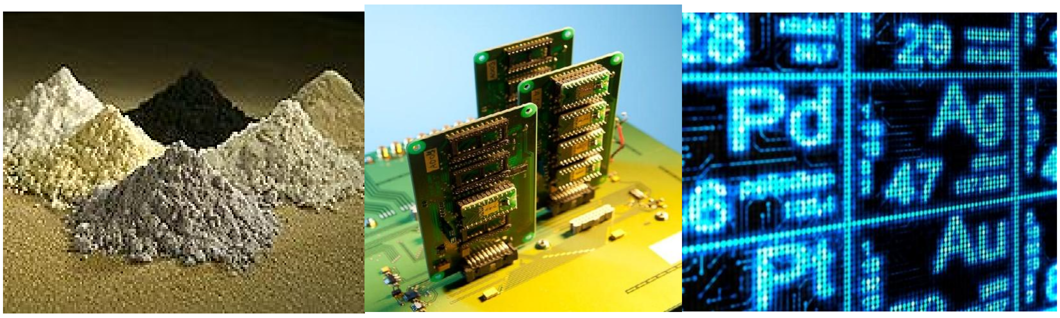
CRM_InnoNet

Substitution of Critical Raw Materials



Deliverable report

D4.4 CRM supply-chain analysis of Energy, ICT and electronics and Transport sectors

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Executive summary

This report summarises the results of analysis of the energy, ICT and electronics and transport sectors to identify critical raw material (CRM) dependencies as well as economic and strategic relevance of CRM containing applications for Europe. The analysis gives indications which applications could be under threat and which future opportunities for industries can be identified related to these applications.

The analysis was performed by examination of the CRM related supply chains of selected key applications in each sector using a common methodology. It was focused on the most relevant applications by screening based on the following criteria:

- Exposure to CRM risk: The use of one or more CRM (EU 2010 list) in the application
- Current economic importance: Share of EU production of the value consumed or used in Europe
- Share of the application production in the sector.

The actual supply chain analysis consisted of:

- Statistical analysis of European production, import, export and jobs describing economical relevance of the application
- Analysis of criticality, strategic relevance and development of vulnerability in future, based on technical and market reports as well as interviews with experts.

In addition, the supply chain analyses were complemented by industry interviews focusing on current risks and risk provision strategies associated with CRM relevant applications.

The summary of key results of both the screening phase and supply chain analysis of the selected applications is presented in this report. The supply chain analysis focused on the following 12 applications:

- Energy sector: Photovoltaics (Copper-Indium-Gallium-di-Selenide (CIGS)-technology), wind turbines and energy storage (Li-ion and NiMH batteries)
- ICT and electronics sector: LED lighting, magnetic resonance imaging (MRI), displays and screens, optical fibre, large household appliances represented by washing machines as well as printed circuit boards (PCB) and electronic components
- Transport sector: Automobiles, heavy vehicles and commercial aeroplanes.

The applications differ considerably in number of CRM containing components and complexity of their value chains. The analysis showed that European manufacturing of the selected key applications is focused especially on end products. With exception of CIGS photovoltaics technology and manufacture of Li-ion batteries, the EU occupies a good position in global production with one or more EU companies in the top ten and significant number of jobs in Europe linked to end product manufacturing. There are also possibilities for future growth, because market reports predict that the demand of almost all of the applications will rise significantly by the year 2020. The only exception are NiMH batteries.

In some applications, including all three transport applications, wind energy, MRI industry and selected electronic components of PCBs, significant component production can also be found in Europe. Several of the end products are, however, dependent on essential CRM containing components manufactured outside of Europe.

The key results of vulnerability assessment of the applications can be summarised as follows:

Energy applications: Exposure of the EU wind power industry to potential CRM issues is significant. The availability of permanent magnets may form a bottleneck for direct drive wind power manufacturers due to the growth of global demand of permanent magnets and concentration of their production in China and US. Battery technology may also be at risk although the current production in Europe is limited. The Li-ion technology for transportation is a growing sector, and due to the active research it can be an opportunity for European industry. The EU CIGS PV does not seem to represent a high risk, because the recent restructuring of the EU industry has significantly decreased the EU exposure on this technology.

The transport applications are dependent on several types of components containing CRMs, such as electric motors containing permanent magnets, electronic control units, and CRM containing alloys. The availability of catalytic converters may form a bottleneck for the European automobile and heavy vehicle manufacturers. The European aviation sector does not seem to be very vulnerable, although disruptions in the availability of Be could cause problems for the industry. Also CRM containing alloys are important for safety reasons. In addition, carbon fibres and titanium are considered critical by the industry, although they are not on the EU list of CRMs.

ICT and electronics applications: Nearly all ICT and electronics applications are exposed to CRM issues through the use of electronic components. Electronic components are dependent on several CRMs with no current substitution options. LED lighting applications, and especially SMEs producing them, may be vulnerable in case of supply shortages of LED dies. The expected very high market growth of LED lighting and manufacture of dies outside of Europe could induce availability problems. About 30% of global germanium is consumed in the production of optical fibre. With no commercial substitution option viable, Ge scarcity may form a bottleneck for increasing production. MRI (magnetic resonance imaging) is dependent on Nb containing superconducting magnets as well as Be and Ho. Europe is strong both in application and superconducting magnet production, and the sector does not seem to be very vulnerable.

The results of the supply chain analyses are presented in more detail in the following three reports:

Brunot, A., Charreyron, V., Chung, C., Mitrofan, L. & Rietveld, E. 2013. Internal report summarising the results of energy sector analysis. CRM_InnoNet Deliverable report D4.1, http://www.criticalrawmaterials.eu/documents/project-dissemination-downloads/report-critical-raw-material-supply-chain-analysis-for-the-energy-sector/

Bacher, J., Punkkinen, H., Mroueh, U-M. & Rietveld, E. 2013. Internal report summarising the results of ICT and electronics sector analysis. CRM_InnoNet Deliverable report D4.2. http://www.criticalrawmaterials.eu/documents/key-project-reports/report-critical-raw-material-supply-chain-analysis-for-the-ICT-sector/

Bolin, L., Stahl, S. & Rietveld, E. 2014. Internal report summarising the results of transport sector analysis. CRM_InnoNet Deliverable report D4.2. http://www.criticalrawmaterials.eu/documents/key-project-reports/report-critical-raw-material-supply-chain-analysis-for-the-transport-sector/

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Terms and definitions

Definitions related to the analysis methodology are presented below:

Centralized data source

The centralized data sources include statistical databases, such as: PRODCOM (Eurostat database providing statistics on the production of manufactured goods), SBS (Structural Business Statistics), BACI/COMTRADE (International Trade Database/The United Nations Commodity Trade Statistics Database), EXIOBASE (global, Multi-regional Environmentally Extended Supply and Use / Input Output database by the University of Leiden).

Application

The special use or purpose to which a technology or product is needed. For instance, “data storage” is an application.

User sector

In this report the user sectors are: energy, ICT and electronics and transport (aerospace and automotive).

PRODCOM sector

The sectors defined in database according to NACE classification and compatible on first digits with PRODCOM product groups, for example “Manufacture of electrical equipment”, “Manufacture of machinery and equipment”.

Product group

When the centralized data sources are used in the statistical analysis, “product group” defines what can be considered an application/product/technology. For instance, if “data storage” is an application (see definition above), the corresponding product group classification is “Digital Processing Units Whether Or Not Presented With The Rest Of The System Which May Contain Storage Units” (and other groups that have similar elaborate descriptions). Product groups are in CPA classification, which is compatible on the first digits with NACE the sector classification.

Statistical analysis

The statistical analysis of the supply chains contains:

- A majority of raw materials and intermediate products related to the product group and containing CRM;
- Production, import and export of raw materials and intermediates expressed in €. If relevant volumes in Tons of raw materials are added;
- A maximum of 3 EU countries that supply the largest share (in €) of parts of the value chain.

Business analysis

A partly quantitative, partly qualitative report and a summary table as addition to statistical analysis (see above). It provides essential information for prioritisation of the applications (see Table 2) and insights on the value chain analysis in the CRM_InnoNet project. The report lists individual stakeholders (companies) if feasible.

Abbreviations

AC	Alternating current
Bn	Billion
BACI	International Trade Database at the Product-level
CAGR	Compound annual growth rate
CHP	Combined heat and power
CIGS	Copper indium gallium selenide thin film photovoltaic technology
CPA	Classification of Products by Activity
CRM	Critical raw materials
ECU	Electronic control unit
EV	Electric Vehicles
GW	GigaWatt
HEV	Hybrid Electric Vehicles
HRE	Heavy Rare Earth elements
HSLA steel	High Strength Low Alloy steel
JRC	Joint Research Centre
LED	Light emitting diode
LRE	Light Rare Earth elements
MFT	Multifunctional Teams
MgH_2	Magnesium hydride
MRI	Magnetic resonance imaging
MWe	MegaWatt electrical
NACE	Nomenclature of Economic Activities
NiMH	Nickel metal hydride
OEM	Original Equipment Manufacturer
OLED	Organic light emitting diode
PCB	Printed circuit board
PEM	Proton exchange membrane
PM	Permanent magnet
PV	Photovoltaic
REE	Rare earth element
REITA	Rare Earth Industry and Technology Association
RMB	Chinese Renminbi
SBS	Structural Business Statistics
SET-Plan	The European Strategic Energy Technology Plan
SMES	Superconducting magnetic energy storage
TF	Thin film
VDI	The Association of German Engineers

Elements and compounds

Al	Aluminium
AlGaAs	Aluminium gallium arsenide
As	Arsenic
B	Boron
Be	Beryllium
CdTe	Cadmium telluride
Ce	Cerium
Co	Cobalt
Cu	Copper
Dy	Dysprosium
Er	Erbium
Eu	Europium
Fe	Iron
Ga	Gallium
GaAs	Gallium arsenide
GaN	Gallium nitride
Gd	Gadolinium
Ge	Germanium
$GeCl_4$	Germanium tetrachloride
GeO_2	Germanium dioxide
He	Helium
H_2	Hydrogen
Ho	Holmium
In	Indium
InAlAs	Indium aluminium arsenide
InGaAs	Indium gallium arsenide
ITO	Indium tin oxide
La	Lanthanum
Li	Lithium
Lu	Lutetium
Mg	Magnesium
MgB_2	Magnesium-diboride
MgS	Magnesium sulphide
Mo	Molybdenum
Nb	Niobium
Nd	Neodymium
P	Phosphorus
P_2O_5	Phosphorus pentoxide
Pd	Palladium
Pm	Promethium
Pr	Praseodymium
Pt	Platinum
Re	Rhenium
Ru	Ruthenium
Sb	Antimony
Sc	Scandium
SiO_2	Silicon dioxide, silica

Sm	Samarium
SmCo	Samarium cobalt
Ta	Tantalum
Tb	Terbium
Tm	Thulium
W	Tungsten
Y	Yttrium
Yb	Ytterbium
ZnO	Zinc oxide

1 Introduction

1.1 Objectives

The aim of this work is to create more understanding about the relevance of critical raw materials (CRM)[1] for the European economy and to give indications of which applications could be under threat. On account of economic importance the following user sectors have been selected for analysis: Energy, ICT and electronics and transport with specific emphasis on aero and automotive transport. Selected key applications from each sector were assessed by examination of the 'CRM supply chain' for each application. This 'CRM supply chain analysis' examined the economic importance, CRM availability and strategic relevance over each stage in the production of the chosen application. In addition, analysis of current risk provision strategies and opportunities for industries was completed. The full assessment methodology is presented below in Chapter 3.

The value chain analysis is part of the project CRM_InnoNet (www.criticalrawmaterials.eu). The data produced will (together with the additional data produced in a materials-orientated analysis of the CRM-landscape (CRM_InnoNet 2013) be used in prioritisation of the applications for elaboration of five roadmaps for the substitution of critical raw materials in specific applications.

1.2 The sectors studied

The three sectors studied: Energy, ICT and electronics and transport, differ in many respects.

The energy sector may be considered as going from the extraction of energetic resources, through their transport, their transformation into intermediate energy vectors, the transport and/or storage of these vectors and their use at customer premises, including the efficiency of this use (e.g. boiler efficiency). Each of these areas covers several underlying technologies, e.g. different types of coal-fired power plant, each of them having potential dependence on CRM and their own specific supply chains.

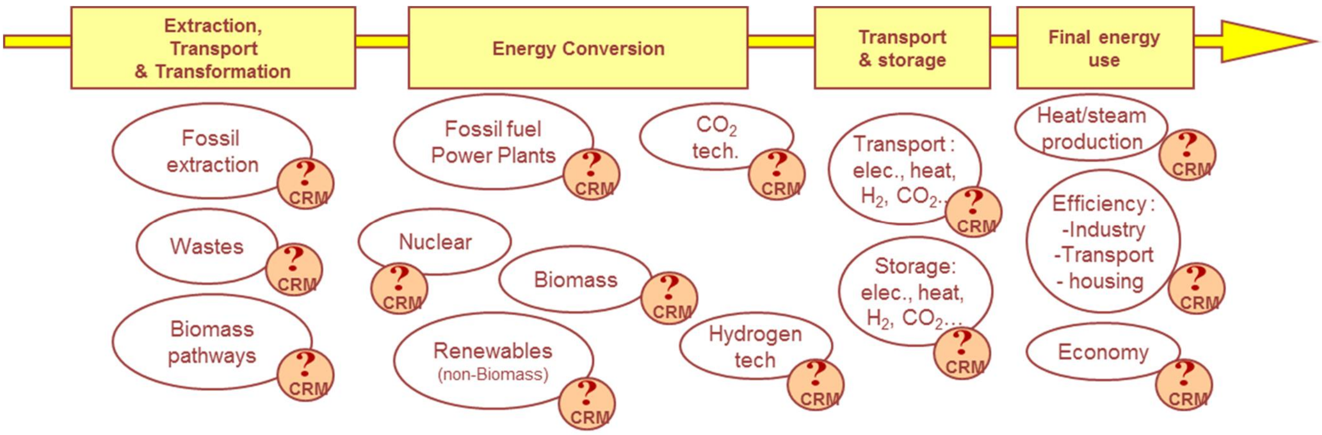

Figure 1: Description of the energy sector

Because the sector is very wide additional focusing was needed. In order to include applications which are *both* economically important *now* and represent a *strategic importance* (future-looking) for the EU, the European Strategic Energy Technologies Plan (SET-Plan) (European Commission, 2009) was used as a

[1] The starting point in this work was the list of 14 Critical Raw Materials highlighted in the EC's report: Critical Raw Materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials. Version of 30 July 2010.

starting point. The more detailed list of 18 technologies (JRC 2011) is illustrated below in Figure 2. “Energy efficiency”, “CO_2 emission reduction” and “Energy performances of buildings” were removed from the list considered in this report, because they have a too diverse technological background to be covered.

European « Strategic Energy Technologies»

- Wind power
- Solar PV
- Concentrated Solar Power
- Hydropower
- Geothermal
- Marine energy
- Cogeneration & CHP
- Carbon Capture & Storage
- Advanced Fossil Fuel power gen.
- Nuclear fission
- Nuclear fusion
- Smart grids
- Bioenergy – power & heat generation
- Biofuel for transport
- Fuel cells & Hydrogen
- Electricity storage
- Energy-efficient & CO_2 emission reduction
- Energy performances of buildings

Figure 2: List of SET-Plan technologies (JRC 2011)

The ICT and electronics sector produces products and services both for consumers, industries and professional users. Because the focus of the study is critical raw materials (CRMs), services were excluded. The applications of the sector include:

- Products which capture, transmit and display data and information electronically, such as computers, phones, displays and other communication equipment and consumer electronics
- Lighting
- Domestic appliances
- Professional applications, such as medical applications, control equipment, sensors and tools
- Electronic components which are used in different applications in all business sectors.

Rapid changes, due to the relatively short lifetimes of the products are characteristic for the ICT and electronics sector. Because of small size and low transport costs, the production and assembly of components and most of the consumer products can be quite easily moved to the countries with lower production costs. The changing character of the products and large number of applications also makes the definition of the sector and statistical classification of the products challenging compared with energy and transport sectors.

The transport sector also produces both products and services for consumers, industries and professional users. Services were excluded from the analysis, and the specific emphasis was on aero and road transport. CRMs are also used in other transport sectors such as railway and sea transport, though those were not included in this study. Examples of products used in the road and air transport sectors that might include CRMs and play a role for the European economy include:

- Automobiles which transport less than 10 people
- Heavy vehicles and buses
- Commercial Aeroplanes
- Bicycles
- Helicopters

The main drivers of change in the sector include environmental regulations (EURO V, VI etc.), greenhouse gas reduction strategies as well as new consumer demands (low cost cars, hybrids, electric vehicles etc.).

2 Supply chain analysis methodology

When starting the work, the objective was to make a value chain analysis of selected applications. However, it was found that using the data sources available, it was not possible to get detailed information on the value addition of components used in the end applications, which is required for a full value chain analysis. Therefore it was chosen to analyse the supply chains instead as a way to get at least partial information on the value chain. For the remainder of this report the approach used will be referred to as “supply chain analysis”.

In developing a methodology for analysing the supply chains of applications the following factors were considered to be important:

- Economic relevance to Europe
  The focus was on understanding where in the supply chains of applications (Figure 3) the value for Europe is produced, creating the basis for assessment of the economic vulnerability of the applications. In other words: from which stage on in the supply chain are activities located within the EU and therefore most relevant to European employment? In previous studies, these economic aspects have been discussed only superficially. The information needed was compiled by analysing the supply chains for the following quantities: production in EU countries, import to and export from these countries.

- Transparency and transferability
  In all three user sectors critical raw materials are used in a wide variety of different applications. In order to produce reliable and comparable results, the same analysis methodology needs to be applicable to all three user sectors and common data sources need to be used. Therefore the quantitative economic analysis was performed using statistical data sources.

- CRM relevance
  Most of the applications are composed of numerous components or intermediate products, making the supply chains of the applications complex. As this study aims to identify bottlenecks arising from lack of availability of critical raw materials, only the parts of the supply chain containing critical raw materials were analysed.

In addition to the analysis of current economic relevance, it is important to point out how the vulnerability of the applications is expected to develop in future, and how the potential disruption would affect Europe’s ability to meet strategic targets. It is not possible to assess such factors on the basis of current market data so a qualitative approach using market and sector reports was adopted.

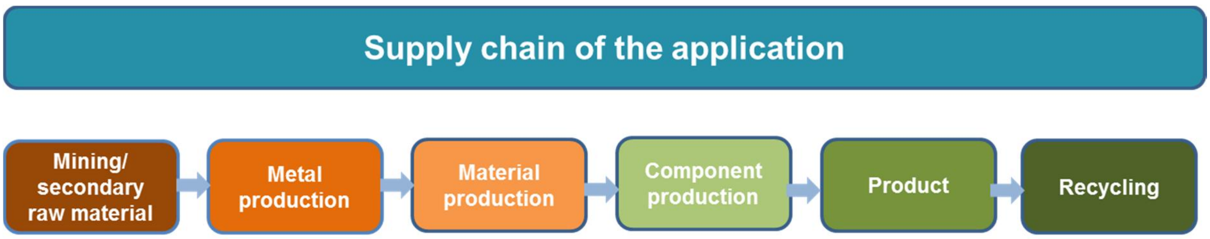

Figure 3: Main stages of a generic supply chain.

In order to highlight the most important applications for the European economy, screening was required to reduce the number of applications to a manageable number for in-depth study via a supply chain analysis. Therefore a two-phase approach, illustrated in Figure 4, was followed:

Phase 1: Screening

The first phase was the identification of suitable applications to progress to full supply chain analysis from a complete list of applications relevant to a particular user sector. The applications were screened by considering three criteria to assess CRM dependency, share of EU production of the value consumed in Europe and share of the application production in the sector.

Phase 2: Supply Chain Analysis

The second phase was the full CRM supply chain analysis of the selected applications. The full analysis approach was composed of a statistical analysis and examination of supporting market and technical qualitative and quantitative data by experts (business analysis).

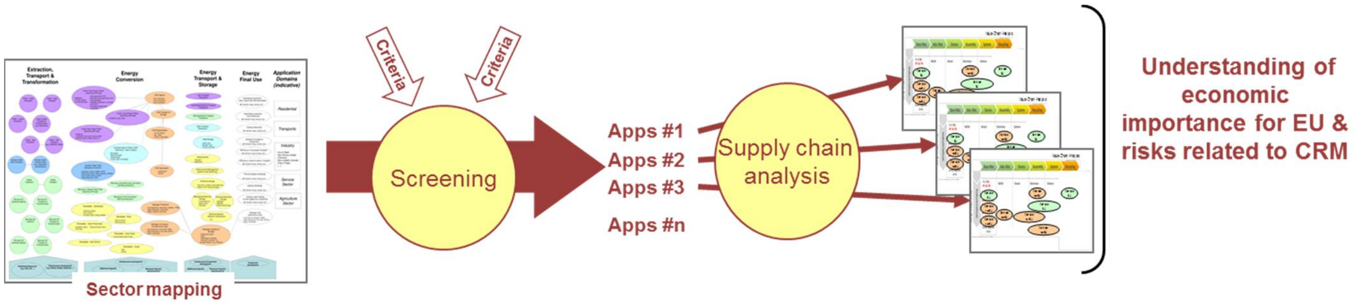

Figure 4: Approach to selection of applications for supply chain analysis.

Because the selection of applications for the supply chain analysis and the implementation of the analysis had to be made in a uniform and transparent way, the same analysis methodology was applied for all three user sectors. The step by step description of the analysis methodology is presented in the following section. The definitions of the terms used can be found on page 6.

2.1 Description of the methodology

2.1.1 Phase 1: Screening

Step	Description
1	The scope of the user sector is defined and a 'long list of relevant applications' is created. (Applications with no CRM dependence or very small markets are not included).
2	The statistically defined product groups corresponding to the applications on the long list are defined using CPA (Statistical classification of products by activity) and HS (Harmonized Commodity Description and Coding System) classifications (see an example in Table 3). The products are analysed for EU share of production and EU consumption/use using centralised databases (PRODCOM). The most relevant applications are selected for full value chain analysis by evaluation against three criteria: A. Are CRMs used in the value chain of the application? This has been pre-evaluated during step 1 and verified here. B. Does the EU produce at least 25% of the value (x) that is consumed/used of this product within the EU? The value x = (EU production)/(EU production + import) is calculated using the data extracted from the PRODCOM data base. C. In order to ensure that the biggest EU industries in the three user sectors are represented, the total size of EU production of the product should have at least a share of 0.2% in the total output of the representative PRODCOM sector. The limiting value has been determined so that for the smallest sector the threshold would be at least €500 million. Consequently for the largest sector the threshold is around €1,100 million. PRODCOM values are used in the calculation. The order of magnitude of the European market for this product should be stated.
Applications that meet the three criteria described above progress to phase two, full supply chain analysis	

2.1.2 Phase 2: The Supply Chain Analysis

1. A 'structural composition' i.e. a list of the CRM containing components and materials in the product is produced (see Table 1).

Table 1: Description of the structural composition of an application (Example: Light Emitting Diode).

Light emitting diode (LED)	CRM content	Comments
LED module		
LED		
Semiconductor die	In, Ga	
Phosphors	Ce, Y, Tb, Lu, Eu, Gd	
Electronics		
Printed circuit board		
Plating	Pd	Not very common to use Pd as plating, generally Ni/Cu and Au are used
Components		
Capacitors	Ta, Pd, Nb	
Resistors	Ta, Ru	
Semiconductors	Ga, Ge, In, Sb	
Transistors	Ga, Ge	
Connectors	Pd, Ru, Be	
Cables		

2. In order to enable statistical analysis, a list of comparable raw materials and intermediate products as defined by statistical classification (CPA and HS classification) is produced. This list represents most relevant parts of the supply chain attached to the application.

3. Quantitative and qualitative market/product information (such as sector reports, company reports, data from strategy consultants, interviews, etc.) is collected and used as input for the business analysis part of the study. The aim of the business analysis is to complement the information produced by statistical analysis and to enable comparison between the centralised and other data sources. The topics to be discussed in the business analysis are presented in Table 2. The jobs figures are collected from the statistical databases.

Table 2: Topics discussed in the business analysis

Dimensions	Sub-criteria
Economic	Economic added value of application in Europe
	Main actors in the supply chain
	Jobs involved in the EU (excluding indirect jobs)
Availability	Amount of CRMs involved
	Expected future market development
	CRM function
	Availability and status of substitutes
Strategic Relevance	Associated to EU policies for CRMs supply, or specific application development

4. Data from centralised sources is collected and analysed for every part of the statistically defined value chain of the selected products. The following methodology is used:
   a) Total EU and EU country level production, export and import data is extracted from PRODCOM, SBS and BACI/COMTRADE databases
   b) Using the statistical data, tables or graphs are produced summarising the following information for every part of the value chain: Total EU production, import and export, 3-5 major EU producer countries, production and trade balance in these countries. Examples of the results in the case of LED lighting are presented in Figures 5 and 6.
   c) The blanks in statistical data are filled using the general market data produced by the business analysis, if available.

5. For comparison and verification of the results, the statistical supply chain data is matched with specific market/product information and any potential discrepancies discussed.

6. The application specific results of the business analysis (the information presented in Table 2), and those of the statistical analysis (graphical presentation of the EU production, export and import data) are reported. The interpretation of the results is discussed in sector specific reports (D4.1 – D4.3) and in Chapter 5 of this report.

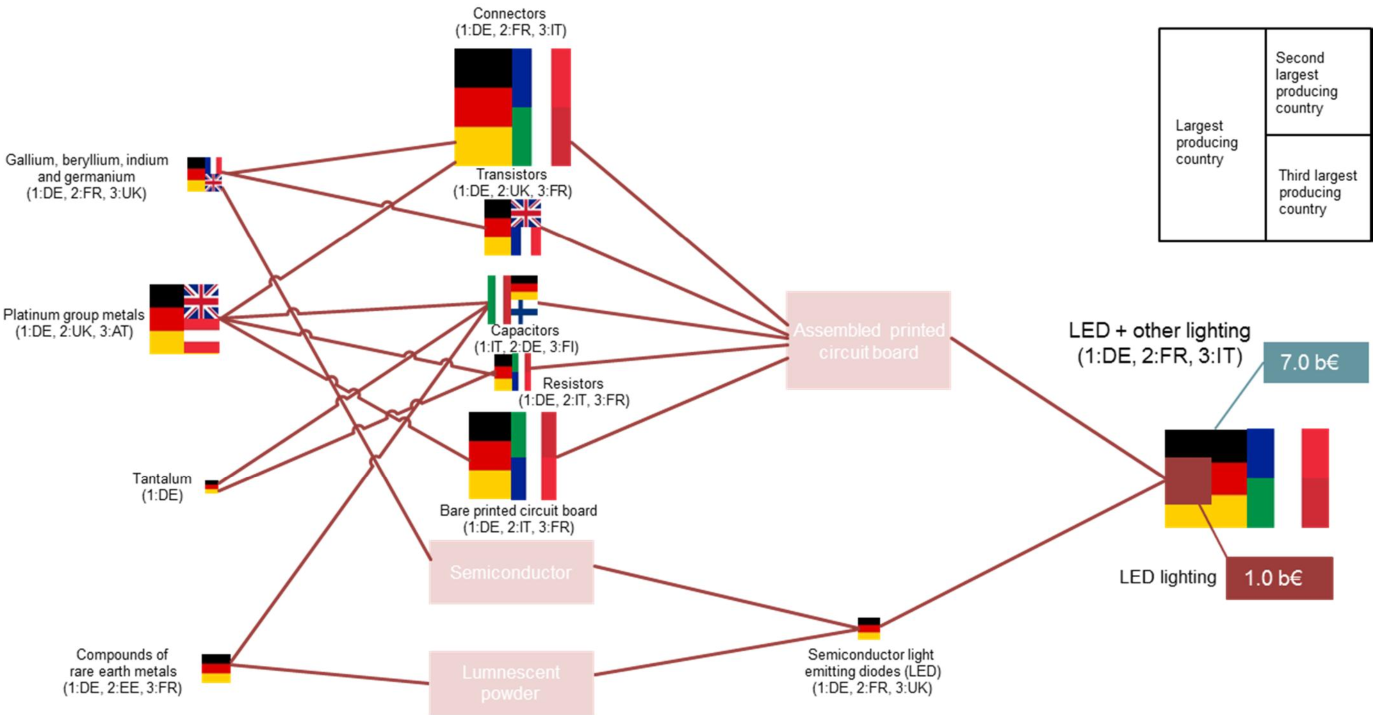

Figure 5: EU production of LED lighting and related (sub)-components and materials. (Sub)-components in pink boxes have no corresponding PRODCOM group and therefore no statistically defined value and are included for completeness. The green box represents the total value for all lighting and therefore red box inset presents the value of LED lighting production based on data from a market report by McKinsey & Company (2011). Each box presents the total production value, not the value of components/materials which are used only in LED lighting applications. In addition, the largest EU producing countries are presented.

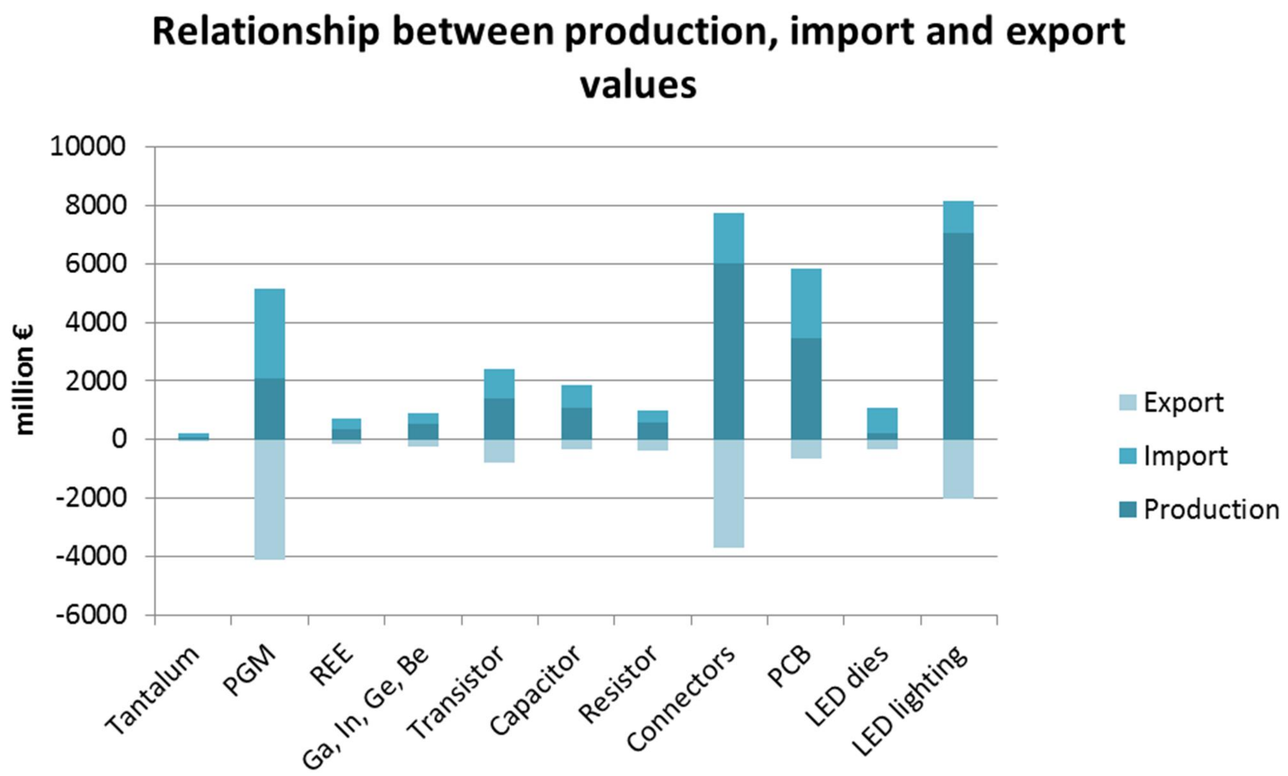

Figure 6: Relationship between production, import and export values for LED and other lighting application, components and materials in Europe 2012. Note the values for components and materials present the whole industry, not the share which is only used in LED lighting.

3 Screening of applications for supply-chain analysis

The applications were selected for further analysis based on their CRM dependence and economic relevance. In the investigation of European economic importance of each application, information from Eurostat's PRODCOM database has been used. In order to enable the analysis, corresponding PRODCOM group/product classifications were matched to each application under study. Two examples of applications and corresponding PRODCOM groups are presented in Table 3. Long lists of correspondences are presented in CRM_InnoNet deliverable reports D4.1 – D4.3. One has to take into account that the PRODCOM groups and the applications do not totally match. Typically PRODCOM groups include several different products or applications, and some applications may be divided into several PRODCOM groups.

Table 3: Examples of corresponding PRODCOM groups for two applications selected for economic evaluation.

Application	Corresponding PRODCOM group (including code)
Washing machines	27511300 - Cloth washing and drying machines, of the household type
Optical fibres	27311100 - Optical fibre cables made up of individually sheathed fibres whether or not assembled with electric conductors or fitted with connectors 27311200 - Optical fibres and optical fibre bundles; optical fibre cables (except those made up of individually sheathed fibres)

The data from PRODCOM 2012 was compiled for each application in order to address whether the economic screening criteria in Phase 1 are met. In addition, the sector production values from year 2011 were used in the calculation of the third criterion: share of products in sector. The results of the screening process for the three sectors are presented in Tables 4, 5 and 6.

Table 4: Energy sector applications screened for the CRM value chain analysis. The applications marked with green passed all the three main screening criteria.

Application	CRM Use (EU-14 CRM)	EU economic importance			Progress to full supply chain analysis
		Value* (2012) in € million	Share of prod. >25%	Share of products in the PRODCOM sector >0.2%	
Wind Power	Nd, Dy	PRODCOM €9.9 billion Market reports €6.5 billion	98%	1.8%	Yes
Solar PV	Ga, Ge, In, (Ru)	PRODCOM €3.98 billion Market reports €6.6 billion	28%	1.54%	Yes
Concentrated Solar Power	No CRMs**				No
Hydropower	No CRMs**				No
Geothermal	Nb, Ta	No PRODCOM data Limited market.	No data	No data	No
Marine energy	No CRMs**				No
Cogeneration & CHP	Medium/large: see fossil fuels power Micro-CHP: Nd	No PRODCOM data Micro-CHP small market	No data	No data	Cf. fossil fuels power
Carbon Capture & Storage	Nb, (Co)	No commercial market today			No
Advanced fossil fuel power gen.	Nb, W, Co, (Re), (Y) alloys with potential alternatives	PRODCOM €3.6 billion	70%	0.65%	No***
Nuclear fission	In, Nb	PRODCOM €1.5 billion	100%	0.33%	No***
Nuclear fusion	Be, Nb, W, (…)	No commercial market today			No
Smart grids	No CRM**				No
Bioenergy-power & heat gen.	See fossil fuel & CHP				Cf.fossil fuels power
Fuel Cells & Hydrogen	Alkaline electrolysis: no CRMs PEM electrolysis: Pt Fuel cells : Pt, La, Y, Ru MgH_2 storage : Mg	No PRODCOM data Limited market	No data	No data	No
Electricity Storage	Batteries : Co, Graphite, La & REE	PRODCOM €690 M	30%	0.24%	Yes
Electricity Storage	Flywheels: Mg Supercapacitors: Ru SMES: Nb, Y, Mg	Limited market Limited market Not commercial			No No No

*For energy sector applications both the production value of the product group in PRODCOM data base and production value based on market reports are presented in the table, if available. Corresponding PRODCOM products could be found only for a part of the energy sector applications.

** Electronic components dependent on CRMs are used in all the applications, but it was decided that they will be addressed separately.

*** Advanced fossil fuel power and nuclear fission pass the criteria for full supply chain analysis. Nuclear fission was, however, not prioritised because the future market in the EU is relatively uncertain. The market of advanced fossil and biomass power is huge. CRMs are mainly used in alloys, and it was judged that there is not enough information about future technical requirements and alternatives to efficiently perform the supply chain analysis.

Table 5: The ICT and electronics sector applications screened for the CRM value chain analysis. The values that did not pass the criteria are market with red fonts. The applications on the rows marked with green passed all the three main screening criteria

PRODCOM sector and its production value (2011)	Application	CRM use (EU-14 CRM)	EU economic importance: Value* (2012) in € million	Share of prod. >25%	Share of products in the PRODCOM sector >0.2%	Progress to full supply chain analysis
Manufacture of electrical equipment €270,000 M	Washing machines	Nd, Dy	4,600	82%	1.7%	Yes
	Dishwasher	Nd, Dy	2,200	85%	0.8%	No*
	Cooling appliances	Nd, Dy	2,400	59%	0.9%	No*
	Air conditioners	Nd, Dy	2,800	63%	0.5%	No*
	Optical fibres	Ge	1,400	69%	0.5%	Yes
	Displays and screens	Ce, Er, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pr, Ru, Ta, Tb, Tm, Sb, Y	15,200	63%	5.6%	Yes
	LED lighting	Ce, Eu, Ga, Gd, Ho, In, La, Ta, Tb, Tm, Sb, Y	7,300	79%	2.7%	Yes
Manufacture of computer, electronic and optical products €260,000 M	Laptops	Br, Dy, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pt, Pr, Rh, Ru, Ta, Sb, Y	2,300	8%		No
	Mobile (Smart) phones	Br, Dy, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pt, Pr, Rh, Ru, Ta, Sb, Y	3,000	10%		No
	Video cameras	Ce, Er, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pr, Ru, Ta, Tb, Tm, Sb, Y	320	17%		No
	Cameras	Ce, Er, Eu, Ga, Ge, Gd, In, La, Nd, Pd, Pr, Ru, Ta, Tb, Tm, Sb, Y	320	8%		No
	Radio sets	Ga, Ge, Nd, Pd, Pr, Ru, Ta, Sb	170	14%		No
	Loudspeakers	Nd, Dy	450	59%	0.18%	No
	MRIs	Dy, Gd, Nb, Nd, Pr, Tb	3,300	81%	1.3%	Yes
Manufacture of machinery and equipment n.e.c sector €550,000 M	Electric tools (cordless)	Nd, Dy	240	27%	0.04%	No

*All large household appliances (washing machines, dishwashers, cooling appliances and air conditioners) include generator/compressors/electric motors which may contain NdFeB magnets. Due to the similarities between all major appliances, washing machine will be handled as a case example since it had the largest production in Europe.

Table 6: The transport sector applications screened for the CRM value chain analysis**.** The values that did not pass the criteria are market with red fonts. The applications on the rows marked with green passed all the three main screening criteria

PRODCOM sector and its production value (2011)	Application	CRM Use (EU-14 CRM)	EU economic importance			Progress to full supply chain analysis
			Value (2012) in € million	Share of prod. >25%	Share of products in the PRODCOM sector >0.2%	
Manufacture of motor vehicles, trailers and semi-trailers €678,906 M	Automobiles	Pt, Pd, Rh, Ta, Nb, Mg, Sb, Nd, Gd, Be, In, Ce, Dy, La, Tb, Tm, Y, Er, Eu, Ga, Ho, Graphite	223,808 M€	95%	40.0%	Yes
	Heavy vehicles	Pt, Pd, Rh, Ta, Nb, Mg, Sb, Nd, Gd, Be, In, Ce, Dy, La, Tb, Tm, Y, Li, Zn, Co, Ag	33,369 M€	91%	4.9%	Yes
	Buses	Assumed similar as auto/heavy vehicles	3,855 M€	86%	0.57%	(Yes)*
	Goods vehicles	Assumed similar as auto/heavy vehicles	2,3878 M€	85%	3.52%	(Yes)*
Manufacture of other transport equipment €198,311 M	Helicopter	Assumed similar as aeroplane	3,709 M€	83%	1.9%	(Yes)*
	Commercial aeroplanes	Sb, Ge, Mg, Gd, Rh, Pd, Be, Pr, Sm, W, Ta, Ru, Nb, Y	7,850 M€	27%	2.5%	Yes
	Motorcycle	Assumed similar as automobile	3,463 M€	68%	1.6%	(Yes)*
	Bicycle	Mg, Sc, Be	2,165 M€	66%	1.1%	No**

* Due to the similarity of CRM dependencies of buses and goods vehicles to heavy vehicles, motorcycles to automobile and similarities in navigation systems and electronics between helicopters and aeroplanes, it was decided that no separate supply chain analysis are required for these applications.

** Due to the limited number of CRMs involved, no supply chain analysis was made for bicycles, although the application passed the screening criteria.

As a result of screening, 12 applications from the three key sectors were moved to supply chain analysis (Table 7). Some of the applications, such as photovoltaics or energy storage batteries, cover a list of different solutions. In these cases the alternatives for supply chain analysis were chosen based on the main CRM dependencies (consumption of EU-14 CRM and market size).

Table 7: Applications selected for full supply chain analysis

Energy sector applications	ICT/electronics sector applications	Transport sector applications
Photovoltaics • Copper-Indium-Gallium-di-Selenide (CIGS) technology	LED lighting	Automobiles
Wind energy • Wind turbines	Magnetic resonance imaging, MRI	Heavy vehicles
Energy storage batteries • Li-ion batteries • NiMH batteries	Large household appliances • Washing machines	Commercial aeroplanes
	Displays and screens	
	Optical fibre	
	Assembled printed circuit boards*	

*In addition to five ICT/electronics applications selected for supply chain analysis in the screening process, it was decided to analyse assembled printed circuit boards, which are critical components present in almost every application in all three sectors (energy, ICT/electronics and transport).

4 Supply Chain Analysis of applications

4.1 Description of the applications selected for analysis

A short description of the applications and their key CRM dependent components is presented in the following Tables 8, 9 and 10.

Table 8: Description of energy sector applications selected for analysis.

Application	Description
Photovoltaics • CIGS technology	Photovoltaic (PV) technologies convert sunlight to energy. The modules consist of PV cells, electric convertors, cables, monitoring and support structures. The cells encounter several material layers, and different types of cells are available: mainly crystalline silicon cells, thin-film (TF) technologies and high-performances multi-junction cells. Due to CRM dependence, this study focuses on the CIGS (Copper-Indium-(Gallium)-di-Selenide) thin film technology which has In and Ga as part of its active materials.
Wind energy • Wind turbines	Wind turbines convert wind energy captured by blades into the rotation of a shaft. This rotation is transformed into electricity through a generator. The main markets are on-shore and off-shore wind turbines. The most significant dependence on CRMs is related to direct-drive (NdFeB permanent magnet-based) generator technologies. Because of performance and maintenance gains, they are preferred over other turbine solutions especially in off-shore applications.
Energy storage batteries • Li-ion batteries • NiMH batteries	Rechargeable batteries are one of the solutions for electricity storage. Main types of batteries include: Lead-acid batteries, alkaline Nickel-Cadmium (NiCd) and Nickel-Metal Hydride (NiMH) accumulators, lithium-ion batteries, molten-salt batteries and Redox-Flow batteries. The main CRM dependence identified relates to NiMH dependence on lanthanide (e.g. AB_5-type NiMH batteries), and the graphite and cobalt dependence of several types of Li-ion batteries.

The supply chains of the applications usually include parallel streams for different components including CRMs. For example almost all systems today contain a share of electronic components which have dependences of CRMs, such as printed circuit boards or sensors. Also permanent magnets, LED diodes, displays and metal alloys are common to several applications. The presence of these components was identified in the analysis of each application, but it was decided that the “common” components are addressed in more detail only once, for example electronic components in the ICT and electronics sector analysis. The other supply chain analyses were focused on the other main CRM dependencies of the application.

Table 9: Description of ICT and electronics sector applications selected for analysis.

Application	Description
LED lighting	Light emitting diodes (LED) are semiconductor devices, which produce light when electric current flows in only one direction. It is expected that the usage of LEDs in lighting will grow rapidly due to small size, efficiency and long usage life. The key user sectors are general lighting, automotive lighting and backlighting of displays. The CRM dependencies relate to gallium and indium in semiconductors and phosphors (Ce, Y, Tb, Lu, Eu, Gd) used for accomplishing the impression of natural light.
Magnetic resonance imaging, MRI	Magnetic resonance imaging is a medical technology used for visualising the internal morphology of the body. It is based on a nuclear magnetic resonance (NMR). Critical raw materials in an MRI system are found in the magnet unit, spring contacts, cold heat pole-piece, computer display and assembled printed circuit boards. Superconducting magnets dependent on niobium have been used in about 75% of the installed MRI systems. Permanent magnets are mainly used in low field systems. Other CRMs essential for MRI system are beryllium and holmium.
Optical fibres	Optical fibres are used for the transmission of high volume data by sending light pulses along long distances enabling global data transmission. A fibre optic system consists of a transmitter unit converting an electrical signal to an optical signal, an optical fibre carrying the light, and a receiver accepting the light and converting it back into an electrical signal. Germanium dioxide (GeO_2) is used as a dopant in the glass fibre to enhance the optical properties.
Displays and screens	Common display-based devices include televisions, mobile phones and computers, but displays and screens are used in a wide range of other consumer products as well as in industrial, automotive and medical applications. LCD (Liquid Crystal Display) is the most prevailing flat panel display technology at the moment, but OLED and e-paper technologies are beginning to penetrate the market. The main use of indium, around 74-80%, is in conductive electrode layers of flat panel displays. In addition smaller amounts of several different CRMs are used in backlights (phosphors), electronics and loudspeaker magnets.
Large household appliances: Washing machines	Large household appliances include refrigeration and washing equipment, air conditioners and other miscellaneous equipment. CRM containing permanent magnets can be found in a part of electric motors included in the appliances. In addition, modern devices also contain electronics. Washing machines were analysed as an example. The information available about the share of washing machines containing permanent magnets is very limited, but some rough estimates could be made.
Assembled printed circuit boards	Every electronic device contains one or more printed circuit boards (PCBs). An assembled printed circuit board consists of electronic components, such as microprocessors, resistors, capacitors, sensors and magnets. The components are connected together with embedded copper wire to form a

	working circuit or assembly. Usually all the electronic components contain CRMs, such as antimony, beryllium, gallium, germanium, indium, niobium, palladium and tantalum. It is difficult to get exact information about the amounts of CRMs used in PCBs, because the composition of PCBs is determined by the performance requirements for electronics and therefore different PCBs can be used in same kind of applications.

Table 10: Description of the transport sector applications selected for analysis.

Application	Description
Automobiles	Automobiles are here defined as vehicles for personal transport of less than 10 people. Critical raw materials with different functions are found in several parts of the modern automobiles. In the catalytic converters platinum is the most commonly used conversion catalyst, but palladium (Pd), rhodium (Rh) and cerium oxide (CeO_2) are also used. High strength steel containing small amounts of niobium (Nb) or tantalum (Ta) is used in the chassis in parts which have a key role for safety reasons. Considerable numbers of small electric motors are needed for running of different systems in modern vehicles, such as steering and air conditioning and many of these rely on rare earth-containing permanent magnets. In electric and hybrid vehicles larger permanent magnets are used in the car motor. Electronics and sensors also play a more and more central role in cars. Basic vehicles have at least 30 electronic control units (ECUs) while luxury cars might have as many as 100. A few examples are fuel injection control, cooling systems, anti-lock breaking systems, air bags and adaptive cruise control systems. The steering, the brake system, the security system and the heat exchanger all contain CRMs. In conventional midsize cars niobium and neodymium are the CRMs found in largest quantities, about 80% of the mass of CRMs.
Heavy Vehicles	Heavy vehicles are defined as vehicles with diesel engines > 2500 cm^3 or goods vehicles with a gross vehicle weight > 5 tonnes. They have mostly the same CRM dependencies as automobiles with some minor differences related to cooling and exhaust after-treatment. Energy storage in the form of lithium ion batteries, zinc-air batteries or ultra-capacitors add Li, Co and Ta to the list of CRMs used. Advanced emission purification systems contain REEs, yttrium and scandium.
Commercial aeroplanes	Aeroplanes studied in this project are jet engine or propeller powered fixed-wing aircraft that are propelled forward by thrust from a jet engine or propeller. CRMs are used both in the body, different components as well as electronics and sensors. The use of magnesium alloys in the body and mechanical components is increasing because of the lightness of Mg. Strong and ductile tantalum and tungsten containing superalloys with high melting points, and Nb containing alloys with lower weight are used in engines. In brake systems Be is needed because of its hardness and high melting point. Antimony and germanium are important in navigation and radar systems, but a long list of other CRMs are found in electronics needed e.g. for different control systems. Also displays with In and several other CRMs are common in passenger aeroplanes.

5 Importance and criticality of the applications

5.1 Economic relevance

Table 11 summarises the structural components and materials containing CRMs in the target applications. Assembled printed circuit boards are presented in the table as a component, which further contains the bare circuit board and the electric subcomponents determined by the requirements of the application.

Europe's position in the applications' supply chains is also summarised in Table 11 and is based on the quantitative analysis carried out on production values from Eurostat PRODCOM database. Some more detail is presented in Tables 12-14. The box colours in Table 11 represent the production for the whole industry, not only the share which is used in production of a specific application. For example for electronic circuits, each box represents the total production of electronic circuits in Europe.

From Table 11 it can be observed that the European manufacturing industry is especially focused on end products. Significant European component production can, however, be found in several sectors where Europe is strong in applications. For example, wind turbine and MRI industries are focused both on end products as well as selected components. Also a significant share of the components used in European automobiles and aeroplanes is produced by European companies. The European electronic components industry has an impact on the EU economy both in production values and in jobs, and the biggest European companies, such as STM Microelectronics are amongst global actors. The production values of displays and screens are also quite significant, because most of the international companies have manufacturing or assembly plants in Europe. The European producers are focused on professional and specialised applications.

Components that are important for European end application manufacturers, but are mainly produced outside Europe, include permanent magnets and semiconductor dies, batteries, catalysts and magnesium alloys. As for materials refining and forming, Europe has production of steel alloys and some production of CRMs either from secondary or from primary sources (e.g. Co production in Finland and Norway from primary and in Belgium from secondary raw materials and REE production in Estonia) (Index Mundi 2014). Most of the production is, however, located outside of the EU.

The amount of jobs related to the applications of producing sectors in Europe was also estimated based on the information from Eurostat SBS and market reports. However, in Eurostat the jobs are reported at the 3-digit NACE sector level and therefore the numbers include jobs which are not directly connected to end application production. On sector level the European motor vehicles industry employed 2.3 million people, the European aeronautic manufacturing industry almost 500,000 and the heavy vehicles sector almost 400,000 people. The wind power industry, electric lightning sector, electric domestic appliances sector and manufacture of electronic components employed 100,000-200,000 persons each. On the consumer electronics sector (including displays and screens) and electro medical equipment sector the number of jobs was between 50,000 and 100,000. Production of optical fibre, CIGS thin film photovoltaics and NiMH/Li-ion batteries employed a maximum of 10,000 people each.

One has, however, to note that the amounts of jobs presented above are those of the total sector, and may in most cases include jobs that are not directly related to the application. For example the number of employees directly involved in the wind turbine direct drive industry was estimated to be about 10% of the wind power total (Table 12), LED lighting industry employed 10-20% of the electric lightning total and MRI production 20-30% of the electro medical total (Table 13). Irrespective of the source of information, the automobile, aeronautics and heavy vehicles industries are the biggest employers from the 12 application industries analysed.

Table 11: A summary of Europe's position in supply chains of the applications.

Supply chain	Application/component /material	MRI	LED lightning	Opt. fibre	Dis-plays	Wash-ing mach	Wind power	Photo voltaic CIGS	Batteries NiMH, Li-ion	Auto-mobile	Heavy vehicle	Aero-plane
End product	MRI											
	LED lighting											
	Optical fibre											
	Displays and screens											
	Washing machine											
	Wind power											
	Photovoltaic power											
	Batteries											
	Automobile											
	Heavy vehicles											
	Aeroplanes											
Component	Display											
	Electric motor											
	LED lightning											
	Wind turbine components*											
	Thin film panel											
	Batteries											
	Catalysts											
	Seats, steering, brakes											
	Assembled PCB											
Sub-component	Electrical circuit											
	Transistors											
	Capacitors											
	Resistors											
	Bare PCB											
	Connectors											
	Permanent magnet											
	Supercond. magnet	?										
	Conducting electrodes											
	Fluorescent tubes											
	Light-emitting diodes (LED)											
	Thin film materials											
	Anodes, cathodes											
Material	Superalloys, HSLA steels											
	Mg alloys											
	Compounds of REE											
	Tantalum											
	Be, Ga, Ge, In, Nb, W											
	PGMs											
	Co oxides											
	Lithium											
	Mg											
	Sb											

Explanations to Table 11	
(green)	Production in the EU and rather good position in global production/jobs in the EU (the sector in which application/component/material manufacturer belong to)
(orange)	Some production in the EU, however main production outside the EU/jobs in the EU (the sector in which application/component/material manufacturer belong to)
(red)	Not much production in the EU /jobs in the EU (the sector in which application/component/material manufacturer belong to)

Table 12: Economic relevance of the energy sector applications

Economic added value in Europe	Wind power • PM direct drive wind turbines	Photovoltaic power - CIGS Thin Film PV	Energy storage batteries - NiMH and Li-ion batteries
EU market and production: 1) application	Wind power total: • Market €12.8-17.2 Bn • Production €6.5-9.9 Bn Permanent magnet direct drive turbines: • Market €1.4-2.2 Bn • Four EU companies in global top 10 with 38% market share	Solar PV total: • Market €26 Bn • Production €4-6.6 Bn CIGS thin film technology: • Market €80 Million • Production reduced because of market decline • 4 EU companies in top 5 in TF equipment supply	Li-ion and NiMH production ~€320 mill (~4% of global) NiMH production much smaller than Li-ion (1/9 in 2012) • Small manufacturers, some leaders on niche markets • Dominated by Asian companies (Japan, Korea)
2) intermediate products	EU production of permanent magnets <2% of global market Production dominated by China, in some extent Japan	EU companies present in integrated CIGS production, scrap recycling and thin film material supply	Umicore world leader in cathode supply with 24% market share, but the plants are in Asia
3) raw materials	Nd an Dy production dominated by China	Secondary In and Ga production from process scrap	20% of global Co refinery production in Europe
Jobs in the EU	135,000 (wind power industry), 12,000 wind turbine direct drive industry	2,000 – 4,000	About 4,000
Future market expectations	Wind power: EU market €32 billion 2017, medium CAGR of 12%	Recovery of global TF market expected: Forecasts for the year 2016 €2.5-5.8 Bn (global market in 2012 €1.5 Bn)	Expected global Li-ion battery market about €13 Bn by 2016 NiMH battery market expected to decrease on the longer run

Table 13: Economic relevance of the ICT and electronics sector applications

Economic value for Europe	LED lighting	Magnetic resonance imaging	Optical fibres	Displays and screens	Washing machines	Assembled PCBs/components
EU market/ production 1) Application	• Market ~€1 Bn • Production €0.6- 0.8 Bn • Share of 3 top producers 62% of EU sales • 750-1,000 EU companies	• Market €0.7-0.9 Bn • Production €0.5-0.6 Bn • Three global top actors have production in Europe	• Market €2 Bn • Production €1.4 Bn • Prysmian one of global top producers	• Market ~€23 Bn • Production ~€14 Bn • Several plants owned by Asian companies • EU company focus on professional and niche markets	• Market €5.7 Bn • Production €4.6 Bn • 2 European companies in global top 5	• Production of electronic components about €23 Bn • Top producers in Asia/USA • One EU company in top 10 • European consumption about 20% of global
2) Intermediate products	• 78% of LED die production in Asia • One EU producer in global top ten, ~7% market share	• Superconducting magnets produced by EU MRI companies • China main PM producer	• Fiber optic preforms mainly produced in China (> 50%), USA + Japan	• Asia dominates in components • Some European production	• China main PM producer • Some EU production	• Production values of components & sub-components presented above
3) Raw materials	Germany and Ukraine in top three Ga producers	>90% of Nb produced in Brazil, > 90% of REEs in China	China main Ge producer, Umicore significant producer of recycled Ge	Some indium recycling in Europe	>90% of REE production in China	Most CRMs produced outside Europe
Jobs in the EU	150,000–200,000 (electric lighting sector), LED lighting 10-20% of total	46,000 (irradiation + electromedical equip. sector total), MRI prod. ~20-30% of jobs	About 9,500	About 80,000 (consumer electronics sector total)	195,000 (Total electric domestic appliances sector)	195,000 jobs in manufacture of electronic components sector
Global market	€9 billion	~€3 billion*	147 million km of fibre	€70 billion	~€130 billion*	€110-200 Bn**
Market expectations	€64 Bn 2020 (global)	~€4 Bn 2018* (global)	205 million km 2017 (global)	€270 Bn 2020 (global)	Respectable growth in Asia, Africa, South America	Over €150 Bn in 2017 (active components)

* Large household appliances

**Depending on definition (active components, active + passive components)

Table 14: Economic relevance of the transport applications

Economic added value in Europe	Automobiles	Heavy vehicles	Aeroplanes
EU market and production: 1) application	• Market €170 Bn • Production €224 Bn • Three EU companies in global top 10 • The global market share of European companies ~30%	• Production €34 Bn • Three European companies in global top three • The global market share of European manufactures ~58%, production mostly out-side Europe	• Production ~€7.85 Bn (57% of global production) • Two European companies in global top three • The global market share of Airbus in large commercial airplanes is ~50%
2) intermediate products	• European companies are significant producers of e.g. following components: exhaust after treatment systems, Pt catalysts, steering, seating, airbags, brakes, tyres castings for vehicles and automobile electronics • Most of these components are used by EU manufacturers • All the production is not in the EU, e.g. most of the catalyst manufacturing	• Component production profiles quite similar with automobiles • European companies are also present in production of most of the components for heavy vehicles	• European producers are strong e.g. in production of mechanical components, navigation systems, pumps, engines, electronics • Rolls Royce – Engines • Airbus • Finmeccanica
3) raw materials	Production of most of the CRMs and some of the alloys is dominated by non-European companies		
Jobs in the EU	• 135,000 • 2.3 million, automobile manufacturing sector total	• Production of trucks ~73,000 • 380,000, heavy vehicle sector total	• Aeronautics manufacturing industry total ~450,000
Global market	63 million automobiles 2012*	7.6 million heavy vehicles	~2,100 aeroplanes/a (€13.8 Bn)
Market ex-pectations	Solid growth of production expected* Emerging markets' share 50% in 2012, 60% by 2020	5.5% growth expected 2012-2022**	~ 29,000 aeroplanes produced by 2032 (Current fleet ~18,000)

*McKinsey Company (2013) and OICA (2014)
**Frost&Sullivan

Market reports predict that both the European and global market of most of the applications will grow significantly by the year 2020, leading to increased consumption of CRMs. From Table 13 one can see that although the amounts of CRMs used in LEDs are quite low, the forecasted demand of LED lighting in 2020 is almost sevenfold compared to that in 2011. Also the growth expectations for displays, wind power, Li batteries and optical fibre are high (Tables 12 and 13). Solid growth is expected in all the transport applications especially in the emerging market.

The only exemption from the growth trend amongst the applications analysed is NiMH batteries, the consumption of which is expected to decrease.

5.2 Criticality and strategic relevance

The shares of the most essential CRMs consumed globally in the manufacture of target applications vary from less than one per cent to over 50% (Tables 15, 16 and 17). Examples of applications which dominate the demand of individual CRMs are for instance catalytic converters (Pd and Pt), displays and screens (In), electronic components (Ta and Ga) and permanent magnets (Dy). The strong European end producer industries, which are dependent on these components, include manufacturers of automobile and heavy vehicles using catalytic converter systems and permanent magnets as well as the manufacturers of direct drive wind turbines using permanent magnets.

Table 15: Energy sector applications: Criticality and opportunities for Europe

	Wind power **PM direct drive turbines**	**Photovoltaic power** **CIGS Thin Film PV**	**Batteries** **NiMH and Li-ion Batteries**
Use of CRMs in main components	Permanent magnets installed in Europe in 2012 (~1,140 tonnes): • About 330 t/a of Nd (2% of global production • 34 t/a of Dy (7% of global production)	CIGS PV modules installed globally in 2012 • About 17 t/a of In (1.5% of global production) • 5.6 t/a of Ga (1.2% of global production)	Global Li-ion battery production: • 21,000 t of Co (~37% of global production) • 18,000 t of graphite (~1% of global production) Global NiMH battery production: • 2,300 t of Co (~3% of global prod.) • REEs as mischmetal in battery anodes
Essentiality of CRMs	• Substitution activities on-going on permanent magnets, but no substitute conceivable for same end properties	• Replacing by crystalline PV or CdTe thin film technology possible • CIGS TF technology using less material could be achieved in short term	• No substitutes for Co-based Li-ion batteries used in portable electronics • Potential non-Co-based substitutes exist for EV and HEV Li-ion batteries • New chemistries for Li-ion batteries and next-generation batteries in research stage
Development of vulnerability over time	Bottleneck reliance of permanent magnets from abroad • Need of permanent magnets installed in Europe grows from 1,140 t/a to 2,460 t/a by 2020 • Dy most sensitive	Only a few percent's of world In and Ga needed for CIGS production in 2016 (in an optimistic growth scenario)	No shortage of Co expected for the next ten years • A surplus of production expected due to new Cu mines • Decrease of the Co content in batteries expected.
Impact on EU policies in case of disruption	Off-shore wind power important for the EU renewable energy strategy	CIGS TF PV of minor importance, in medium term no impact on EU energy policy	Li-ion technology is key to electric & hybrid vehicles
Opportunity for Europe	• Opportunity for increased integration towards magnet production or setting strong agreements with suppliers • Recycling of REE from permanent magnets	• Dynamic nature of PV enables EU positioning on new PV technologies through R&D	• Europe's position in R&D creates opportunities for good positioning in next generation batteries • Development of EV and HEV creates possibilities for new local suppliers

Table 16: ICT and electronics sector applications: criticality and opportunities for Europe

Economic value for Europe	LED lighting	Magnetic resonance imaging	Optical fibres	Displays and screens	Washing machines	Assembled PCBs/components
Use of CRMs in main components	LED diodes and phosphors: • Ga, In, Gd, Y <0.1% of global supply in 2010 • PCBs: Several CRMs in small amounts	• Superconducting magnets: Nb <3% of global supply • PMs (Nd, Dy) in low field systems (in 5-15% of MRIs) • Be, Ho, REEs etc. in spring contacts, motors, PCBs, displays • He essential	Dopant in optical fibre • 30% of global Ge supply used • Er doped fibres produced in small amounts	FPD modules: • 50% of primary and 80% of total (primary + recycled) In • REEs used in LED backlights, loudspeaker magnets and electronic components (smaller amounts)	Perm. magnets in ~20-30% of washing machines • ~1-2% of Nd and 3-7% of Dy consumed in Europe	Several CRMs used in components, small amounts/unit • Significant shares of global supply of e.g. Ga, Ge, and Ta consumed in electronic components
Essentiality of CRMs	Very essential	Nb, Be, Ho essential, no substitutes or development needed (Nb)	Ge very essential, substitution leads to low performance	Potential substitutes for In studied, still in development	Not essential, reduce energy consumption	Most CRMs still essential
Development of vulnerability over time	• Availability of LED bulbs may form a bottleneck • Shares of CRMs used in LED production low, market growth expected	• Not very vulnerable • Availability of Nb, Be (+ He) may form a bottleneck, the share of total Nb used in MRIs is small	• Growing market Ge shortage may cause problems • Risk reduced by availability of Ge from European recyclers	• Growing market • Scarcity of In potential bottleneck • Potential risk of mass production moving out from Europe	• Not very vulnerable	• Demand of several CRMs expected to grow • Development of vulnerability difficult to estimate
Impact on EU policies in case of disruption	• Reduction of energy efficiency • Economic risks for SMEs • Harder to achieve GHG reduction goals	• Losses in high added value market	• Relevant for digital agenda for Europe • Losses in energy efficiency	• May enhance market penetration of OLEDs • Risk of unemployment	• Use of AC motors (no permanent magnets) leads to higher energy consumption	• Significant for production of electronic devices, ICT systems, etc. • Significant for employment
Opportunity for Europe	• OLED technology/products • Innovative LED applications • Greener product/manufacturing solutions	• Keeping EU's strong position in medical applications • R&D for less CRM consuming, energy efficient technologies	• Development of efficient wire-less technology and CRM-less cables with high efficiency	• Development of OLED/other less CRM dependent technologies	• Innovative machines with lower energy and water consumption	• Clustering • Electronics for innovative professional applications • Additive manufacturing, flexible and printed circuits

When analysing the supply chains it was found that several European end products are dependent on CRM containing components manufactured outside of Europe. The global consumption of some of these important components will grow significantly in the future. The increased need of electronic components is ensured by the use of electronics almost everywhere. The same applies to permanent magnets, which are used in several applications with growing markets, including electric or hybrid cars, wind power and small electric motors for instance in transport applications, consumer electronics and domestic appliances.

The majority of permanent magnets are produced in China and current substitute solutions still suffer from performance problems. Therefore their availability may form a bottleneck for European producers of especially direct drive wind power and transport applications. They are at highest risk because of the essentiality and high demand for permanent magnets. According to the market reports dysprosium will be the limiting element because a high percentage of total production is consumed in permanent magnets.

LED bulbs are a second example of potentially critical components, which are mainly produced in China. In addition to conventional lighting applications, they are used for instance in car lights and as backlights in LED TVs. The amounts of CRMs used in LEDs are small, and in spite of the high market growth expectations only a small percentage of total production will be consumed in LEDs in 2020. However, disturbances in availability of LED dies may form a bottleneck in the value chain of LED lighting.

Printed circuit boards and electronic components are common for almost all the target applications. It was not possible to define exactly, how dependent the European producers are on the components produced outside Europe. The data available in market reports shows, however, that the European producers are focused on production of electronics used in the applications in which Europe is strong, including transport, energy, medical and other industrial applications. Therefore it can be estimated, that the potential bottlenecks may be more related to the availability of CRMs for component production than availability of components. It is estimated that over half of the total supply of gallium, ruthenium and tantalum and about 20% of the supply of platinum and beryllium is used in production of electronic components. The amounts of CRMs used in individual components are small, and from the industry viewpoint miniaturisation of components seems to be more feasible than substitution of CRMs.

Other components that are mainly produced outside the EU include catalytic converters, Li-ion batteries and magnesium alloys.

Table 17: Transport sector applications: criticality and opportunities for Europe

	Automobiles	Heavy vehicles	Aeroplanes
Use of CRMs in main components	Catalytic converters: • Pt, Pd, Rh, Ce Electric motors: • Nd, Dy Mg alloys • High and ultra-high strength steels Electronics and sensors • Several metals	CRM dependencies mostly similar to automobiles The following components are unique for heavy vehicles: • Energy storage batteries Li, Ta, Co • Advanced cooling and emission purification: REE	Brakes: • 32 t/a Be (~11% of global production) Alloys: • Mg in light-weight Al alloys • Ta and Nb used in superalloys and HSLA steels Navigation system: • Ge and Sb
Essentiality of CRMs	• Pt essential for catalytic converters, Pd potential substitute - no non-CRM substitutes • Nb and Ta high-strength steels essential for safety • In future composites or polymers may substitute some uses for alloys • Electronics and electric motors are very essential for modern cars, availability of components and PMs potential bottleneck	• Nb and Ta high-strength steels essential • Electronics and electric motors also essential • Li and Co significant for energy storage	• The above mentioned CRMs are essential for the industry • Substitution of Nb is somewhat possible • Potential substitutes of Be and Mg suffer from poor performance • New chemistries for Li-ion batteries and next-generation batteries in research stage
Development of vulnerability over time	• Shortages in supply of Pt and Pd potential, availability of catalytic converters may form a bottleneck • Transition to electric and hybrid vehicles can lead to increased use of REE (permanent magnets) • Manufacture of automobiles may shift to the east (bigger market, lower cost)	• Most of the production of batteries is outside Europe. No indications of Li and Co availability risks in near future • Availability of electronic components and permanent magnets a potential bottleneck	• Overall aeroplane markets do not seem very vulnerable • Be may form a bottleneck for European industry (growing use, high cost, toxicity). • No indications of Li and Co availability risks in near future. • Potential surplus of Co production expected
Impact on EU policies in case of disruption	Disruption in availability of Pt and Pd may favour shift to electric vehicles, which do not need catalytic converters	Disruption in availability of Pt and Pd may favour shift to electric vehicles, which do not need catalytic converters	Loss of competitiveness
Opportunity for Europe	• Good positioning in exhaust after treatment systems favours further development and export	• Good positioning in exhaust after treatment systems favours further development and export	• Europe's leading position in aeroplane manufacturing, recycling, new materials and substitution a big opportunity to increase competitiveness and export

The criticality aspects of the target applications can be summarised as follows:

Energy applications:

- Permanent magnets may form a bottleneck in direct drive wind turbine production.
- The CIGS thin film PV does not seem very vulnerable, because only a few percent's of global In and Ge production will be used, even if the market recovers.
- Almost 40% of world cobalt production is used in Li-ion battery production, but it is expected that there may be even surplus of Co in the future because of new Cu mining activities.

ICT and electronics applications:

- In spite of the expected very high growth of the LED lighting market, the shares of CRMs used in LEDs will be small. The availability of LED dies may form a bottleneck in European production, especially for SMEs, because the main part of the bulbs is manufactured by non-European companies.
- Europe is strong in the production of MRI (magnetic resonance imaging) and the key component: Nb containing superconducting magnets. The other CRMs essential for the application include Be and Ho. The sector does not seem very vulnerable and only small percentages of the total production of the CRMs are used. No significant growth in the use of CRMs is expected.
- The market for optical fibres will grow due to the shift to high-speed broadband in data transfer, leading to growing consumption of germanium. Currently about 30% of Ge is consumed in optical fibre and no substitutes are available. The availability of Ge may form a bottleneck for EU industry, although the risk is reduced by the availability of recycled Ge.
- Significant parts of the European production of screens and displays are in possession of large Asian companies. European manufacturers are focused on professional and niche applications. Instead of availability of CRMs, the main risk may be the shift of Asian producers from Europe because of production costs.
- Permanent magnets are used in washing machine motors for better performance and energy savings. It is possible to use alternative motors, although this reduces energy efficiency.
- European production of electronic components is important for several sectors, which produce innovative end applications. The production is also economically important for Europe. Although the sector and end users have not seen substitution of CRMs as a priority, the shortages in availability of some CRMs may be a risk to the European companies, especially when the main competitors are Asian companies.

Transport applications

- All the transport applications are dependent on the use of components containing CRMs. The most important dependencies of automobiles and heavy vehicles include catalytic converters, permanent magnets, magnesium alloys, superalloys and electronic components. Li-batteries are important for heavy vehicles. The substitutes of the above mentioned components are either non-existent or suffer from performance problems. Especially problems in availability of catalysts and permanent magnets may form a bottleneck for European producers, if there will be shortages of Pd and Pt for catalysts or Dy for permanent magnets.
- European companies are strong in production of aeroplanes and their components. The most significant CRM dependencies include use of Be in brakes, Mg in alloys and Ge in navigation systems. The substitutes still suffer from performance problems, and especially availability of Be may form a bottleneck. However, the aeroplane sector does not seem to be very vulnerable.

6 Industry perspective of CRM

To obtain detailed, reliable information which is not available from existing sources, semi-structured expert interviews were conducted with nine industrial companies from different countries. The focus was on current and anticipated future risks associated with critical raw material dependent applications as well as current risk provision strategies. This chapter presents information about the methodology used and the sample as well as the outcomes of the conducted interviews. The sub-chapters describe the interviewees' views on CRMs, risk management measures, possible future developments / expectations towards the EU and implications.

6.1 Methodology and sample

6.1.1 Methodology

The study originated from the need to explore (best) practices for CRM strategies from an up-to-date industrial perspective. A qualitative research approach was chosen to find out about practical experiences with CRMs and to obtain an overview of the present and future risk management measures of companies from different sectors (ICT and electronics, energy and transport).

Semi-structured interviews were conducted, which are the most commonly used type of interview in qualitative research (Stuckey, 2013). This approach allows the use of predetermined lists of questions and free conversation covering the breadth and depth of the subject as well as obtaining both multifaceted and comparable material (Clifford et al., 2010). In contrast to structured interviews, the semi-structured approach allows the interviewer to apply a relatively open, flexible and fluid structure; sequences of questions do not have to be asked in the same way in all the interviews which provides a chance to identify new ways of seeing and understanding the topic (Mason, 2004). However, the pre-defined key aspects ensure the same interests are addressed in all the interviews. Reliable and comparable qualitative data can thus be obtained (Stuckey, 2013).

Content analysis was then used to interpret and organise the obtained data. As a first step, the recorded interviews were transferred into interview protocols. In the next step, to reduce complexity, key issues were identified. The topics were structured based on the interview guideline, e.g. sourcing, substitution and recycling. After that, all the interviews were analysed and each statement was extracted which comprised direct or indirect information concerning the selected key issues. Finally, the collected statements were interpreted.

6.1.2 Sample

In total, nine large industrial companies from different countries were interviewed between June and October 2013, either by telephone or face-to-face. In preparation for the interview, the EU-14 list of CRMs (European Commission 2010) was sent beforehand to the experts so that they could identify which of these materials are critical for their respective company. In each interview, the companies were represented by one to three managers with a background in at least one of the following fields: materials, product, quality, sustainability, innovation, risk or supply chain management, which underlines the interdisciplinary character of the topic. For the electronics and ICT sector, three interviews were conducted with producers of mobile phones, of magnetic resonance imaging systems (MRIs) and of magnetic components. Three interviews with producers of wind turbines, permanent magnets and gas turbines were conducted for the energy sector. Companies from the transport sector included car suppliers, airplane and automobile producers. Table 18 gives an overview of the conducted interviews.

Table 18: List of conducted interviews

Company	Sector	Application	Country	Position in value chain	Interview form
Company A1	ICT and electronics	Magnetic resonance imaging	Western Europe	OEM	📞
Company A2	ICT and electronics	Smart phones	FIN	OEM	👥
Company A3	Energy	Wind turbines	GER	OEM	📞
Company A4	Transport	Automobile production	SE	OEM	📞
Company A5	Transport	Aviation	GER	OEM	👥
Company A6	Energy	Gas turbines	USA	OEM	📞
Company B1	Energy	Permanent Magnet Generators	FIN	Tier 1-2	📞
Company B2	Transport	Drives/motors	GER	Tier 1	👥
Company C1	ICT and electronics	Magnetic components	SLO	Tier 2-3	📞

When evaluating the interviews, one has to keep in mind that the strategies of original equipment manufacturers (OEMs) differ from companies at other positions along the value chain. The producer of magnetic components for instance is at a lower step of the supply chain, 1 to 2 tiers beneath the OEM. In the present sample, OEMs are over-represented to obtain information about the extent to which large companies at the end of the value chain are aware of the CRM issue and how they are dealing with this challenge. The following figure gives a simplified overview of the interviewed companies with respect to their position in the value chain.

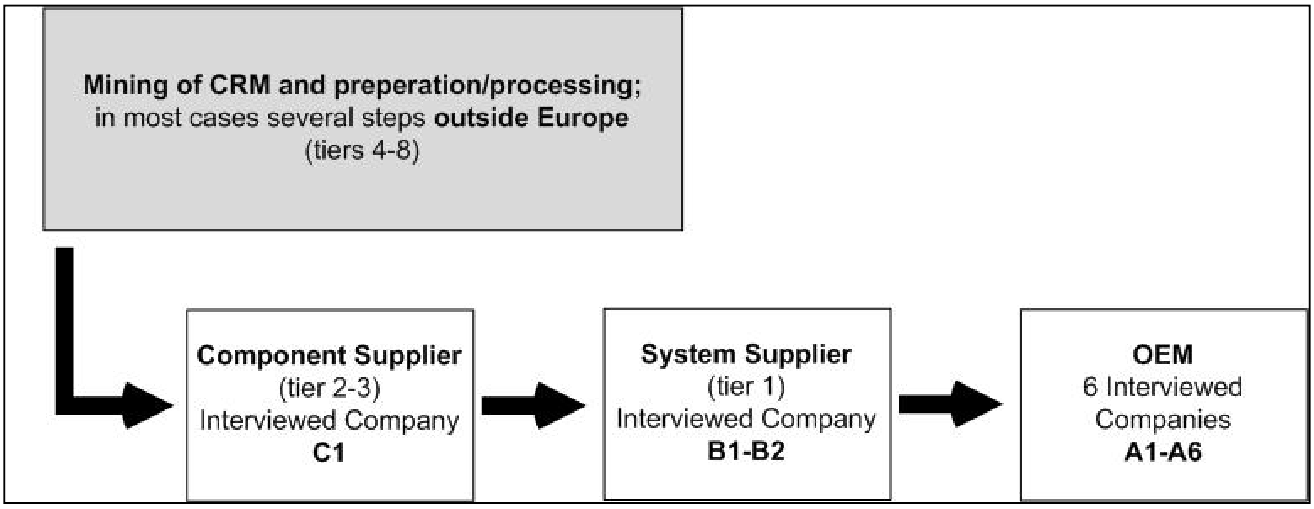

Figure 7: Companies' position in the value chain

Another important notion is that CRMs play a different role depending on the lifetime of a product – while smart phones have a rather short lifespan of about four years, planes have a longer serviceable life of about thirty years. Also, the absolute volume of CRM needed differs due to the size of the targeted products.

Overall, it can be stated that it was difficult to find interview partners who were able and willing to talk about critical raw materials. One reason might be the advanced interdisciplinary knowledge needed for the topic. Another is certainly that companies want to avoid disclosing critical information about possible supply risks. Therefore, confidentiality was assured here by anonymising the sample. Another lesson learned when looking for interview partners is that many companies cannot relate to raw materials as defined in the EU list of CRMs – depending on the company's position in the value chain and on the size of the company, components or compounds are more relevant. Last but not least, the financial crisis impeded access to some industries and some countries, e. g. photovoltaic producers in southern Europe.

Since the outcome of the interviews shows a clear overlapping of issues across sectors, a problem-oriented approach was chosen to structure the following sub-chapters.

6.2 Critical Raw Materials according to the interviewees

The experts agreed that the term "critical" should **not only** be used to describe a resource that is **scarce**, but a resource that provides **unique properties and functions** and therefore has few alternatives. Important functions of CRMs named by the interviewees were:

High degree of storable magnetic energy
Weight savings which lead to high efficiency
High degree of hardness
Good corrosion sensitivity
High temperature resistance
Low maintenance requirements
Usage for metal refining and in catalysts
Long lifetime of products
Superconductivity

Many interviewees claimed that an actual physical scarcity was not the reason for criticality, except for the materials dysprosium and terbium. Furthermore, indicators for the "criticality" of materials are also seen in the relationship with the supplier and in the price of the materials. Besides functionality, the following indicators were named as defining the criticality of a raw material:

- Fluctuations in prices (due to higher demand or speculation)
- Cost increases in mining
- Increasing demand due to new technologies / due to emerging economies
- Strong political influence (monopoly position, export quotas and taxes)
- Dependence on and monopoly status of supplier
- Lack of suitable technology to open up new resources

Figure 8 shows which CRMs were named by the interviewed companies. Neodymium (named seven times), dysprosium and terbium (each named five times) are classified as the most vital / critical for production by the sample companies. However, one has to keep in mind that magnetic components (which are also used in smart phones, wind turbines and MRIs) were over-represented in the sample. Some of the interviewees suggested adding helium (He, named by companies A1 and A6, used as operating supply), rhenium (Re, named by company A6, used as an additive for superalloys in gas turbines) and molybdenum (Mo, named by company A4) to the EU's list of CRMs. According to companies A4 and A5, magnesium should not be on the list as it is not rare and can increasingly be substituted by new synthetic materials. However, two other companies claimed magnesium was a CRM for them, saying it is not rare but hard to replace (companies A2 and A6). Company C1 stated that materials like steel also deserve special attention, simply because so much of it is needed (due to C1, Nd amount needed in the yearly production is around 0.002% of steel amount needed).

Antimony (Sb)	2*	Holmium (Ho)	1	Promethium (Pm)	
Beryllium (Be)	2	Indium (In)		Rhodium (Rh)	1
Cerium (Ce)		Iridium (Ir)		Ruthenium (Ru)	
Cobalt (Co)	2	Lanthanum (La)		Samarium (Sm)	
Dysprosium (Dy)	5	Lutetium (Lu)		Scandium (Sc)	1
Erbium (Er)		Magnesium (Mg)	2	Tantalum (Ta)	2
Europium (Eu)		Neodymium (Nd)	7	Terbium (Tb)	5
Fluorspar (CaF_2)		Niobium (Nb)	1	Thulium (Tm)	
Gadolinium (Gd)		Osmium (Os)		Tungsten (W)	1
Gallium (Ga)	1	Palladium (Pd)		Ytterbium (Yb)	
Germanium (Ge)	1	Platinum (Pt)		Yttrium (Y)	2
Graphite	3	Praseodymium (Pr)	3		

* Named by the different interviewed companies

Figure 8: CRMs named by the sample companies

Due to confidentiality concerns, detailed information on which CRM is used in the different components was difficult to collect. However, in the following, more technical details of the different applications are elucidated.

Companies A3 (wind turbines), B1 (permanent magnet generators), B2 (drives/motors) and C1 (magnetic components) identify Dy, Nd, Tb, Pr as the most critical raw materials.

Rare earth elements (REE), which are a subgroup of the CRMs listed above, can be divided into heavy (HRE[2]) and light RE (LRE[3]). Dy and Tb are HRE. HRE are currently only sourced in China and defined as critical by company B2 with a market price of €700-800 /kg. However, LRE, such as Pr and Nd are also sourced in other countries and are thus less critical with a current market price of US$70-80 /kg.

NdFeB permanent magnets are typical components which are used by several of the interviewed companies, such as C1 and A3. These are based on the LRE element Nd and are vital for achieving high magnetic field strength. On average, a NdFeB magnet consists of around 32% of total rare earths (Nd, Pr, Dy, Tb), in which some 22 - 30% is Nd. Nd is alloyed with the HRE elements Dy and Tb, which are vital for magnetic field strength and for temperature resistivity. Thus, they provide stable temperatures during magnetization which leads to a long-term stability of magnets. Dy and Tb can be up to 10% of a magnet, enabling working temperatures of up to 200 °C. Other advantages of these magnets are their lighter weight and better durability.

At present, the Chinese market is the biggest supplier of REE. Company B2 states that 95% of REE are sourced in China. However, the emergence of mining corporations outside China such as Lynas (Australia) and Molycorp (USA) shows some development in the CRM market that will lead to lower prices, especially for LRE (e.g. Nd and Pr) elements.

[2] Heavy rare earth elements are Y, Tb, Dy, Ho, Er, Tm, Yb, and Lu.
[3] Light rare earth elements are Sc, La, Ce, Pr, Nd, Pm, Sm, Eu, and Gd

The interviewee from company B2 stated that REE are used in 25% of their products, e.g. in motors for steering wheels or propulsions for automatic transmission systems. In total, the company needs approximately 350t of REE. When purchasing REE magnets, the company spends around €60-70 million , whereas the price of the raw material is about €25-30 million. Thus, a cost increase factor of 2.3 applies to the production of REE magnets.

Company C1 also claimed graphite to be critical for them due to a five-fold price increase from 2010 to 2011. Graphite serves as an "intrinsically" lubricated current conductor which, in combination with carbon (graphite) brushes, reduces abrasion of the commutator (compared to commutators which use Cu) and therefore means a longer lifetime for motors that drive fuel pumps (for example a Cu-based commutator runs for around 5,000 hours, while a graphite-based commutator runs for 10,000 hours). Additionally, graphite-based commutators are more resistant to "dirty" fuels.

In smart phones, the metals Nd and Dy are used in the powerful loudspeaker magnets and the passive components Co and Li in the battery; In is used for the LEDs and displays and Ga for the processor. Around 106 tons of REE metals are used each year to produce smart phones, which constitutes 0.09% of global production. If the use per phone of all smart phone producers is approximately the same, the smart phone sector's rare earth metals use would have been 290 tons in 2008 (corresponding to 0.25% of yearly rare earth metals' production). Nd is the most commonly used REE in the mobile phones of this producer (80-90% of all rare earths), as it provides the required magnetic properties using far less space than other magnetic materials. Thus, Nd cannot be replaced, even though just a small quantity is used – the available space in mobile phones is just too constrained. Other CRMs are important for mobile phones as well, e.g. advanced smart phones use about 10 times more Ta than simple smart phones or normal cell phones.

Company A1 named the following three materials from the EU-14 list as critical for the production of MRIs, due to their irreplaceable functionalities.

- Be: has certain mechanical qualities combined with electric qualities (especially used in spring contacts – Be-Cu – for shielding the magnet and to obtain a durable, solid resolution; other materials would break), sourced in the USA;
- Nb (part of the magnet): used in superconductive threads, sourced in Brazil;
- Ho: used in the coldhead as a He-liquefier to prevent evaporation of He and be able to reuse it. Ho is sourced in China, USA, Australia and Sri Lanka.

Additionally, He is regarded as a CRM for the MRI industry. Liquid He is needed to achieve superconductivity and is becoming scarcer with no proper alternative at hand. He slowly evaporates and the coldhead is used to liquefy it again (with the help of Ho).

Company A6 states that coatings containing Y are needed for high temperature resistance in the high pressure section in gas turbines – otherwise the performance of gas turbines would be too inefficient.

Company A5 regards Sc, which is used for the lightweight construction of airplanes**,** as a very critical material. It provides a refined grain structure (limits grain growth in Al alloys) and therefore permits easier welding, which is important, as welding replaces riveting in construction. Cu content in Al allows welding too, but also increases the risk of corrosion. Sc is extremely rare and, even though very little is required; its scarcity is a threat. Supply could be artificially restricted by China and Russia, which would drive up prices. Al-Li alloys may be a possible substitute (see chapter on substitution below).

6.3 Risk management measures

6.3.1 Substitution

Company A2 stated that a proactive approach to substitution allows companies greater flexibility before legislation forces action. Certainly, all the experts agreed that substitution is a demanding task since usually not just one material is replaced but a complete process might need to be reconfigured. Also, the supply chain needs to be alerted early on, as substitution might require significant rearrangements. Substitution of CRMs by process or application innovation takes a long time and even a change in just one material could change the entire product.

Companies C1 and A3 stated that a general approach in industry is to not substitute a single material, but to replace the product application or the specific material containing CRMs. Thus, solutions to substitution challenges have to be looked at from a functional perspective in order to find one which uses a less critical material. One example was mentioned by C1 for a brushless motor (which runs the air-conditioning compressor in a car): if NdFeB magnets were used, the motor itself would be 5 cm long; with SmCo magnets, the motor would be 6 cm long and with ferrite magnets, the motor would be 10 cm long. Hence, if there is enough space for the motor and the OEM agrees to use this space, there is no problem in changing the material. However, this is not possible in most cases and the material with the best characteristics is used, which generally means the smallest application in order to save space.

Company A6 also points out that substitution can be done both ways: from a material point of view, for instance, one could replace one coating formulation with a different one, or, a complete system substitution might be conceivable that eliminates the need for the coating entirely (eliminating the substituting material by changing the overall system design).

Furthermore, differences in the respective industries have to be noted. In fast-paced technology life-cycles, substitutions need to be made on time, otherwise it is hard to cover lost ground and major redevelopment may be required. On the other hand, the aircraft industry, for instance, is rather conservative/long-term oriented; if one material qualifies for production, it will be used for the next 20-30 years (approximately 60,000 hours of operation). Material qualification is therefore very expensive (several million euros). It has to be proven that the material is reliable i.e. constantly provides the same properties with regard to corrosion and fatigue – important factors for aircraft safety. Problems, e.g. with adhesive materials, may cause a delay of one year, meaning costs of about 1 billion Euros. Company A5 stated that, apart from smaller electronic or interior materials, it is not possible to change materials more often than every 5 to 10 years (due to qualification/longevity requirements). In the aviation industry it can take up to two years to find suppliers and optimize a material, another two years to qualify the new material and, generally, at least three to five years to substitute a material. An example of successful substitution is the replacement of Sc by Al-Li: Li is not rare and reduces the weight of a component while increasing stiffness by 10% (for a Li content of approximately 1%). At the same time, it has a negligible effect on solidity.

The other experts also emphasised that no inferior materials should be used – quality always comes first. However, it is the CRMs that often provide the best (known) functionalities. To give an example, company C1 stated that Cu can be used instead of graphite (for the same price) e.g. in a fuel pump, but this causes service time decreases from 10,000 working hours to 5,000 working hours.

Additionally, substitution is often not seen to be worthwhile. Company A3 remarks that the influence of raw material prices depends on the complexity of the product due to the added value in production – raw material prices often have little influence on the final product price. On the other hand, company A6 points out that the quantities of CRMs used are small, but – at the same time – the added value is relatively high, so that price increases can often be absorbed.

Several examples of substitutions also showed that one CRM was replaced by another CRM, e.g. substitution of Pt with Pd or Dy replaced by Tb and Nb replaced by W.

Company A2 stated that it is frequently not an actual physical shortage that drives substitution or efficiency efforts, but higher demand leading to higher prices (e.g. the increasing demand for smart phones and tablets; price as a natural trigger for substitution). One example is indium tin oxide (ITO), which is not rare, but underwent significant price increases due to growing demand. Since no direct substitution was possible, a focus on minimizing/optimizing became necessary (fewer layers of ITO).

Company C1 stated that overestimations of demand also caused price fluctuations in the past, in particular demand for Nd-Dy based permanent magnets or for flake graphite for Li-Ion batteries for electric vehicles. However, as company C1, which is closer to the raw materials than other interviewed companies stated, demand does not follow predictions.[4]

The experts also emphasised the difference between critical and hazardous materials. However, some of them are both, such as Be, which was substituted by the producer of smart phones in 2009, or Sb, which was substituted in 2010. The phase-out of Be, which is used in connectors of mobile phones, took six to seven years. It was necessary to identify how much and where Be was used. Suppliers were contacted to find out their thoughts about phasing-out Be, what alternatives there are and what the supplier's plans were for the substitution.

In 2008/2009, company A6 addressed the consumption of Re over a period of five years, using several approaches, including the qualification of substitutes. Rhenium is used in gas turbines but also in aircraft engines and the market is very small.

Company A1 stated that research on using pure Cu instead of Be-Cu in the radio frequency shielding of MRIs had failed – this does not represent a sustainable solution for the parts as it constantly needs replacing and does not retain its strength. This company also created new technologies to preserve He, which they also regard as critical (see above). While the old system evaporated He so that it had to be refilled, a zero boil-off system makes He reusable by re-liquefying the He, meaning that much less He is needed over the lifetime of the system.

Companies A3, B1 and B2 all reported efforts to reduce / substitute Dy (heavy RE) by reducing temperature resistance, using Tb or different magnet technologies (with limitations, as referred to above, e.g. ferrite magnets are heavier, which is critical for lightweight constructions).

Company B1 (permanent magnet generators) could not refer to examples of CRM substitution. The company claimed it produced big applications, where no real alternatives to Nd magnets can be found. Additionally, B1 is – compared to the other interviewed companies – smaller (even though still classified as a large company) and therefore claims to have greater difficulties in changing the existing product line.

According to the interviewees, substitution projects are only initiated after a thorough business impact analysis and take several years in which lots of different criteria have to be taken into account. Questions asked by such an analysis include:

- What are the substituting materials?
- What are competitors doing?
- What are the impacts on the components?
- Who are the providers of the components?
- How will substitution change the product?

Multifunctional teams (MFT) evaluate technologies early on in a cross-disciplinary approach with team members from engineering, procurement and manufacturing. Accordingly, reviews allow the system to be modified early on.

[4] C1 stated that demand does not follow predictions and gives the following example: In 2009, demand was predicted to grow from 110,000 tons rare earth oxides per year to 200,000 tons in 2015. Today, (2013) however, demand is still around 110,000 tons per year. The predicted demand was based on full electric vehicles using permanent magnet drives and wind power generators using REE permanent magnet generators. This demand has not (yet) materialized.

6.3.2 Sourcing

Companies A1 to A6 are OEMs assembling ready-made components and operating at the very end of the supply chain with 6 to 8 tiers beneath them. Therefore, a risk strategy that considers becoming part / owner of a mine is largely denied. Company A3, however, is involved in the material supply chain (incl. REE magnets) and is also reporting negotiations with mining corporations about possible cooperations.

All companies try to ensure they are not too dependent on just one supplier. Company A1 (MRIs) suggests that even if one is not dependent on a single (component) supplier, the different manufacturers could obtain e. g. Ho from just one supplier; therefore there is still a supply risk. The supply chain is simply too long for many OEMs to monitor in detail and they do not track where every material comes from. According to company A1, a code of conduct is therefore advisable, also to make sure all suppliers act within the legal framework.

Company A5 (aviation) states that a differentiation between critical and non-critical parts is necessary. For critical parts, it may be reasonable to move downstream in the supply chain, 'closer' to the mines. Class 1 parts for instance are critical for safety; the suppliers know of their importance which increases the price. There are strong dependencies because of the few providers and the qualification requirements. Supply contracts can last up to 20 years. Parts of the primary structure of a plane are not bought via intermediaries, but directly from wholesalers/manufacturers (e.g. aluminium, composites). For less critical parts, it is possible to switch suppliers within months, which leads to lower risks. Multifunctional teams are also beneficial in sourcing: involve manufacturing, procurement and engineering early on for front loading risks. Generally, supplier networking is regarded as being of great importance.

The expert of company C1 visited around 10 NdFeB magnet producers between 2011 and 2013. According to C1, input stock of rare earths materials is high. Some PrNd, FeDy barrels carry a delivery date of April 2011 and are still not being used today. If a company bought stock for 14,000 Chinese Renminbi (RMB)/kg and stored it – today it could only be sold for 1,800 RMB/kg. Other experts agreed that stockpiling is only rarely done. Long-term supply contracts, as reported by company B1, are another option.

Company A2 refers to the fact that specific requirements e.g. of microchip manufacturers may include material requirements.

The interviews showed that companies which are tier 2 or 3 suppliers are more likely to be affected by volatile CRM prices, because their intermediary products contain bigger amounts of CRMs than the final products of OEMs. Hence, the contracts for their customers are based on price quotations and include changes in the raw material price index, so that they have the possibility to pass on price changes to the customer. The location of the supplier is not relevant for the interviewed companies – suppliers are located around the world.

6.3.3 Recycling

The experts agreed that CRMs are mostly used in small absolute quantities, rarely as pure metals and more commonly as countless different compounds which makes recycling quite a challenge and the recycled material (pure) not cheaper to obtain that the primary source.

Company A5 stated that some parts of a plane can be recycled but especially the fuselage poses a large challenge because different materials are melted together and have to be separated. In aviation, every research project now includes recyclability – each material qualification requires a concept dealing with the ecological and health impacts (introduced about 8 years ago). Thus, there is a trade-off between recycling and fuel efficiency.

Company A1 has a refurbishment program for MRIs. When a customer buys a new system, A1 repurchases the old one, refurbishes it and sells it again (another 10 years of serviceable life). At the end-of-life, the MRI will be recycled by recycling partners around the world because there are so many expensive materials and components.

There are also parts of gas turbines that can be replaced. One can swap and exchange many parts in large appliances. The company experts prefer refurbishment approach to recycling of large pieces of industrial equipment.

Companies B1 and B2 see recycling within production as a task for the magnet producer. 30 to 40% of production scrap are collected and returned to a company focusing on processing which leads to a yield rate of 90%.

For NdFeB magnets, there is a EU FP7 project REMANENCE (http://www.project-remanence.eu/), which deals with recycling as reported by company C1.

The experts agreed that recycling is a long-term topic that requires cooperation with external partners from both the public and private sectors. Recycling is regarded as more relevant with rising costs.

6.3.4 Other measures

All experts reported an increasingly proactive approach to dealing with supply risks, e.g. by introducing a special department focusing on a raw material strategy. Company B2 introduced such a department in 2013 as one of the corporate functions. A department on the topic of sustainability of materials was founded by company A3 two and a half years ago to specifically look at today's and tomorrow's risk management of raw materials (not limited to REE). The overall goal is to create transparency, as the company mainly buys semi-finished products and systems. Additionally, international and national research projects with universities and other institutions are taking place to foster the "replace, reduce, reuse" philosophy.

Active market monitoring is another applied strategy, which is being pursued by company A6: This company has an active source organisation that tries to keep track of what is available and does its best to manage price and supply ability using whatever tools are available to legally obtain supplies.

Networking and cooperation with public and private entities are becoming more important according to the experts. To minimize long-term risks concerning CRMs, company C1 is a partner in two of the FP7 programs: ROMEO (deals with development of magnetic materials which contain no or reduced REE) and REMANENCE (recycling NdFeB magnets). Company B1 joined REITA (Rare Earth Industry and Technology Association) to discover other sourcing opportunities for raw materials and learn about hot topics and future trends. Company B2 is a member of the German industry network "Rohstoffallianz" ("raw materials alliance") to develop solutions/strategies dealing with sourcing and cost risks related to critical raw materials.

Company A3 is contributing to the creation of a new VDI (The Association of German Engineers) guideline (together with other companies such as OEMs, system level suppliers and companies further down the value chain) regarding the evaluation of resources and criticality. The guideline focuses amongst other things on the identification of different types of criticality and the definition of indicators regarding functionality and substitution. Innovation strategies are seen in conjunction with suppliers because suppliers deliver the functionality of the materials and have a strong self-interest in reducing the criticality of their materials. Long-term approaches of more than five years are typical. Being integrated in EU networks is also regarded as important by company A3.

Companies B1 and C1 inform and coach their customers about issues related to costs and suggests different possibilities (e.g. production possibilities of the defined machine, reducing efficiency by changing the grades of the magnets, reducing temperature specifications to reduce the amount of Dy). In order to meet the customer's specifications, optimization decisions are made together with the customer.

Reducing CRM use is also a possible strategy for the companies. For instance, company A1 stated that some MRIs components containing CRM are very expensive and they try to reduce the use and number of these components as much as possible. But it is technologically difficult due to system/product constrains.

6.4 *Future developments and expectations towards the EU*

For the experts it is hard to foresee possible developments, since something that is critical today may not be critical tomorrow. For example, new technologies might replace the need for a certain material or new mining technologies might lead to new profitable mining areas.

The following examples were highlighted by the interviewed companies:

- Company A1 foresees no changes in any MRI application caused by CRMs in the next three to five years, nor any signs of immanent future shortages. The lifecycle of an MRI system lasts from 10 to 30 years. Physically, today's MRIs still work similarly to the ones from 30 years ago, only single components have changed (software etc.). Refurbishments of MRIs are possible, so that the experts of company A1 cannot think of any foreseeable change that would replace the current setup with He, Be, Nb and Ho.
- The expert of company A5 sees a clear trend towards composites in aircraft construction.
- Company A3 sees an increasing awareness of resource scarcity and reduced availability. On a system level, fallback options are increasingly being considered to find a balanced trade-off between technically optimal solutions and secure supplies.

The interviewees agreed on the following points:

- Supply chain collaborations will become increasingly important
- New technologies require different material mixes in manufacturing
- Price trends are difficult to forecast due to the strong dependency on demand
- New sources and mines outside China will become more important (due to rising prices)
- Recycling of high-quality CRMs needs to be improved (no downcycling)

Generally, public support is seen as sufficient by company A5. However, different efforts need to be better coordinated globally, especially with the USA, according to the expert. Company B2 expects the EU to support its industry by gathering critical data concerning raw material markets, and by helping to fund public research institutes that publish the respective data.

The experts of company A2 see a problem when different groups (different EU projects) work in silence on different issues, e. g. one group working on substitution and another on recycling. These topics are closely interrelated according to the experts – if a material is to be substituted, what is the point of developing a recycling process for it?

7 Conclusions

7.1 Analysis methodology

The main aim of the analysis of the applications in the three sectors was to describe the relevance of applications to the European Union from a supply chain point of view. The analysis methodology had to be transparent, uniform and suitable for all the applications. It had to cover the main dimensions of relevance identified: economic importance, risks related to the criticality and strategic importance.

The analysis of economic relevance, described by European production, import, export and jobs related to target applications, was mainly based on the use of centralised data sources, such as Eurostat PRODCOM and SBS. This approach provided a number of advantages, including:

- Use of uniform data, based on generic classifications, in screening and analysis of the applications
- Use of public data
- Data is not exposed to manipulation to serve interests of particular stakeholders
- Market values are put in the context of the whole economic system of the EU
- Quick, efficient and repeatable data collection method.

The main challenges of the use of European statistics in the value or supply chain analysis include:

- Additional work and experience in general classification systems are needed to assess to which statistical product group or groups an application or the corresponding product belongs.
- The difficulty of assessing the share of a product in the size of a certain product group. The applications to be analysed and the statistical product groups are not always corresponding: the application may belong to several product groups or the statistical product group may contain several products
- Only the total production values of product groups can be found in Eurostat PRODCOM. Therefore it is not possible to estimate the share of a certain component that is used in the production of a certain application. E.g. only the total production, import and export values of permanent magnets can be found, not the share of permanent magnet production and import used in European wind power applications.
- In some cases difficulties in identifying import of a certain material or product to Europe or export from Europe because the total values on country level cover also export and import between EU countries. Values on EU level on the other hand exclude intra-EU trade.

It was found, that the current European statistical data can be used in estimation of the economic relevance of single products and components. However, it is not possible to get information on the value addition of components used in the end applications at the level of detail, which is required for a full value chain analysis. Therefore it was chosen to rather make an analysis of the supply-chains as a way to get at least partial information on the value chain. Notwithstanding the difficulties, the use of centralised and public data leading to a repeatable analysis is in the long term of great value for many types of research.

In the case of ICT and electronics and transport sectors the data was well applicable for screening of the applications for further analysis. Some of the applications in the energy sector, such as fossil fuel power plants or some specific energy-generating technologies, were more complicated to assess, because it was not possible to match the applications with the statistical product groups. In this case also data from market reports was used in the screening stage.

In addition to statistical analysis, the analysis focused on the criticality of the applications, including current market and expected future development, CRM dependency, essentiality of CRMs for the application and availability of substitutes. Also the strategic relevance for Europe was discussed. This part of the analysis was essential in complementing the data compiled by the statistical analysis and in understanding in which point of the supply chain the availability of materials or components containing CRMs may form a critical bottleneck to the European manufacturing industry. Study of the supply chains also enables identification of the components that are critical for several economically and strategically relevant applications, and thus may need specific consideration.

7.2 Importance and criticality of the applications

Based on economic analysis, it can be concluded that in terms of production value and jobs Europe is well positioned in the end production of most of the 12 target applications. With the exception of energy storage batteries and CIGS PV, one or more European companies are amongst the global top ten, in case of heavy vehicles, aeroplanes, magnetic resonance imaging and automobiles amongst the global top three. Considering market growth, almost all the applications represent high future opportunity.

When studying the value chains, it was found that several applications which are economically important for the EU are exposed to significant CRM issues. Although presence of European companies in component production is characteristic to the sectors where Europe is strong in the end products, most of the applications are dependent on some essential CRM containing component(s), which are mainly produced by non-European companies. In mining and refining of the critical raw materials Europe is totally or almost totally dependent on the outside world.

PCBs and electronic components are common in and essential to almost all target applications. The shortages in availability of some CRMs may be a risk to the European companies, especially when the key competitors are large Asian companies. Dependence on permanent magnets which are mainly manufactured outside of Europe is a potential risk for the EU wind power industry, automobiles and other transport applications. Also catalytic converters and magnesium alloys, which are essential for automobiles and heavy vehicles (magnesium alloys both for vehicles and aeroplanes), are produced outside of Europe. LED lighting is a growing sector where Europe is well positioned. The industry is dependent on semiconductor dies produced abroad. As for optical fibre, due to the reliance of germanium dopant in the fibre and with no commercial substitution option viable, germanium scarcity may create a potential bottleneck for optical fibre production. For all of these components, the substitution solutions are either in very early phase of development or they suffer from performance problems.

The substitution of CRMs, especially new kinds of substitute solutions offering new functionalities can in many cases be seen as an opportunity for Europe. In most of the target applications European companies are already focused on innovative industrial or professional applications. There is also active research in Europe. Although the main focus has until now not been on substitute solutions, there is a feasible environment for further development.

From the industry point of view substitution was seen as one of the potential risk provision strategies. Other examples of risk management measures are presented in Figure 9 below. The figure summarises the main outcomes of the expert interviews which were conducted with nine industrial companies from different countries.

The companies emphasised that solutions to substitution have to be looked at from a functional perspective. Instead of substituting single material, the approach may be to replace the application or a component containing CRMs. In most cases the whole process or system needs to be reconfigured, which makes substitution a demanding task. Therefore substitution projects should be initiated based on a thorough business impact analysis and the whole process takes several years. One of the challenges is that during this period the criticality of the materials may change, e.g. because new technologies are developed or new resources found. In some industries, such as aviation and automobile industry the materials can be changed only after a long and demanding material qualification process.

Although it seemed that most of the companies did not rank the CRM issue as having the highest relevance, it was noted that a proactive approach to substitution gives companies greater flexibility before legislation forces action – awareness therefore needs to be raised.

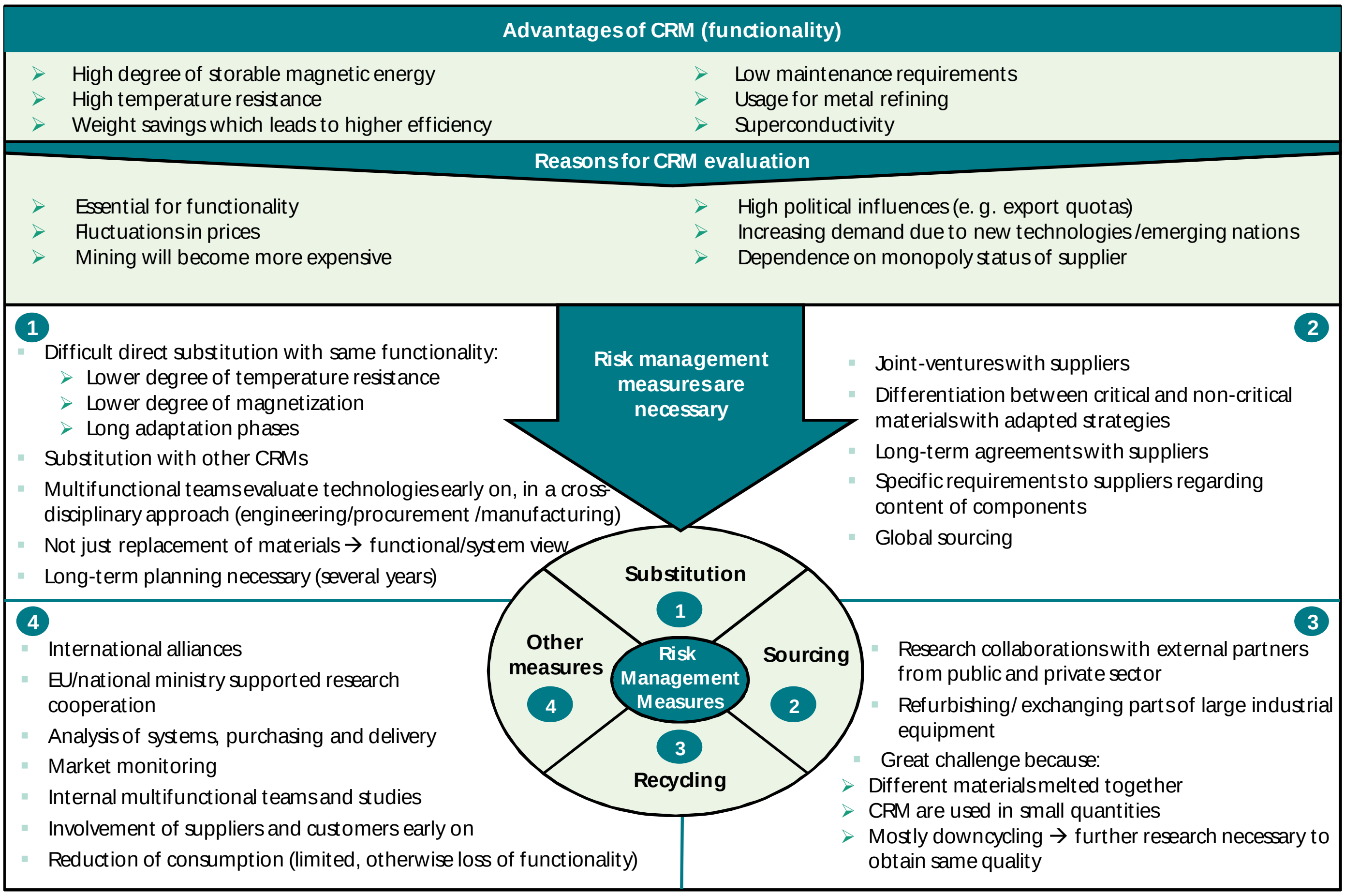

Figure 9: Main outcomes of the expert interviews

References

Brunot, A., Charreyron, V., Chung, C., Mitrofan, L. & Rietveld, E. 2013. Internal report summarising the results of energy sector analysis. CRM_InnoNet Deliverable report D4.1. http://www.criticalrawmaterials.eu/documents/project-dissemination-downloads/report-critical-raw-material-supply-chain-analysis-for-the-energy-sector/

Bacher, J., Punkkinen, H., Mroueh, U-M. & Rietveld, E. 2013. Internal report summarising the results of ICT and electronics sector analysis. CRM_InnoNet Deliverable report D4.2. http://www.criticalrawmaterials.eu/documents/key-project-reports/report-critical-raw-material-supply-chain-analysis-for-the-ICT-sector/

Bolin, L., Stahl, S. & Rietveld, E. 2014. Internal report summarising the results of transport sector analysis. CRM_InnoNet Deliverable report D4.2. http://www.criticalrawmaterials.eu/documents/key-project-reports/report-critical-raw-material-supply-chain-analysis-for-the-transport-sector/

Clifford, N.; Frenchs. & Valentine, G. 2010. Key Methods in Geography, Sage Pub Inc., London.

Cobalt: World Refinery Production, By Country. Index Mundi. http://www.indexmundi.com/en/commodities/minerals/cobalt/cobalt_t10.html

CRM_InnoNet, Critical Raw Material Substitution Profiles, September 2013, http://www.criticalrawmaterials.eu/documents/project-dissemination-downloads/raw-material-profiles/

European Commission 2009. Communication from the EC (…) on Investigating in the development of Low Carbon Technologies (SET-Plan), A technology roadmap. COM(2009) 519 Final. EC. 2009.

European Commission 2010. Critical Raw Materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials. http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf)

JRC 2011. Technology Map of the European Strategic Energy Technology Plan (SET-Plan) – Technology Description. Joint Research Center of the European Commission. 2011.

Mason, J. 2004. Semistructured Interview. In: Michael S.; Beck, L.; Bryman A.; Futing Liao, T. (2004). The SAGE Encyclopedia of Social Science Research Methods

MarketsAndMarkets, 2013. Advances in Magnetic Resonance Imaging (MRI) Market (2013-2018) - Technology Trend Analysis – By Architecture, Field Strengths, Technology & Applications in Medical Diagnostics with Market Landscape Analysis – Estimates up to 2018. Report description. http://www.marketsandmarkets.com/Market-Reports/MRI-advanced-technologies-and-global-market-99.html.

McKinsey & Company 2011. Lighting the way: Perspectives on the global lighting market.

McKinsey Company 2013. The road to 2020 and beyond: What's driving the global automotive industry? Advanced Industries report.

Stuckey, H. 2013. Three types of interviews: Qualitative research methods in social health. Methodological Issues in Diabetes Research 1(2), 56 -59.