Source of Raw Materials, Available: http://www.siemens.com/innovation/en/news/2011/e_inno_1137_2.htm (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
Strategic Metals Committee (*Comité des Métaux Stratégiques*, COMES)	French Ministry of Industry; representatives from research institutes and companies (e.g.Areva, Rhodia et Eramet.) involved in this topic, covering all the metals related sectors starting with geology and up to recycling issues.	FR	Aims in general to secure strategic metals supply for France *COMES mission is to:* • Improve information about the needs of industry in the area of strategic metals • Identify the most critical resources • Bring up to date the mining inventory and re-launch mining exploration, on land and at sea • Accelerate the carrying out of recycling projects • Increase efforts in research and development, especially in the area of substitution and • Develop the necessary European and international cooperation.[253]	
Strategic metals plan	Government of France	FR	*Aims:* Improve supply of metals which are important for French industry, especially those used in the area of technology that relates to the green economy. *Planned instruments cover:* • Targeted minerals exploration campaigns • Promoting sustainable use of resources • Developing new tools for exploration and processing of strategic metals/CRM • Installing a recycling policy for strategic metals • Strengthening governmental action by appointing an official responsible for strategic metals agenda.[254]	

[253] Ministry of Industry, 2011, Création du Comité pour les métaux stratégiques (COMES) (Creation of the Committee for Strategic Metals), Available: http://www.economie.gouv.fr/economie/creation-comite-pour-metaux-strategiques-comes, Décret n° 2011-100 du 24 janvier 2011 portant création du comité pour les métaux stratégiques (COMES) (Decree no. 2011-100 of January 24th 2011), NOR: INDI1032803D, Available at: http://www.legifrance.gouv.fr/affichTexte.do;jsessionid=931360064F1082ABE36F9EBB721C365F.tpdjo02v_2?cidTexte=JORFTEXT000023474859&categorieLien=id# (Accessed 22.2.2012).

[254] European Environment Agency, 2011, 2011 Survey of resource efficiency policies in EEA member and cooperating countries, Country profile: France, Available: http://www.eea.europa.eu/themes/economy/resource-efficiency/france-2014-resource-efficiency-policies (Accessed 13.3.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
Renewable energies and raw materials	French Environment and Energy Management Agency ADEME	FR	*Goals include:* • Resisting climate change through reduction of emissions/pollution • Protection of resources, especially fuels • Conservation of environment and health *Instruments:* • Supporting research on clean technologies • Providing financial and technical assistance on feasibility studies on new energy technologies • Promoting initiatives on efficient energy use • Providing information on energy efficiency and available technologies[255]	
Working together for a World without Waste/Waste & Resources Action Program (WRAP)	Not for profit corporation, backing from regional governments of England, Scotland, Wales and Northern Ireland	UK	*Aims:* Wrap works across sectors with local governments and industry to reduce waste, and to promote good practices *Instruments:* • Grants and capital loans for waste reduction and development of recycling technologies • Tenders for technical and environmental/sustainable management[256]	

[255] French Environment and Energy Management Agency - About ADEME –Strategic Directions, Available: http://www2.ademe.fr/servlet/KBaseShow?sort=-1&cid=96&m=3&catid=17550 (Accessed 13.3.2012).

[256] WRAP - Working together for a world without waste, 2011, Towards Resource Efficiency: WRAP Business Plan: 2008-2011, A Report on Impact, Available: http://www.wrap.org.uk/downloads/WRAP_Business_Plan_Review.73273d02.11459.pdf; WRAP - Working together for a world without waste, 2011, Business Plan: 2011-2015, Available at: http://www.wrap.org.uk/downloads/Bus_Plan_2011_Final_WEB_22.13e2f880.10869.pdf (Accessed 9.2.2012).

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
European Pathway to Zero Waste (EPOW)	Environment Agency UK, WRAP	UK	*Aims:* • EPOW will investigate practical ways to achieve zero waste to landfill in South-East of England and share the results and best practices within the EU Partly funded by EU LIFE+ programme[257]	Eight (sub-)projects:[258] • Developing end-of-waste protocols for sustainable products • Tackling waste crime through public sector activity and development of recycling value chains • Creating markets for sustainable product through Green Public Procurement • Creating trading platforms for sustainable products • Developing waste sector infrastructure and partnerships • Increasing Green compliance • Supporting Best Practices • Presenting data management techniques to stimulate recycling
Dutch Government Policy Document on Raw Materials	Dutch Ministry of Foreign Affairs	NL	The Dutch Government position is that the role of government is to facilitate, encourage, create frameworks and coordinate action in trade and industry. *The policy has three aims:* • Securing and increasing supply of CRM • Limiting demand and, where possible, improving sustainability of CRM supply • Improving the sustainability and efficiency of raw materials consumption[259]	

Source: Please refer to the appropriate footnotes presented above

[257] Environment Agency UK, European Pathway to Zero Waste (EPOW), Available: http://www.environment-agency.gov.uk/aboutus/wfo/epow/123624.aspx (Accessed 13.2.2012).
[258] Environment Agency UK, European Pathway to Zero Waste (EPOW) – Projects, Available: http://www.environment-agency.gov.uk/aboutus/wfo/epow/123915.aspx (Accessed 13.2.2012).
[259] Dutch Government Policy Document on Raw Materials, op. cit.

ANNEX 4: SUMMARY OF POLICIES DIRECTED TOWARD SUBSTITUTION OF CRM IN THE US, JAPAN AND KOREA

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
Critical Materials Strategy	Federal Government, US DOE	USA	*Goals:* Diversifying supply, Developing substitutes and Improving recycling[260]	Workshops to discuss the issues regarding CRM supply and use[261]
ARPA-E	DOE	USA	*Goals:* Funding of transformative research on advanced energy technologies, not specifically on substituting CRM[262]	• 122 funded projects through 12 open calls, worth approx 370MUSD • 12 programmes to develop high performance innovative technologies for power generation, distribution and use.[263]
An elemental strategy project	Ministry of Education, Culture, Sports, and Science and Technology (MEXT)	JP	*Goals:*[264] • Rare and harmful elements, aims for drastic or complete substitution • Aims to propose a new paradigm for materials research • May be continued as a METI RDI project after the first 5 year of programme	Projects kicked off since 2007 include:[265] • High Performance Anisotropic Nano composite • Permanent Magnets with Low Rare Earth Content • Self-forming Nano-particle Catalyst without Precious Metals • Development of TiO2-based Transparent Electrode
Rare metal substitution material development project	Ministry of Economy, trade and Industry (METI), New Energy and Industrial Development Organisation (NEDO)	JP	• Aims for reduction in the use of critical metals by 30-80% during the programme period • Promotes RDI activities to develop practical substitutes[266]	Projects since 2007 include:[267] • Development of Substitute Materials for Indium in Transparent Conducting Electrodes • Development of Technology to Reduce Dysprosium Use in Rare Earth Magnets • Development of Technology to Reduce Platinum Group Use by Utilising Substitute Transition Elements and Aggregation Inhibitor of Platinum Group • Development of Technology to Reduce Platinum Group Use in Catalysts for Diesel Exhaust Emission • Development of Technology to Reduce Cerium Use for Precision Polishing by Utilising the Substitute Abrasive

260 US DOE, op.cit.
261 US DOE, Office of Policy and International Affairs, 2011 Critical Materials Strategy, Available: http://energy.gov/pi/office-policy-and-international-affairs/downloads/2011-critical-materials-strategy (Accessed 13.3.2012); workshop documentation also available.
262 DiGiovanni, 2009. op.cit.
263 Advanced Research Projects Agency – Energy – Programs & Projects – Projects list, Available: http://arpa-e.energy.gov/ProgramsProjects/ViewAllProjects.aspx (Accessed: 13.3.2012).
264 Kishi, T. 2011, op.cit.
265 Kishi, T. 2011, op.cit.
266 Kishi, T. 2011, op.cit.
267 Kishi, T. 2011, op.cit.

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
				Grains and Innovative Polishing Technology
Korea Resources Corporation - KORES	Government of ROK, Ministry of Knowledge Economy	ROK	KORES is a public (not-for-profit) corporation with a book value of 1,6 Billion EUR *Mission:* • Further Korea's access to strategically important mineral resources Engaging directly, or indirectly through joint ventures or in the form of investments, in overseas exploration, development and production of strategically important mineral resources Managing Korea's stockpile of rare mineral resources. *Means:* Provide and catalogue information about mineral deposits around the world Support and encourage Korean companies prospecting and development efforts of deposits globally with investments and capital loans[268]	-

[268] Korea Resources Corporation – About KORES – Vision, Available at: http://eng.kores.or.kr:8080/gpms/user.tdf?a=common.HtmlApp&c=2001&page=/english/cor/cor_02.html&mc=ENG_COR_020 (Accessed 7.2.2011); Korea Resources Corporation Act (English translation) Act No. 9182, Dec. 26, 2008, Available at: http://eng.kores.or.kr:8080/gpms/eng/gpms/resources/down/eng_law1.pdf

Strategy/ Programme	Owner/ Implementing body	Country	Aims/goals	Projects/Results (such as are available)
The G8 Research Councils Initiative on Multilateral Research Funding – 2nd call: Interdisciplinary Program on Material Efficiency – A first step towards sustainable manufacturing	G8 Research Councils, Participating agencies are: • Natural Sciences and Engineering Research Council of Canada (NSERC) • French National Research Agency (ANR) • Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) • Japan Society for the Promotion of Science (JSPS), • Russian Foundation for Basic Research (RFBR) • Research Councils of the United Kingdom (RCUK) • U.S. National Science Foundation (NSF)	International	*Goals:* "This Call aims to support collaborations between experts in research areas related to the global challenge of materials efficiency to address one or more of seven potential strategies for reducing material demand through material efficiency • longer-lasting products • modularisation and remanufacturing • component re-use and re-cycle • designing products with less material • rethinking products and their use • redesigning the manufacturing processes • replacement of scarce and expensive elements, notably those critical for energy applications."[269] The total budget for the programme in this second call is approximately 10 MEUR over three years, and it is expected that 8-10 research consortia will be funded starting in May 2012. [270]	

Source: Please refer to the appropriate footnotes presented above

[269] The G8 Research Councils Initiative on Multilateral Research Funding, Second Call for Proposals from an initiative between Research Councils from Canada, France, Germany, Japan, Russia, the UK, and the USA, available at: http://www.jsps.go.jp/j-bottom/g8-initiative.html (Accessed 24.2.2012).

[270] The G8 Research Councils Initiative on Multilateral Research Funding, Second Call for Proposals from an initiative between Research Councils from Canada, France, Germany, Japan, Russia, the UK, and the USA, available at: http://www.jsps.go.jp/j-bottom/g8-initiative.html (Accessed 24.2.2012).

EUROPEAN PARLIAMENT

CATALOGUE BA-31-12-127-EN-C

DIRECTORATE-GENERAL FOR INTERNAL POLICIES

POLICY DEPARTMENT A
ECONOMIC AND SCIENTIFIC POLICY

Role

Policy departments are research units that provide specialised advice to committees, inter-parliamentary delegations and other parliamentary bodies.

Policy Areas

- Economic and Monetary Affairs
- Employment and Social Affairs
- Environment, Public Health and Food Safety
- Industry, Research and Energy
- Internal Market and Consumer Protection

Documents

Visit the European Parliament website: **http://www.europarl.europa.eu/studies**

PHOTO CREDIT: iStock International Inc.

ISBN 978-92-823-3869-8
doi: 10.2861/53633

Publications Office

Substitutionability of Critical Raw Materials