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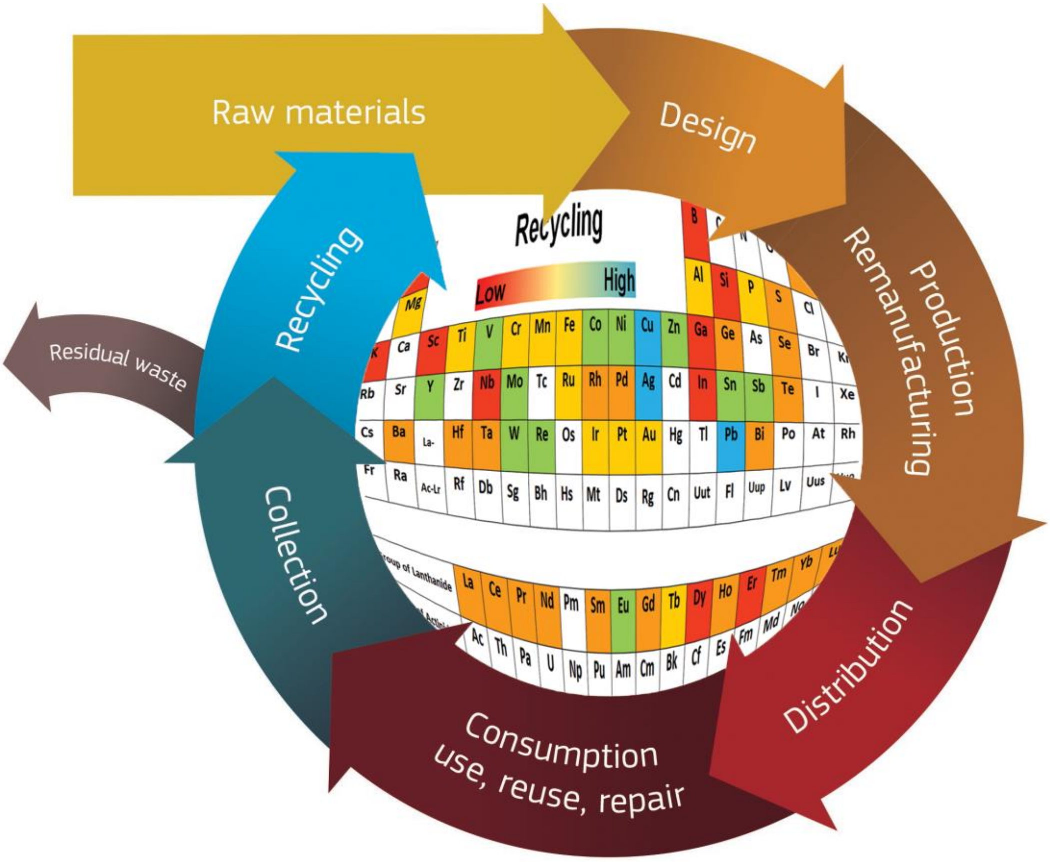
Critical raw materials and the circular economy

Background report

Fabrice Mathieux, Fulvio Ardente, Silvia Bobba, Philip Nuss, Gian Andrea Blengini, Patricia Alves Dias, Darina Blagoeva, Cristina Torres de Matos, Dominic Wittmer, Claudiu Pavel, Tamas Hamor, Hans Saveyn, Bernd Gawlik, Glenn Orveillon, Dries Huygens, Elena Garbarino, Evangelos Tzimas, Faycal Bouraoui, Slavko Solar



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Contact information
Name: Fabrice Mathieux
Address: Joint Research Centre, Via E. Fermi 2749, 21027 Ispra, ITALY
Email: fabrice.mathieux@ec.europa.eu
Tel.: +39 332789238

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Critical raw materials and the circular economy — Background report
This report is a background document used by several European Commission services to prepare the EC report on critical raw materials and the circular economy, a commitment of the European Commission made in its Communication 'EU action plan for the Circular Economy'. It represents a JRC contribution to the Raw Material Initiative and to the EU Circular Economy Action Plan. It combines the results of several research programmes and activities of the JRC on critical raw materials in a context of circular economy, for which a large team has contributed in terms of data and knowledge developments. Circular use of critical raw materials in the EU is analysed, also taking a sectorial perspective. The following sectors are analysed in more detail: extractive waste, landfills, electric and electronic equipment, batteries, automotive, renewable energy, defence and chemicals and fertilisers. Conclusions and opportunities for further work are also presented.

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Authors

All the inputs of provided by several units of the JRC have been coordinated by JRC.D.3 Unit Land Resources

Editor: Fabrice Mathieux (JRC.D.3)

The following authors have contributed to the preparation of this report:

Chapter 1: Fabrice Mathieux, Gian Andrea Blengini (JRC.D.3)

Chapter 2: Gian Andrea Blengini, Fabrice Mathieux, Philip Nuss (JRC.D.3)

Chapter 3: Cristina Torres de Matos, Philip Nuss, Tamas Hamor, Silvia Bobba, Gian Andrea Blengini (JRC.D.3)

Chapter 4: Dominic Wittmer, Gian Andrea Blengini, Tamas Hamor, Fulvio Ardente (JRC.D.3); Glenn Orveillon, Hans Saveyn, Elena Garbarino (JRC.B.5)

Chapter 5: Fulvio Ardente, Gian Andrea Blengini (JRC.D.3)

Chapter 6: Fulvio Ardente, Fabrice Mathieux, Philip Nuss, Slavko Solar (JRC.D.3)

Chapter 7: Silvia Bobba (JRC.D.3), Patricia Alves Dias (JRC.C.7)

Chapter 8: Patricia Alves Dias, Darina Blagoeva (JRC.C.7); Silvia Bobba, Philip Nuss (JRC.D.3)

Chapter 9: Darina Blagoeva (JRC.C.7); Fulvio Ardente, Silvia Bobba (JRC.D.3)

Chapter 10: Claudiu Pavel, Evangelos Tzimas (JRC.C.7)

Chapter 11: Cristina Matos, Dominic Wittmer, Philip Nuss (JRC.D.3); Bernd Gawlik, Faycal Bouraoui (JRC.D.2); Hans Saveyn, Dries Huygens (JRC.B.5)

Chapter 12: Fabrice Mathieux, Philip Nuss, Fulvio Ardente, Gian Andrea Blengini (JRC.D.3)

Annexes: Fulvio Ardente, Philip Nuss (JRC.D.3)

Abstract

This report is a background document used by several European Commission services to prepare the EC report on critical raw materials and the circular economy, a commitment of the European Commission made in its Communication 'EU action plan for the Circular Economy'. It represents a JRC contribution to the Raw Material Initiative and to the EU Circular Economy Action Plan. It combines the results of several research programmes and activities of the JRC on critical raw materials in a context of circular economy, for which a large team has contributed in terms of data and knowledge developments. Circular use of critical raw materials in the EU is analysed, also taking a sectorial perspective. The following sectors are analysed in more detail: extractive waste, landfills, electric and electronic equipment, batteries, automotive, renewable energy, defence and chemicals and fertilisers. Conclusions and opportunities for further work are also presented.

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List of acronyms

BREF	Best Available Techniques Reference documents
BEV	battery electric vehicle
CCFL	Cold Cathode Fluorescent Lamps
CEN/CENELEC	European Committee for Standardization/the European Committee for Electrotechnical Standardization
CSA	Coordination and Support Action
CRMs	critical raw materials
EC	European Commission
EIP	European Innovation Partnership on raw materials
EIP-SIP	Strategic Implementation Plan of the European Innovation Partnership on raw materials
EEE	electric and electronic equipment
ELVs	end-of-life vehicles
EOL	end-of-life
EOL-RIR	end-of-life recycling input rate
EU	European Union
EURELCO	European Enhanced Landfill Mining Consortium
EURMKG	European Raw Materials Knowledge Gateway
EV	electric vehicles
FAO	Food and Agriculture Organization
HEV	hybrid electric vehicles
HREEs	heavy rare earth elements
IR	infrared
IT	Information Technology
JRC	Joint Research Centre
LCA	life cycle assessment
LCD	liquid crystal displays
LCO	lithium-cobalt-oxide
LED	light emitting diode
LFP	lithium-iron-phosphate
LMO	lithium-manganese-oxide
LREEs	light rare earth elements
LUCAS	land use/ land cover area frame survey
MEErP	Methodology for the Ecodesign of Energy-related Products

MFA	material flow analyses
MSA	material system analyses
MSW	municipal solid waste
NdFeB	neodymium-iron-boron
NiMH	nickel metal hydride
NCA	lithium-nickel-cobalt aluminium-oxide
NMC	lithium-nickel-manganese-cobalt
OECD	Organisation for Economic Co-operation and Development
OEMs	Original Equipment Manufacturers
PGMs	platinum group metals
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic
REEs	rare earth elements
RMCs	Raw Material Commitments
RMI	Raw Materials Initiative
RMIS	Raw Materials Information System
SIP	Strategic Implementation Plan
SRMs	secondary raw materials
UWWTP	urban wastewater treatment plants
WEEE	waste electric and electronic equipment
WSSTP	water sanitation and supply technology platform
WWTPs	wastewater treatment plants

1 Introduction

Raw materials form the basis of Europe's economy today and tomorrow to ensure jobs and competitiveness, and they are essential for maintaining and improving quality of life. Non-energy raw materials are linked to all industries across all supply chain stages. They are also fundamental to drive change, for instance, through digital technologies, low-carbon energy technologies (e.g. solar panels, wind turbines, energy-efficient lighting), sustainable mobility (e.g. electric vehicles), in which they are currently irreplaceable.

Although all raw materials are important, some of them are of more concern than others in terms of secure and sustainable supply. Thus the list of critical raw materials (CRMs) for the EU, and the underlying European Commission (EC) criticality assessment methodology, are key instruments in the context of the EU raw materials policy. CRMs are both of high economic importance for the EU and have a high risk of supply disruption. Examples of CRMs include rare earth elements, cobalt and niobium.

For the third list of CRMs for the EU released in September 2017 (EC, 2017a), the EC has applied a revised criticality methodology, which is an evolution of that used to establish the 2011 and 2014 lists. As the EC's in-house science service, the Directorate-General Joint Research Centre (DG JRC) identified specific aspects of the EU criticality methodology and adapted them to better address the needs and expectations of the resulting CRMs list to identify and monitor critical raw materials in the EU. The modifications were introduced in the revised methodology giving high priority to the comparability with the previous two exercises, which in turn reflects the overall objective of effectively monitoring trends, and maintaining the highest possible policy relevance.

Already in 2008 and 2011 in its two Communications COM(2008)699 'The Raw Materials Initiative' (EC, 2008) and COM(2011)25 'Tackling The Challenges in Commodity Markets and on Raw Materials' (EC, 2011), the European Commission had put forward the regular identification of CRMs and the improvement of resource efficiency and of conditions for recycling as crucial components of its raw materials policy. The importance of these two components and their close interrelation was recently reinforced in the Communication COM(2015)614 on the 'EU action plan for the Circular Economy' (EC, 2015a) where critical raw materials are identified as one of the five priority areas where actions should be taken. The action plan identified several actions in this area, including the commitment to issue a report on critical raw materials and the circular economy in 2017, 'in order to ensure a coherent and effective approach, to provide key data sources and to identify [best practices and] options for further action'.

In line with the EU Circular Economy action plan (EC, 2015), a mandate was given to the JRC to assess the prominent role of recycling as a risk-reducing factor in the supply risk calculation in the criticality assessment. Related to this, JRC was asked to identify more representative data of the EU recycling situation taking into account recently published material stocks and flows data, in particular based on Deloitte Sustainability (2015). The revised criticality methodology hence contains a revised recycling risk-reducing factor together with new sources of data (Blengini et al., 2017a, 2017b).

The most recent criticality assessment considered 78 non-energy, non-agricultural raw materials (58 individual and three grouped materials HREEs, LREEs and PGMs), out of which 27 were identified as critical in the 2017 list COM(2017)0490Final (EC, 2017a), see Table 1.

Table 1. The 2017 List of Critical Raw Materials to the EU (EC, 2017a).

(HREEs = heavy rare earth elements ([1]), LREEs = light rare earth elements ([2]), PGMs = platinum group metals ([3]))

Critical raw materials			
Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

This report is a contribution of the JRC to the abovementioned policy objectives and puts together in a structured way the results of several research programmes and activities for which a large team has contributed in terms of data and knowledge developments, across the JRC activities on CRMs in a context of circular economy, taking a sectorial

([1]) Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium.
([2]) Cerium, lanthanum, neodymium, praseodymium, samarium.
([3]) Iridium, platinum, palladium, rhodium, ruthenium.

perspective. It also contributes to improve the availability of data on secondary (critical) raw materials, as set out in the Circular Economy Action Plan.

The report is structured as follows: following this introduction, the current circular use of CRMs in the EU is analysed (Chapter 2) and general sources of data are identified and briefly discussed (Chapter 3). Then Chapters 4 to 11 summarise JRC analysis concerning CRMs and the Circular Economy for various sectors, namely mining waste, landfills, electric and electronic equipment, batteries, automotive, renewable energy, defence and chemicals and fertilisers. For each sector, data, relevant data sources and a couple of best practices are presented and analysed. Conclusions and perspectives are then presented in Chapter 12.

2 Current circular use of critical raw materials in the EU

Recycling is an important source of secondary raw materials (SRMs). It can contribute to the security of raw materials supply and in advancing towards a more circular EU economy. A good measure of the circular use of critical raw materials is the recycling's contribution to meeting materials demand in the EU. For this, the end-of-life recycling input rate (EOL-RIR) measures how much of the total material input into the production system comes from recycling of 'old scrap' (i.e. post-consumer scrap) (Blengini et al., 2017a).

Although several CRMs have high recycling potential, and despite the encouragement from governments to move towards a circular economy, the EOL-RIR of CRMs is generally low (see Figure 1).

This can be explained by several factors: sorting and recycling technologies for many CRMs are not available yet at competitive costs; it is impossible to recover materials which are in-use dissipated; the supply of many CRMs is currently locked up in long-life assets, hence implying delays between manufacturing and scrapping and hence directly influencing the recycling input rate; demand for many CRMs is growing in various sectors and recycling contribution is largely insufficient to meet the demand.

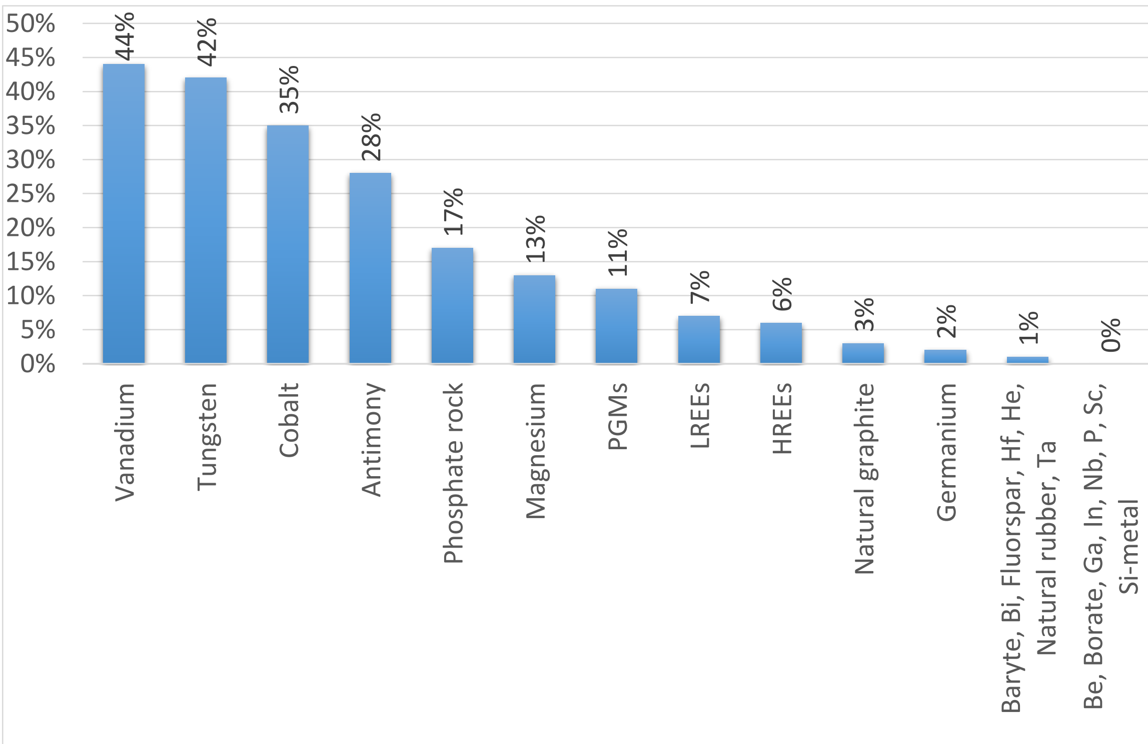


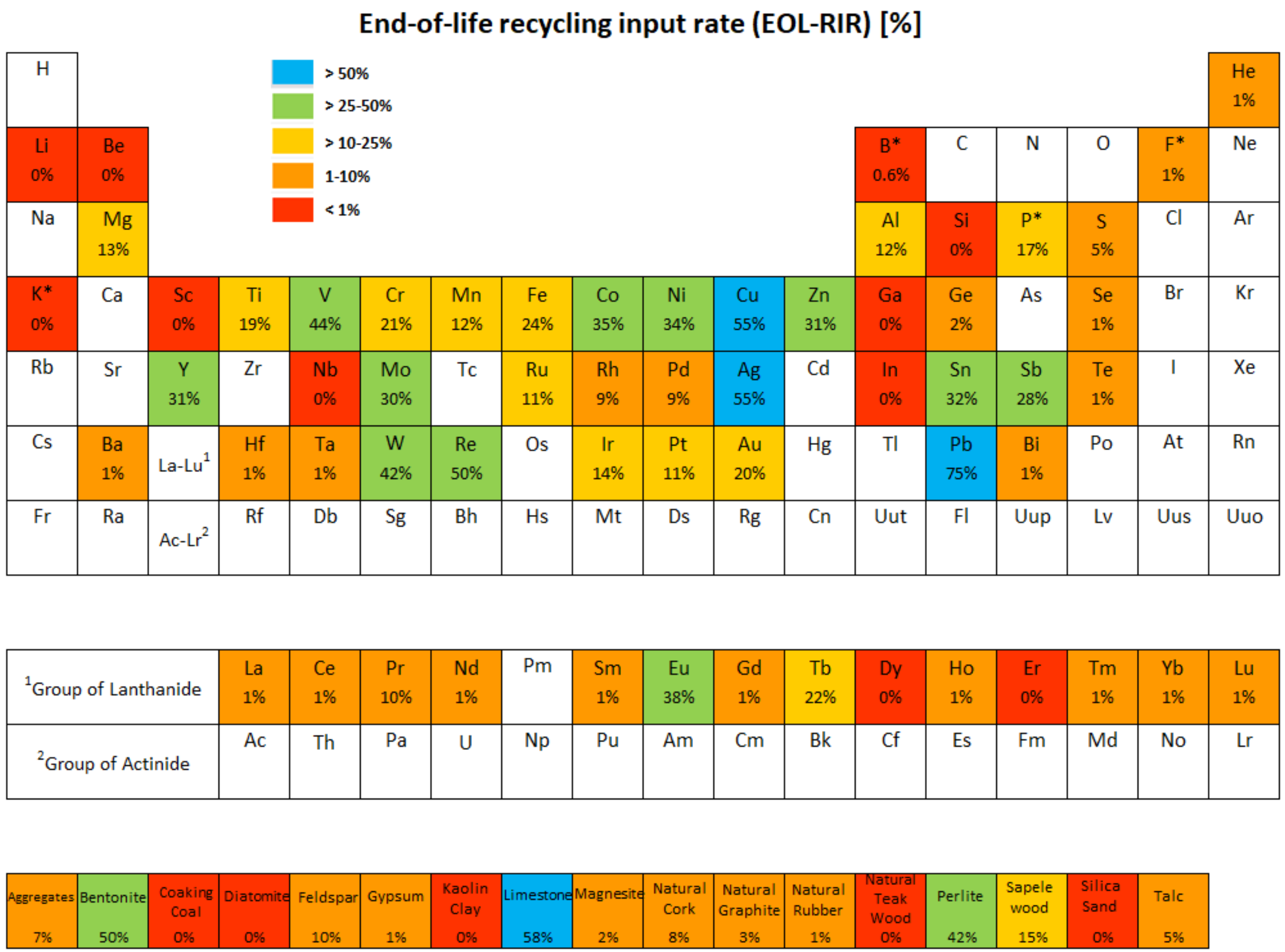
Figure 1. Current contribution of recycling to meet EU demand of CRMs: end-of-life recycling Input Rate (EOL-RIR). *Source:* JRC elaboration based on (Deloitte Sustainability, 2015) and (Deloitte Sustainability et al., 2017)).

A few CRMs, namely vanadium, tungsten, cobalt and antimony have a high recycling input rate. Such good performances can be explained by the fact that the collection rate at end-of-life is high: tungsten is mainly used in machine tools and vanadium in steel alloys (both mostly handled by businesses) that are hence well collected at end-of-life; Cobalt and Antimony are used primarily in batteries, that are well collected at end-of-life because of waste legislation.

Some other CRMs have a good rate of recycling at end-of-life (e.g. recycling rates for PGMs reaches up to 95 % for industrial catalysts and 50-60 % for automotive catalysts) but this gives a contribution that is largely insufficient to meet the growing demand and thus the recycling input rate is low (e.g. 14 % for PGMs).

When looking at an element like indium, that is massively used in flat display panels, only very small amounts of indium are currently recycled due to lack of infrastructures and volatile prices of the metal. Hence the recycling input rate is currently nil. However, exemplary recycling processes to extract indium from displays panels in an economical way are currently under research and development (Ardente and Mathieux, 2014).

Figure 2 presents similar values for a broader range of raw materials, i.e. those that were in the 2017 EU criticality assessment (Deloitte Sustainability et al., 2017).



* F = Fluorspar; P = Phosphate rock; K = Potash, Si = Silicon metal, B=Borates.

Figure 2. Current contribution of recycling to meet EU demand of CRMs: end-of-life recycling Input Rate (EOL-RIR). *Source:* JRC elaboration based on (Deloitte Sustainability, 2015) and (Deloitte Sustainability et al., 2017))

These values of end-of-life recycling input rate (EOL-RIR) are repeated for CRMs in Annex I together with qualitative information on their current recycling.

As a summary, the circular use of CRMs depends on many parameters. It should be pointed out that circularity is very much influenced by the sectors in which CRMs are used: applicability or performances of recycling technologies usually depend upon the nature of the scrap (or end-of-life products) the CRMs are embodied in; the demand and the duration of the use of the CRMs is strictly dependent on the products CRMs are embodied in; circularity of several CRMs strongly benefits from take back-schemes that are implemented in various sectors. The need to adopt a sectorial approach for the analysis of flows of CRMs, including considering circularity aspects, was confirmed by a recent report (Sebastiaan et al., 2017) of the SCRREEN project (see also section 3.4). This is why a sectorial analysis of the circularity of CRMs will be presented in the following chapters of the report.

3 Data sources

This chapter summarises relevant sources of data and knowledge concerning critical raw materials in a context of circular economy. These sources of data can be permanent platforms (see section 3.1 on the RMIS), analysis that are led regularly (see section 3.2 on MSA studies) or temporary initiatives in the form of projects (see section 3.3 and 3.4). Section 3.5 summarises general sources of data. These general sources will be completed in following chapters by sources of data that are specific to each sector.

3.1 The EU Raw Materials Information System including the CRM factsheets

Securing the undistorted supply of raw materials and, in particular, of critical raw materials is crucial and requires a sound and continuously updated knowledge base, namely the European Raw Materials Knowledge Base (EURMKB) ([4]), as highlighted and stressed in the EU Raw Materials Initiative (RMI) (EC, 2008). This need was further recognised by the Strategic Implementation Plan of the European Innovation Partnership on raw materials (EIP-SIP) of 2013, particularly in the Action area No II.8 (EC, 2017b). In this context, and responding to a specific action of the 2015 Circular Economy Communication, the DG JRC of the European Commission in close collaboration with DG GROW, is developing the EU Raw Materials Information System (RMIS). The Action Plan on Circular Economy (EC, 2015a) is explicitly calling for the 'further development of the EU Raw Materials Information System', in particular in the context of secondary raw materials.

The first version (RMIS 1.0) ([5]) was launched in March 2015. The advanced RMIS (RMIS 2.0) to be launched at the end of 2017 (see Figure 3), intends to become a one-stop information gateway and knowledge service centre for non-energy, non-food primary and secondary raw materials.

([4]) https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/knowledge-base_en [accessed on 16/10/2017].
([5]) http://rmis.jrc.ec.europa.eu [accessed on 16/10/2017].

Figure 3. Front page of the EC's Raw Material Information System (RMIS 2.0).

RMIS 2.0 ambition is (a) to support European Union (EU) policy with tailor-made applications like the periodical Raw Material Scoreboard (Vidal-Legaz et al., 2016) and Criticality assessments, and (b) to help coordinate other EU-level data and information on raw materials (EUKBRM). This will be made available directly in the RMIS from different data sources. It will be facilitated by enhanced cooperation with Member States, industry representatives, and other stakeholders. The other functionalities of RMIS 2.0 will also directly serve the implementation of the circular economy policy, examples include: material flow analysis (MFA) including the EC material system analysis (MSA); the new trade policy application; information and data on Secondary Raw Materials; contents on sustainability issues and research & innovation.

Raw materials factsheets and RMIS 2.0

RMIS 2.0 is also intended to make easily available and further exploitable the huge amount of information and data collected during the criticality assessments, which represent the background of the lists of CRMs for the EU adopted in 2011, 2014 and 2017. Such information and data is compiled and systematically organised in raw materials factsheets that are a necessary complement to the list of CRMs and represent, under several aspects, an even more important piece of information.

Criticality is necessarily a **screening tool** mainly intended to highlight and easily communicate issues of concern, which can subsequently be followed up with more detailed studies and assessments. The results of criticality assessments should therefore be considered a call for attention, not the final word, as it is very unlikely that all aspects that could influence the risk of supply and the consequences can be included in a screening methodology, while keeping the calculation equations short, simple, and objective.

Also for these reasons, the EC has developed single **raw materials factsheets**, where the detailed information and data used in the 2011, 2014 and 2017 CRMs lists are available in a structured and systematic form, available in RMIS 2.0 under the Criticality Raw Materials tile. Such factsheets include an element of analyses of supply from mining/harvesting, supply from recycling, trade, end-uses and related economic sectors, substitution, as well as supply chain analysis. They contain and explain the data used in the criticality assessment, as well as data not used in the definition of the supply risk and/or economic importance, but that are fundamental elements of information for a better understanding and subsequent decision processes. Key facts and figures are collected and summarised in the front page of each factsheet, as for example the one for Antimony shown in Figure 4.

Raw materials factsheets equally bring together further information and data that third parties might want to use in their ad hoc criticality assessments, for example to more specifically target single sectors, or smaller sets of key technologies. Additionally, RMIS 2.0 includes a section called 'Raw material profiles'. These profiles are intended to be dynamic sources of information that will be regularly updated and that will serve multiple proposes, including the next revision of the critical raw materials list.

1. ANTIMONY

Key facts and figures

Material name and element symbol	Antimony, Sb	World / EU production (tonnes)[1]	42,833 / 0
Parent group	n.a.	EU import reliance[1]	100%
Life cycle stage /material assessed	Processing/ Sb metal	Substitution index for supply risk [SI(SR)][1]	0.93
Economic importance (EI) (2017)	4.3	Substitution Index for economic importance [SI(EI)][1]	0.91
Supply risk (SR) (2017)	4.3	End of life recycling input rate (EOL-RIR)	28%
Abiotic or biotic	Abiotic	Major global end uses in 2014	Flame retardants (43%) Lead-acid batteries (32%) Lead alloys (14%)
Main product, co-product or by-product	Main product or co or by product of Au, Pb, Zn	Major world producers[1] (Sb metal production)	China (87%) Vietnam (11%)
Criticality results	2011	2014	2017
	Critical	Critical	Critical

[1] average for 2010-2014, unless otherwise stated.

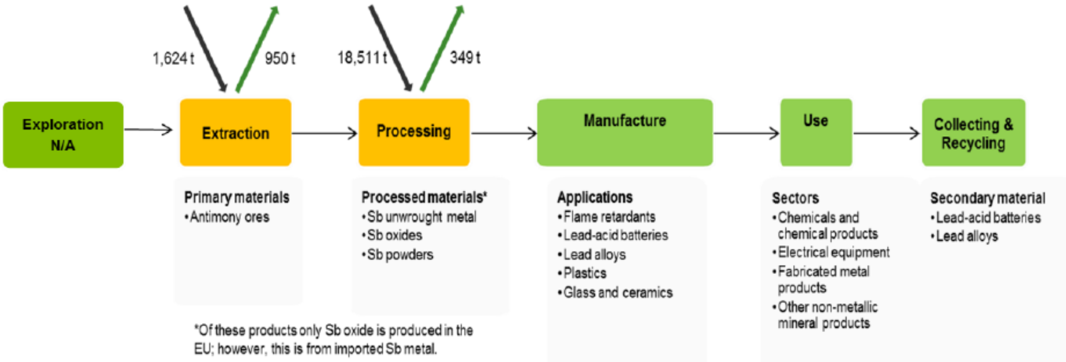


Figure 4. Example of a 2017 Raw Material Factsheet for Antimony (snapshot of the front page with key facts) to be soon inserted into the RMIS 2.0.

3.2 Material Systems Analysis 2015

The raw materials system analysis (MSA) (Deloitte Sustainability, 2015) was carried out in 2015 and investigates the flows and stocks of 28 raw materials from 'cradle-to-grave', that is, across the entire material life cycle from resource extraction to materials processing to manufacturing and fabrication to use and then to collection, processing, and disposal/recycling (Figure 5).

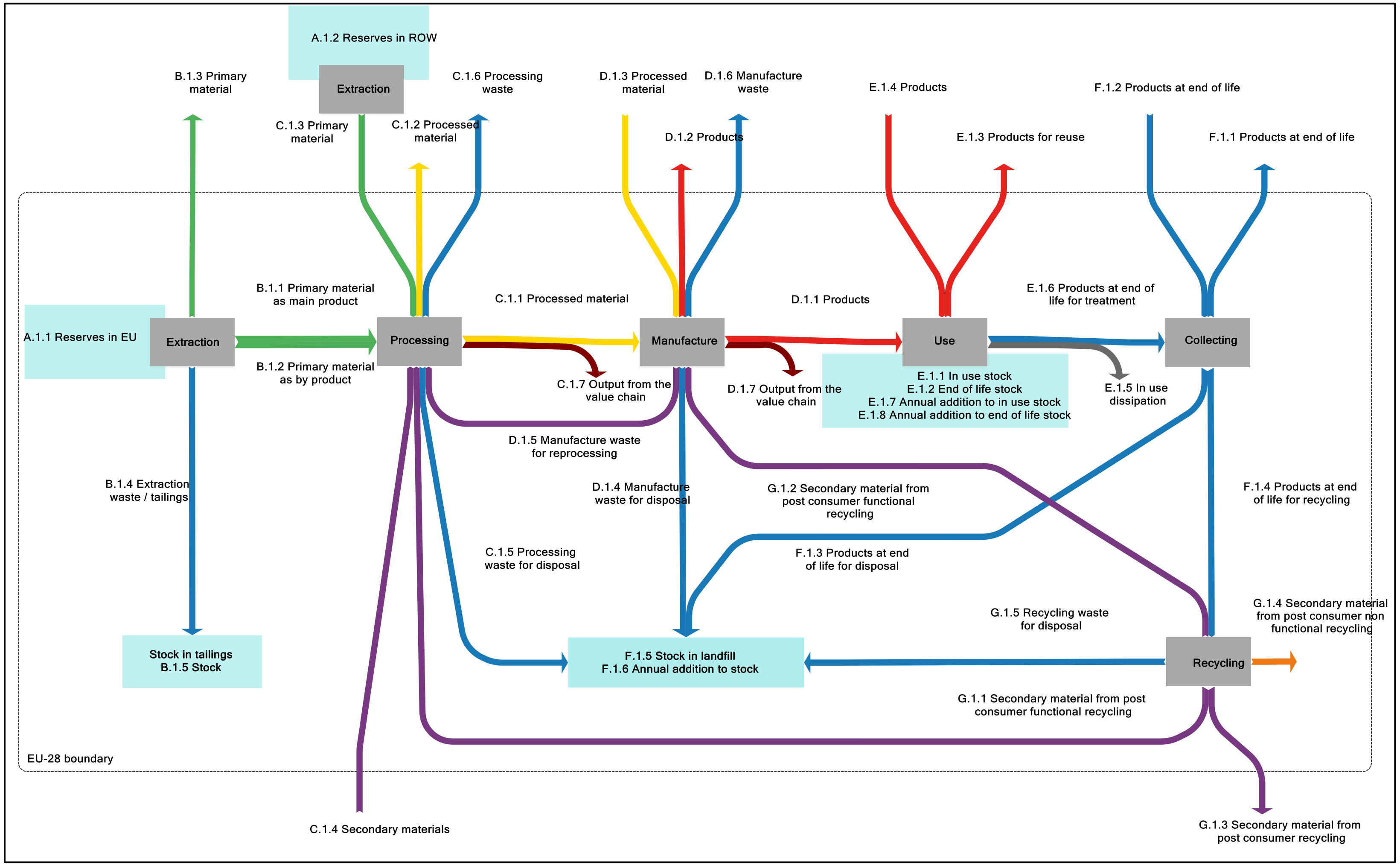


Figure 5. MSA framework and flows/stocks considered.

The study has been carried out by DG GROW with the consultation of experts and stakeholders. It is a follow-up of the 'Study on Data Needs for a Full Raw Materials Flow Analysis', launched by the European Commission in 2012 within the context of the European Raw Materials Initiative's strategy. This strategy, which is a part of the Europe 2020's strategy for smart, sustainable, and inclusive growth, aims at securing and improving access to raw materials for the EU. The objective of the MSA study is to provide information on material stocks and flows and to assist the European Commission on the development of a full MSA for a selection of key raw materials used in the EU-28, some of them considered as critical.

By tracking materials throughout their full life cycle, MSAs can help to quantify potential primary and secondary source strengths, support monitoring of their 'level of circularity' in the EU-28, and manage metal use more wisely. This is particularly important for CRMs for which public information on their trade is sometimes unknown, their uses are not well understood, and their recovery and reuse once discarded is problematic. An accurate assessment of global and EU-wide mineral resources must include not only the resources available in ground (reserves), but also those that are present as stocks within the technosphere and become available through recycling. The data resulting from the MSA study for CRMs provides an important base of background information from which future materials criticality can be better addressed, and sustainable development pathways, with an EU-wide scope, designed. A lot of this data will be presented in the sectorial chapters of this report.

3.3 ProSUM H2020 project

ProSUM (Prospecting Secondary raw materials in the Urban mine and Mining waste, Horizon 2020 research and innovation programme, grant agreement No 641999, 2015-2017) ([6]) is a Coordination and Support Action (CSA) establishing a European network of expertise on secondary sources of critical raw materials, vital to today's high-tech society. The project aims at providing data about arisings, stocks, flows and treatment of various product groups, e.g. waste electrical and electronic equipment (WEEE), end-of-life vehicles (ELVs), batteries and mining wastes. Information concerning products placed on the market, products stocks and waste flows of the EU countries derive from both measured data, coherent estimates based on statistical information, experts' assumptions and extrapolation. Quality level, uncertainty and error propagation of the gathered information are harmonised in order to obtain high quality data that will be

([6]) http://www.prosumproject.eu [accessed on 16/10/2017].

available in a centralised Urban Mine Knowledge Data Platform. Moreover, the data structure eases the regular update and maintenance of the information.

ProSUM produced the EU Urban Mine Knowledge Data Platform (EU-UMKDP) providing user-friendly, seamless access to data and intelligence on secondary raw materials arising from various waste flows. This deliverable is key for the creation of a European raw materials knowledge base and it is contributing to the above-mentioned EU Raw Material Information System.

This CSA is already contributing to policymaking activities in the field of circular economy and resource-efficiency. ProSUM directly supports the European Innovation Partnership (EIP) on Raw Materials and its Strategic Implementation Plan (SIP). The project is complementary to a few other Horizon 2020 and FP7 actions focused on primary raw materials and it is concurring on unlocking new possibilities for a sustainable supply of raw materials. It is contributing to the Raw Material Information System (RMIS) developed by JRC under DG GROW initiative.

3.4 European expert network on critical raw materials Scrreen

Scrreen (Solutions for Critical Raw materials — a European Expert Network) is a Coordination and Support Action aiming at gathering European initiatives, associations, clusters, and projects working on CRMs into a long-lasting Expert Network on Critical Raw Materials, including stakeholders, public authorities and civil society representatives. This network will combine forces to address all the CRMs issues including mining, processing, recycling, substitution and final applications in relation to the cross-cutting aspects: policy/society, technology, standards and markets.

Scrreen will contribute to the CRM strategy in Europe by (i) mapping primary and secondary resources as well as substitutes of CRMs, (ii) estimating the expected demand of various CRMs in the future and identifying major trends, (iii) providing policy and technology recommendations for actions improving the production and the potential substitution of CRM, (iv) addressing specifically WEEE and other end-of-life (EOL) products issues related to their mapping and treatment standardisation and (vi) identifying the knowledge gained over the last years and easing the access to these data beyond the project. Scrreen has just published a report that reviews the use of CRMs in the European Union, considering the 2014 CRM list and underlying methodology. It takes an economy-wide approach (like the Material System Analysis and criticality studies, see sections 3.1 and 3.2) and complements it with bottom-up perspective by addressing material composition of products. The approach is hence complementary to the MSA and criticality approaches used widely in the following sectorial chapters 4 to 11. The knowledge gathered within the Scrreen project will be collected and maintained in the Raw Materials Information System.

3.5 Other general sources

Table 2. List of general sources

N°	Name and link/ref.	Scope			Reference period /date of publ.	Language(s)	Free/ subscription	Comments
		Subsectors	CRMs	Geographic area				
1	Criticality study (Deloitte Sustainability et al., 2017)	Various	All	EU-27	2014 (updated every 3 years)	English	Free	
2	MSA study (Deloitte Sustainability, 2015)	Various	All	EU-28	2016 (updated every 3-5 years)	English	Free	
3	Rohstoffe für Zukunftstechnologien (Marscheider-Weidemann et al., 2016)	Emerging technologies	Several	Germany	2016	German	Free	This report entitled 'Raw materials for emerging technologies 2016' is a revised edition of the 2009 study.
4	Scrreen report (Sebastiaan et al., 2017)	Various	2014 list of CRMs	EU-28	2017	English	Free	
5	Recycling Rates of Metals — A Status Report (Graedel et al., 2011)	All	Several	Worldwide	2011	English	Free	

Many other sources of data relevant for specific sectors will be described in the following chapters of the report.

4 Extractive waste

4.1 Data

Extractive industries provide mineral raw materials, including critical raw materials, that are essential to the downstream industries and economic sectors. During the prospecting, extraction, treatment and storage of mineral resources and the working of quarries, extractive wastes may be generated. Extractive wastes may include mineral excavation wastes (e.g. overburden or waste-rock), mineral processing/treatment wastes (e.g. tailings, waste gravel, waste sand and clays) and drilling muds and other drilling wastes (e.g. discarded drill cuttings). As the management of extractive wastes may pose risks to the environment and to human health, minimum requirements are laid down in Directive 2006/21/EC, the Extractive Waste Directive, in order to prevent or reduce as far as possible any adverse effects on the environment or on human health brought about as a result of the management of extractive wastes (EC, 2006).

In certain cases, extractive wastes, such as discarded tailings, may contain CRMs in relevant amounts and concentrations (for example, indium or germanium in residues of treated zinc ores, or gallium in bauxite tailings) for which the recovery could be carried out at a profit as long as the market demand exists and the commodity price makes the re-processing economically viable. Important influencing variables are the CRMs amounts, their concentration, the mineralogical composition of the extractive wastes as well as the grading and fabric of the extractive waste that resulted from the treatment processes performed earlier.

As a starting point, the potential for the recovery of CRMs from extractive wastes depends on the extractive waste volumes and their concentrations. Eurostat collects and reports data, bi-annually, on volumes of extractive wastes divided into two categories (hazardous, non-hazardous) since 2004 (see Table 3). However, no systematic and consistent collection of data relevant to CRMs contained in extractive wastes is carried out.

In particular, at present no database at EU or Member State-level reports:

- the volumes of the extractive waste deposits (for closed and active mines), divided on the basis of the main mineral exploited and/or on the basis of the detailed waste types;
- the volumes of the different extractive waste streams.

For the above reasons, only rough estimates of the (bi-)annual flows and extrapolations of the accumulated amounts are possible, such as the one provided by the MSA study (Deloitte Sustainability, 2015). The MSA study forms a comprehensive data inventory of the material flows in industrial and societal uses in the EU-28, where extractive waste is depicted by two parameters:

- 'Extractive waste disposed in situ/tailings' is the annual quantity of the element in the extractive waste disposed in situ. This indicator refers to tailings, i.e. 'the waste solids or slurries that remain after the treatment of minerals by separation processes (e.g. crushing, grinding, size-sorting, flotation and other physico-chemical techniques) to remove the valuable minerals from the less valuable rock' (Extractive Waste Directive 2006/21/EC);
- 'Stock in tailings' is the quantity of the element in tailings in EU. This amount corresponds to the 'extractive waste disposed in situ/tailings' accumulated over time.

A preliminary analysis from the MSA study (Deloitte Sustainability, 2015) on annual flows and stocks of CRMs in extractive waste over the last 20 years is reported in Figure 6. Quantities are indicative and mostly derived from mass balances and expert assumptions. Moreover, CRMs accumulated in tailings have likely undergone chemical and physical changes, which must be further evaluated under several aspects, in view of their possible recovery. Due to natural attenuation processes, revegetation, and internal cementation or compaction, the opening of some historical extractive waste sites for recovery can be of relatively higher risk by reactivating pollution sources and pollution pathways, than applying the 'don't touch it' principle.

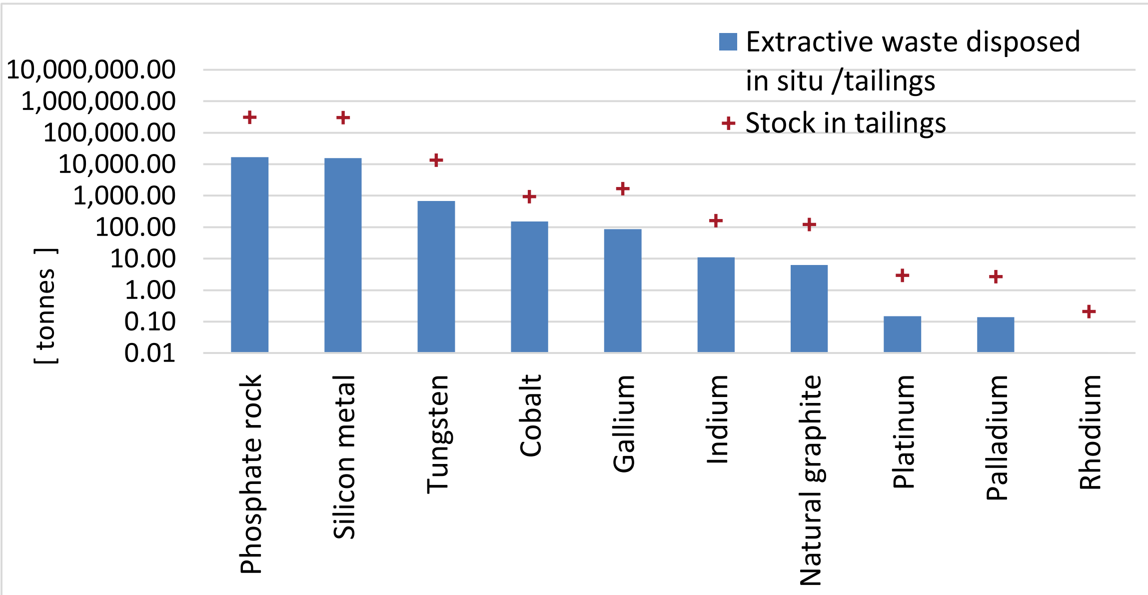


Figure 6. Amounts of some CRMs in EU-28 as 'Extractive waste disposed in situ/tailings' and 'Stock in tailings'. *Source:* JRC elaboration based on 2015 MSA study (Deloitte Sustainability, 2015).

CRMs ending up in extractive waste vary significantly across commodity groups. For example, extraction and processing of aggregates and several industrial minerals usually generate limited quantities of extractive waste. In contrast, the extraction and especially the processing of certain ores with low metal concentrations (in the range of ppm or less) are accompanied by extractive residue volumes several orders of magnitude larger, generating possibly significant amounts of extractive wastes.

In harmony with circular economy principles, extractive waste is a potential source of valuable materials that are currently not recovered routinely, including CRMs. Increased recovery of CRMs from extractive wastes (a) can reduce, in certain cases, the need for active or passive treatment and storage of extractive waste and the associated environmental impacts; and (b) decreases the need for their primary extraction. So far, recovery of CRMs from extractive waste is rather low, since it is rarely economic and the technology required may not yet exist.

4.2 Data sources

Table 3. List of sources relevant for the mining sector.

N°	Name and link/ref.	Scope			Reference period/ date of publ.	Language (s)	Free/ subscription	Comments
		Subsectors	CRMs	Geographic area				
1	Eurostat (7)	Mining waste	-	EU-28	2004-2014	English	Free	Data on the generation of hazardous and non-hazardous waste by country and sector 'mining and quarrying' and the manufacturing of metals and non-metallic minerals. Consistency is limited due to differing reporting methods.
2	ProSUM (8)	Mining Waste	All	EU-28 (focus on Geological Surveys that are project members)	H2020 projects: ProSUM 2015-2017	English	tbd	Mining waste data based on a flow and stock model
3	Minerals4 EU(9)	Mining Waste	All	EU-28 (focus on Geological Surveys that are project members) and other European states	Minerals4 EU 2014-2015	English	tbd	Mining waste data based on a flow and stock model
4	SMART GROUND (10)	Mining Waste	All	EU-28 (with focus on Italy as case-study country)	H2020 project (2015-2018)	English	tbd	Improving knowledge on CRM, including characterisatio n of mining waste deposits for CRMs.

(7) Eurostat, Hazardous waste generation (http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics#Hazardous_waste_generation) [accessed on 16/10/2017].
(8) http://www.prosumproject.eu [accessed on 16/10/2017].
(9) http://www.minerals4eu.eu [accessed on 16/10/2017].
(10) http://www.smart-ground.eu [accessed on 16/10/2017].

4.3 Best practices

Best practice case 1: Recovery of CRMs from mine waste in some Member States

Mines of yesterday often focused on the production of one or few commodities, while technological advancements increasingly allow the production of additional co-products and by-products. Thus, it is common that associated minerals and/or elements, not known or exploited during the mining activities, are still present (and potentially exploitable) in the old extractive waste deposition areas. Furthermore, ores with concentrations below the cut-off grade at the time of mining may become valuable and their extraction become economic due to technology changes, and elevated market prices for the metals contained in the ore.

This is the case of Penouta mine, located in the Northern Spain (Orense, Galicia), where mining operations restarted in 2011, due to the increasing demand of some metals for technological uses. After the mine closure in 1985, leaving a degraded area, the mine was reopened in 2011 with an expected life-time of 15-20 years. The investment was at least EUR 350 million for the first 10 years. It produces concentrates of tin and tantalum, niobium, and other minerals obtained in co-production.

Building on the principle that all valuable metals contained in the ore should be recovered rather than ending up in e.g. the tailings dam, the BRAVO (Bauxite Residue and Aluminium Valorisation Operations) project in Ireland is targeted to the recovery of CRMs from bauxite residues (red mud). Using red mud as a source of critical raw materials (e.g. gallium, titanium, selenium, germanium, dysprosium and cerium) simultaneously brings environmental benefits due to the additional treatment of the red mud itself, which potentially causes environmental damage due to its alkaline content.

Best practice case 2: Improving the state of knowledge on Extractive Waste Sites

Building on the experience gained through the MSA study (Deloitte Sustainability, 2015), which substantially contributed to identify and partially fill some major data gaps, the currently ongoing EC-funded H2020 projects SMART GROUND and ProSUM are targeted to advance further in respect to data availability on CRMs in extractive wastes. In view of a comprehensive pan-European database on mining waste sites, which is currently missing, ProSUM ([11]), Minerals4EU ([12]) and SMART GROUND ([13]) projects contribute to

([11]) http://www.prosumproject.eu [accessed on 16/10/2017].

an improved and harmonised overview on EU extractive waste sites, their waste volumes, composition and origin. The ProSUM database development contributes to the harmonisation across Member States, and contributes to a currently developed INSPIRE classification of extractive waste deposition area. The abovementioned projects are also supposed to contribute to a better interpretation of the current and future usefulness of the datasets for assessing the CRM potential from EU mining waste sites.

Best practice case 3: BREF on the Management of Waste from the Extractive Industries

Based on the Extractive Waste Directive, the BREF (Best Available Techniques reference documents) on the management of extractive wastes, currently under revision, provides information on certain extractive waste characteristics and on the possibility to recover valuable materials from extractive wastes. The implementation of best available techniques throughout EU extractive waste management sites, and recovery of extractive waste, can contribute to an improved recovery of valuable secondary raw materials, including CRMs, and in a broader context to the enhanced implementation of the circular economy principles in the extractive sector.

([12]) http://www.minerals4eu.eu [accessed on 16/10/2017].
([13]) http://www.smart-ground.eu [accessed on 16/10/2017].

5 Landfills

5.1 Data

Landfills are waste disposal sites for the deposit of the waste onto or into land (Directive 1999/31/EC). Controlled landfills are divided into three categories ([14]): landfills for hazardous waste, landfills for non-hazardous waste and landfills for inert waste ([15]). The quantity and the composition of waste in landfills across the European countries reflect differences in the economic structure, the consumption patterns and the different waste policies of member states. The number of active landfills in the EU has decreased in the last decades from the numbers of the late 1970s ([16]). Similarly, the average size of the landfills has increased notably. However, there are overall between 150 000 and 500 000 landfills in EU, the majority of which are not active anymore, which could potentially represent a significant source of secondary materials and energy ([17]). Other estimations ([18]) indicated that the total amount of landfills in Europe is most likely even bigger, 90 % of those being non-sanitary landfills ([19]) predating the Landfill Directive in 1999 and essentially containing municipal solid waste (MSW). Only 20 % are landfills containing more specific industrial waste and residues.

Eurostat ([20]) provides yearly statistics about the flows of MSW disposed in landfills. These statistics show a trend of reduction of waste landfilled, moving from 144 million tonnes in 1995 to 61 million tonnes (– 58 %) of waste landfilled in 2015 by the EU-27, even though more waste is being generated over these years.

Landfills were and are used for a very large variety of waste, representing nowadays an accumulation of large amount of very different materials, including CRMs. However, no systematic collection of data specific to CRMs ending up in landfills is carried out and, subsequently, no precise statistics are currently available. Only rough estimates of the flows and amount of CRMs ending up in landfills are presently possible, such as the one provided by the MSA study (Deloitte Sustainability, 2015), a comprehensive data

([14]) http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=URISERV:l21208&from=EN [accessed on 16/10/2017].
([15]) Waste which will not decompose or burn, such as gravel, sand and stone.
([16]) For example, in Italy the number of active landfills have decreased since the 1980s from the 900 to current 28 (whose 13 non-hazardous waste landfills, 13 inert waste landfills and 2 hazardous waste landfills). In the same period, the number of landfills in the UK reduced from 2 300 non-hazardous landfills and 938 hazardous landfills to 200 and 12 respectively [data from SMART GROUND H2020 project].
([17]) http://www.smart-ground.eu [accessed on 16/10/2017].
([18]) http://www.eurelco.org/infographic [accessed on 16/10/2017].
([19]) Sanitary landfills are sites where waste are isolated from the environment and managed in a safe way.
([20]) Eurostat, Municipal waste statistics (http://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics) [accessed on 16/10/2017].

inventory of the material flows in industry and society in the EU-28, through two parameters:

- The 'Annual addition to stock in landfill' that quantifies the amount of element that is annually added to landfill (in the EU), including the processing waste, the manufacturing waste, the products at end of life and the recycling waste that are sent for disposal; and
- The 'Stock in landfill' that quantifies the amount of element in landfill (in the EU). For the calculation of the stock, one considers the amount of material accumulated in landfill over the last 20 years ([21]) as a maximum level.

The estimated amounts of CRMs annually sent to landfills and the estimated accumulation in landfill over the last 20 years in the EU are plotted in Figure 7. Quantities reported in Figure 7 are indicative and are mostly derived from mass balances and expert assumptions. Moreover, CRMs accumulated in landfills have likely undergone chemical and physical changes for which their possible recovery must be carefully evaluated under several aspects.

The concentration of metal in mined ores is often less than 1 %, while in landfill their concentration can be as high as 20 % ([22]). It was estimated that 10 hectares MSW landfill might contain 188 000 t of steel and 10 000 t of aluminium (Cohen-Rosenthal, 2004). A recent study (Gutiérrez-Gutiérrez et al., 2015) provided a first estimate of the concentration of CRMs in British landfills operating between 1980 and 2011 and receiving MSW, commercial and industrial waste. This study also found that the concentration of overall CRMs in the landfills was about 380 mg/kg ([23]). If these concentrations were generalised to the EU-27 landfills between the years 1995-2014, the rough estimated total content of materials would be ([24]): 470-520 thousand tons of REEs; and 340-370 thousand tons for other materials (Li, Ln, Sb, Co). Larger amounts could be available considering also the landfills operating before the 1980, but no detailed data are available on their composition.

([21]) This period of 20 years can be smaller if the material is used in specific products that did not exist 20 years ago. For example, steels with niobium have been used for construction for more than 20 years but buildings and bridges have not yet reached end of life, and therefore these flows to landfills are null. Indium has been used to make flat panel liquid crystal displays (LCD) in electronics for about 18 years. LCD waste started to arise about six years later (i.e. 12 years ago).
([22]) http://www.smart-ground.eu [accessed on 16/10/2017].
([23]) In particular, it was reported that the concentration of REEs (Sc, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) was 220 ±11 mg/kg, PGMs; concentration of PGMs (Pt, Pd, Ru) was 2.1 ±0.2 mg/kg; concentration of other metals (Li, Ln, Sb, Co) was 156 ±7 mg/kg. Concentration of other valuable metals (such as Cu, Al, Ag, Au) in such landfills was 6.6 ±0.7 g/kg.
([24]) Estimations provided by the SMART GROUND H2020 project [http://www.smart-ground.eu].

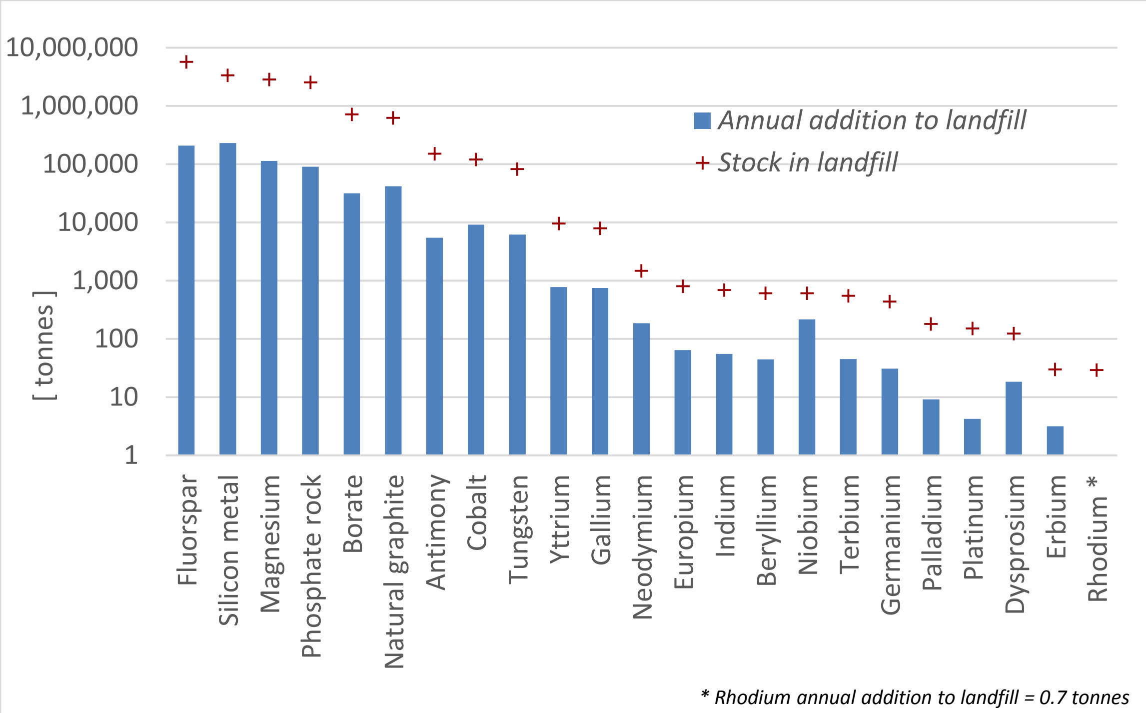


Figure 7. Amounts of some CRMs as 'Annual addition to stock in landfills in EU' and 'Stock in landfill in EU'. *Source:* JRC elaboration based on 2015 MSA study (Deloitte Sustainability, 2015).

5.2 Data sources

Table 4. List of sources relevant for the sector landfills

Nº	Name and link/ref.	Scope			Reference period/ date of publ.	Language (s)	Free/ subscription	Comments
		Subsectors	CRMs	Geographic area				
1	Eurostat ([25])	Municipal waste statistics	-	EU-28	1995-2015	English	Free	Data on municipal waste generated and treated in the EU. It includes statistics on waste landfilled.
2	MSA study (Deloitte Sustainability, 2015)	Various	All	EU-28	2015	English	Free	Flows of materials landfilled estimated for 28 raw materials (including all the CRMs identified in the CRM study of 2014)
3	Eurelco ([26])	Landfills	All	EU-28	2014-onward	English	tbd	Network for the enhancement of landfill mining.
4	SMART GROUND ([27])	Landfills	All	EU-28 (with focus on certain case-study countries)	H2020 project (2015-2018)	English	tbd	Improving knowledge on secondary raw materials (SRM), including characterisation of landfills for CRMs.

([25]) Eurostat, Municipal waste statistics (http://ec.europa.eu/eurostat/statistics-explained/index.php/Municipal_waste_statistics) [accessed on 16/10/2017].
([26]) http://www.eurelco.org/mission [accessed on 16/10/2017].
([27]) http://www.smart-ground.eu [accessed on 16/10/2017].

5.3 Best practices

Best practice case 1: Creation of EU network for landfill mining

The Eurelco (European Enhanced Landfill Mining Consortium) is one of the Raw Material Commitments (RMCs) ([28]) that have been recognised within the European Innovation Partnership (EIP). The RMCs is a joint undertaking by several partners, who commit to activities aimed at achieving the EIP's objectives between 2014 and 2020. In particular, the goal of the Eurelco RMC is to be an open, quadruple-helix (multi-stakeholder) network that supports the required technological, legal, social, economic, environmental and organisational innovation with respect to 'Enhanced Landfill Mining' within the context of a transition to a circular, low carbon economy. 'Enhanced Landfill Mining' is defined as: the safe exploration, conditioning, excavation and integrated valorisation of (historic, present and/or future) landfilled waste streams as both materials (waste-to-material) and energy (waste-to-energy), using innovative transformation technologies and respecting the most stringent social and ecological criteria. Partners of Eurelco committed to focus also on the separation and recovery of valuable and CRMs from landfilled industrial residues by hydrometallurgical routes with the aim to recycle both the recovered metals as well as the matrix material. In February 2017, 58 organisations from 13 EU Member States were united in Eurelco. One of the achievements of the Eurelco was the publishing of an infographic on the situation of landfills in the EU-28 ([29]), based on a bottom-up approach with data collected from several public bodies in Europe.

Best practice case 2: Investigation and characterisation of landfills in the EU

The SMART GROUND H2020 project ([30]) aims at improving the availability and accessibility of data and information on secondary raw materials, including CRMs. In particular, it includes some tasks on the characterisation of some pilot landfills (located in Hungary, Italy, Spain and UK) based on qualitative and quantitative data. The method proposed for the analysis mainly includes: to gather information from the landfills, including landfill characteristics, the type of the waste and the period of exploitation, since these are essential parameters relating to the economical profitability of landfill mining projects; to develop quantitative indicators related to the investments and economical utilisation of SRMs, as for example estimations of the volume of waste stored; to extract waste samples for laboratory analysis to verify the potential of the

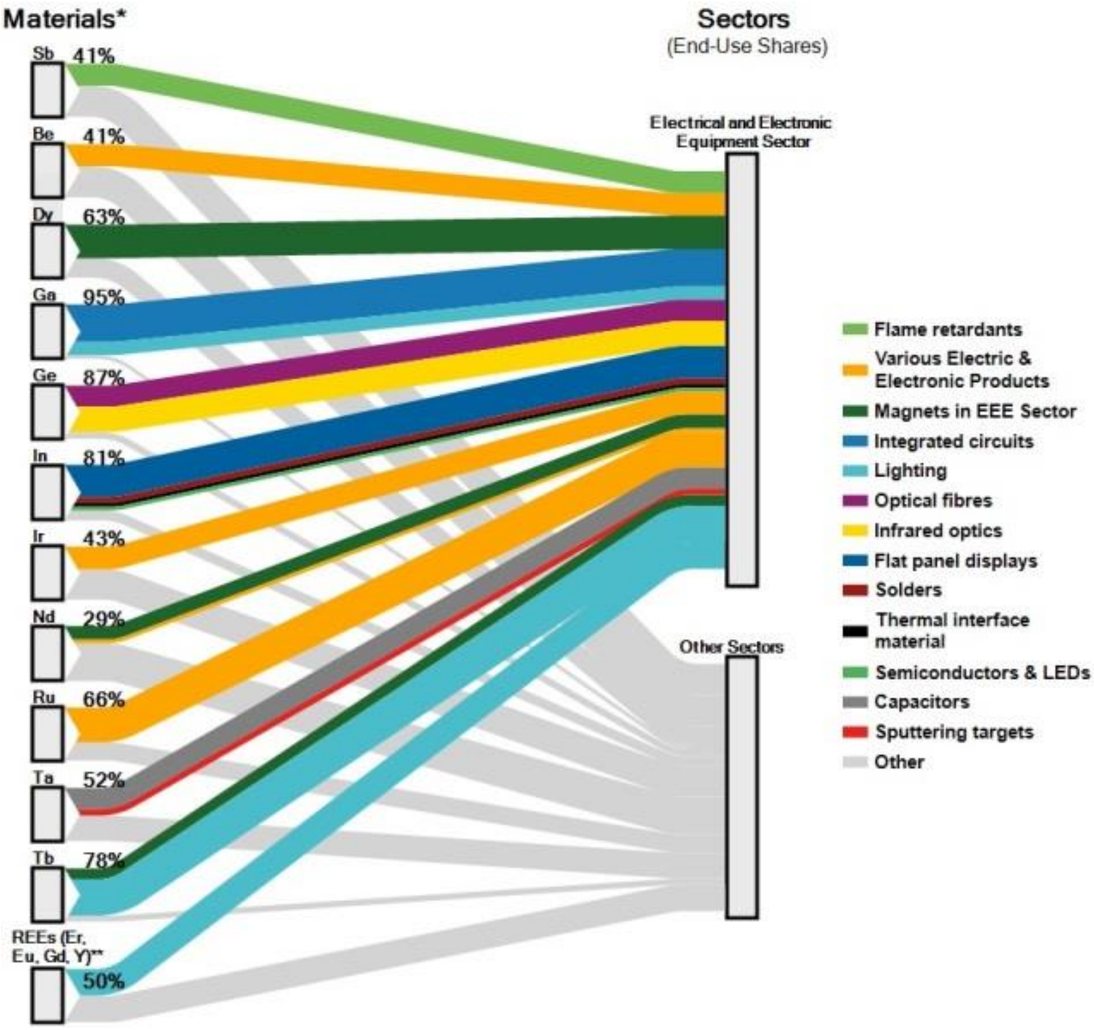
([28]) https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/call-commitments [accessed on 16/10/2017].
([29]) http://www.eurelco.org/infographic [accessed on 16/10/2017].
([30]) http://www.smart-ground.eu [accessed on 16/10/2017].

landfills. The SMART GROUND project does not necessarily aim to optimise the economic benefits of landfill mining but to find the best harmonised practices and cost-effective methods that enable the more effective utilisation of SRMs from landfills. The project also recognised the need for the cooperation with the landfill owners and the need to raise their interests toward landfill mining projects for the overall success of the initiative.

6 Electrical and electronic equipment

6.1 Data

The electrical and electronic equipment (EEE) sectors in Europe depend on a variety of critical raw materials including antimony, beryllium, cobalt, germanium, indium, PGMs, natural graphite, REEs, Silicon metal, and tungsten (Figure 8). EEE are subject to several EU policies, including the WEEE Directive 2002/96/EC and the Ecodesign Directive 2009/125/EC.



*Only a subset of CRMS used in the EEE sector are included. Additional CRMs linked to the EEE sectors include Ce, Co, Fluorspar, Hf, He, La, Mn, Natural rubber, Pd, Pt, Pr, Rh, Sm, Si, W, and V. **Average share for Er, Eu, Gd, and Y.

Figure 8. Share of CRMs used in the electric and electronic sector according to the 2017 CRM assessment. *Source:* JRC elaboration based on data from the 2017 EU criticality assessment (Deloitte Sustainability et al., 2017) and other references ([31]).

([31]) The EEE sector consists of two NACE sectors (C26 — Manufacture of computer, electronic and optical products and C27 — Manufacture of electrical equipment). The

For example, gallium finds widespread use in integrated circuits and light emitting diodes (LEDs) for lighting. Other important product application associated with the EEE sector includes, e.g. magnets, flat screen displays, and optical fibres. Figure 8 also shows that the EEE sectors are the major user of gallium (95 % of the element is used in the EEE sector), germanium (87 %), indium (81 %), and several REEs (e.g. used in lighting applications).

Some flows of CRMs reach indirectly EEE, and these flows are not always captured by statistics. For example, 52 % of the overall flow of antimony is used to produce flame retardant for plastics ([32]), afterwards used to manufacture EEE. Additional information of these flows is necessary to capture CRMs' final uses. This proves also that the relative relevance of certain CRMs for EEE can be even higher than shown in Figure 8.

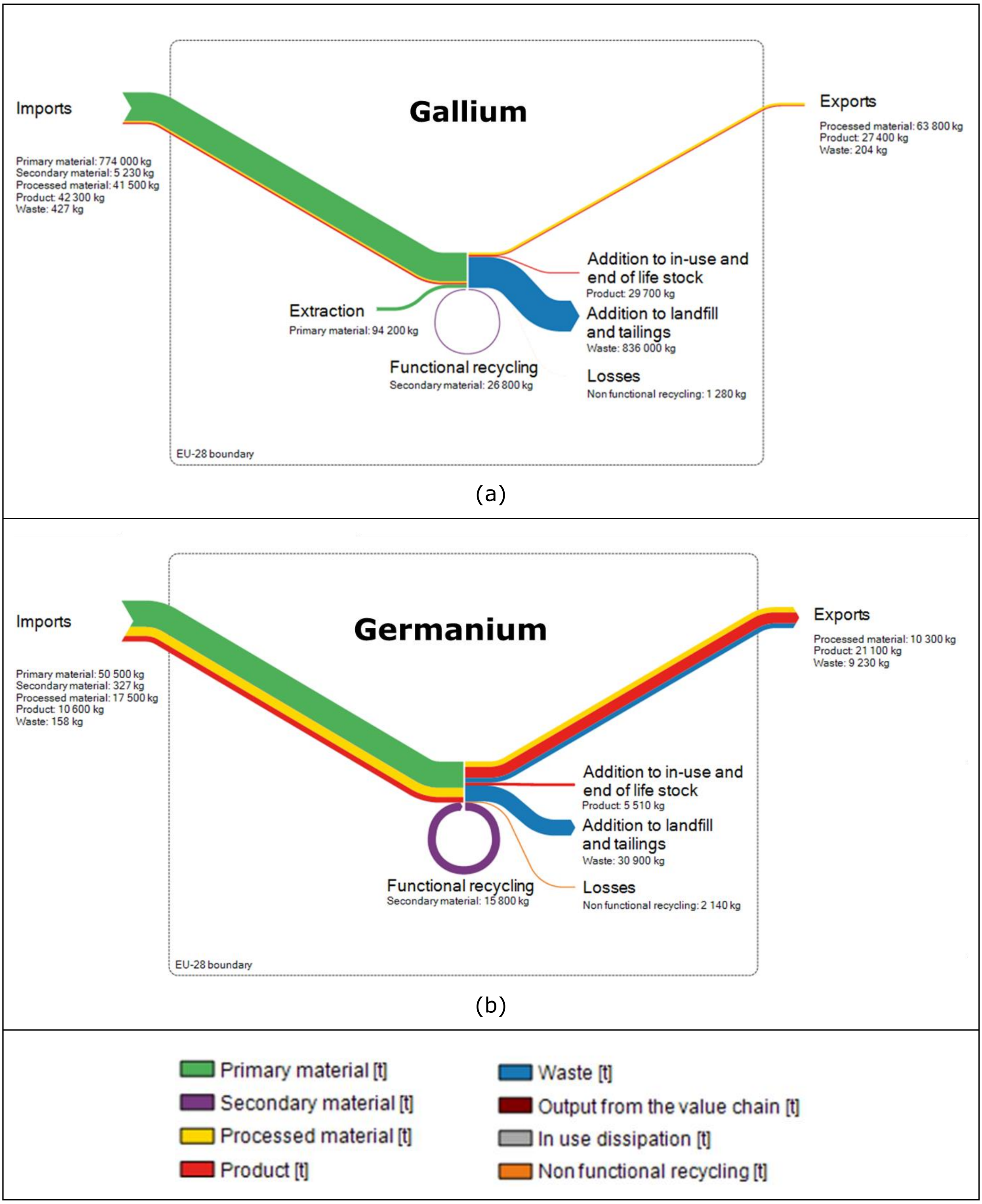
However, Figure 8 does not yet show the level of circularity of CRMs in the EU-28. For materials used predominantly in the EEE sectors (i.e., gallium, germanium, indium, and dysprosium (as an example of a heavy REE ([33])), provides an indication of the amounts of secondary raw materials functionally recycled to contribute to EU demand in 2012 (see purple coloured Sankey arrow in the Figure).

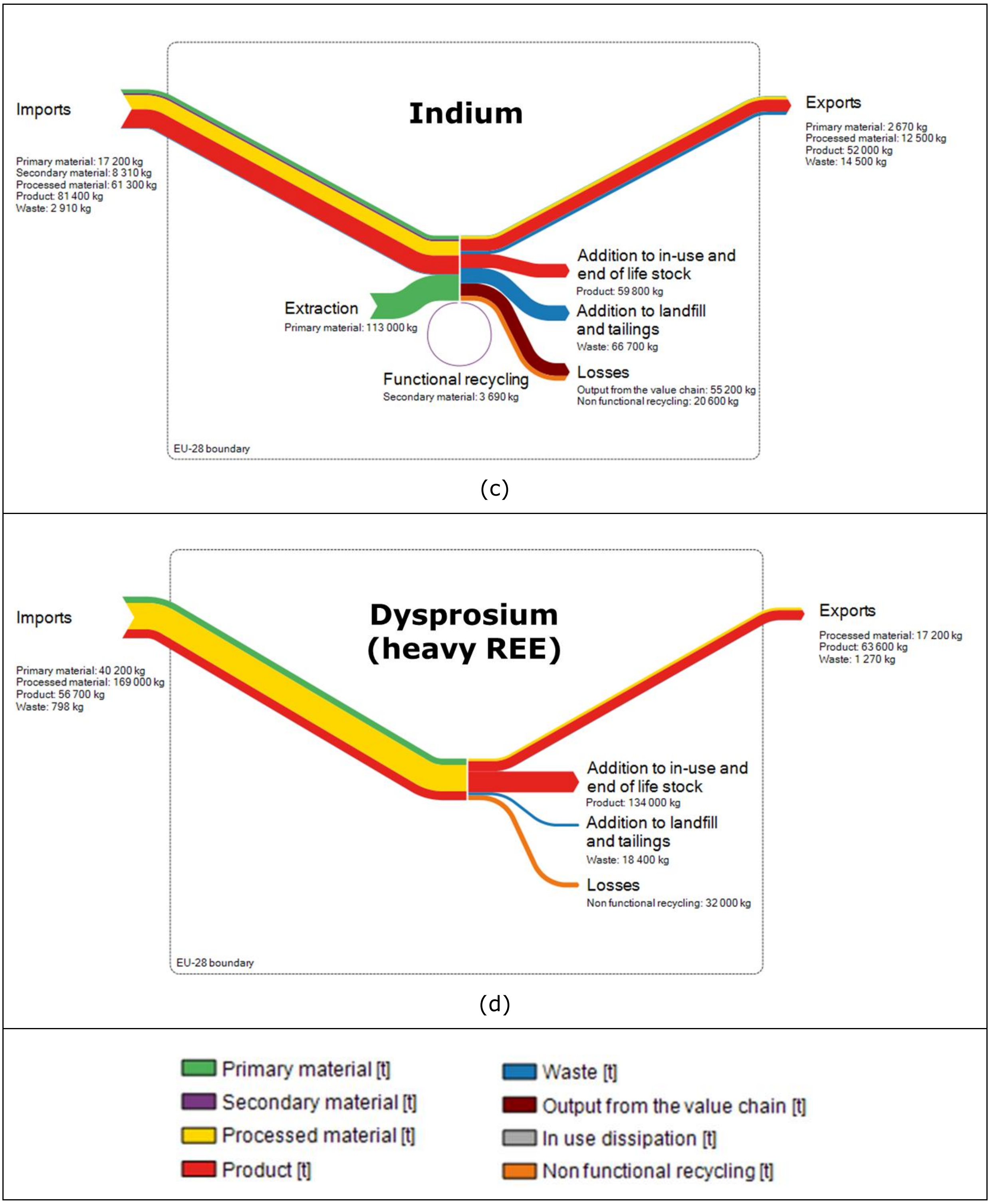
share of Sb in flame retardants used in the EEE sector is estimated at 96 % (Parker and Arendorf, 2012). The fraction of Nd, Pr, Dy, and Tb in magnets used in the EEE sector is based on a global average figure given in (Du and Graedel, 2011).

([32]) Antimony is generally applied as a synergist (antimony trioxide) for brominated flame retardants used into EEE (http://www.weee-forum.org/system/files/documents/rohs20in20mixed20plastics_empa_final_2010200920171.pdf [accessed on 16/10/2017]).

([33]) Heavy rare earth elements are important constituents of tri-band phosphor lighting used for linear fluorescent tubes and compact fluorescent lamps, as well as CCFL LCD backlights for flat panel displays.

Figure 9. Level of circularity of materials used predominantly in the EEE sector: (a) Gallium (b) Germanium (c) Indium and (d) Dysprosium. Values for the EU-28 expressed in t/year for the year 2012 based on the 2015. *Source:* (Deloitte Sustainability, 2015)





For example, Figure 9 shows that currently only a small fraction of CRMs remains inside Europe's socio-industrial metabolism through functional recycling. For dysprosium (one of the heavy REEs), recycling is not observed. The potential to improve recycling of materials depends on various factors such as recycling infrastructure, market prices, possibility to disassemble products, and the amount of material becoming available from products reaching their end-of-life. In some cases, material flows are going to stock (e.g. when used in durable products) and they cannot be available for recycling for various years. This, however, ensures a continuous service of the materials to society and contributes to maintaining their value within the economy, in line with the circular economy principles.

Lifetime of CRMs in EEE largely depends on the type of application and the end-use product. For example, lifetimes of REEs can vary from a few years (or months) for lamps, up to decades in high efficiency motors. Analogously, it is not possible to generalise on the ease of disassembly (and hence of repair and reuse) of certain parts containing CRMs, since this depends on the type of product and even its brand. It is observed that the trend of miniaturisation of electronics is generally making disassembly of components increasingly challenging.

At the same time, the recycling of CRMs contained in EEE largely depends on the type of application and on the value of the raw materials. For example, precious metals in electronics (e.g. PGMs in printed circuit boards) are generally separated according to the WEEE Directive and recycled because this is economically viable ([34]). On the contrary, according to a JRC report (Chancerel et al., 2016b), the recycling of materials such as gallium, germanium, indium, silicon metal, and REEs is more challenging because of their disperse use in products.

Useful data can be already obtained from ProSUM project (See section 3.3) on CRMs contained in WEEE. As an illustration, the ProSUM EU-UMKDP provides data on stocks and flows of Secondary Raw Materials arising from products such as end-of-life screens, including end-of-life cathode ray tube (CRT) TVs and monitors, liquid crystal display (LCD) based TVs and monitors, laptops, and tablets[35]. The ProSUM project has processed a large variety of data sources to estimate the material content of screens placed on the market over time (see Figure 10). This includes the content of precious metals such as gold (Au) and silver (Ag) but also CRMs such as indium (In), neodymium (Nd) and palladium (Pd).

([34]) http://www.umicore.com/en/about/elements [accessed on 16/10/2017].

[35] More detailed information can be found on http://rmis.jrc.ec.europa.eu/?page=contributions-of-h2020-projects-236032

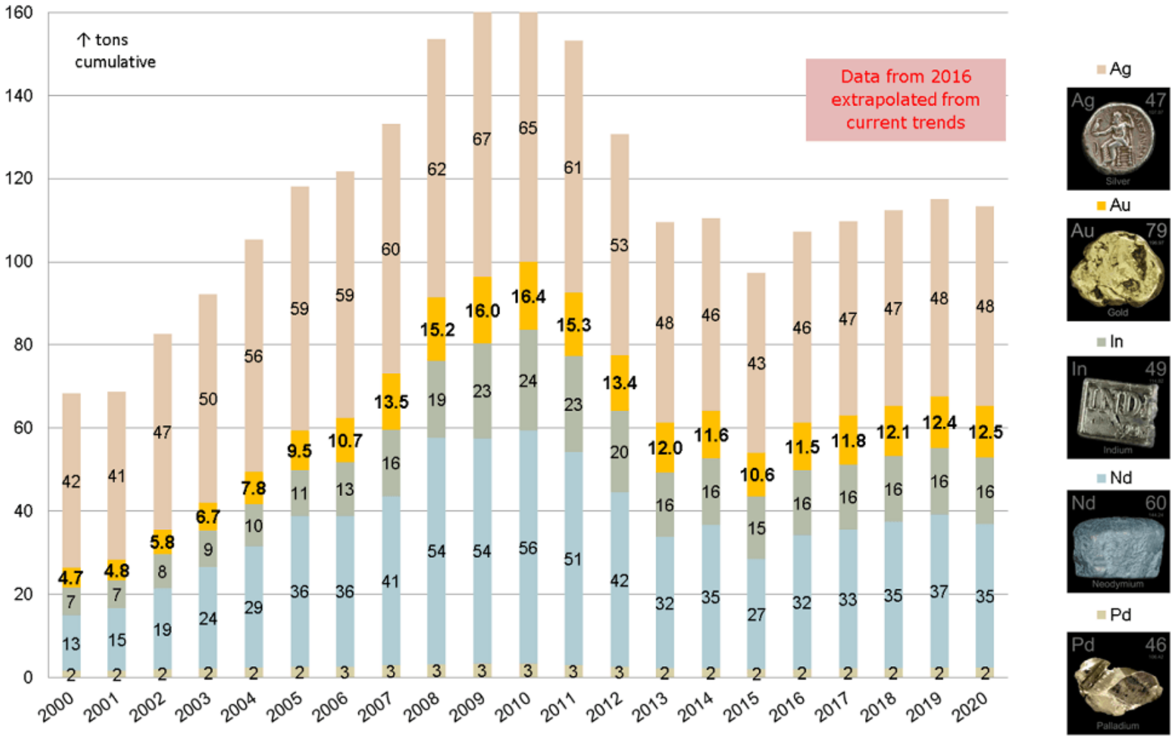


Figure 10. Selected precious metals and CRMs in screens placed on market 2000 – 2020, in tonnes. *Source:* ProSUM Project[36]

The ProSUM project has quantified the key (those present in products in relatively high concentrations) raw materials contained in electrical and electronic equipment in the urban mine in Europe. Table 5 illustrates the amount of gold (Au) and indium (In) contained in screens in European stocks in 2015.

Table 5. Stocks of Gold (Au) and Indium (In) in Screens in 2015 (in tonnes). *Source:* ProSUM Project[36]

Stock 2015 (tonnes)	Au	In
CRT TV and Monitors	8.2	14
LCD TVs and Monitors	52	115
Laptops and Tablets	46	21
Total	106	150

Based on the flows of materials leaving the stocks in the form of end-of-life screens (See Figure 11), the ProSUM project has calculated that the amount of In in reported collection as 25% of the total waste generated: 3.8 tonnes of In are reported as

[36] http://www.prosumproject.eu/ [accessed on 18/12/2017]

collected for recycling compared with 15.3 tonnes estimated to be generated as waste screens. These differences are caused by substantial trade in laptops and tablets which may be reused, recycled and/or traded but are not collected, hence not reported, through the producer compliance system.

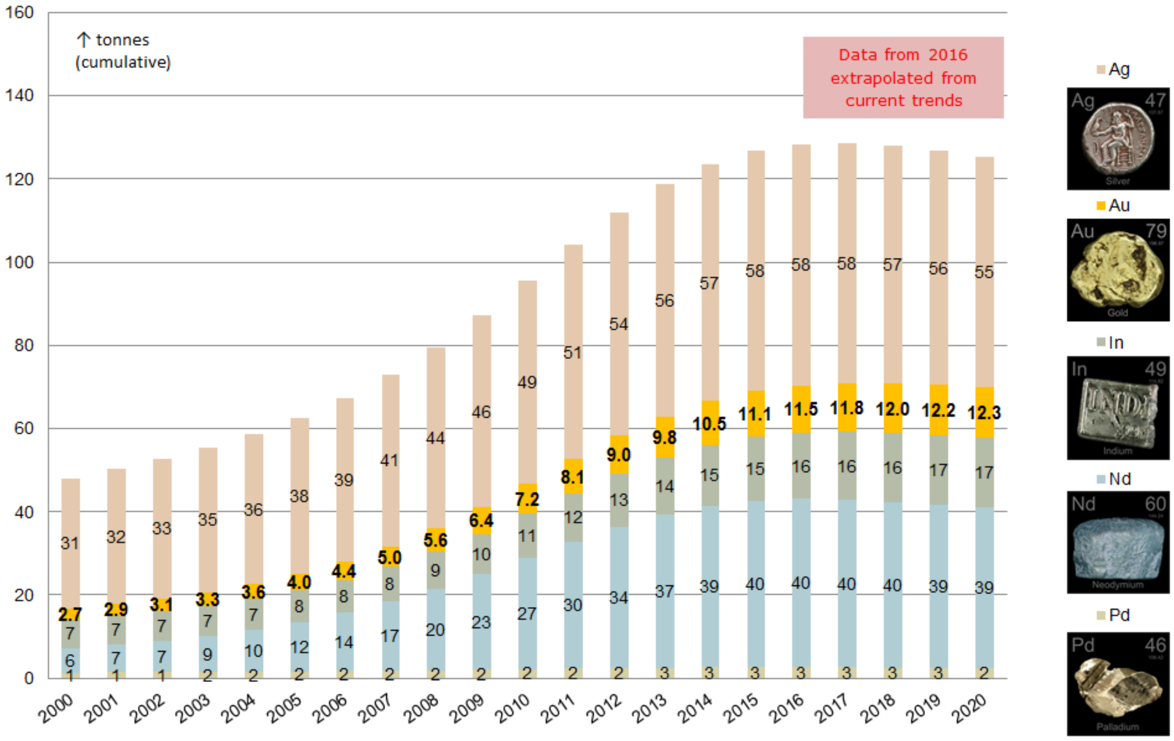


Figure 11. Selected precious metal and CRM content estimated in waste screens generated in the EU 2000 – 2020, in tonnes. *Source:* ProSUM Project[36]

Few data are available about the reuse of EEE, as a means to extend the lifetime of raw materials. Preparation for reuse of e-waste is generally not much established in the EU, except for some durable household products (e.g. washing machines and dishwashers) and IT products, for which the reuse rate in certain EU countries can amount to a few percent of the waste flow collected, as stated in JRC study (Tecchio et al., 2016).

6.2 Data sources

Table 6. List of sources relevant for the electr(on)ic sector

N°	Name and link/ref.	Scope			Reference period/ date of publ.	Language (s)	Free/ subscription	Comments
		Subsectors	CRMs	Geographic area				
1	Eurostat ([37])	WEEE	-	EU-28	2005-2014	English	Free	Data on WEEE collected and treated by Member States can be combined with other data sources to produce some specific figures for CRMs.
2	Ecodesign preparatory study on enterprise servers (Berwald et al., 2015)	Enterprise servers	All	EU-27	2014	English	Free	Example of preparatory study investigating the relevance of certain CRMs for the product group and potential measures to enhance their recycling. The preparatory study was led in conjunction with a study by the JRC on material efficiency aspects of servers (Talens Peiró and Ardente, 2015).
3	Review of Ecodesign preparatory study on fan (Van Holsteijn en Kemna B.V., 2015)	Fans	Rare Earths	EU-27	2015	English	Free	Example of preparatory study investigating the relevance of using and recovering rare earths in 'fans'
4	Recovery of rare earths from electronic waste: an opportunity for high-tech SMEs. Study for the ITRE Committee IP/A/ITRE/ 2014-09.	EEE	REEs	EU-28	2014	English	Available upon request	

([37]) Eurostat, Waste electrical and electronic equipment (WEEE) (http://ec.europa.eu/eurostat/web/waste/key-waste-streams/weee) [accessed on 16/10/2017].

6.3 Best practices

Best practice case 1: Improving the design of EEE to increase the recycling of CRMs

A circular economy requires a holistic approach: CRMs contained in products can only be efficiently recycled if products are designed in a way that key components can be easily extracted at end-of-life. The Ecodesign Directive is a powerful and efficient instrument to address the circularity of CRMs in EEE. Several Ecodesign regulations are asking to manufacturers to provide technical documentation 'information relevant for disassembly, recycling or disposal at end-of-life' at the product level. More specifically, the regulation on ventilation units (EU, 2014) requires information on 'detailed instructions (…) for the manual disassembly of permanent magnet motors, and of electronics parts' that generally contain significant amounts of CRMs (in particular REEs).

Recently, in accordance with the Circular Economy Action Plan, more emphasis has been given to use of critical raw materials and circular economy aspects in preparatory studies, following the MEErP methodology (see Annex II). This is for example the case for the electronic display product group (where indium is contained as indium tin oxide in display panels) (Ardente and Mathieux, 2012) and for the enterprise server product group (where neodymium is present in NdFeB magnets in hard disk drives) (Berwald et al., 2015; Talens Peiró and Ardente, 2015). These analyses have been a valuable source of information for recycling activities and the basis for proposing circular economy requirements concerning CRMs under Ecodesign Directive. Such information on the quantity of CRMs contained in products put on the EU market can be useful to trace the flows of CRMs in products and to stimulate the investments to develop large scale plants for the recycling of CRMs. Such declaration will be enhanced by the current standardisation work kicked off by CEN/Cenelec in September 2016 under mandate M/543 concerning 'general method to declare the use of critical raw materials in energy-related products'. This standardisation work, that is a commitment of the Circular Economy Action Plan, is expected by March 2019.

Best practice case 2: Developing innovative recycling technologies for CRMs

The European Commission has been funding several research projects concerning the development of innovative solutions for the recycling of CRMs from EEE. For example, the RECLAIM project ([38]) (namely 'Reclamation of Gallium, Indium and Rare Earth elements from photovoltaics, solid-state lighting and electronics waste') allowed the

([38]) http://www.re-claim.eu [accessed on 25/10/2017].

design and construction of an innovative plant for the recycling of yttrium and europium (belonging to REEs) from spent fluorescent lamp powders. These powders are extracted from compact fluorescent lamps and lighting systems of electronic displays, and successively treated by an hydrometallurgical process (based on chemical pre-treatment, leaching and precipitation) (Alvarez et al., 2015). The pilot plant allows the processing of around 50 kg/day of lighting powders and the recovery of 5.5 kg/day of yttrium and europium carbonate (overall 2 kg/day of yttrium and 0.11 kg of europium, with a recovery efficiency of 70 % and 57 % respectively) (Lopez et al., 2016). According to the project, this technology can be scaled up in full industrial applications.

7 Batteries

7.1 Data

According to the Battery Directive (2006/66/EC), there are three types of batteries: portable, industrial and automotive batteries (EU, 2006). In the last decades, new battery chemistries diffused into the market due to the development of new applications (e.g. electric vehicles, e-bikes). Depending on the battery chemistry, the main CRMs embedded in waste batteries are antimony, cobalt, natural graphite, indium and some rare earth elements (see Figure 12 and 13). Antimony is mainly used for lead-acid batteries, and its use has declined due to new battery technologies: due to higher longevity and performance dynamics calcium is favoured as an additive rather than antimony (EC, 2015b). In contrast, the development of the battery market in recent years is linked to the increasing amount of cobalt in this sector: from 25 % of global end uses of cobalt in 2005 to 44 % in 2015 (Deloitte Sustainability, 2015). This is mainly related to specific Li-ion chemistries (e.g. LiNMC suitable for new applications, see Figure 13). Concerning natural graphite, almost 10 % of worldwide uses of graphite in 2010 was for the batteries sector (EC, 2015b; Labie et al., 2015). In fact, graphite is widely used in several rechargeable and non-rechargeable batteries (both portable and industrial) as anode. In the quickly growing Li-ion battery market (see Figure 13), graphite is favoured for anodes of such batteries (EC, 2015b). About 5 % of indium over 2010 and 2017 was used as additive to alkaline batteries (Deloitte Sustainability, 2015). Finally, among rare earth elements, 10 % of the worldwide lanthanum and 6 % of cerium are used for NiMH batteries (Deloitte Sustainability, 2015) (see Figure 12).

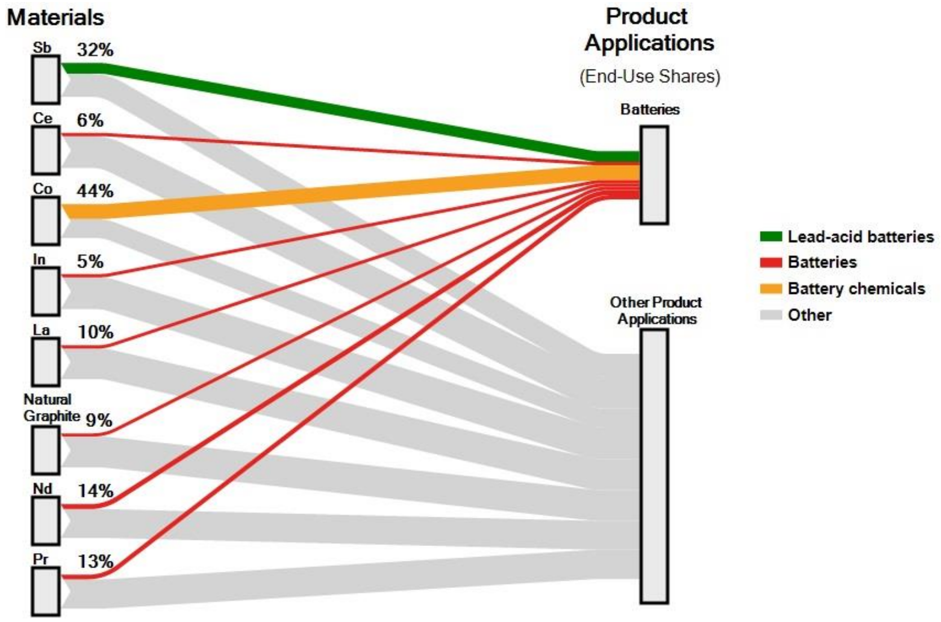


Figure 12. Share of some CRMs used in battery applications according to the 2017 CRM assessment. *Source:* JRC elaboration based on data from the 2017 EU criticality assessment (Deloitte Sustainability et al., 2017).

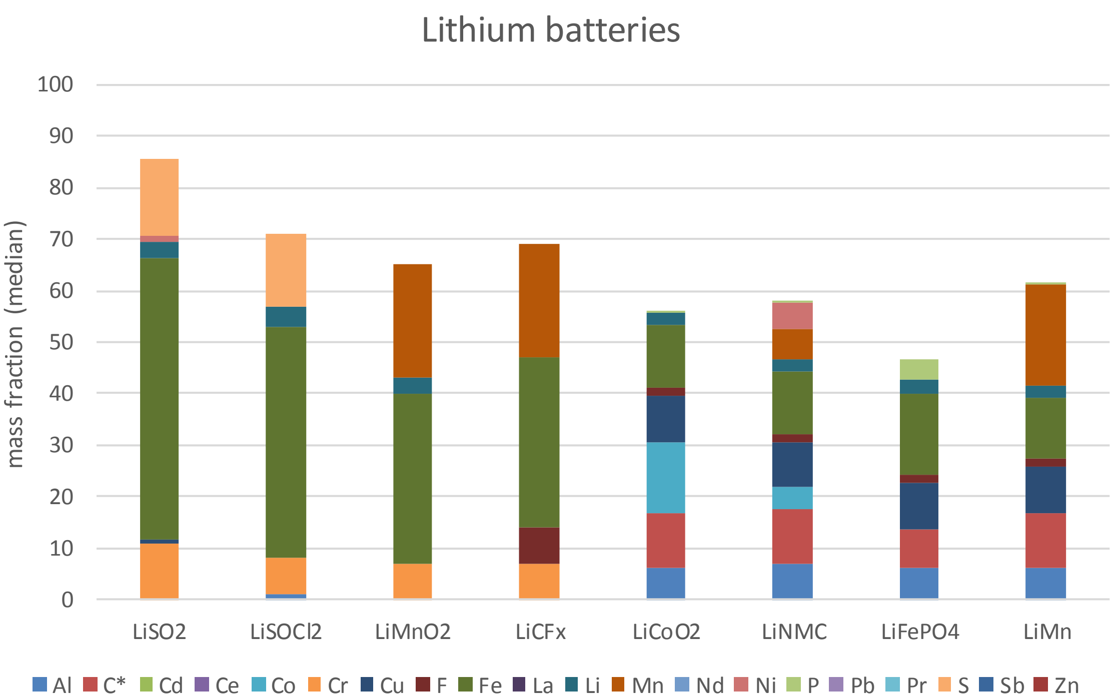


Figure 13. Elements embedded in Li-ion batteries according to specific chemistries *Source:* ProSUM project[36].

At EU level, targets for collection rates are explicitly defined for portable batteries only. In addition, for automotive batteries, obligations in terms of weight of recycled end-of-life vehicles are also defined.

For almost all Member States, the recycling rate of batteries reached the legal requirements established by the Batteries Directive (25 % collection rate for waste portable batteries to be achieved by September 2012) (Tsiarta et al., 2015). In more detail, non-rechargeable batteries make up 73.2 % of the recycled battery market in Europe, and the remaining 26.7 % refers to rechargeable batteries.

Especially for automotive batteries (See also Chapter 8), the collection and the recycling rates are much higher: automotive lead-based batteries supposedly reach 99 % in Europe (IHS Consulting, 2014; Mudgal et al., 2014).

Actual collection rates of waste batteries depend on the battery technology/type (e.g. rechargeable/non-rechargeable batteries, Lithium/Ni-Cd batteries), on the lifetime of batteries, and on the end-use behaviour. Lowest collection rates correspond to Lithium and NiMH batteries, those with the highest content of cobalt (e.g. NMC, LCO and NCA batteries) (Eucobat, 2013; RECHARGE, 2015a). This is also true for automotive batteries, for which the average lifetime is 10 years (Eurobat, 2015, 2014a).

Material produced from battery recycling can be used for the battery industry (e.g. cobalt) or steel and other industries, depending on the material quality. Batteries that do not enter recycling channels are disposed of (very small amount would be incinerated) (ECSIP, 2013).

The decline of the use of antimony lead-acid batteries, due to new technologies, reflects also in the lower amount of secondary antimony, for which batteries constituted the most relevant source (Deloitte Sustainability, 2015). The recycling of cobalt mainly occurs due to the lower costs of the recovered cobalt compared to cobalt extraction from ores and due to the environmental reasons (to prevent damage caused by landfilling of batteries) (Deloitte Sustainability, 2015). With regard to graphite, its recycling is quite limited. In the recycling process of batteries, graphite is not targeted and is usually lost in the recovery processes. However, in the hydrometallurgical process, the recovery of graphite is possible (Deloitte Sustainability, 2015; Moradi and Botte, 2016). Finally, the end-of-life recycling rates for lanthanum and cerium are below 1 % (Deloitte Sustainability, 2015). These values are captured in Figure 14.

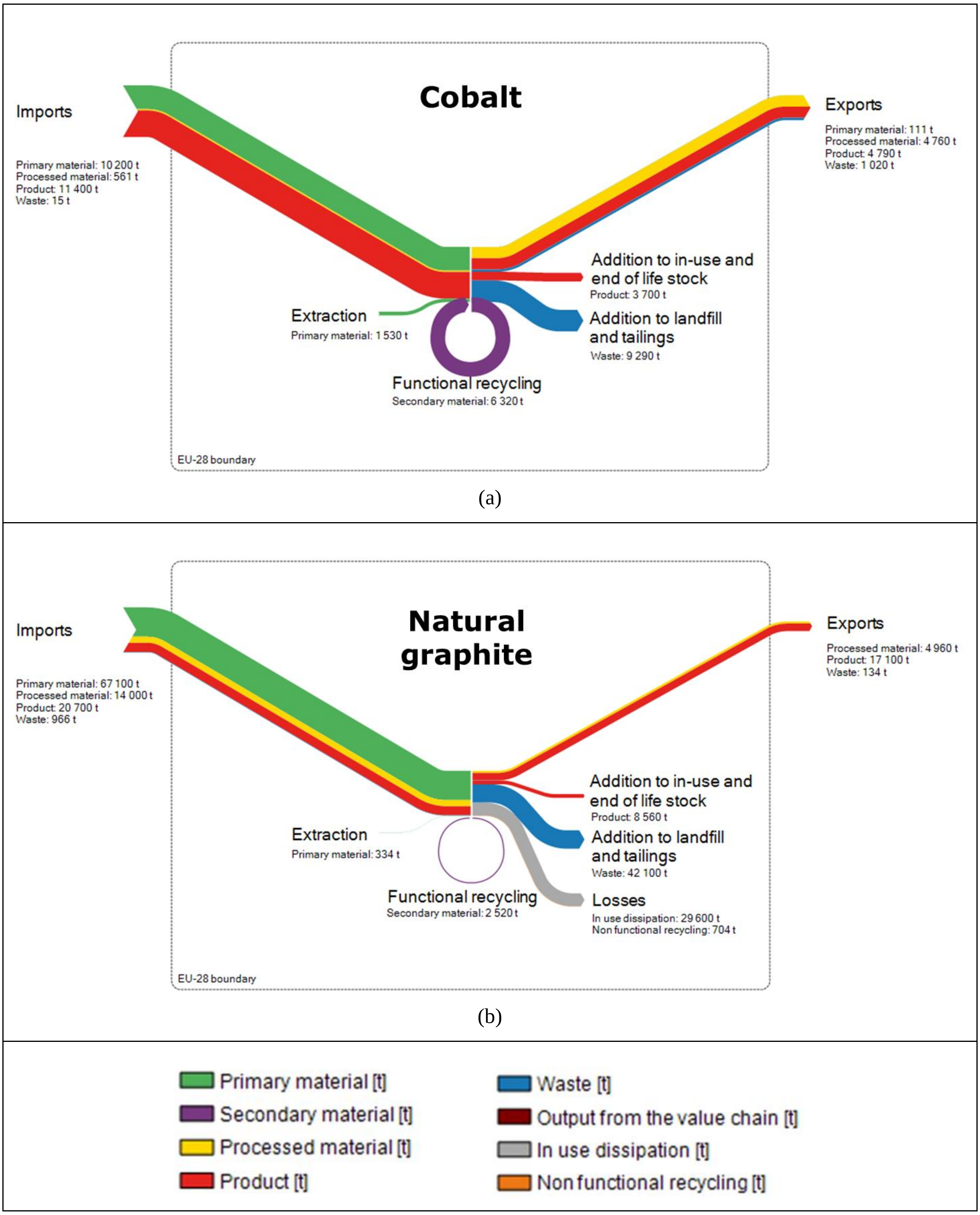


Figure 14. Simplified Sankey diagrams for (a) cobalt and (b) natural graphite. Values for the EU-28 expressed in t/year for the year 2012 based on the 2015. *Source:* (Deloitte Sustainability, 2015)

Among the waste batteries flows, it is worth noting that the export flow of waste batteries to non-EU Member States is low; on the contrary, there is significant movement of waste batteries and accumulators between Member States (Tsiarta et al., 2015). However, batteries contained in EEE, especially rechargeable portable batteries, can enter in a second-hand market outside of Europe (e.g. a study in the UK showed that about 10 % of WEEE transports were shipped illegally to non-OECD countries) (EPBA, 2015). Together with these waste flows, unremoved batteries from (W)EEE or batteries removed from WEEE but treated without recording their treatment contribute to increase the data uncertainty (EPBA, 2015).

7.2 Data sources

Table 7. List of sources relevant for the battery sector

N°	Name and link/ref.	Scope			Reference period/ date of publ.	Language (s)	Free/ subscription	Comments
		Subsectors	CRMs	Geographic area				
1	Eurostat (39)	'Lead batteries', 'Ni-Cd batteries', 'Other batteries and accumulators'	No specific data on CRMs	EU-28	2009-2015	English	Free	Data about recycling of batteries and accumulators
2	Eurostat (40)	Portable and batteries accumulators	No specific data on CRMs	EU-28	2009-2015	English	Free	Data about sales and collection of portable batteries and accumulators
3	European portable Batteries Association (EPBA, 2017)	Portable batteries	No specific data on CRMs	EU-28	1995-2014	English	Free	Information about the waste batteries' collection scheme and data on the collection rate achievement for the EU countries
4	European Association for Advanced Rechargeable Batteries (RECHARGE, 2015b)	Li-ion batteries	No specific data on CRMs	EU-28	2006-2013	English	Free	Data about collection rate of portable batteries in Europe

(39) Eurostat, Recycling of batteries and accumulators (http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasbat&lang=en) [accessed on 16/10/2017].

(40) Eurostat, Sales and collection of portable batteries and accumulators (http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_waspb&lang=en) [accessed on 16/10/2017].

5	Eurobat European Automotive and Industrial Battery Manufacturers (Eurobat, 2017a, 2017b)	Automotive and industrial batteries	Considerations about antimony and cobalt in the 'Resource Availability of Metals used in Batteries for Automotive Applications'	EU-28	2011-2015	English	Free	Data about battery market volume
6	Eucobat European association of national collection schemes for batteries (Eucobat, 2013)	Portable batteries	No specific data on CRMs	EU-28	2000-2012	English	Free	Data about the collection rate of portable batteries
7	EBRA European Battery Recycling Association ([41])	Batteries' recycling	No specific data on CRMs	EU-28	2009-2012	English	Free	Statistics about battery recycling
8	Cobalt market review (Darton, 2016)	All sectors with specific data on Li-ion batteries	Cobalt	Worldwide	2015-2016	English	Available upon request	
9	Natural and Synthetic Graphite Market Outlook (Roskill, 2015a)	All sectors with specific data on Li-ion batteries	Graphite	Worldwide	2015-2020	English	Free	

7.3 Best practices

Best practice case 1: Improving the knowledge on material flows for batteries

Disposing of a better knowledge of material flows in batteries (e.g. batteries placed on the market, exports, collected waste batteries and their composition) is a key element to improve a sustainable management of those materials and the collection and recycling rates of waste batteries and accumulators.

In the framework of the ProSUM (Prospecting Secondary raw materials from the Urban Mine and Mining waste) project ([42]), gathered data on waste flows, products, components, materials and elements can be used to identify the availability of a specific

([41]) http://www.ebra-recycling.org/releases [accessed on 16/10/2017].
([42]) http://prosumproject.eu [accessed on 16/10/2017].

material/element (e.g. cobalt) in a certain waste flow. For example, already available data about the cobalt embedded in batteries highlighted that the cobalt content rapidly increased between 1998 and 2011, which corresponds to the increase of available cobalt in waste batteries (Chancerel et al., 2016a). Concerning the data collection, not all datasets about collection rate of batteries are available and the reporting does not have the same granularity in all European countries. Thus, dynamic stock model is realised for each product category placed on the market and in which batteries are used, and waste flows of specific batteries chemistries are defined through data extrapolation from aggregated sources ([43]).

Best practice case 2: improvement of efficiency in the recycling of CRMs in batteries

In Europe, cobalt is recovered from batteries by several recyclers and through different processes and its recycling rate can vary between 90 % and 100 %. Recyclers invested in research projects in order to increase the recycling efficiency. For instance, Recupyl patented a hydrometallurgical process for the recovery of valuable materials, among which cobalt ([44]). In 2011, Akkuser (battery recycler in Finland) patented the Dry Technology for the extraction of metals (nickel, cobalt and iron) as well as compound materials; the recovery rate of these metals achieve 90 % ([45]). Recently, ACCUREC Recycling GmbH (treatment company in Germany) joined the H2020 project 'CloseWEEE' in order to further increase the recycling rate of antimony and significantly improve the recovery yield of graphite, cobalt, nickel and copper from Li-ion batteries ([46]).

In order to increase the efficiency of recycling processes as well as the adoption of secondary cobalt, collaboration between various actors of the battery value chain already exist. In the framework of the 'Recovery of raw materials from Li-ion batteries' project funded by the German Federal Ministry of Education and Research, ACCUREC Recycling GmbH and UVR-FIA GmbH (technical engineering facility) developed a recycling process dedicated to portable Li-ion batteries combining a mechanical pre-treatment with hydro- and pyrometallurgical process steps in order to increase the recycling potential of cobalt

([43]) ProSUM meeting in Brussels (10/11/2017), http://www.prosumproject.eu/content/prosum-project-final-information-network-event-presentations [accessed on 04/12/2017].
([44]) http://www.recupyl.com/121-20-31-lithium-polymer-battery.html, http://recupyl.com/44-used-batteries-recycling-plant.html [accessed on 16/10/2017].
([45]) http://www.akkuser.fi/en/news.htm [accessed on 16/10/2017].
([46]) http://www.accurec.de [accessed on 16/10/2017].

and lithium ([47]). Since 2007, in Finland, OMG Kokkola Chemicals (refiner and manufacturer of cobalt inorganic salts, oxides, powders and metal carboxylates) and AkkuSer collaborate in order to adopt cobalt recovered from waste Li-ion accumulators, in new Li-ion accumulators ([48]).

([47]) http://www.at-minerals.com/en/artikel/at_Effektiv_getrennt_319111.html [accessed on 16/10/2017].
([48]) http://www.akkuser.fi/en/news.htm [accessed on 16/10/2017].

8 Automotive sector

8.1 Data

In the automotive sector, including conventional (internal combustion engine vehicles), hybrid (HEVs) and electric vehicles (EVs), several vehicle components contain CRMs. Some examples are graphite (in brake linings, exhaust systems, motors, clutch materials, gaskets and batteries), cobalt (in lithium-ion batteries especially for EVs), platinum group metals (palladium, platinum and rhodium in auto-catalysts and particulate filters), niobium (as an alloying agent in high-strength steel and nickel alloys used in the body structure, engine system and structural components (Cullbrand and Magnusson, 2013)) and rare earth elements (in permanent magnets, auto-catalysts, filters and additives) (Bolin, 2014; EC, 2015b; Roskill, 2015a, 2015b). About 14 % of worldwide uses of graphite in 2011 refer to automotive parts (EC, 2015b). In 2012, the EU demand of palladium for petrol engines was 69 %, 70 % of platinum was used for light-duty diesel engines, and 80 % rhodium for 3-way catalytic converters used to reduce tailpipe emissions from vehicles (EC, 2015b). With respect to niobium, in 2012 44 % of the EU demand was intended to the automotive sector (Deloitte Sustainability, 2015). Among the REEs, neodymium, praseodymium and to a lesser extent dysprosium and terbium are used in large high-performance neodymium-iron-boron magnets for HEVs and EVs electric motors. These are also used in small electric motors and electronic sensors for the standard automotive industry including starter motors, brake systems, seat adjusters and car stereo speakers (Roskill, 2015b). Moreover, lanthanum and cerium are embedded for example in nickel metal hydride (NiMH) batteries used in HEVs designs. Cerium is additionally used in auto-catalysts, which accounted for 35 % of consumption in 2013 (Roskill, 2015b). The factors of the car design that mainly can influence the quantities of potentially critical materials in vehicles are the electrification (especially concerning neodymium, some REEs, manganese and PGMs) and the higher equipment level (especially concerning neodymium, some REEs, niobium and PGMs), while the size of car seems to not be relevant (Cullbrand and Magnusson, 2013).

Although the internal combustion engine is likely to remain dominant in the short and medium term, the market for HEVs and EVs is expected to experience significant and rapid growth over the coming decades. The CRMs embedded in vehicles are expected to increase proportionally. Cobalt, graphite ([49]) and rare earths employed in Li-ion batteries and electric motors are among the most targeted by increasing EVs demand (Figure 15).

([49]) Flake graphite is the natural graphite form suitable for the production of spherical graphite used in batteries.

Lithium-ion is the reference technology for EV batteries. Many different Li-ion chemistries are currently available ([50]) and are being tested to improve the performance and lower the battery costs. For example, in recent years Li-ion chemistries have shifted in favour of lower cobalt compositions. Natural graphite in turn is the reference anode material. In comparison to available alternatives, natural graphite had a market share of 64 % in 2014 ([51]).

Levels attained by the EV market in the EU in 2015 have created a demand of respectively 510 t and 8 330 t for cobalt and graphite for batteries, as stated in the JRC report (Blagoeva et al., 2016). With regards to the rare earths for electric traction motors, in 2015, new EVs sold in the EU have used about 50 t of neodymium, 16 t of praseodymium and 16 t of dysprosium. In turn, the demand for HEVs was around 33 t of neodymium, 11 t of dysprosium and 11 t of praseodymium (Figure 16).

([50]) Li-ion chemistries available include: LCO (lithium-cobalt-oxide), NMC (lithium-nickel-manganese-cobalt), NCA (lithium-nickel-cobalt aluminium-oxide), LMO (lithium-manganese-oxyde) and LFP (lithium-iron-phosphate).
([51]) Available alternatives include: artificial graphite, mesocarbon microbeads, Si and Sn composites/alloys, and (lithium-titanium-oxide LTO) (Pillot, 2013).

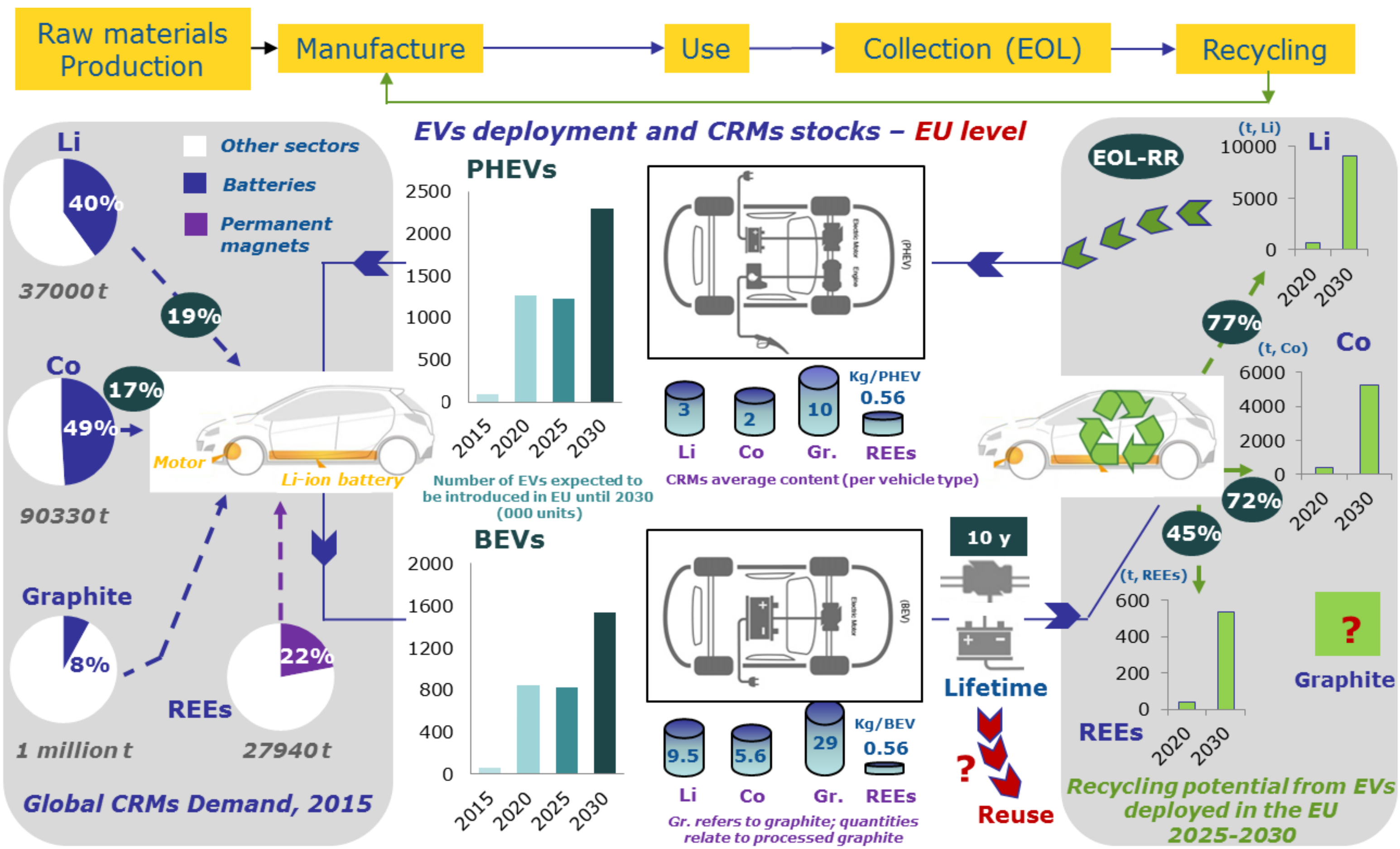


Figure 15. CRMs use in the EVs sector and potential flows resulting from recycling of EVs deployed in the EU[52]

([52]) Data sources are either explained in the text or given in JRC report (Blagoeva et al., 2016).

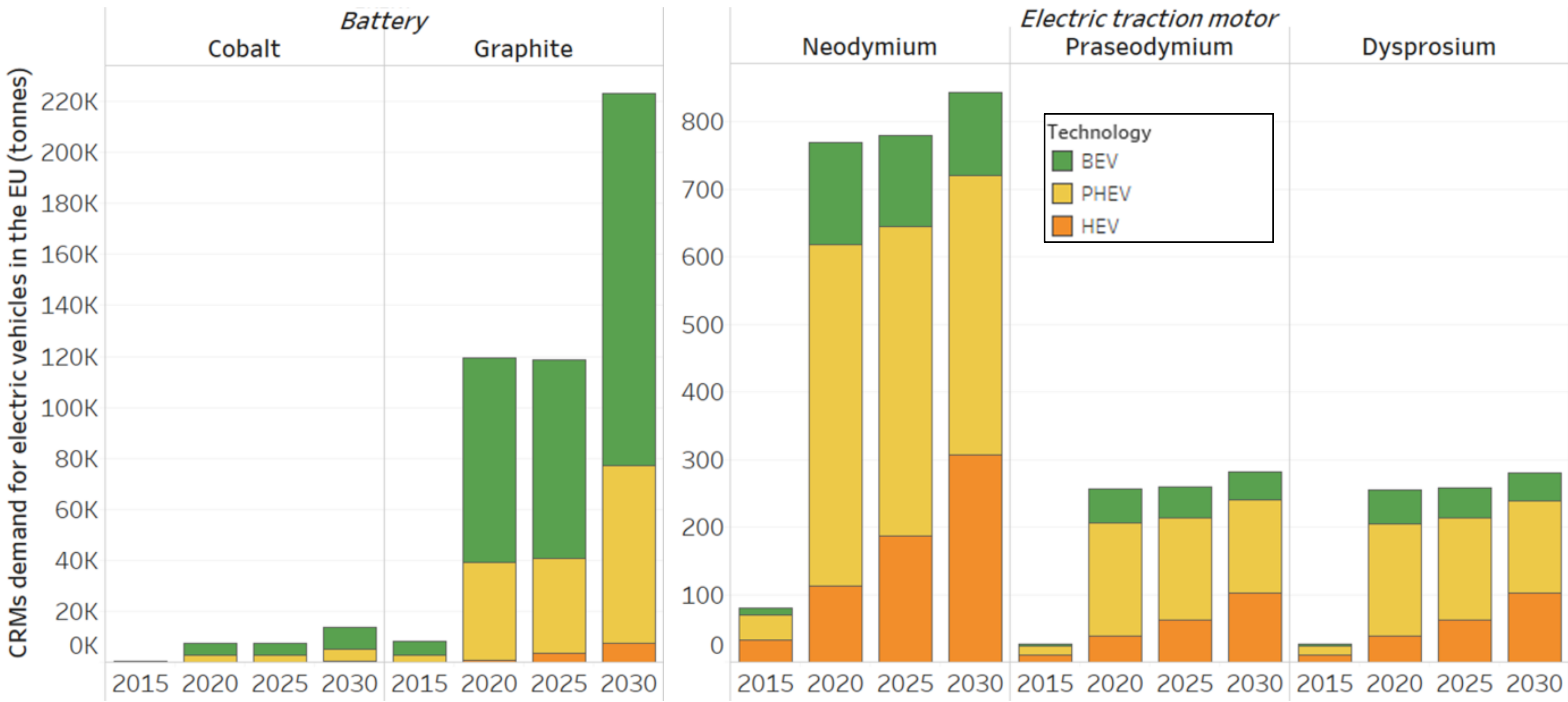


Figure 16. CRMs demand forecast in the EU for the hybrid and electric vehicles segments[53]

([53]) Demand forecasts up to 2030 are based in penetration scenarios put forward by ERERT (European Roadmap for Electrification of Road Transport) for BEVs and PHEVs and on Avicenne Energy projections for HEVs. Details concerning the calculations are given in the JRC report (Blagoeva et al., 2016).

Given the recent introduction of EVs in global and European markets, and taking into account the average lifetime of EV components (estimated to be approximately 10 years) (Blagoeva et al., 2016 and references therein), a significant number of EVs have not yet reached end-of-life. Large-scale recycling is not expected before 2020 and should only be more effectively realised beyond 2025 (Blagoeva et al., 2016).

Currently, the material of most interest to Li-ion battery recyclers is cobalt. Specifically in the EV batteries sphere the recycling potential is significant as these batteries may be easier to collect if a dedicated system of return is established. However, specific challenges related to the declining use of cobalt in most appropriate Li-ion chemistries may make recycling unattractive, if economic practicality is not extended to the other materials (lithium and graphite) (CEC, 2015). For example, whilst graphite anode materials are currently not recycled there are no obvious barriers to its recovery by hydrometallurgical and direct physical recycling processes (Moradi and Botte, 2016). It can be argued that from the technology point of view, due to the chemistry of the new generation of Li-ion batteries being used in the EV sector, no need for new recycling processes and metallurgical routes are expected. Nevertheless, processes will have to adapt to the dimensions and energy content of EV batteries giving rise to safety issues (RECHARGE, 2013).

Regarding the rare earths contained in electric traction motors, although the current level of recycling from post-consumer permanent magnets is still very limited (Tsamis and Coyne, 2015), several studies estimate the potential level of recycling of REEs to be around 40 % in the next 20 years (Blagoeva et al., 2016).

About the PGMs, the expected increase of fuel cells in EVs will turn up in an increasing demand of platinum and palladium (belonging to the PGMs group) to be used for auto-catalysts for emissions control (EC, 2015b). Concerning the recycling of platinum, palladium and rhodium, the auto-catalysts recycling is estimated to be between 50 and 60 % (EC, 2015b) (See also Chapter 11).

8.2 Data sources

Table 8. List of sources relevant for the automotive sector.

Nº	Name and link/ref.	Scope			Reference period/ date of publ.	Language (s)	Free/ subscription
		Subsectors	CRMs	Geographic area			
1	Cobalt market review, 2015-2016 (Darton, 2016)	All sectors with specific data on Li-ion batteries	Co	Worldwide	2015-2016	English	Available upon request
2	Natural and Synthetic Graphite Market Outlook (Roskill, 2015a)	All sectors with specific data on Li-ion batteries	Graphite	Worldwide	2015-2020	English	Subscription required
3	Rare Earths: Global Industry, Markets & Outlook (Roskill, 2015b)	All sectors with specific data on permanent magnets	REEs	Worldwide	2015-2020	English	Subscription required
4	JRC Report (Blagoeva et al., 2016)	Low-carbon energy applications (with specific chapters on EVs)	Co, Graphite, REEs	EU-28	2015-2030	English	Free
5	Recovery of rare earths from electronic waste: an opportunity for high-tech SMEs (Tsamis and Coyne, 2015)	WEEE	REEs	EU-28	2014	English	Free
6	'Recycling of rare earths: a critical review' (Binnemans et al., 2013)	All sectors with specific data on permanent magnets	REEs	Worldwide	2010-2020	English	Free
7	Reuse and Second use of Rechargeable Batteries (Recharge, 2014)	Li-ion Batteries	-	EU-28	2014	English	Free
8	Eurobat (Association of European Automotive and Industrial Battery Manufacturers) (Eurobat, 2014b)	Battery material analysis in the automotive batteries	Co, Sb, Graphite, REEs	EU-28	2009-2013	English	Free
9	Chalmers University of Technology (Cullbrand and Magnusson, 2013)	Information of CRMs in automotive	REEs, Co, Ga, In, Mg, Mn, Nd, Nb, PGMs, Te	EU-28	---	English	Free

8.3 Best practices

Best practice case 1: implementing recycling and developing innovative recycling technologies for HEV/EV batteries and electric motors

Under current circumstances of low lithium and rare earth prices, high costs for technology largely untested at an industrial scale and the absence of substantial waste streams, the EU recycling infrastructure targeting EV batteries and electric motors is still weakly developed. Moreover, progress appears to depend to a large extent on future developments, leading to significant reduction in costs as a result of innovative recycling solutions. On the positive side, however, certain companies have already begun to implement schemes for the recycling of used EV batteries. The expected growth in demand of EVs in coming decades is the long-term growth driver for companies such as Umicore, which has in 2011 opened an industrial-scale recycling facility for end-of-life rechargeable batteries in its Hoboken plant (Belgium). Umicore provides recycling services for Li-ion, Li-polymer and NiMH rechargeable batteries through its unique ultra-high temperature process which enables highly efficient metal recovery ([54]). In France, Recupyl collects and recycles batteries from EVs using its patented hydrometallurgical recycling process. In addition, Recupyl has formed partnerships with the manufacturers of batteries and electric vehicles in order to design environmentally friendlier batteries that can be recycled more easily and to develop high-yield processes to recycle next-generation batteries ([55]).

The recycling of rare earth from vehicles is very challenging due partly to their very dispersed use (e.g. cerium in diesel fuel additives, UV cut glasses, catalytic converter and batteries, lanthanum in diesel fuel additive, in catalytic converter and batteries; neodymium in electric motor and generator, and headlight glass; etc.). However, some experiences about recycling of neodymium and dysprosium from HEV and PHEV motors are already available. As an example, in collaboration with magnet manufacturers, Toyota received support to conduct a verification project for separating magnets from motors and then, a recycling system for extracting these two REEs from hybrid motors was launched in order to reprocess them back into new magnets ([56]). Moreover, together with SNAM (recycler in France), Toyota is working jointly on the issue with Panasonic to recycle lanthanum and neodymium from hybrid vehicle batteries (this also involves joint working with SNAM in France) (Scottish Government, 2013). Honda is working together

([54]) http://www.umicore.com/en/industries/recycling/umicore-battery-recycling [accessed on 16/10/2017]
([55]) http://www.recupyl.com/104-batteries-the-future.html [accessed on 16/10/2017].
([56]) http://www.toyota-global.com/sustainability/environment/challenge5 [accessed on 16/10/2017].

with Japan Metals & Chemicals to recapture rare earth elements from Honda parts, claiming that up to 80 % of rare earth elements can be recovered from nickel metal hydride batteries (Scottish Government, 2013). Moreover, some European projects proved the existing added value of the potential REEs recovery from batteries as well as the potential substitution of CRMs (e.g. MARS EV ([57]) and APPLES ([58])).

Best practice case 2: developing collection and recycling networks in conjunction with HEV/EVs manufacturers

Effective networks are necessary to ensure availability of suitable waste from which critical materials can be economically recovered.

In France, SNAM (Société Nouvelle d'Affinage des Métaux) collects and recycles hybrid and EV batteries. In 2015, SNAM teamed up with PSA Peugeot-Citroën to collect and recycle high voltage industrial batteries, including lithium-ion, from the Peugeot and Citroën networks of accredited auto repair shops and dealerships in Europe (SNAM, 2015). Moreover, the company is able to recycle up to 80 % of the weight of this type of battery, far exceeding the 50 % minimum target for recycling efficiency set by European regulations. Also, Tesla and Umicore work together, aiming at performing a closed loop recycling system; the Umicore battery recycling technology transforms the cobalt into LCO, that is resold to battery manufacturers ([59]).

In Europe, a specific battery-recycling network was developed by Toyota with certified companies; among these companies, there are SNAM and Citron (France), Accurec (Germany), Batrec (Switzerland) and Saft (Sweden).

Best practice case 3: develop reuse potential for batteries from electric vehicles

The concept of promoting the reuse of end-of-life EV batteries is spreading, from the viewpoint of using resources effectively (Recharge, 2014). In specific cases, no more usable batteries in their first application still have a residual capacity that could be employed for other purposes (second use). A number of research initiatives and pilot projects have been developed for assessing the reuse of batteries that are no longer suitable for EVs in energy storage applications. Batteries2020 ([60]), Energy Local Storage

([57]) http://www.mars-ev.eu/homepage [accessed on 16/10/2017].
([58]) http://www.applesproject.eu/index.php [accessed on 16/10/2017].
([59]) https://www.tesla.com/it_IT/blog/teslas-closed-loop-battery-recycling-program [accessed on 16/10/2017].
([60]) http://www.batteries2020.eu [accessed on 16/10/2017].

Advanced system (ELSA) ([61]), ABattReLife ([62]) and Netfficient ([63]) are examples of EU-funded projects about the most suitable and sustainable second-use applications for EV batteries. Uncertainty around this strategy (especially in the case of Li-ion technology) remains anchored to safety issues (Recharge, 2014).

Industries are also addressing this strategy. For example in the Netherlands, the project 2BCycled aim to determine the business case for second life for discarded EV-batteries, evaluating the economic potential of the local household system ([64]). BMW and Vattenfall, began a research project in Germany looking at the secondary use of high-voltage EV batteries from MINI-E and BMW ActiveE vehicles for a multipurpose second life application (trading, frequency regulation, etc) ([65]). Renault and Connected Energy collaborate on E-STOR energy storage product ([66]). Nissan and Eaton have partnered to introduce unit home energy storage system with second-life EV batteries ([67]). As another example, 280 second-life batteries will provide 4 MW of power and 4 MW of storage capacity to the Amsterdam ArenA ([68]).

([61]) http://www.elsa-h2020.eu [accessed on 16/10/2017].
([62]) http://www.abattrelife.eu [accessed on 16/10/2017].
([63]) http://netfficient-project.eu [accessed on 16/10/2017].
([64]) http://www.arn.nl/en/news/2bcycled-investigating-second-life-for-li-ion-batteries [accessed on 16/10/2017].
([65]) http://www.bosch-presse.de/pressportal/de/en/a-second-life-for-used-batteries-64192.html [accessed on 16/10/2017].
([66]) https://chargedevs.com/newswire/renault-and-connected-energy-collaborate-on-e-stor-energy-storage-product [accessed on 16/10/2017].
([67]) https://chargedevs.com/newswire/nissan-and-eaton-introduce-home-energy-storage-system-with-second-life-ev-batteries; http://www.eaton.eu/Europe/OurCompany/News/PRCompany/PCT_2967726 [accessed on 16/10/2017].
([68]) http://www.amsterdamarena.nl/default-showon-page/amsterdam-arena-more-energy-efficient-with-battery-storage-.htm [accessed on 16/10/2017].

9 Renewable energy

9.1 Data

Wind and photovoltaic (PV) energy are the most advanced and mature renewable energy technologies. Their markets have been growing most rapidly in recent years, and are expected to expand to account for large share of renewables growth.

The EU has been the front-runner in wind power generation. At the end of 2015, on average, wind power produced about 315 TWh of electricity, representing 11.4 % of the EU's total electricity production, through the cumulative installed capacity of 142 GW (Corbetta et al., 2016). Today, the wind sector represents over 300 000 jobs and generates EUR 72 billion in annual turnover. It is expected that the sector can secure up to 366 000 jobs by 2030 in Europe (Corbetta and Ho, 2015).

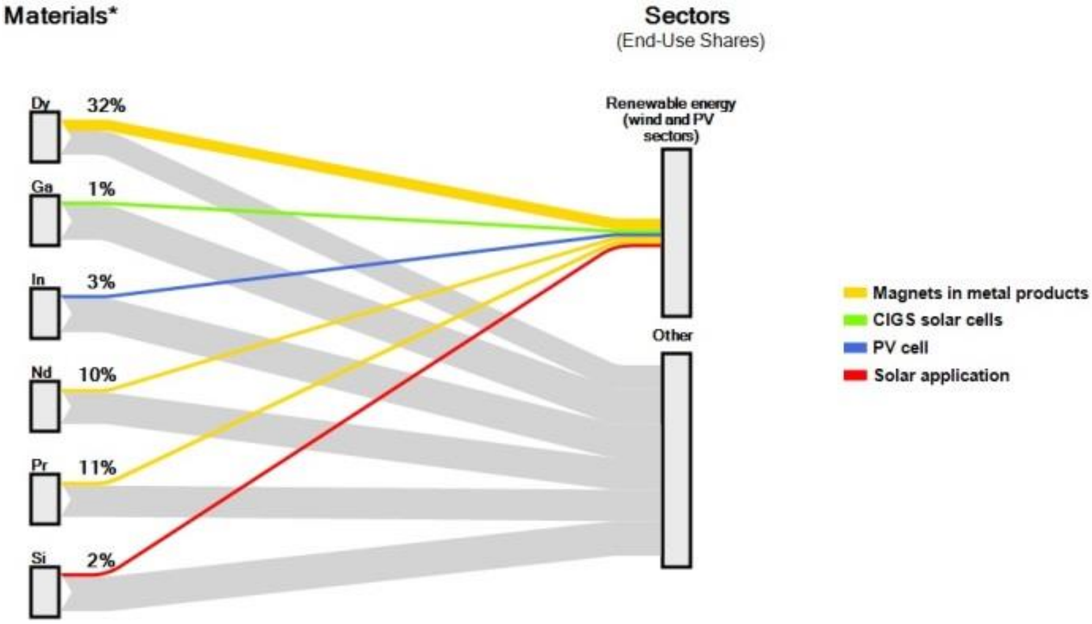
Photovoltaic energy has gained significant relevance in power systems around the globe. The EU was accounting for more than 75 % of newly installed capacity in 2010. At the end of 2015, Europe still held the major global share with its 97 GW total capacity. Solar PV supplies 4 % of the electricity in the EU (Solar Power Europe, 2016) and this share is expected to increase to 4.8 % in 2020, 7 % in 2030 and up to 11 % in 2050 (EC, 2016a). The contribution of this sector to job and wealth creation in Europe is expected to grow from EUR 6 billion and 110 000 jobs (2014 data) to almost EUR 7 billion gross value added and nearly 140 000 jobs by 2020 ([69]).

Wind and photovoltaic energy technologies rely on variety of materials. Six of these materials, namely neodymium (Nd), praseodymium (Pr), dysprosium (Dy), indium (In), gallium (Ga), and silicon metal (Si) ([70]) are identified as critical materials in the 2017 CRM list (see *Only a subset of CRMS used in renewable energy sector are included.

Figure 17). The EU demand for these materials will evolve in future depending on the deployment rates of wind and PV technologies as well as the developments in the technology mix. For instance, most of the wind turbines currently installed in the EU do not use permanent magnet generators and thus do not require rare earths. However, the situation can significantly change in the next 10-15 years due to sizing up of the wind energy: introduction of large and more efficient turbines as well as more offshore

([69]) Solar Power Europe, http://www.solarpowereurope.org/home [accessed on 16/10/2017].
([70]) Silicon metal is the base from which the ultra-pure Silicon used for photovoltaic cell manufacturing is ultimately derived.

wind power entails the use of permanent magnets, which require rare earth elements. The expected evolution in the EU demand for the six CRMs is given in Figure 18 ([71]).



*Only a subset of CRMS used in renewable energy sector are included.

Figure 17. Share of CRMs used in the renewable energy sector (wind and PV) according to the 2017 CRM assessment. *Source:* JRC elaboration based on data from the 2017 EU criticality assessment (Deloitte Sustainability et al., 2017).

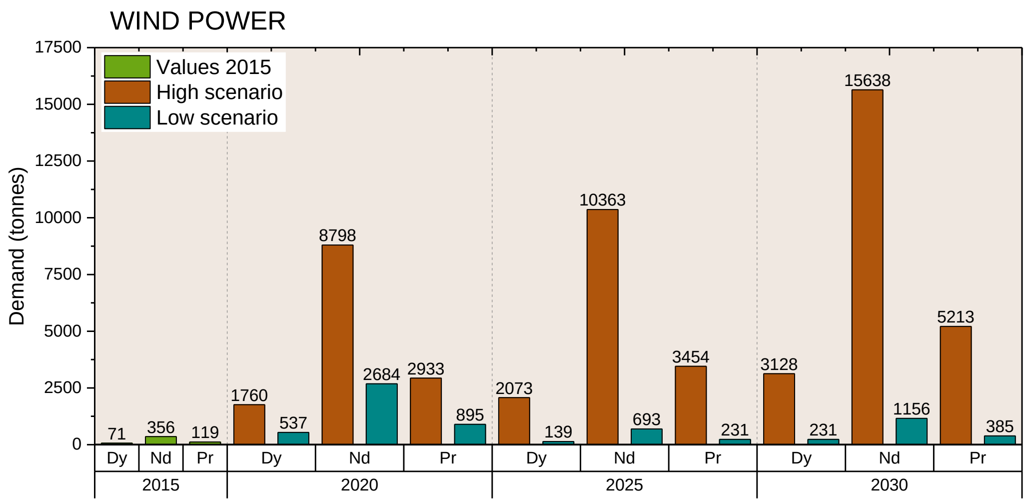
No supply issues are anticipated in the case of low deployment scenario (EU reference scenario, 2016). In the case of high deployment scenarios — European Wind Energy Association and Solar Power Europe high penetration scenarios — respectively for wind and PV — the EU demand is expected to increase notably by 2030 for all six materials, as shown in JRC report (Blagoeva et al., 2016). In addition, other big economies such as China and USA also have ambitious plans for clean energy deployment and thus competing for the same materials. This can represent a serious challenge to the suppliers to cope with the rapid global increase of the demand.

Recycling of Nd, Dy and Pr required in wind energy

Several projects dedicated to permanent magnet recycling are either approved or under way in China (Roskill, 2015b). Currently, there is no recycling of these three rare earth elements in the EU. The main emerging applications able to assure a tangible material

([71]) Silicon metal demand in Figure 18 denotes the amount of solar grade Silicon required to achieve the PV deployment rates.

flow to justify recycling business in the EU would be wind turbine generators and electric vehicle motors. However, up to 2030, most of the wind turbines will still be in operation (assuming a 30 years lifetime). Therefore, the initial push for the recycling companies in Europe is anticipated to come from the electric vehicle sector.



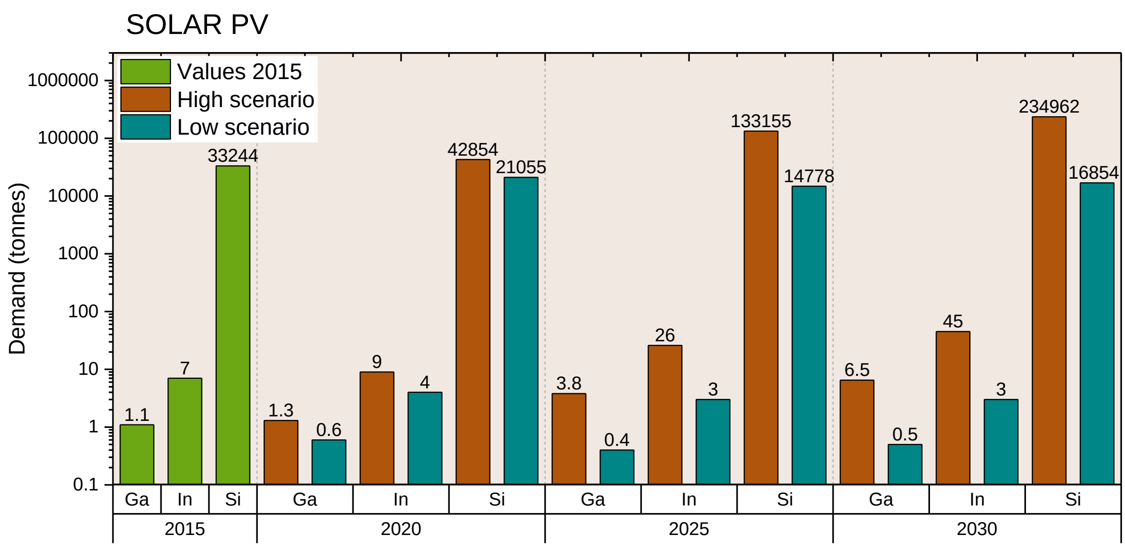


Figure 18. Expected evolution in EU demand for the six CRMs required in wind and PV sectors: existing low and high deployment scenarios considered.

Recycling of Si, In and Ga required in PV energy

Recycling of Si, In, Ga and other raw materials from PV modules, such as glass, aluminium, copper, silver, germanium and others, has a high potential: more than 95 % is claimed as an achievable recycling rate without cost or even as a profit. Modules manufactured with newly produced silicon need three times as long to generate the energy required for their manufacturing as compared to modules of equal capacity using recycled materials, making them more cost-effective (Hahne and Gerhard, 2010).

Due to the long lifetime of the PV modules — more than 25 years, this still young technology has generated little waste so far — only 1 % of the recycled panels are end-of-life, which makes recycling of PV panels not economically viable at present. Yet, the potential is huge: between 2 and 8 million tonnes of PV waste is estimated to be generated in 2030 depending on the failure scenario. The figures will substantially increase by 2050 — 60 to 75 million tonnes (Weckend et al., 2016). Recycling of such quantities requires companies to be prepared by setting a standard for the industry. Moreover, if not disposed of properly, the end-of-life PV panels can cause series of negative environmental impacts, such as leaching of lead or cadmium and loss of resources, e.g. aluminium, glass and rare metals such as indium, silver, gallium and germanium.

9.2 Data sources

Table 9. List of sources relevant for the renewable energy sector.

N°	Name and link/ref.	Scope			Reference period/ date of publ.	Language(s)	Free/ subscription
		Subsectors	CRMs	Geographic area			
1	Wind energy scenarios for 2030 (Corbetta and Ho, 2015)	Wind	Nd, Dy, Pr	EU-28	2015	English	Free
2	Solar Power Europe (SPE). European Photovoltaic Industry Association. (Solar Power Europe, 2016)	PV	Si, In, Ga	EU-28	2016	English	Free
3	EU reference scenario 2016 (EC, 2016a)	Wind and PV	Nd, Dy, Pr, Si, In, Ga	EU-28	2016	English	Free
4	BINE, Recycling of photovoltaic modules (Hahne and Gerhard,2010)	PV	Si, In, Ga	EU-28	2010	English	Free

5	IRENA, International Renewable Energy Agency and Energy Technology System Analysis Programme. Solar Photovoltaic. Technology Brief; 2013 ([72])	PV	Si, In, Ga	EU-28	2013	English	Free
6	JRC report (Blagoeva et al., 2016)	Wind and PV	Nd, Dy, Pr, Si, In, Ga	EU-28	2016	English	Free
7	Roskill (Roskill, 2015b)	Wind	Nd, Dy, Pr,	Worldwide	2015	English	Subscription required
8	Photovoltaic module decommissioning and recycling in Europe and Japan, Master's Thesis (Auer, 2015)	PV	Si, In, Ga,	Europe and Japan	2015	English	Free

9.3 Best practices

Best practice 1: Early adoption of mandatory recycling targets: a push for higher recycling and recovery rates

The WEEE Directive sets minimum requirements as regards recycling of PV systems, which Member States may adjust when they transpose the directive into their own legislation, e.g. defining more stringent requirements or target quotas. Every Member State has implemented slightly varying definitions of extended-producer responsibility which poses challenges for producers. No statistical data on PV collection and recycling is available yet for the EU.

Including recycling strategy into the manufacturing process could improve the image of the PV manufacturers and also maximise their profits: less energy intensive to recycle and reuse the materials compared to processing of raw materials. The early adoption of mandatory recycling targets, unified for all Member States can encourage higher recycling and recovery rates, as happened already in Japan and Sweden (Auer, 2015).

In addition, unification of the classification of the waste streams from PV panel across Europe is desirable: varying definitions used by different Member States have implications for collection and recycling financing as well as waste responsibilities.

([72]) http://www.irena.org [accessed on 16/10/2017].

In Europe, PV CYCLE association ([73]) has been established since 2007, representing 85 % of the European PV market. The association will collect and treat PV waste free of charge; the target is to collect 65 % of all end-of-life PV modules. PV CYCLE is already recycling solar panels (mainly production scrap, panels damaged during delivery or installation or failed before reaching end-of-life) from Belgium, the Czech Republic, Germany, Greece, Spain and Italy.

Best practice 2. Innovative recycling of renewable energy plants for the recovery of CRMs

The recycling of renewable energy plants is challenging since those technologies are relatively recent, with a long lifetime and largely dispersed in the European territory. Still few numbers of plants reached their end-of-life and low amount of waste was a limiting factor for the development of industrial scale recycling plants. However, several pieces of research have been devoted to develop concrete and economically viable pilot plants for the recovery of CRMs. For example, the European research project 'Full Recovery End Life Photovoltaic — FRELP' developed a pilot plant, which allows, based on mechanical, thermal and hydrometallurgical treatments, the recovery of around 35 kg of metallurgical grade silicon metal from 1 000 kg of waste crystalline PV panels, as explained in a JRC report (Latunussa et al., 2016). This work also assessed the environmental performance of this innovative recycling process in comparison with the current treatment of PV waste in generic WEEE recycling plants ([74]). The results proved that the FRELP recycling plant implies slightly larger impacts for the processing of PV waste compared to typical WEEE recycling plants, but it implies much higher benefits in terms of larger amount of recycled materials (mainly silicon metal, precious and base metals, and glass) and avoided production of primary materials.

([73]) http://www.pvcycle.org [accessed on 16/10/2017].
([74]) Current treatment of waste PV panel is mainly based to the dismantling of aluminium frame and cables, and the further undifferentiated shredding of the panel.

10 Defence

10.1 Data

The defence industry in Europe depends on a variety of raw materials, which are necessary to build a large spectrum of key defence capabilities, including land, air, space and maritime. Thirty-nine raw materials have been identified as important ([75]) for production of high-performance processed and semi-finished materials (e.g. alloys, composites, etc.) needed for manufacture of a large variety of defence-related components and subsystems (Pavel and Tzimas, 2016).

Seventeen of these thirty-nine raw materials, namely beryllium, cobalt, dysprosium, gallium, germanium, hafnium, indium, neodymium, niobium, platinum, praseodymium, other REEs, samarium, tantalum, tungsten, vanadium and yttrium are evaluated in 2017 as critical for the EU economy (Deloitte Sustainability et al., 2017), see Table 10.

Table 10. Critical raw materials (2017 list) used in the European defence industry, their role in defence industry and major end-use defence sectors (JRC source — Pavel and Tzimas, 2016).

Critical raw material	Role in defence industry	Major end-use defence sub-sector
Beryllium	As an oxide and in various alloys with copper or aluminium to produce different components, for instance in fighter airframes, landing gears, connectors, electronic/optical systems for communication and targeting	Aeronautics, naval, electronics
Cobalt	Mainly in nickel-based superalloys for turbine, compressors and fans in fighter aircraft propulsion, and in electric motors (magnets) and batteries in combination with samarium and other elements (e.g. nickel or lithium)	Aeronautics, naval
Dysprosium	As a minor additive in high-powered neodymium-iron-boron (NdFeB) permanent magnets for electric motors, guidance, control systems, actuators and amplifications (e.g. voice coil motors and audio speakers, satellite communication)	Missiles
Gallium	Communication (e.g. transmitter) and electro-optical systems and on-board electronics as gallium arsenide and gallium nitrite; missile guidance	Electronics
Germanium	On-board electronics for inertial and combat navigation, IR tracking systems, binoculars (including night vision), GPS/SAL guidance system; canopy; as substrate in solar cells powering military satellites	Electronics

([75]) The term 'important' is used to denote materials with unique properties, necessary to fulfil the stringent requirements of defence applications.

Hafnium	As oxide in electro-optical systems for radar and in a small percentage of superalloys for aircraft propulsion	Aeronautics, electronics
Indium	Laser targeting, sensors, identification equipment for IR imaging systems and inertial navigation as well as in on-board electronics for phased array radar	Electronics
Neodymium	Component of high-powered neodymium-iron-boron permanent magnets for a variety of applications: electric motors, guidance, control systems, actuators and amplifications (e.g. voice coil motors and audio speakers, satellite communication, etc.); in lasers as neodymium: yttrium-aluminium-garnet crystals	Aeronautics, space, electronics
Niobium	Guidance section of missiles and in small quantities in composition of nickel super-alloys for high-temperature section of jet turbines	Aeronautics, missiles
Platinum	Thin coating of turbine blades (to increase thermal barrier) in combination with nickel and aluminium	Aeronautics
Praseodymium	In neodymium-iron-boron permanent magnets (usually in mixture with neodymium in a ratio Nd:Pr = 4:1) with the same applications as for neodymium	Missiles
REEs (other ([76]))	Rather limited and specialised application in defence, such as magnets, radar (signal generation, surveillance and missile launch detection), lasers, sensors, other electronic components, phosphor (avionic display), heat-resistant superalloys and steel alloys	Aeronautics, electronics
Samarium	With cobalt in samarium-cobalt permanent magnets used in electric motors and diesel electric for propulsion, and electronic applications	Aeronautics, naval, electronics
Tantalum	Capacitors for on-board applications: binoculars, identification equipment/IR, inertial navigation, radars; in superalloys used in jet turbines and other propulsion systems; as a liner in shaped charges and explosively shaped penetrators	Aeronautics, electronics
Tungsten	Alloy element for ballast, warheads, shaped charges, throats, soldering, electrics, armour piercing and tank ammunition; also used in alloys in aeronautics for shells (arrowhead), fuselages, wings and turbine engines; tungsten carbide is essential for cutting machines	Aeronautics, land
Vanadium	Additive to improve the resistance to wear and deformation of steel; vanadium-containing alloys are used for the hull of submarines, in structural parts, engines and landing gear, but also in gun alloy elements, armour, fuselages and wings	Aeronautics, naval
Yttrium	Laser crystals for targeting weapons, finding and sight communication, electrolyte for fuel cells, phosphors for display screens, vision and lighting; in composition in equipment for signal generation, detection and surveillance, in thermal barrier coatings, and as alloying element for special steel grades	Electronics

([76]) Other REEs: cerium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, scandium, terbium, thulium, ytterbium.

Aeronautic and electronic defence sub-sectors are the major users of CRM, indicating that they are the most vulnerable to potential material supply constraints.

Various CRMs, such as beryllium, rare earth elements, etc., but also non-CRMs, such as rhenium, are indispensable in many defence applications, ranging from surveillance and targeting systems, precision-guided munitions, communication devices, radar systems to propulsion of the combat aircrafts. The EU is dependent on foreign suppliers for many of these raw materials, thus raising concerns about the security of supply linked to materials.

The demand for raw materials in the European defence industry is relatively low; it is estimated that about 5 % of the total EU demand is requested by the defence sector (European Defence Agency, 2014).

A further concern among the European defence industries lies in the security of supply of high-performance materials, as most defence applications have very stringent requirements for purity and quality of material. These applications integrate a large number of semi-finished and finished products made from special alloys, composites, etc., which have special properties and characteristics that ensure the performance of the defence applications.

Considering the economic and strategic importance of the defence sector, it is imperative that the industrial production operates under uninterrupted conditions. The defence industrial sector is also a major contributor to the European industry. It provides 1.4 million jobs, directly or indirectly, for highly qualifies people in Europe, with a turnover of EUR 100 billion per year (EC, 2016b). Therefore, the European defence industry must rely on a secure supply chain of materials, which must not be conditional on the quantities required.

Precise information on the type, composition and quantity of materials used in the European defence applications is limited mainly due to sensitivity reasons. Accurate information about the reuse of waste streams generated during production of high-tech components for defence applications, management of the end-of-life military products and recycling of materials from these products is also not readily available.

Overall, technological and economic barriers to recycling critical and scarce materials from the defence industry could be expected. From an economic perspective raw materials represent for some applications only a small fraction of the total value of the product (for example, the value of the materials contained in a jet engine may account for up to 2 % of the engine cost — US Congress — Office of Technology, 1985)). Even though an alloy which is recycled from defence or civil applications contains valuable and high-priced CRM, the separation into its constituent might not be cost-effective.

To a large extent, the defence and civil sectors are using the same materials. Often industrial actors in the defence sectors are led by large original equipment manufacturers (OEMs) that are 'dual' in nature, in the sense that their civil activities coexist with military ones. This means that the recycling opportunities and technologies could be applied to both types of activities. For instance, in the aerospace industry recycling of materials from aircraft was not under a major consideration until recently and little information is currently available, in particular in official statistics. Now it has become a common practice to account for all metals used in the aerospace industry, for instance in the manufacture of a jet engine; any excess metal is fed into a closed-loop recycling operation (National Research Council, 2008). Some publications argue that now the recycling rate of an aircraft has reached about 60 % and the aerospace industry is aiming to increase it to 80-90 % (Mouritz, 2012). Carbon fibre composite materials are becoming more popular in the aeronautic applications, such as jet fighters, and large industrial players (e.g. Airbus, Boeing, etc.) have already initiated the development of programmes for recycling the carbon fibre material. Aluminium, magnesium, titanium as well as steel are several materials which are currently recycled both from waste generated during the production of aircraft structure and engine components, as well as from reclaimed components from retired aircraft. However, other CRMs and scarce metals, such as rare earth elements, are still recycled only in small quantities, mainly from permanent magnet scrap.

10.2 Data sources

Table 11. List of sources relevant for the defence sector

N°	Name and link/ref.	Scope			Reference period/ date of publ.	Language(s)	Free/ subscription
		Subsectors	CRMs	Geographic area			
1	JRC report (Pavel and Tzimas, 2016)	Air, Naval, Land, Space, Electronic, Missile		EU-28	2016	English	free
2	US National Academy of Science (National Research Council, 2008)	The USA military sector in the context of the National Defence Stockpile	Rare earth elements, beryllium	USA	2008	English	Subscription required (paperback: USD 46)
3	US Department of Defence, Strategic and critical materials 2015 Report on stockpile requirements (US Department of Defense, 2015)	The US defence, essential civilian and essentials industry applications	About 60 raw and processed materials analysed	USA	2015	English	Free (some appendixes are classified)
4.	Study on the dual-use potential of key enabling technologies (KETs) (Scalia et al., 2017)	EU civilian and defence sectors		EU-28	2017	English	Currently, only distributed at the Commission level

10.3 Best practices

Best practice case 1: Adoption of collaborative defence research funding

Future EU research programmes could be used to mitigate supply risks linked to raw materials needed for the development of key defence capabilities by Europe's defence industry. The European Commission intends to launch a Preparatory Action on Defence Research for the period 2017-2019 to test the added-value of the EU budget supporting defence research (EC, 2016b). If agreed by the Member States, the next multiannual financial framework (post 2020) will include a specific programme for defence research. This future programme may also meet civil needs, and conversely, civil research could also be used to support the defence industry. Moreover, the Commission intends to bring together defence industries and civil innovative industries, which were benefiting from Horizon 2020 funding to encourage spillover concerning potential disruptive technologies and new processes into the defence industry. Therefore, future EU research programmes could contribute to finding solutions for improving resource efficiency and recycling, substitution and adapting sources and supply strategies also for Europe's defence industry.

Best practice case 2: Strengthening EU resilience to the supply chain risks for raw materials in the defence sector

To improve the EU's ability to respond to potential material supply disruption, the Circular Economy principles should also be applied to the defence sector. The European Defence Action Plan, adopted by the Commission in November 2016, outlined this way forward as part of need to strengthen security of supply. For example, adoption of new technological solutions and business models (see Box 1) with more sustainable production, consumption and waste managements is essential in building a competitive and sustainable European defence technological and industrial base.

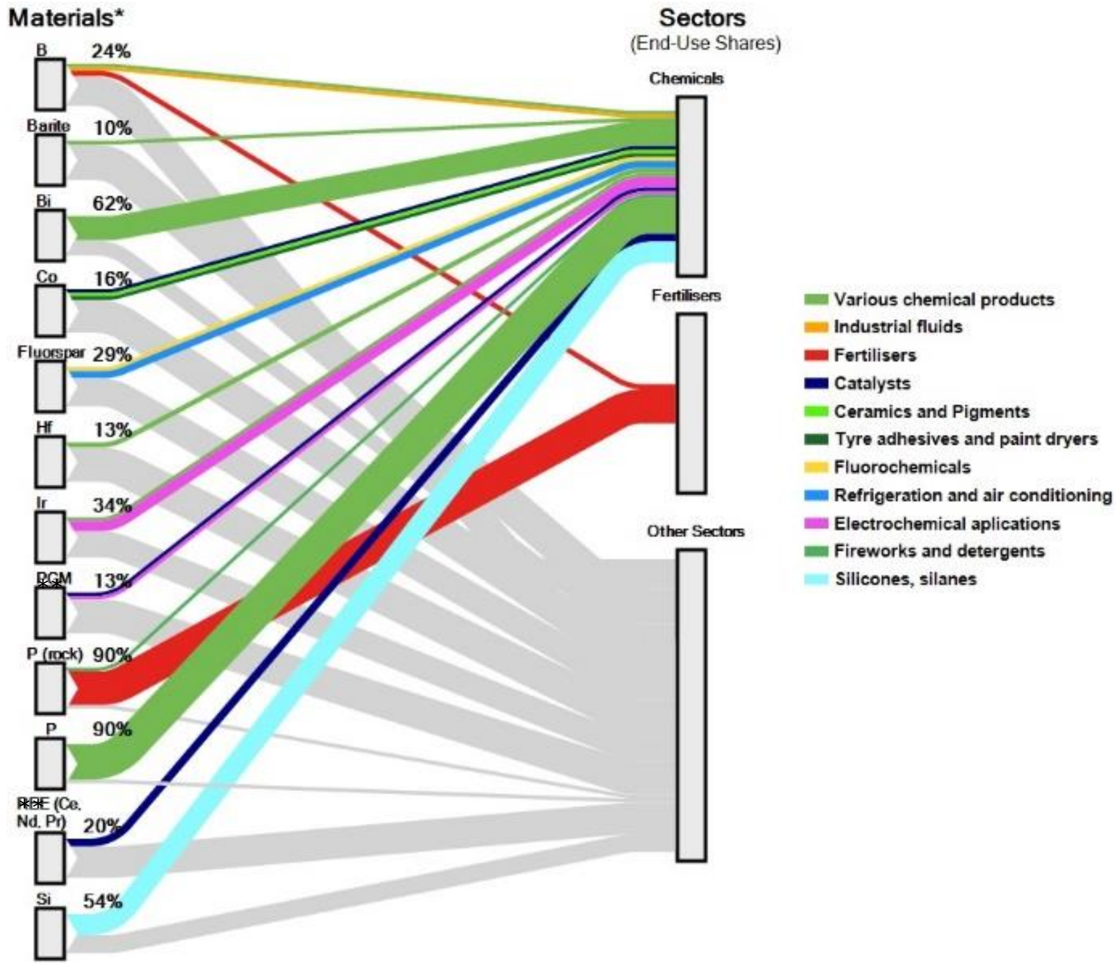
Box 1. Example of business model initiated by Rolls-Royce in response to material supply risk

Rolls-Royce — the second largest provider of defence aero-engine products — has developed a business model which looks to strengthening the supply of titanium and nickel used in gas turbine engine production. Rolls-Royce has taken steps to engage with its suppliers to create a recycling process for titanium and nickel, in which waste materials from production and end-of-life components is collected, cleaned and returned to the original materials supplier for reprocessing back into high quality aerospace grade alloys (Clifton and Lloyd, 2014).

11 Chemicals and fertilisers

11.1 Data

The production of several chemicals and fertilisers in Europe relies on multiple CRMs (see Figure 19), such as: antimony, baryte; bismuth; borate; cobalt; fluorspar; hafnium; natural graphite; niobium; PGMs; phosphate rock; phosphorous; REE; Silicon metal; tantalum; tungsten; vanadium.



*Only a subset of CRMS used in chemicals and fertilisers are included. **Average share for: Pt, Pd, Rh, Ru in PGM (except Ir); Ce, Nd, Pr in REE. P (rock) is phosphate rock.

Figure 19. Share of CRMs used in chemicals and fertilisers according to the 2017 CRM assessment. *Source:* JRC elaboration based on data from the 2017 EU criticality assessment (Deloitte Sustainability et al., 2017).

The main applications of CRMs in the chemical and fertilisers sectors include their use in the production of catalysts, phosphorous (P) fertilisers, micronutrient fertilisers (e.g. boron), polymers, pharmaceutics and dyes. Examples include: 86 % of phosphate rock are used in the production of fertilisers; 90 % of white phosphorous (produced from phosphate rock by thermal reducing furnaces) is used in the production of detergents and other chemicals; 60 % of bismuth is used in the manufacture of pharmaceuticals and other chemicals; and 54 % of Silicon metal is used for making silicones and silicates (final applications in e.g. shampoos, fixing materials and insulating materials).

Chemicals containing CRMs are produced for a broad variety of other sectors, e.g. 43 % of antimony is used in the production of flame retardant chemicals, which are incorporated in polymers used mainly in the electric and electronic equipment (EEE) sector (see Chapter 6). Likewise, 11 % of fluorspar is used in the production of solid fluoropolymers for cookware coating and cable insulation. Therefore, the importance of chemical containing CRMs for the manufacturing industry is higher than what is represented in Figure 19.

For the majority of CRMs used in chemicals and fertilisers, the EU industry is completely relying on imports, Figure 20 illustrates two examples of this dependency.

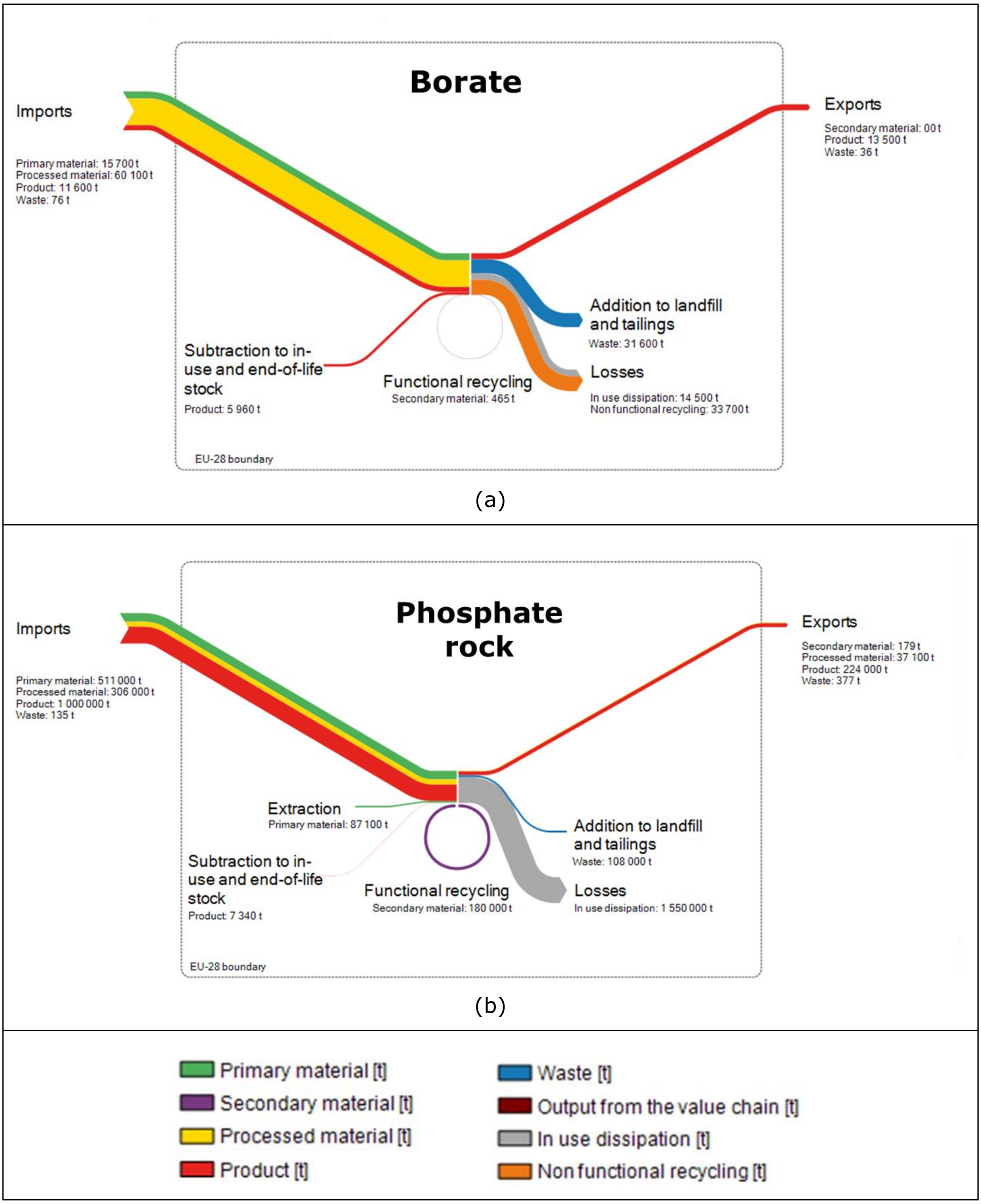


Figure 20. Examples of CRMs used in flows of chemicals and fertilisers: (a) Borate and (b) Phosphate rock. Values for the EU-28 expressed in t/year for the year 2012 based on the 2015. *Source:* (Deloitte Sustainability, 2015).

According to the findings of the Raw Material System Analysis study (Deloitte Sustainability, 2015), CRMs used in several chemical applications are lost to the environment due to dissipative use or to landfill. Examples of these losses include: natural graphite used in lubricants, Silicon used in different chemicals, tungsten used in the production of catalysts and a large percentage of borates and phosphate used in fertilisers. On the other hand, examples where recycling of chemicals represent the main source of secondary CRMs include recycling of PGMs from catalysts (both autocatalysis and catalysts used in the chemical industry). While for the case of borates and phosphates, the sources of secondary materials are biogenic wastes (e.g. manure or other animal by-products, bio- and food wastes, wastewater) (Schoumans et al., 2015), for which recovery is considered as functional recycling (see Figure 20) because it replaces boron and phosphorous fertilisers (produced from phosphate rock). The recycling of phosphorous rich wastes can also prevent water eutrophication, since phosphorous can leak from wastewaters or animal manure to water bodies.

11.2 Data sources

Table 12. List of sources relevant for the chemicals and fertilisers sector

N°	Name and link/ref.	Scope			Reference period /date of publ.	Language (s)	Free / subscription	Comments
		Subsectors	CRMs	Geographic area				
1	Eurostat ([77])	Fertilisers	Phosphorus	EU-28	2006-2015	English	Free	Data on P gross balance, including consumption of fertilisers, P inputs and removals from soil by different sources (e.g. manure inputs).
2	Eurostat ([78]): data on chemical productio n	Chemicals	-	EU-28	1995-2015	English	Free	Chemical production statistics (Prodcom), NACE 2 sector 20.
3	LUCAS ([79]): Land Use/Land Cover Area Frame Survey	Land Use/ Land Cover	Phosphorus	LUCAS Soil Survey 2009/2012: EU-272015:EU-28	2009/2012 and 2015 Next soil survey in 2018	English	Free	Information on physical and chemical properties of topsoil (0-20 cm) in the EU, including concentration of P.
4	FAO Statistics on fertilisers ([80])	Various (including Fertilisers)	Phosphorus	Worldwide	2002-2014	English	Free	Information on fertilisers flows.
5	Van Dijk et al. (van Dijk et al., 2016)	Various (including Fertilisers)	Phosphorus	EU-27	2005	English	Free	Phosphorus flows in EU-27 and its Member States; it includes the following flows: food and non-food production, consumption, and waste.

([77]) Eurostat, Gross nutrient balance (http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=aei_pr_gnb&lang=en) [accessed on 16/10/2017].
([78]) Eurostat, http://ec.europa.eu/eurostat/web/prodcom/overview [accessed on 31/01/2017].
([79]) Eurostat, http://ec.europa.eu/eurostat/web/lucas/overview [accessed on 31/01/2017].
([80]) http://www.fao.org/faostat/en/#data [accessed on 31/01/2017].

11.3 Best practices

Best practice case 1: Recycling of catalysts containing CRMs

Catalysts are key substances for the chemical industry, used to promote and accelerate chemical reactions (e.g. by providing an alternative reaction path with lower activation energy or increasing yield/resource efficiency). Their production depends on the use of CRMs such as antimony, bismuth, cobalt, hafnium, tungsten, vanadium, PGMs and REE (neodymium, praseodymium and cerium). Catalysts are used in the entire chemical sector, while 43 % of the global catalysts market is used in the automotive sector (autocatalysts) (Molotova et al., 2013). The recycling of CRMs from spent catalysts may be accomplished through their regeneration and reuse or through recovery of CRMs from them, depending on the chemical and structural changes occurring during use. The European Catalysts Manufacturers Association (a sector group of European Chemical Industry Council) produced general guidelines for the management of spent catalysts that can be applied by the industry for recycling CRMs (ECMA, 2012).

PGMs recycling from catalysts used in chemical process achieves globally recycling rates of 80-90 % (global data, (Hagelüken, 2012)). This is a good example that may be used as a benchmark for other CRMs in catalysts. These rates are possible due to the existence of recycling technologies with high efficiency up to 95 % and due to recycling cycles typically taking place in a business-to-business environment, where in most cases ownership of the spent and recycled materials remains the same (Hagelüken et al., 2016). Cases where such 'closed-loop cycles' are more challenging present lower recycling rates: for example, PGMs recycling from automotive catalysts achieves lower rates, between 50-60 %.

Best practice case 2: *Wastewater and water reuse as secondary sources of phosphates in agriculture*

Untreated urban waste is a source of phosphates gaining increasingly importance in a circular economy. While traditional techniques aim at phosphate recovery from sewage sludge, either by direct use of it in agriculture with substantial risks or upon sludge incineration, innovative water treatment technology aim at integrating phosphate recovery in the wastewater treatment process itself. The respective process is based on the precipitation of crystallised phosphate as magnesium ammonium phosphate, known as struvite (see also best practice case 3).

This integrated process for recovery of phosphate from biological wastewater treatment plants (WWTPs) may achieve extraction of over 80 % of the phosphate content, while at the same time reducing the overall quantity of sludge waste produced by the WWTP.

Other advantages include a reduction in oxygen demand and energy, both necessary to reduce levels of ammonia in the wastewater. Overall operating costs for the biological WWTP are expected to decrease by around 15 %.

Likewise, treated wastewater after its secondary treatment (necessary to be in compliance with the Urban Wastewater Treatment Directive, UWWTP), still yields an effluent with useful fertiliser properties such as a phosphate content from 5 to 10 mg/L, which based on the crops to be irrigated can be a viable option to decrease both water abstraction as well as use of additional fertilisers. Thus, in particular water reuse has become an interesting economic option for agricultural irrigation in the Mediterranean Basins. In the EU, Cyprus recycles 90 % of its treated wastewater compared to 60 % in Malta and 5 to 10 % in Spain, Italy and France. The Commission is preparing a set of regulations, promoting the reuse of treated wastewater.

The Water Sanitation and Supply Technology Platform (WSSTP) estimates that more than EUR 1 300 million could be gained if only 10 % of Europe's wastewater would be fully exploited for P recovery, accompanied by a 5-10 times increase in the valorisation of water by extracting and exploiting fully: heat, energy, nutrients, minerals, metals, chemicals, etc. in used water, opening up various new multi-billion euro markets in Europe for recovered resources (WssTP, 2005). Therefore, wastewater can be considered as a significant secondary source of phosphate and this should contribute to decreasing the quantity of phosphate rock used in the production of fertilisers.

Best practice case 3: Struvite, biochar and incineration ashes: a new generation of fertilisers ready to return nutrients to the economy?

One of the key actions under the Circular Economy Package, launched by the European Commission at the end of 2015, was to facilitate the recognition of organic and waste-based fertilisers in the single market and support the role of bio-nutrients. This resulted in the adoption by the Commission, in March 2016, of a proposal for a revision of the Fertilisers Regulation (EC) No 2003/2003 (EC, 2016c). If adopted by the legislators, the new proposal will create a level playing field by granting organic and waste-based fertilisers the same market access rights as traditional fertilisers manufactured from primary raw materials and contribute to reducing the exposure to cadmium, a highly toxic contaminant present in phosphate rocks and manufactured phosphorous fertilisers which affects the health of European consumers through the contamination of the food chain. In this context, the JRC is currently focusing its efforts on studying a new generation of fertiliser products with great potential to become an important secondary source of phosphorous, and decreasing the quantity of phosphate rock used in fertilisers.

The materials that could become CE marked fertilisers include **struvite**, a material recoverable via chemical precipitation of phosphorus-rich liquid streams (see Best practice case 2), as well as **biochar** and **incineration ashes**, obtained via distinct thermal process pathways. The main input sources are currently being discarded or used inefficiently, including manure, and sewage. They constitute a theoretical feedstock of about 1.5 Mtonne of P per year, more than the annual 1.2 Mtonne of P currently consumed by the EU-28 as mineral fertilisers. Possible access to the single market will ultimately depend on whether they will be able to meet ambitious criteria to safeguard human health and the environment, whether they have a proven agronomic value and whether they can deliver overall positive socioeconomic impacts, elements that are currently being investigated in detail.

12 Conclusions and perspectives

This report is a contribution of JRC to the Circular Economy Action Plan (Action V.3.1 concerning critical raw materials and the circular economy) and to Raw Material Initiative (specifically concerning the third pillar on improvement of resource efficiency and of conditions for recycling). It puts together, in a structured way, the results of several research programmes and activities of the JRC, for which a large team has contributed with data and knowledge developments, taking a sectorial perspective. This report is a background document used by several European Commission services to prepare the EC report on critical raw materials and the circular economy, a commitment of the European Commission made in the Communication 'EU action plan for the Circular Economy' (EC, 2015a).

The richness of the analysis brought by looking at criticality and circular economy in individual sectors is an important lesson of this exercise. We recommend that similar analysis will be carried out for additional sectors. Furthermore, we note that the present analysis uses as a starting point the list of CRM according to the 2017 criticality assessment, which provides an economy-wide criticality assessment and perspective on raw material issues (i.e. looking at the use of raw materials across the full spectrum of its uses in the EU-28) (EC, 2017a). However, from the perspective of an individual sector, industry, or product application, a different set of raw materials might be critical (i.e. found at high economic importance and supply risk), because the set of raw materials required by single sectors as well as the individual supply chains used to obtain these materials (and intermediate products) might differ from an economy-wide assessment. For example, rhenium (a non-critical raw material according to the 2017 EC assessment) is used as an alloying element in superalloys for turbine engines used, e.g. in aerospace and defence applications, where it is difficult to substitute (Graedel et al., 2015). Similarly, selenium and tellurium are important from the perspective of photovoltaics applications, but not considered critical in an economy-wide perspective because of their widespread use also in other sectors. Therefore, we recommend complementary sector-specific assessment to be carried out for sectors of high important to the EU economy (e.g. as identified by the gross-value added).

Looking at CRMs in individual product applications, and not only in sectors, seems particularly relevant in a context of circular economy since collection schemes usually target individual waste streams (i.e. end-of-life products). Looking at individual product groups, it could also be possible to bridge criticality assessment and life cycle assessment (LCA), a well-established methodology usually applied to product groups. There is indeed a need for the scientific community to investigate appropriate ways to account for resource consumption of CRMs and non-CRMs in LCA (Mancini et al., 2016).

In this context, further work will be necessary to develop methods to account for dissipative uses of materials within product life cycles. This approach would be particularly important for the accounting of the impacts of CRMs, which are often dispersed in small amount in several dissipative applications (e.g. indium, gallium, germanium, rare earth elements and silicon metal in several EEE and renewable technologies). LCA can be used to help assess the environmental implications of CRMs, and therefore guide towards strategies for material savings or recovery during each life cycle step. Similarly, further life cycle inventory data for critical raw materials will be necessary.

As shown in the report, the use of critical raw materials in the EU economy is far from being fully circular and there are several improvement opportunities. Many further actions should be taken to improve the situation. For example, policy actions should improve the legislative framework concerning processes to facilitate the extraction of CRMs from input flows (e.g. concerning mining but also waste treatment). Preventive policy initiatives concerning products to be put on the market should also be developed further. Such policies will definitely benefit from the support of standardisation activities. Not only policy actions need to be undertaken: it will also be important to support research and development so that innovative, efficient and cost effective technologies for the extraction of CRMs from the flows of materials and products are made available. Research and industry initiatives will also need to foster material efficient solutions in the use of CRMs in various sectors: not only recycling has to be looked at, but also re-use, product lifetime extension, new business models, etc. All these actions will need sectorial focuses but will also benefit from synergies across sectors. It will be also important to raise public awareness, to underline that (critical) raw materials are fundamentals to current lifestyles and to foster collection rate of many products and materials at end-of-life.

Because good decision-making requires good and sufficient data, the effort of gathering and analysing data and knowledge on (critical) raw materials in a context of circular economy needs to be continued and even intensified: the supply chain will have to be analysed further, technological developments (e.g. emerging applications, new processes) will have to be monitored, material flows will have to be better understood, CRMs will have to be tracked in the applications, practices from end-of-life operators will have to be analysed, etc. The Raw Material Information System (RMIS) could be very instrumental in keeping this knowledge base up-to-date.

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Annex I. Major applications of CRMs and information on recycling

(JRC elaboration based on (Deloitte Sustainability, 2015) and (Deloitte Sustainability et al., 2017)).

CRM	Major applications	Recycling	
		End-of-life recycling input rate	Recycling from products at end-of-life
Antimony	Flame retardants; Lead acid batteries; Lead alloys.	28 %	Secondary antimony is mainly recovered from lead acid batteries.
Baryte	Weighting agent in oil and gas well drilling fluids or 'muds'; Filler in rubbers, plastics, paints and paper; Chemical industry	1 %	Little baryte is recovered at drilling sites
Beryllium	Electronic and telecommunications equipment; Transport and Defence (Vehicle electronics, Auto components, Aerospace components)	0 %	Beryllium is not recycled from end finished products
Bismuth	Chemicals; Fusible alloys (low-melting alloys) and other alloys; Metallurgical additives	1 %	Bismuth is difficult to recycle because it is mainly used in many dissipative applications, such as pigments and pharmaceuticals.
Borates	Glass (insulation); Glass (excl. insulation); Frits and Ceramics; Fertilisers	0.6 %	Borates can be replaced by secondary sources as from the recycling of biogenic waste flows such as food and vegetal waste, manure and sewage sludge
Coking coal	Base metal production.	0 %	End-of-life recycling input rate for coking coal is estimated to be non-existent.
Cobalt	Battery chemicals, Superalloys, hardfacing/HSS and other alloys; Hard materials (carbides and diamond tools)	35 %	Cobalt-bearing end-of-life scrap can be in the form of used turbine blades or other used parts from jet engines, used cemented carbide cutting tools, spent rechargeable batteries, magnets that have been removed from industrial or consumer equipment, spent catalysts, etc.
Fluorspar	Solid fluoropolymers for cookware coating and cable insulation; Refrigeration and air conditioning ; Refrigeration and air conditioning; Steel and iron making; Fluorochemicals; Aluminium making and other metallurgy	1 %	Although fluorspar itself is not recyclable, a few thousand tons of synthetic fluorspar are recovered each year during the uranium enrichment
Gallium	Integrated circuits; Lighting	0 %	The rate of recovery of gallium from end-of-life products is close to null and this is due to the difficulty and cost to recover it from items where it is highly dispersed.
Germanium	Optical fibres; Infrared optics; Satellite solar cells	2 %	Only few amount of Germanium is recycled from old scrap of IR optics such as used mobile phones
Hafnium	Base metals; Machinery parts; Chemical products; Optics	1 %	It is likely that little to no post-use recycling is being carried out currently, given its contamination in the nuclear industry and the low percentage content in super alloys.
Helium	Cryogenics; Controlled atmospheres; Welding; Pressurisation and purging; Semiconductors, optic fibres; Balloons	1 %	Helium used in large-volume applications is seldom recycled.

CRM	Major applications	Recycling	
		End-of-life recycling input rate	Recycling from products at end-of-life
Indium	Flat panel displays; Solders	0 %	Very little old scrap is recycled worldwide because of minor indium concentrations in final products, a lack of appropriate technology, or low economic incentives compared to recycling costs
Magnesium	Transportation; Packaging; Desulfurisation agent	13 %	In the EU, a large share of magnesium is used as an alloying element in the production of aluminium alloys and derived applications. Most of end-of-life magnesium scrap is recycled as part of the aluminium value stream. In addition, magnesium alloys are entirely recyclable once they are collected from end-of-life products.
Natural Graphite	Refractories for steelmaking; Refractories for foundries	3 %	Efforts toward recycling post-consumer products containing natural graphite are dampened by oversupply and low prices. There is some recycling of used refractory material.
Natural rubber	Automotive	1%	End-of-life recycling is limited either due to contamination issues or due to the mere impossibility to recycle the application
Niobium	Steel (structural, automotive, pipeline)	0 %	The amount of niobium physically recovered from scrap is negligible,
PGMs	Autocatalyst; Jewellery; Electronics	11 % *	The high value of PGMs make their recycling attractive. The majority of the recycling volumes come from the recycling of spent automotive catalysts and electronics
Phosphate rock	Mineral fertilizer; Food additives	17 %	Phosphate rock can be replaced by secondary sources of phosphorous as from the recycling of biogenic waste flows such as food and vegetal waste, manure and sewage sludge
Phosphorous	Chemical industry applications	0 %	
REEs (Heavy)	Phosphors: lighting, displays; Magnets; Chemical (other)	6% *	Recycling of REEs is often difficult because of the way they are incorporated as small components in complex items or as part of complex materials. The processes required for recycling are energy intensive and complex
REEs (Light)	Magnets; Glass Polishing; FCCs; Metallurgy	7 % *	
Scandium	Solid Oxide Fuel Cells; Al-Sc alloys	0 %	No recycling circuit is known for scandium in end-of-life products
Silicon metal	Chemical applications; Aluminium alloys	0 %	Silicon metal is not currently recovered from post-consumer waste. Most chemical applications are dispersive, thus not allowing for any recovery. There is research on recycling of silicon wafers, however it has not yet materialised in marketable solutions.
Tantalum	Capacitors; Aerospace; Sputtering targets; Mill products; Carbides	1 %	Tantalum can be recovered from end-of-life capacitors and spent sputtering targets.
Tungsten	Mill and cutting tools; Mining and construction tools; Other wear tools	42 %	Recycling of tungsten in high speed steel is high. On the other hand, recycling in applications such as lamp filaments, welding electrodes and chemical uses is low because the concentration is low and so not economically viable
Vanadium	Ferrovanadium; Tubes and pipes; Turbines and electromotors	44 %	Two kinds of secondary vanadium scrap can be discerned: steel scrap, which was recycled along with the vanadium content, and spent chemical process catalysts.

* average values

Annex II. Examples of CRMs discussed in Ecodesign preparatory studies

Year of conclusion	Preparatory study on:	Details
2007	Space and combination heaters	The study mentions the use of PGMs in catalytic combustion
2007 (review ongoing)	Personal computers and servers	The initial study discussed the content of silicon metal in computers. The ongoing revision study specifically mentions the EU CRMs and it analyses their content in the products (based on a research conducted by JRC).
2010	Sound and imaging equipment	The study discusses the content of silicon metal in the products
2007 (review ongoing)	Televisions/electronic displays	The initial study discusses the content of indium (as ITO) in the products. Potential measures on the declaration of indium were discussed in the review process (based on a research conducted by JRC).
2007	Linear and compact fluorescent lamps	The study discusses the presence of some materials as REEs, gallium and indium.
2007 (review on-going)	Domestic washing machines	The review study discusses the content of REEs in motors
2007 (review 2017)	Domestic dishwashers	The review study specifically mentions the EU CRMs and it discusses the content of REEs in motors
2007	Simple set top boxes	The study discusses about content of silicon metal in products
2007	Domestic lighting; incandescent, halogen, LED and compact fluorescent lamps	The study discusses the content of some CRMs (as gallium and indium) in the products.
2008	Electric motors	The study mentions some REEs used in high performance motors
2009	Room air conditioning appliances, local air coolers and comfort fans	The study discusses the content of rare earth elements and their relevance for high efficiency motors
2009	Directional lighting: luminaires, reflector lamps and LEDs	The study discusses the content of some CRMs (as gallium and indium) in the products.
2011 (review 2015)	Ventilation fans in non-residential buildings	The review study discusses the content of rare earth elements and the relevance of their recycling
2014	Uninterruptible Power Supplies	The study mentions the use of some CRMs (as gallium, cobalt, silicon metal) to improve efficiency
2014	Electric Motors and Drives	The study discusses the use of some rare earths in high-performance magnets
2015	Power cables	The study mentions the EU CRMs, however no CRM was found relevant for this product group
2015	Enterprise servers	The study specifically refers to the EU CRMs and it is a first example of study which assesses the content of CRMs in the products (based on a research conducted by JRC)
2015	Ecodesign Preparatory Study on Light Sources (ENER Lot 8/9/19).	The study specifically refers to the EU CRMs and it is a first example of study which specifically assesses the content of CRMs in the products.

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