European Commission

A report by the partners of:

European Remanufacturing Network

# Advanced Materials

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# Contents

# Glossary

| | |
|---|---|
| B2B | business-to-business |
| CRM | 'critical' raw material |
| CT | computed tomography (scan) |
| ECU | electronic control unit |
| EEA | European Economic Area |
| EEE | electrical and electronic equipment |
| EIP-RM | European Innovation Partnership on Raw Materials |
| ERN | European Remanufacturing Network |
| HDOR | heavy-duty and off-road equipment |
| ICT | information and communication technology |
| MRI | magnetic resonance imaging |
| OEM | original equipment manufacturer |
| PM | parts manufacturer |
| WP | work package |

# Units

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

# Contents amendment record

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# 1 Advanced materials

## 1.1 Introduction – critical and advanced materials

Materials are key in every technological activity that humans have ever undertaken; we even name our historical phases after the materials that dominated that phase of history, for example, the ‘bronze age’ or ’the iron age’.

Over time, there has been a shift from renewable materials to non-renewable materials. This transition happened about the time of the industrial revolution, as the steel age began. Non-renewables form the majority of materials in remanufacturing activities today. Ashby highlights this, stating metals are the dominant materials in engineering[1].

Presently, the world is undergoing another far-reaching materials transition towards a closed loop or circular economy, triggered by increasing pressures on the supply of energy and minerals resources in a world of 7-10 billion people. Work by the EU in defining the most at-risk and economically important materials was published in 2010[2] and updated in 2014[3]. The materials in question are termed critical materials and are components of advanced materials essential in a wide range of high-tech products and equipment, not least products that are vital in Europe’s transition to a low carbon economy.

The advanced materials considered in this report largely find use as metals, ceramics and alloys and comprise a particular range of metals termed critical materials. The rationale for this choice follows the concerns of the EU (along with many other developing economies) about the future security of supply of these materials. The European Innovation Partnership (EIP) on Raw Materials, Strategic Implementation Plan, 2013[4] highlights the following objective:

> *The overall objective of the EIP on Raw Materials is to contribute to the 2020 objectives of the EU's Industrial Policy – increasing the share of industry to 20% of GDP – and the objectives of the flagship initiatives 'Innovation Union'[5] and 'Resource Efficient Europe'[6], by ensuring the sustainable supply of raw materials to the European economy whilst increasing benefits for society as a whole.*

Within these objectives, it can be seen that there are a number of touchpoints with the ERN project. In particular, the themes of resource efficiency, critical and scarce raw materials, framework conditions for reuse (remanufacturing) and raw materials-efficient product design are key. Furthermore, the proposal to establish sustainable raw materials management organised as a Knowledge and Innovation Community (KIC) has been realised as the KIC European Institute of Innovation and Technology[7] - Raw Materials (EIT RM)[8].

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1 Ashby M. Materials and the environment – eco-informed materials choice. 2nd ed. Butterworth-Heinemann; 2012.

2 Catinat M et al, (2010) *Critical Raw Materials for the EU – Report of the ad-hoc working group on defining critical raw materials*, Brussels, Belgium, EU,

3 Pellegrini, M (W.G. chair), (2014) *Report on Critical Raw Materials for the EU, Report of the Ad hoc Working Group on defining critical raw materials*, European Commission, DG Enterprise and Industry, May 2014.

4 https://ec.europa.eu/eip/raw-materials/en/content/strategic-implementation-plan-sip-0

5 http://ec.europa.eu/research/innovation-union/index_en.cfm

6 http://ec.europa.eu/resource-efficient-europe/

7 http://eit.europa.eu/

8 http://eitrawmaterials.eu/

Several of the ERN partners are members of the EIT RM in which critical materials (being advanced materials) are a focus with remanufacturing, as part of a circular economy, playing an important role.

It is the purpose of this section of the report to shed light on the contribution remanufacturing can play in ensuring the availability of advanced, critical materials in products and technologies in three target products from the energy, transport and electronics sectors. It demonstrates significant market size and/or growth potential; and show that they possess characteristics of products/technologies suitable for remanufacturing. For these target products, further data from a previous EU project[9] has been collected to gauge whether any remanufacturing activities currently occur for these products. This data and discussions have been used to create an estimate of the size of total European remanufacturing activities for these products.

## 1.2 The scope of advanced materials

This report does not purport to provide a comprehensive definition of critical materials in relation to advanced materials. However, a literature review of 30 existing published definitions and descriptors of critical materials has been conducted to explore the relationship between the two, and to manufacturing processes. This has established with some certainty that most were not written with remanufacturing in mind, or in particular regarding the practical issue of material choices for parts and sub-assemblies at the design stage.

The obvious starting point for a consideration of the relationship is the list of critical raw materials (CRMs) as published by the EU and reported in Table 1.

*Table 1: Critical materials for the EU, 2014[10]*

| Elements | Non elements |
|---|---|
| Lithium, Beryllium, Magnesium, Scandium, Chromium, Cobalt, Gallium, Germanium, Niobium, Platinum Group Metals, Indium, Antimony, Tungsten, Light Rare Earth elements (not Polonium), Heavy Rare Earth elements including Yttrium. | Borates, Magnesite, Silicon metal, Coking coal, Fluorspar, Natural graphite & Phosphate rock. |

This list evolves over time due to the shifting balance of factors which contribute to the assessment of criticality. However, there are some elements that do appear frequently on the EU List and other national assessments globally. Of note are those elements that form the so-called rare earth elements[11] and the platinum group metals[12]. As a basis, this report will use the 2014 EU list of CRMs, excluding the non-elements shown in Table 1.

A further consideration of the topic draws on the approach of Peck et al. (2015).[13] In general the CRMs of interest are elements, whereas advanced materials are typically alloys, ceramics, polymers or other composite, multi-element substances. In simple terms,

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9 See project reports at http://www.criticalrawmaterials.eu/

10 Pellegrini M (WG chair). Report on critical raw materials for the EU, report of the ad hoc working group on defining critical raw materials, European Commission, DG Enterprise and Industry; May 2014.

11 Cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, promethium, samarium, scandium, terbium, thulium, ytterbium, yttrium

12 Iridium, osmium, palladium, platinum, rhodium, ruthenium

13 Peck D, Kandachar P and Tempelman E, *Critical materials from a product design perspective,* Journal of Materials and Design 65, (Jan 2015) Pages 147-159.

elements have properties, but materials have functions. Typically, it is the nature of the elemental contribution to these functions which defines their uniqueness and – potentially - their criticality. In support of this, a recently concluded EU FP7 project entitled CRM_Innonet[14] made the following observations: the term 'critical' should not only be used to describe a resource that is scarce, but also a resource that provides unique properties and functions and therefore has few substitutes.

## 1.3 Remanufacturing as a 'substitution' strategy

In the context of remanufacturing, it is therefore highly relevant to consider which functional properties are beneficial and which materials contribute to these benefits. In turn, this directs the search for products that embody those functions, and the strategies that might be employed to recover and preserve these materials. The results of work by CRM_Innonet are highly relevant in this activity. In a series of expert interviews, important functions of CRMs were named by respondents, as shown in the left hand column in Table 2. These functions confer mechanical properties which mean that products are mechanically suitable for processing and life extension. They are also properties that might be enhanced or upgraded during remanufacture to offer performance which is better than 'like new'.

The right hand column in Table 2 shows the direct benefit of the CRM advanced material to remanufacturing. Note that whilst some of the benefits will apply to non-remanufacturing product providers as well, many do not.

*Table 2: Desirable functional properties enhanced by CRMs in advanced materials*

| CRM-derived mechanical attributes relevant to remanufacturing | Benefits to remanufacturing |
|---|---|
| Weight savings leading` to high efficiency | Weight savings = lower costs & impacts |
| High degree of hardness | Hardness = less wear = lower costs |
| Good corrosion sensitivity | Lower corrosion = lower costs |
| High temperature resistance | Temp resistance = less damage = lower costs |
| Low maintenance requirements | Low maintenance = lower costs |
| Long lifetime of products | Long life = improved revenues |

The important point is the essential role that remanufacturing itself delivers by providing a longer life of CRM-containing advanced materials. Longer life is achieved by the cycles of use-remanufacturing-use-remanufacturing etc. This reduces the rate of material consumption and loss of the advanced materials. Remanufacturing offers further advantages: the organised and controlled removal of components also enables higher value recycling of components beyond repair.

The functions in the right hand column in Table 2 are relevant because remanufacturing provides a mechanism for preserving those components which embody those attributes and benefits. It is these functional aspects that form the basis for choosing the products to examine in this section of the report.

The results of CRM_Innonet also suggest that remanufacturing forms a valid substitution strategy. It proposed that the concept of substitution is broadened to include changes to processes, new technology (engineering) approaches and the introduction of a service to

[14] Critical Raw Materials Innovation Network – *Towards an integrated community driving innovation in the field of critical raw material substitution for the benefit of EU industry*

take up products at the end of a first life, are all 'substitution' approaches. Service can include reuse, remanufacturing and recycling activities.

In summary, the current practice for product designers is that they select materials - not elements - when designing products. The elements are therefore selected implicitly not explicitly. However, there is a range of substitution strategies that, were the product designer aware of them, could be used to address advanced material challenges. This approach includes remanufacturing activities, as be shown below.

## 1.4 Advance materials in three remanufacturing markets / products

This section focuses on three markets / products: automotive (alternators / motors / exhausts), renewable energy (wind-turbines) and electronics / ICT (including medical imaging equipment). An assessment is made of the opportunities that remanufacturing can provide which in turn supports Europe's critical material security of supply.

### *1.4.1 Automotive*

*Identification of CRM dependencies and current status*

The automobile manufacturing sector employed around 2.3 million people in Europe in 2012. Three European car companies are in the top ten producers and several Japanese companies, such as Toyota, have manufacturing plants in Europe. The market segment in Europe is highly competitive and is driven by high pricing pressure, hence the success of low cost sub-brands such as Skoda or Dacia. Based on data from Eurostat, production in Europe is distributed over the whole supply chain but clearly concentrated to the later steps of the chain.

Table 3 lists which sub-sectors of the transport sector are dependent on the use of CRMs. It also reports their economic impact and status.

*Table 3: Economic screening for CRM supply chain analysis*

| Sector and its production value (2011) | Application | CRM-Use | EU economic importance | | | Progress to full Supply chain analysis |
|---|---|---|---|---|---|---|
| | | | Value (2012) | Share of prod. >25% | Share of products in sector >0.2% | |
| Manufacture of motor vehicles, trailers and semi-trailers €678906 M | Automobiles | Pt, Pd, Rh, Ta, Nb, Mg, Sb, Nd, Gd, Be, In, Ce, Dy, La, Tb, Tm, Y, Er, Eu, Ga, Ho, Graphite | 223808 M€ | 95% | 39.97% | Yes |
| | Heavy vehicles | Pt, Pd, Rh, Ta, Nb, Mg, Sb, Nd, Gd, Be, In, Ce, Dy, La, Tb, Tm, Y, Li, Zn, Co, Ag | 33369 M€ | 91% | 4.9% | Yes |
| | Buses | Assumed similar as auto/heavy vehicles | 3855 M€ | 86% | 0.57% | (Yes) |
| | Goods vehicles | Assumed similar as auto/heavy vehicles | 23878 M€ | 85% | 3.52% | (Yes) |
| Manufacture of other transport equipment €198311 M | Helicopter | Assumed similar as aeroplane | 3709 M€ | 83% | 1.9% | (Yes) |
| | Commercial aeroplanes | Sb, Ge, Mg, Gd, Rh, Pd, Be, Pr, Sm, W, Ta, Ru, Nb, Y | 7850 M€ | 27% | 2.5% | Yes |
| | Motorcycle | Assumed similar as automobile | 3463 M€ | 68% | 1.6% | (Yes) |
| | Bicycle | Mg, Sc, Be | 2165 M€ | 66% | 1.1% | No |

*Data from 2011, except sector values from 2012*

One of the main CRM dependencies is the use of platinum and palladium in catalytic converters. Leading European auto producers do not have catalytic converter production of their own. Availability of raw materials could be a potential CRM-related bottleneck and, since catalytic converters are mainly produced outside the EU and not by the European automotive companies themselves, chances to influence availability of catalytic converters in case of shortage of raw materials might be limited. Both platinum and palladium production are concentrated in South Africa and Russia. In terms of the substitution of platinum in vehicle applications, the current shift is toward palladium which is less expensive and with more diverse production areas. However, substituting one CRM with another does not reduce CRM dependency. There are currently no other substitutes for the CRMs used as catalysts in catalytic converters. The same is true for exhaust after-treatment applications that replace catalytic converters.

Platinum and other platinum group metals are recycled to some extent, but represent an exception when it comes to recycling CRMs from cars. No dedicated procedures or processes for recovering and recycling the content of gold, neodymium, tantalum and niobium of components or material fractions from end of life vehicles (ELVs) have been found in the current Swedish ELV system. Directives on recycling from ELVs in the EU are not focused on critical raw materials but more on e.g. plastic parts. However, issues related to short term supply risks and the long term increasing global demand of scarce metals can potentially be addressed through the recycling of rare materials.[15]

Different types of high strength steels are of great importance for automobiles due to safety requirements. Niobium alloyed steel is mainly used and, in some parts of the car, tantalum alloyed steel. Any material used to replace those in safety functions must meet the same requirements as the steel currently used. Composites may replace some of those steel parts in the future, as long as that does not impair the performance of the material.

The chassis contains some parts that are made of high strength or ultra-high strength steel. These parts usually have a key role in safety; for example, in the pillars that support the windscreen and in car seats. The alloys contain small amounts of niobium (Nb) or tantalum (Ta). The steering, the brake system, the security system and the heat exchanger all contain CRMs.

Table 4 gives more detail of the uses of CRMs in automotive applications in particular. They are, for example, found in exhaust treatment systems. In the catalytic converter, harmful substances in exhaust gases (such as carbon monoxide, nitrogen oxides and unburnt hydrocarbons) are converted to less harmful substances. Platinum (Pt) is the most widely used catalyst but palladium (Pd) and rhodium (Rh) are also used. While platinum is used both as a reduction and oxidation catalyst, rhodium is a reduction catalyst only and palladium an oxidation catalyst only. Cerium oxide ($CeO_2$) is also used in catalytic converters; cerium (IV) oxide can give up oxygen without decomposing and is therefore used to 'store' the oxygen for the oxidation reactions.

[15] Andersson, M., Ljunggren Söderman, M. and Sandén A. (2014). *Scarce metals in Swedish end of life vehicle recycling*. SUM 2014, Second Symposium on Urban Mining

*Table 4: Uses of critical raw materials in the automotive sector*

| Sector and its production value (2011) | Sub-level Application | CRM-Use | EU economic importance | | |
|---|---|---|---|---|---|
| | | | Value (2012) | Share of prod. >25% | Share of products in sector >0.2% |
| Manufacture of motor vehicles, trailers and semi-trailers €678906 M | Auto catalyst | Pt, Pd, Rh, Ce | 31 M€ | 21% | 0.01% |
| | Chassis | Ta, Nb, Mg, Sb | 1587 M€ | 97% | 0.23% |
| | Seating | Nb | 12010 M€ | 99% | 1.77% |
| | Steering | Nd | 7452 M€ | 88% | 1.10% |
| | Brake system | Gd, Rh, Pd, Be | 7000 M€ | 84% | 1.03% |
| | Security airbag | In, Er, Be | 3118 M€ | 90% | 0.46% |

Electronics play an increasingly central role in cars. Basic cars have at least 30 electronic control units (ECUs) while luxury cars may have up to 100.[16] Some systems, such as fuel injection control, anti-lock braking systems, air bags, cooling systems and adaptive cruise control systems, depend on ECUs in a vehicle. As significant amounts of CRMs are used in electronics within those products[17], the car's ability to function is more and more dependent on CRMs.

Many of the electronic motors used in modern cars (e.g. for adjusting the seats, in the steering system and in the climate control system) use permanent magnets containing rare earths. In the future, with an increased number of electric or hybrid vehicles, permanent magnets will be of even greater importance. An electric motor of 50 kW used in a hybrid vehicle uses around 1.3 kg of permanent magnets. The supply chain for permanent magnets is examined in more detail in the CRM_InnoNet report on energy applications using CRMs.[18]

### 1.4.2 Wind turbines

This section identifies specific advanced materials dependencies of the energy sector through analysis of the value chain specifically of wind-power technologies (Table 5). These are dependent on permanent magnets, typically using rare-earth elements: neodymium, and dysprosium.[19] There are further CRM-containing technologies in the wind turbines such as control electronics and batteries which are excluded from this analysis.

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[16] New York Times (2010). *The dozens of computers that make modern cars go (and stop)*, available at http://www.nytimes.com/2010/02/05/technology/05electronics.html?_r=0

[17] Bachér, John et al., (2013). *CRM_InnoNet - Internal report summarising the results of ICT and electronics sector analysis*. http://cdn.awsripple.com/www.criticalrawmaterials.eu/uploads/D4-1-ICTsector-reportfinal.pdf

[18] Brunot A, Charreyron V, (2013) Rapport technique DTBH/DR/2013/133 *CRM-Innonet Project - Internal report summarising the results of energy sector analysis*

[19] Institute for Energy Research, 2013. *Big wind's dirty little secret: Toxic lakes and radioactive waste*, available at http://instituteforenergyresearch.org/analysis/big-winds-dirty-little-secret-rare-earth-minerals/

*Table 5: Uses of critical raw materials in the wind power sector*

| Application | CRM-Use (EU-14 CRM) | EU economic importance | | |
|---|---|---|---|---|
| | | Value[2] (yearly) | Share of prod. >25 % (Eurostat) | Share of products in sector >0.2 % (Eurostat) |
| Wind Power | Nd, Dy | 12.6 GW<br>12.8-17.2 b€ market<br>6.5 b€ EU production<br>9.9 b€ prod. Eurostat | 98% | 1.8% |

***Wind power technologies and CRM dependence***

A key contributor to renewable energy is observed to be wind energy and it is estimated that approximately 15% of the 2030 average EU electricity mix will potentially come from wind for short, medium and long term energy provision. [20]

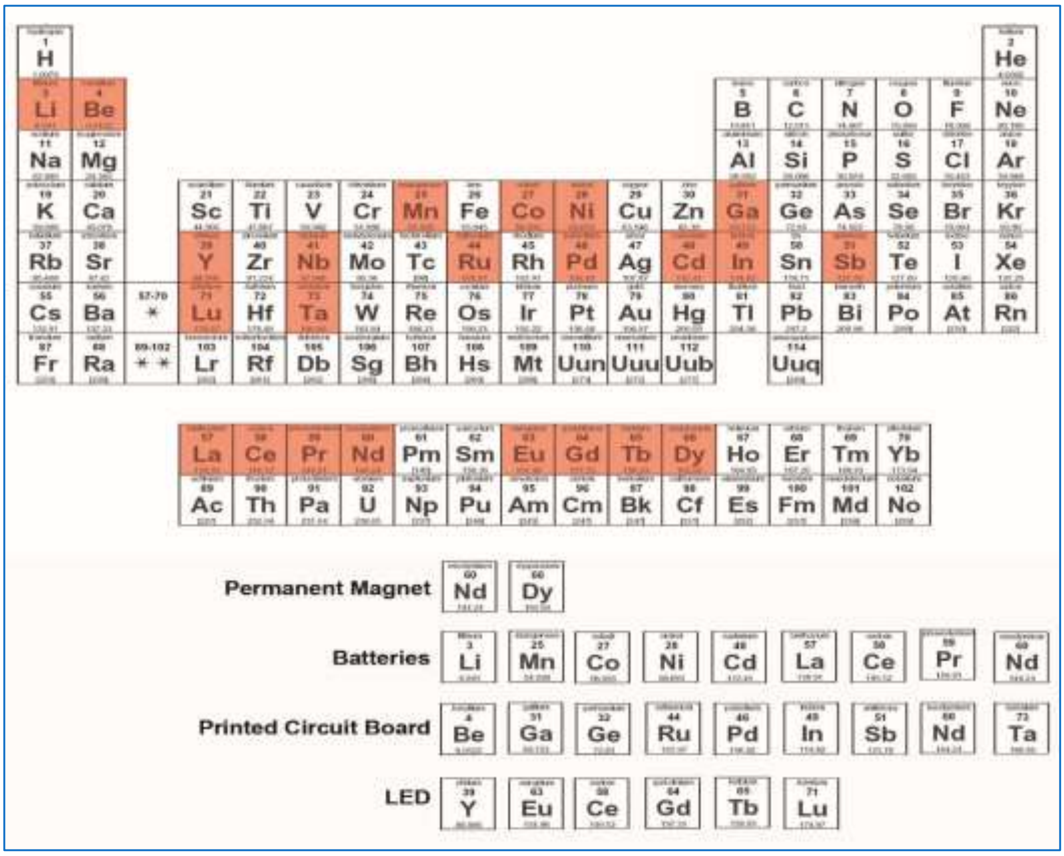
Wind turbines convert wind energy captured by blades into the rotation of a shaft. This rotation is then transformed into electricity through a generator. Two main markets exist, with different requirements on equipment: on-shore and off-shore wind turbines. The latter obviously operates in a more demanding environment (weather conditions, saline and corrosive environments) and is potentially more difficult to access. A general trend towards larger and more powerful wind turbines is observed, particularly for the off-shore market.

Wind turbines are typically made of a tower supporting a nacelle and a rotor, connected through a rotating shaft. Typical components of the nacelle are the gearbox (when necessary) to which the shaft is connected, the electric generator, and other systems components - shaft brake, controller, weather sensors, yaw control system, cooling system - all containing CRMs as shown in Figure 1. The tower also contains some electrical components, in particular related to yaw control, and the connection to the electrical cable.[21]

[20] European Commission, 2010b. *EU energy trends to 2030*, update 2009, EC – Directorate-General for Energy, 2010

[21] Wilburn, D.R., (2011) *Wind energy in the United States and materials required for the land-based wind turbine industry from 2010 through 2030*: U.S. Geological Survey Scientific Investigations Report 2011–5036, 22 p. Available online at http://pubs.usgs.gov/sir/2011/5036

*Figure 1: Critical raw materials used in wind turbines*




*Source: Fromberg E, Peck D, Kandachar P, Critical materials, circular economy and wind turbines, 4th International Symposium "Circular Economy inspiring Sustainable Innovation", Mexico City, 2015*

### *Future supply chain issues*

Wind turbine manufacturers expect future challenges with CRMs to be 'not unmanageable' within the next three to five years and they expect to find the key solution in addressing this problem in product innovation management.[22] They assert that, currently, the main goal of wind turbine designers is to reduce the cost of energy. Expecting that wind turbine designers will develop solutions for the challenges with respect to CRMs is problematic, not least because they are usually 'invisible' to product designers.[23] This position is more complex as there has been a significant design focus on CRMs in the generator magnet.

### *Refurbishment / remanufacturing of wind turbines*

Wind turbines that were manufactured and installed decades ago are currently being retired as they reach the end their first design life. There is a third-party market developing to refurbish / remanufacture these wind turbines, which are then sold on at approximately half of the original equipment price. The warranty of new wind turbines is on average 2-5 years despite their 20 year designed life span; even though the average lifespan of a reconditioned

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[22]Vroom, M., (2012) *Critical materials from a wind turbine industry perspective*, Sustainable Energy Technology, Faculty of Applied Sciences, Delft University of Technology, Delft, p. 11, 2012.

[23] Peck D, Kandachar P and Tempelman E, *Critical materials from a product design perspective*, Journal of Materials and Design 65, (Jan 2015) Pages 147-159.

unit is typically lower at 10-15 years, it is still given the same 2-5 year warranty.[24] The third-party remanufacturer therefore has some legitimacy in claiming that these remanufactured units are 'like new'.

### 1.4.3 *Electronics / ICT (medical / healthcare)*

The ICT and electronics sector provides products and services both for consumers, industries and professional users (**Error! Not a valid bookmark self-reference.**). The products may be used in various sectors as end applications or as components; for clarification, the product applications can be roughly categorised as:

- products which capture, transmit and display data and information electronically e.g. computers, phones, displays, consumer electronics
- lighting
- domestic appliances
- professional applications e.g. medical applications, control equipment, sensors and tools
- electronic sub-components used in various applications e.g. printed circuit boards.

*Table 6: CRMs in the supply chain of the ICT + electronics sector*

| 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 sector >0.2% | |
| 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 |

*Note: Data from 2011, except sector values from 2012*

[24] Ortegon, K., Nies, L.F. and Sutherland, J.W. (2013) *The Impact of Maintenance and Technology Change on Remanufacturing as a Recovery Alternative for Used Wind Turbines*, 21st CIRP Conference on Life Cycle Engineering, v15, 2014 pp182-188

The ICT and electronics sector is typified by rapid product development leading to short lifetimes. Because of small size and low transport costs, the production and assembly of components and most ICT consumer products can be quite easily relocated to countries with lower production costs - not the case for larger medical applications.

CRMs are widely used and vital to the function of many different applications in the ICT and electronics sector. Therefore, reducing the number of applications and highlighting the most important applications for the European economy is required. This section focuses on magnetic resonance imaging (MRI) equipment.

### *MRI technologies and CRM dependence*

MRI is a medical imaging technique used for visualising the internal morphology of the body. It enables imaging of soft tissues and organs in such great contrast that the technique is especially suitable for neurological, cardiovascular, musculoskeletal, as well as oncological imaging. MRI is based on nuclear magnetic resonance (NMR), measuring a radio frequency signal emitted by the nucleus of hydrogen atoms in a magnetic field. An MRI system includes magnets, a pulsed field gradient system, radio-frequency transmit coils, transmitters, a radio-frequency receiver and a computer system.[25]

CRMs in an MRI system are found in the magnet unit, spring contacts, cold heat, pole-piece computer display and printed circuit boards. There are three alternative MRI technologies based on three different types of magnets used: permanent, resistive and superconducting. The CRMs in the permanent and superconductive magnets are discussed here.[26] A superconducting electromagnet is the most frequently used magnet, accounting for over 75 % of MRI equipment installed. Almost all MRI systems use superconducting coils where a central field strength of more than 0.35 tesla is present.[27]

The manufacture of superconducting magnet based MRI systems uses niobium (Nb) alloys and chemicals, for example niobium-titanium, niobium-tin and niobium nitrite.[28] Niobium-titanium and niobium-tin are used for making coil windings for superconducting magnets, and can be fabricated into superconducting wires. Most superconductive materials produced in the world are destined for use in MRI systems. MRI magnet manufacturing consumes approximately 60% of all superconducting wire and 40% of niobium-tin alloy.[29] However, of the total amount of niobium produced annually, the MRI industry uses only few percent.[30]

Around 21% of the total rare earth consumption, corresponding to 24 thousand tonnes of rare earth metals, was used for producing permanent magnets in 2010, consisting of neodymium (Nd); prometheum (Pr); dysprosium (Dy); gadolinium (Gd); and terbium (Tb).

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[25] Fishbein *et al.* (2005). *Hardware for Magnetic Resonance Imaging*, available at https://www.irp.nia.nih.gov/branches/lci/nmr/mri-hardware-2005.pdf

[26] MRI systems that contain resistive magnets have a minor role in the magnetic resonance imaging market due to their limited field strength, high energy consumption and cooling system dependence, and are excluded from the analysis.

[27] Cosmus & Parizh 2011. *Advances in whole-body MRI magnets*. IEEE Transactions on Applied Superconductivity, 21, Issue 3, 2104-2109, available at http://ieeecsc.org/sites/ieeecsc.org/files/ST196.pdf

[28] Moreno, L. (2011). *Tantalum and Niobium Primer, Two Critical Metals*. Jacob Securities Inc. Equity Research, July 19th, 2011.

[29] Marken, K (2004). John Hulm Memorial Session. Applied Superconductivity Conference, Jacksonville, FL, October 2004, unpublished.

[30] NioCorp Developments Ltd. (2013). *About Niobium*. http://www.quantumrareearth.com/about-niobium.html

Around 98 % of these CRMs were used for NdFeB[31] magnet production.[32] In 2012, the rare earth demand for permanent magnets was estimated to be around 25,500 tonnes,[33] with some 860 kg of NdFeB magnets of rare earths on average per MRI unit.[32]

In addition, various electric motors are needed to move units or parts in the MRI systems, and these motors may also use NdFeB magnets because of their small size. However, they are not the most essential components in terms of substitution. Various components of the computer unit controlling the MRI system, such as printed circuit boards and the display, also contain CRMs.

## 1.5 CRM considerations by remanufacturers

It is noted that that the involvement and views of remanufacturing companies are not widely considered in work covering materials. Some of the publications reviewed outline the role of 'recycling' (which includes 'remanufacturing' in its scope) in mitigating critical material risks. The literature suggests that the demand for critical materials is experiencing volatility and there is currently no response based on remanufacturing. The question of how companies are actually responding to critical material risks remained largely unanswered. To understand whether companies are responding to critical materials risks via remanufacturing, the research from 2012-13 on CRM considerations was revisited and reassessed for remanufacturing aspects.[34]

### *1.5.1 Method*

Each of the five categories tackles a subject tightly connected to critical materials:

- **Familiarity with the term 'critical materials' in the company**
  This section in the questionnaire helps to introduce the participant to the subject and more importantly provides data on awareness of the participant concerning the subject.
- **Role of critical materials in the company**
  This section concerns consumption of critical materials and provides an overview of the most consumed materials; insight into whether defined materials are indeed critical for the companies; and whether the term 'critical' is interpreted by the companies in the same way as by the researchers.
- **Risk-management and critical materials**
  Whether critical materials are a part of risk management policy of the company can be a strong indicator of the awareness and understanding of the subject by the participating company concerning the subject. This section explores that connection.
- **Business and critical materials**
  Readiness of the company to react to the risks posed by the materials criticality can be seen in the way the company tailors its business. This section explores related business opportunities and threats posed by CRMs.
- **Support concerning critical materials**
  It is highly unlikely that any company is capable of dealing with the materials criticality

[31] Neodymium-Iron-Boron, 'neodymium' magnets

[32] Peiró, L.T., Méndez, G.V & Ayres, R.U. 2013a. Supporting information: Material flow analysis of scarce byproduct metals: sources, end-uses and aspects for future supply

[33] Shaw, S. & Constantinides, S. 2012. Permanent Magnets: the Demand for Rare Earths. 8th International Rare Earths Conference, November 2012

[34] Moerland-Masic, I, (2012) *Critical materials in the Netherlands – response from the technological industry*, TU Delft Library

on its own. The issues are too complex. This section explores the kind of support that companies say is needed.

Each of the categories contains one or more questions that cover that aspect of the materials' criticality as required for the research. Questions in the questionnaire are categorised into three different types:

1. Multiple choice questions, with one or more than one answer possible
2. Ranking questions (Likert scales)
3. Open-ended questions

Although the first two types have great utility for large volumes of data and for conducting analysis, this study concentrated on using open-ended questions. This is because it was expected that, for many participants, the topic would be unfamiliar; this research has sought to uncover participants' views on the matter, an outcome best served by open questioning.

Table 7 outlines the exemplar types of companies, their description and typical product classes addressed during interviews. Due to confidentiality agreements specific products cannot be named.

*Table 7: Company types and product classes considered during interviews*

| Company type | Description | Product examples |
|---|---|---|
| **Material producers** | Processed raw materials | Copper (bar, wire) |
| **Component producers** | Producing components (mostly B2B market), using metals, basic metals and intermediate goods | Electronics, LEDs |
| **Sub-assemblers** | Producing sub-assemblies: more complex assemblies | Computing, lighting |
| **Producers** | Producing relatively simple products with relatively simple supply chain | Domestic appliances, electric tools |
| **Integrators** | Producing complex products and equipment (OEM) with a complex supply chain | Medical equipment, production systems |

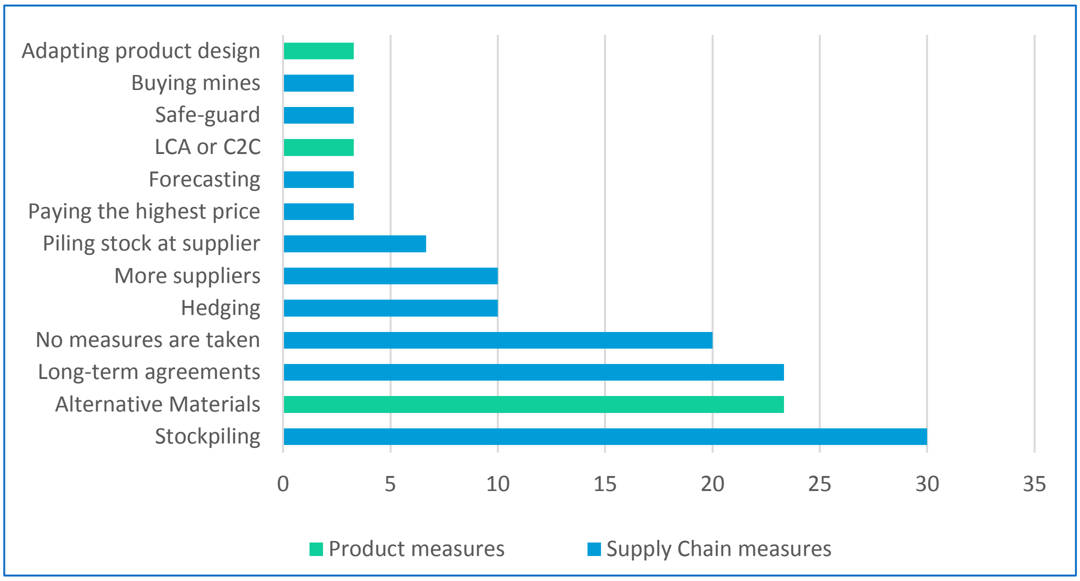
Due to the complexity of the research subject and expected lack of prior knowledge of the participants, a questionnaire was administered via a face-to-face interview. This allowed the interviewer to clarify possible misunderstandings in the questionnaire. One important advantage of a structured interview is that it ensures comparability of the data. As the questions are predetermined by the questionnaire and all questions are asked in the same order, data is more easily compared. Another advantage is the personal contact the interviewer has with the participant.

### 1.5.2 Responses

This report has a focus on Question 1.6: 'Can you name the measurements your company has taken as a reaction to issues caused by critical materials?'

Figure 2 illustrates the results obtained from the participants. It is apparent that few participants have provided answers which indicate product-oriented (and therefore remanufacturing) reactions to the issues caused by the critical materials.

*Figure 2: Actions taken by respondents' companies over 'critical materials' issues*




## 1.6 Conclusions

This section has framed advanced materials prevalent in modern manufacturing in terms of their component critical materials and the unique functions they confer. It describes how remanufacturing, in particular the redesign for remanufacturing activity, can create closed loop systems which preserve the material and functional content of critical materials. This is highly aligned to the EU's drive to address the availability of a wide range of critical (raw) materials.

This work has drawn upon the CRM_Innonet (FP7) research, with focus on three markets (automotive, renewable energy and electronics / ICT). It reveals that the opportunities that remanufacturing can bring to facilitate in supporting the security of Europe's critical materials appears to be limited at this time. Recycling was deemed to be poor and if remanufacturing is a subset of recycling then it was not addressed.

A set of selected manufacturers are assessed to ascertain if considerations of critical material aspects are considered via the remanufacturing of a product / equipment. Again it was clear that the companies did not propose remanufacturing as a strategy to address CRMs, despite some of the companies being remanufacturing companies.

These results show a gap: policy makers see a significant opportunity in remanufacturing in securing raw materials supply and this is seen in the EU Circular Economy Package expected in December 2015. The academia (CRM publishers), companies and other RTOs do not see the role for remanufacturing.

All CRMs are 'accessible' via remanufacturing as long as the component or sub-assembly is not scrapped. Critical to this is knowledge of embedded CRMs is if the company carrying out the remanufacturing does not know where the CRMs are they cannot make an informed decision on treating the product or component. The EU Horizon2020 project ProSUM is looking into developing such information for remanufacturers (amongst others).

## 1.7 Further work

It is proposed that the European Remanufacturing Network should look to promote materials agenda items into the remanufacturing sector.

The Circular Economy Package from the European Commission should be consulted to look for synergies.

The ERN project to use the KIC EIT Raw Materials to promote remanufacturing and CRM awareness / opportunities.

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