SCRREEN

Coordination and Support Action (CSA)

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Start date : 2016-12-01 Duration : 30 Months
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Identification and quantification of secondary CRM resources in Europe

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Summary

Identification and quantification of secondary CRM resources in Europe

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DELIVERABLE 3.2:

Identification and quantification of secondary CRM resources in Europe

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CONTENT

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1. BACKGROUND AND OBJECTIVES

1.1. SCRREEN: A BRIEF INTRODUCTION

In 2010, the first list of Critical Raw Materials (CRM) was published by the Ad-hoc Working Group on CRM. Since then, numerous European projects have addressed the role of CRM in the modern world.

The main objective of the SCRREEN project is to improve the CRM strategy for the European market by:

- mapping primary and secondary resources as well as substitutes of CRM;
- estimating the expected demand of various CRM in the future;
- providing policy and technology recommendations for actions improving the CRM production;
- providing policy and technology recommendations for the CRM substitutions;
- addressing the WEEE and other EOL products issues in relation to CRM recycling and recovery problems;

SCRREEN is a networking project, aiming at gathering European initiatives, associations, working expert groups, and projects addressing CRM topics.

One of the long-term goals of SCRREEN is to establish an EU Expert Network that covers the whole value chain for present and future critical raw materials supply.

The SCRREEN project builds on previous, on-going and starting networks and projects such as ERECON, CRM_InnoNet, MSP-REFRAM, Minerals4EU, MICA, MINATURA, MIN-GUIDE, PROSUM, EURARE, Smart Ground, INTRAW, cycLED, etc. Information has also been gathered from various EU documents, governmental publications such as policies and national strategies. Invaluable amounts of data have been obtained from European geological surveys, which over the decades have gathered high competence in collecting geological and mineral resources information.

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1.2. PURPOSE AND STRUCTURE IN RELATION TO WP3 & D3.2

The main aim of the WP3 is to identify and quantify CRM resources in primary and secondary sources including mining wastes, industrial wastes, fabrication scraps, EOL products and 'urban mines', according to the updated EU list of 27 CRM published by the European Commission 2017. Additionally, technology metals/metaloids such as tellurium, selenium and lithium, not currently included in the EU CRM list, but which are in part by-products of the extraction of the major industrial metals are under consideration.

While Task 3.1 carries out the comprehensive identification and quantification of primary CRM resources in ore deposits in Europe, Task 3.2 focuses explicitly on secondary CRM resources. The main sources of secondary CRM resources are classified in materials such as mine wastes, industrial waste, fabrication scraps, EoL products recycling (in close cooperation with WP8) and 'urban mines', which constitute old landfills and waste dumps in Europe.

The D 3.2 provides a comprehensive review of currently available information in the public domain, including data and information from past and present projects such as e.g. Minventory, Minerals4EU, ProMine, EURARE, ProSUM, SmartGround and MICA.

Part of the outcome of this task is recommendations regarding data collection and harmonisation of CRM resources in Europe.

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2. EUROPEAN RAW MATERIALS (CRM)

2.1. GLOBAL MARKET

Critical Raw Materials are essential for the industry and production of a broad range of equipment and devices used in everyday life. They are also fundamental for future innovations and the development of sustainable and competitive technologies. The growing consumption of the CRM generates the demand for new production of pure CRM, both from primary (ore deposits) and secondary (mineral-based and non-mineral-based wastes) sources. Identification of potential secondary sources (via extraction and recycling technologies) becomes urgent in the light of the global scale of waste generation and demand for circular economy. Recycling is unlikely to close the wide gap between future demand and supply by 2050, but in the long term, secondary supply from recycling will be able to meet almost 50 % of the demand, i.e., by 2100.

Already in 2010 the EC identified a number of Critical Raw Materials for the intra-European industry and the list was extended in 2014, and then again in 2017 with 26 minerals and metals with natural rubber excluded (Table 1). To be qualified as critical, a raw material must be exposed to high risk regarding disruptions to its supply and be of high economic importance to major European industry sectors. Access to CRM, their resource efficiency and responsible sourcing are at the forefront of the EU political debate. As mentioned, recycling is part of the discussed solutions in terms of contributing to raw materials supply and better energy efficiency, but also minimising the environmental impacts. However, during the next decade, recycling, due to poorly developed extraction technologies, is unlikely to substantially contribute to the global CRM supply.

Our review focuses on mineral-based CRM, therefore natural rubber is not considered.

By the end of 2017, China remains the biggest producer of most critical raw materials for the European market, with a strong monopoly (>80% of the global total) for production of Sb, Be, Bi, LREE and HREE, magnesium and tungsten (Table 2). Other important producers are

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for example Brazil, Russia, the Republic of South Africa and the USA. Supplies of CRM from EU sources have been zero or very limited in the recent years (Fig.1).

Table 1. The list of the Critical Raw Materials (excluding natural rubber), updated in 2017 by the EC (COM (2017)).

2017 Critical Raw Materials				
Antimony	Cobalt	Hafnium	Magnesium	Phosphorus
Baryte	Coking coal	Helium	Natural graphite	Scandium
Beryllium	Fluorspar	HREEs	Niobium	Silicon metal
Bismuth	Gallium	Indium	PGMs	Tantalum
Borate	Germanium	LREEs	Phosphate rock	Tungsten
				Vanadium

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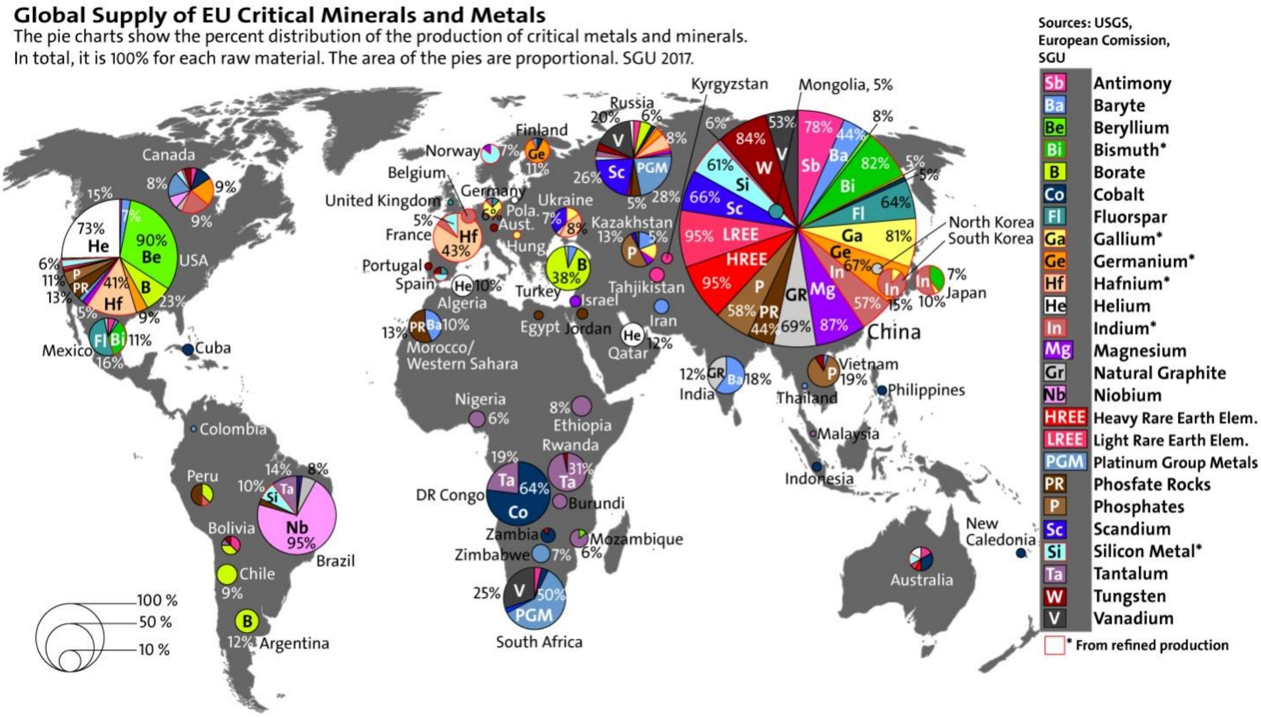

Figure 1. Countries accounting for largest share of global supply of CRMs (source: SGU).

In Table 2, the CRM global production figures include all 43 minerals and metals by considering all individual metals of the REE and PGM groups. Table 3 presents main suppliers to the EU and main sources of EU imports in years 2010-2014 (extracted from COM (2017) 490 final). Interestingly, while the big players such as China and Russia are main suppliers of CRM to Europe, the intra-EU sources are more variable and represented by a number of EU countries. This implies that for many EU countries, CRM production can be an important industry in the future when demand for CRM continues to increase. The main sources of supply in Table 3 include both primary (mining) and semi-primary (extraction of a by-product in another country) as well as secondary production. An example is metal production from

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smelters located in EU countries which themselves do not carry out mining activities, e.g. indium production in Belgium.

Table 2. Global supply of the CRMs – individual materials (Study on the review of the list of Critical Raw Materials. Executive summary. 2017, p.9). Explanation of abbreviations: E = Extraction stage P = Processing stage; HREEs: Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium; LREEs: Cerium, lanthanum, neodymium, praseodymium and samarium; PGM: Iridium, palladium, platinum, rhodium, ruthenium.

nr	Material	Stage	Global supplier	Share	nr	Material	Stage	Global supplier	Share
1	Antimony	P	China	87%	23	Natural graphite	E	China	69%
2	Baryte	E	China	44%	24	Natural Rubber	E	Thailand	32%
3	Beryllium	E	USA	90%	25	*Neodymium*	E	China	95%
4	Bismuth	P	China	82%	26	Niobium	P	Brazil	90%
5	Borate	E	Turkey	38%	27	*Palladium*	P	Russia	46%
6	*Cerium*	E	China	95%	28	Phosphate rock	E	China	44%
7	Cobalt	E	DRC	64%	29	Phosphorus	P	China	58%
8	*Dysprosium*	E	China	95%	30	*Platinum*	P	S. Africa	70%
9	*Erbium*	E	China	95%	31	*Praseodymium*	E	China	95%
10	*Europium*	E	China	95%	32	*Rhodium*	P	S. Africa	83%
11	Fluorspar	E	China	64%	33	*Ruthenium*	P	S. Africa	93%
12	*Gadolinium*	E	China	95%	34	*Samarium*	E	China	95%
13	Gallium*	P	China	73%	35	Scandium	P	China	66%
14	Germanium	P	China	67%	36	Silicon metal	P	China	61%
15	Hafnium	P	France	43%	37	Tantalum	E	Rwanda	31%
16	Helium	P	USA	73%	38	*Terbium*	E	China	95%
17	*Holmium*	E	China	95%	39	*Thulium*	E	China	95%
18	Indium	P	China	56%	40	Tungsten	E	China	84%
19	*Iridium*	P	S. Africa	85%	41	Vanadium	P	China	53%
20	*Lanthanum*	E	China	95%	42	*Ytterbium*	E	China	95%
21	*Lutetium*	E	China	95%	43	*Yttrium*	E	China	95%
22	Magnesium	P	China	87%					

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Table 3. List of CRM and their main importers and main sources of the EU supply. EU and associated countries (Norway and Switzerland) are marked in bold (from COM (2017) 490 final).

CRM	**Main importers to the EU (av.2010-2014)**	**Main sources of the EU supply (av.2010-2014)**	**End-of Life recycling input rate (the ratio of recycling from old scrap to EU demand)**
Antimony	China (90%) Vietnam (4%)	China (90%) Vietnam (4%)	28%
Baryte	China (53%) Morocco (37%) Turkey (7%)	China (34%) Morocco (30%) Germany (8%) Turkey (6%) United Kingdom (5%) Other EU (4%)	1%
Beryllium	n/a	n/a	0%
Bismuth	China (84%)	China (84%)	1%
Borate	Turkey (98%)	Turkey (98%)	0%
Cobalt	Russia (91%) Democratic Republic of Congo (7%)	Finland (66%) Russia (31%)	0%
Fluorspar	Mexico (38%) China (17%) South Africa (15%) Namibia (12%) Kenya (9%)	Mexico (27%) Spain (13%) China (12%) South Africa (11%) Namibia (9%) Kenya (7%) Germany (5%) Bulgaria (4%) United Kingdom (4%) Other EU (1%)	1%
Gallium	China (53%) United States (11%) Ukraine (9%) South Korea (8%)	China (36%) Germany (27%) United States (8%) Ukraine (6%)	0%

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CRM	Main importers to the EU (av.2010-2014)	Main sources of the EU supply (av.2010-2014)	End-of Life recycling input rate (the ratio of recycling from old scrap to EU demand)
		South Korea (5%) Hungary (5%)	
Germanium	China (60%) Russia (17%) United States (16%)	China (43%) Finland (28%) Russia (12%) United States (12%)	2%
Hafnium	Canada (67%) China (33%)	France (71%) Canada (19%) China (10%)	1%
Helium	United States (53%) Algeria (29%) Qatar (8%) Russia (8%)	United States (51%) Algeria (29%) Qatar (8%) Russia (7%) Poland (3%)	1%
Indium	China (41%) Kazakhstan (19%) South Korea (11%) Hong Kong (8%)	China (28%) Belgium (19%) Kazakhstan (13%) France (11%) South Korea (8%) Hong Kong (6%)	0%
Magnesium	China (94%)	China (94%)	9%
Natural graphite	China (63%) Brazil (13%) Norway (7%)	China (63%) Brazil (13%) Norway (7%) EU (< 1%)	3%
Niobium	Brazil (71%) Canada (13%)	Brazil (71%) Canada (13%)	0.3%
Phosphate rock	Morocco (31%) Russia (18%) Syria (12%) Algeria (12%)	Morocco (28%) Russia (16%) Syria (11%) Algeria (10%) EU – Finland (12%)	17%

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CRM	Main importers to the EU (av.2010-2014)	Main sources of the EU supply (av.2010-2014)	End-of Life recycling input rate (the ratio of recycling from old scrap to EU demand)
Phosphorus	Kazakhstan (77%) China (14%) Vietnam (8%)	Kazakhstan (77%) China (14%) Vietnam (8%)	0%
Scandium	Russia (67%) Kazakhstan (33%)	Russia (67%) Kazakhstan (33%)	0%
Silicon metal	Norway (35%) Brazil (18%) China (18%)	Norway (23%) France (19%) Brazil (12%) China (12%) Spain (9%) Germany (5%)	0%
Tantalum	Nigeria (81%) Rwanda (14%) China (5%)	Nigeria (81%) Rwanda (14%) China (5%)	1%
Tungsten	Russia (84%) Bolivia (5%) Vietnam (5%)	Russia (50%) Portugal (17%) Spain (15%) Austria (8%)	42%
Vanadium	Russia (71%) China (13%) South Africa (13%)	Russia (60%) China (11%) South Africa (10%) Belgium (9%) United Kingdom (3%) Netherlands (2%) Germany (2%) Other EU (0.5%)	44%
PGM	Switzerland (34%) South Africa (31%) United States (21%) Russia (8%)	Switzerland (34%) South Africa (31%) United States (21%) Russia (8%)	14%
HREEs	China (40%) USA (34%) Russia (25%)	China (40%) USA (34%) Russia (25%)	8%

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CRM	Main importers to the EU (av.2010-2014)	Main sources of the EU supply (av.2010-2014)	End-of Life recycling input rate (the ratio of recycling from old scrap to EU demand)
LREEs	China (40%) USA (34%) Russia (25%)	China (40%) USA (34%) Russia (25%)	3%

From the secondary resources point of view, several CRM are supplied from non-mineral-based secondary resources, particularly industrial waste and fabrication scraps (or new scrap), which are recycled at source. Based on CRM Factsheets published by the EC DG Growth in June 2017, significant recycling rates have been identified for beryllium, cobalt, gallium, germanium, indium, magnesium, palladium, platinum, ruthenium and tantalum.

However, when referring to EoL products recycling, CRM Factsheets (EC 2017) show that end of life recycling input rates (EoL-RIR) are generally poor for most CRM, with some exceptions like antimony, selected PGM and some REE. Particularly, the focus with regards to CRM is on EoL products and components containing a high mass fraction of CRM, such as laptops and mobile phones. For many other applications, there are very few studies or other publications which include reliable data on concentrations. The results obtained by previous projects addressing CRM secondary sources such as ProSUM and MSP REFRAM show that there are still significant gaps concerning the information on the content of CRM in end-of-life products, and thus their potential recyclability. Indeed, no official, publicly available databases containing information on CRM content in products have been identified, with an exeption of the Urban Mine Platform which is still under construction (http://www.urbanmineplatform.eu/homepage).

Finally, regarding the potential of urban mining, information is even more scarce. The SmartGround project is currently developing a platform on secondary raw materials (SRM) which is collecting available information regarding landfills and dumps. This platform will be delivered in 2018.

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2.2. APPLICATIONS AND USES

The current uses of CRM have been extensively studied in D.2.1 "Report on the current use of critical raw materials" of SCRREEN project (Deetman et al., 2017). The report reviews and maps the current use of critical raw materials (CRM) in the European Union based on the list of materials identified as being critical by the European Commission in 2014. The uses for 31 critical materials in various sectors and applications at the highest possible level of detail are collected (p. 14-16) based on a review of available data sources listed individually in its Annex 1. The MSP REFRAM public final report (Bertrand et al. 2016) provides information about tungsten, niobium and tantalum applications. Compilations such as Gunn (2014) also contain relevant information on CRM applications and uses.

In this section, uses and applications have been collected according to the updated list of CRM and CRM Factsheets published by EU in June 2017, e.g. baryte has been included while chromium has been excluded, and the products which are potential recyclables have been identified as shown in Table 4. Of the CRM presently included in this classification, a majority are metals with several well-specified uses in particular technologies and applications.

For a metal like antimony, while important uses include alloys, batteries, glasses, ceramics, and plastics, the overall biggest range of applications is within the production of fire (flame) retardants. In this specific case, a large part goes into fire-retardation of plastics, but also into a variable range of other products such as textiles, paints and rubbers, which cannot be readily recycled.

The mineral barite, barium sulphate, is extensively used in the oil and gas drillings industry, and is therefore dissipated and cannot be recycled. Barite used for fillers, ceramics, plastics and paint, have more potential in this sense, but are presently considered not to be easily recyclable.

Beryllium is mainly used for alloys and in ceramics, but is also utilised in its pure form, as beryllium metal for specialised high-tech applications. While products can be expected to have a long life, some of them, including those employed for military technology, are not

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returned to the industry. On the other hand, the aerospace industry can be a major source for recycling.

The metal bismuth is used in a broad range of products, dominated by solders and alloys, and various pharmaceutical products, as well as electronics and coatings. As a majority of e.g. pharmaceutical applications are dissipative, bismuth cannot be recycled. In the alloys and related products, it is mostly a minor metal, and is not recycled.

Borates, boron-oxygen compounds, comprise a broad suite of minerals which may also include borosilicates (despite being included in the grouping "borates"), that are used for the production of different boron compounds, chiefly boric acid. The boron compounds are used in a great number of applications including glass and fibre glass, household products, ceramics, and nutrients for agriculture. Because of the nature of these applications, boron/borate recycling is mainly prevented.

The metal cobalt has a wide range of uses including pigments, but is increasingly used in high-tech applications for battery technology, catalysts and various alloys and hard materials. While glass and other materials pigmented by cobalt cannot be recycled, spent catalysts, batteries and high-cobalt metal scraps can be successfully recycled.

Fluorite (or fluorspar) is a calcium-fluoride mineral, and used mainly for the production of fluorine compounds, such as hydrofluoric acid. Fluorine compounds are used in the production of fluoropolymers as well as fluorochemicals for air-conditioning, refrigeration, pharmaceutical and allied applications. Large amounts of fluorite is also used in the production of fluxing materials used in metal and ceramics production, and some still go into the production of specialised optical products. Because of the consumption of the fluorite or fluorine-rich chemicals utilised in these processes, fluorite cannot be said to be recyclable.

Gallium and germanium are two rare metals that are primarily used for their electrical properties, particularly when used in semiconductors in the wider sense, in a range of applications at the core of modern high-tech electronics, in photovoltaics, fibre optics, as

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well as modern LED technology. Depending on product, recycling can be feasible to supply a significant component back into production.

Hafnium is a rare metal with a limited, yet important range of applications, which comprise super alloys and nuclear reactor technology, as well as in high-refractory materials. Because of the limitations from its applications, such as radioactive contamination or low contents in special alloys, hafnium is presently not recycled.

Another rare metal is indium. It has gone from relative obscurity to wide-ranging use in the form of different chemical compounds in, particularly, the semiconductor, photovoltaics, and flat screen technologies. Indium is also used in solders and alloys. Depending on product types and regions, it can be successfully recycled from diverse, higher-grade scrap sources, such as indium-tin oxide film products.

Magnesium is a light metal that does not, however, occur naturally in its pure state but in a number of different minerals. Major applications are alloys and structural applications, because of its high strength to weight ratio, as well as for desulphurisation in iron and steel production. Because of its many applications in which it occurs in comparatively high contents in simple materials, magnesium is amenable to recycling.

Natural graphite is the most common mineral form of carbon on Earth. It is used in simple products such as pencils, but most importantly in steel making and foundries, because of its refractory properties, and for its use in recarburising. It is also extensively used in lubricants and friction products, and increasingly so, in battery technology, as well as high-tech applications of the refined end-product graphene. Due to its application types, most graphite cannot be recycled.

Niobium is a rare, hard and refractory metal, which is used in high-strength alloy steels, superconducting magnets, hard materials, and special glass coatings. Presently, despite the overall possibility to recover niobium from special steel scrap, the actual rate of recycling is low to non-existent.

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The platinum group metals (PGM) are among the least abundant of the metals in the continental crust. They, and in particular group members platinum, palladium and rhodium, which are most widely used, are valuable precious metals as well as industry metals of major importance. The absolute largest application is in automotive catalysts, in addition to petroleum refining, electrical products and jewellery products. As the PGM are high-value metals that are utilised in often very specific applications, the potential for recycling is very good, and is also steadily increasing, with the exception of jewellery.

Phosphate rocks supply one of the most vital components to the production of fertilisers, phosphorous. The importance of fertilisers for modern agriculture cannot be overstated, and despite the broad range of countries with suitable geology for phosphate production, supply is threatened in a growing world. Due to the nature of its main uses, phosphates and phosphate rocks cannot be recycled yet, however, alternative uses of waste streams from biological/vegetable sources may become increasingly functional.

The rare earth elements (REE) are a group of metals consisting of the 15 lanthanoids together with yttrium and scandium. They play an increasingly important role in a very broad range of technological applications, ranging from nuclear energy, via green or low-carbon energy production, research, consumer and military electronics as well as the automotive industries. Because of their intrinsical chemical similarities they are very difficult to purify, and they are also used in relatively small total quantities in many applications, which combine to make recycling problematic. Specialised products with higher contents such as magnets and some alloys may however be more functional to recover.

Silicon is the most common metal in the crust of the Earth. It is used extensively in the metallurgical and chemical industries, with the latter producing numerous silica compounds used in insulating materials, whereas electrical grade silicon metal is used in the electronics industry for applications such as semiconductors and photovoltaics. Much silicon is presently not recycled, yet good potential lies in the recovery of silicon from alloys and semiconductor industry refuse.

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The rare metal tantalum is used primarily in electronic applications, such as cell phones, in high-tech alloys, sputtering technology, and hard materials such as cutting tools. The present status of recycling is very low, but there is potential in the recovery from specialised alloy and tool products as well as electronics.

Tungsten is another relatively rare metal, with highly specialised applications, particularly within old-style incandescent lamp manufacture, special alloys and hard materials, as well as catalysts and military applications. Due to its characteristics, specific applications and relatively high value, tungsten is very amenable to recycling.

Vanadium is a moderately rare metal, especially in the form of commercially exploitable deposits. It is very widely used as an alloying metal and catalyst. The abundant use of it in alloys, including tool steel, means that it is very amenable to recycling.

Table 4. CRM applications and related products with potential for recycling.

Name	Symbol	Applications	Identified products (potential recyclables)
Antimony	Sb	lead alloys mechanical equipment & industrial motors	scrap
		fire (flame) retardants	
		wire and cable (plastic)	wire and cable
		lead-acid batteries	lead-acid batteries
		electric and electronic equipment (EEE)	WEEE

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Name	Symbol	Applications	Identified products (potential recyclables)
		plastics (catalysts, heat stabilizers) textiles ceramics	secondary material (not functional recycling)
Baryte	BaSO4	filler additive in rubber, paint, ceramics, paper, plastics, glass, high density concrete and plaster weighting agent in oil and gas well drilling fluids	secondary material (not functional recycling)
Beryllium	Be	steel alloys aircrafts shipbuilding & trains mechanical equipment & industrial motors	old scrap new scrap
		auto electronics audio systems Cu-Be spring connectors	ELV WEEE
		glass insulation	
Bismuth	Bi	solder alloys in electronic equipment;	WEEE
		pigments and pharmaceuticals	dissipative uses (not recyclable)
Borates		metals	old scrap

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Name	Symbol	Applications	Identified products (potential recyclables)
			new scrap
		animal feed&fertilizer, feed and food additives chemical products industrial fluids detergents	
		ceramics borosilicate glass textiles	secondary material (not functional recycling)
		electrical equipment	WEEE
Cobalt	Co	superalloys hardfacing metals/high strength steel mining&construction tools	od scrap new scrap
		pigments	dissipative use (not recyclable)
		chemical catalysts	chemical catalysts
		batteries	batteries
Fluorite (fluorspar)		uranium enrichment stainless steel pickling (as calcium fluoride),	recycling at source

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Name	Symbol	Applications	Identified products (potential recyclables)
		aluminium production	
		chemical products (hydrofluoric acid production, fluorochemicals)	refrigeration equipment
		petroleum alkylation enamel production cooking utensils glass	
		crystals in lenses, telescopes, cameras and microscopes	WEEE
Gallium	Ga	photovoltaic modules (thin film CIGS) permanent magnets opto-electronics	new scrap
		semiconductor devices: integrated circuits (ICs) and light emitting diodes (LEDs) electronics&IT sensors	WEEE
Germanium	Ge	photovoltaic modules night vision equipment; semiconductors; fibre optics	old scrap new scrap

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Name	Symbol	Applications	Identified products (potential recyclables)
		IR optics	
Hafnium	Hf	alloys and superalloys metal insulators	old scrap new scrap
Helium	He	scientific R&D and industrial applications	
Indium	In	photovoltaic modules (thin film CIGS)	new scrap (spent ITO -tin-doped indium oxide- sputtering targets to produce thin films)
		architectural&automotive glass	
		batteries	batteries
		Liquid-Crystal-Displays (LCD): monitors, televisions. computers	WEEE: LCD televisions Notebook computers Desktop monitors
Magnesium	Mg	aluminium packaging aluminium alloy construction elements steel making (desulphurisation) nodular cast iron magnesium die-casting	new scrap (secondary magnesium) old scrap (part of aluminium value chain)

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Name	Symbol	Applications	Identified products (potential recyclables)
Natural Graphite	C	steel making (recarburising, foundries, refractory goods) X-ray tubes automotive friction parts lubricants lead-acid batteries electric and electronic equipment (EEE): carbon brushes	dissipative uses (not recyclable)
Niobium	Nb	high-strength low-alloy steels (HSLA) for building construction, pipelines, etc. superalloys (aircraft engines, gas turbines for electricity generation) stainless and heat resistant steels	ferrous scrap (not functional recycling)
		superconductors	WEEE: computers ELV
		ceramics catalysts	
PGMs		autocatalysts (Pd, Pt, Rh)	autocatalysts

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Name	Symbol	Applications	Identified products (potential recyclables)
	Pt, Pd, Rh, Ir, Ru	chemical catalysts (Pd, Pt, Rh) (bio)medical, including dental (Pd, Pt) oil-refining (Pt) glass insulation (Pt, Rh) photovoltaics (Ru)	
		audio systems (Pd, Pt) solders (Pd)	WEEE ELV
		jewellery (Pd, Pt)	jewellery
Phosphate Rock and white phosphorous		animal feed&fertilizer, feed and food additives detergents	sewage sludge, incineration ash, meat and bone meal ash
Rare Earth Elements	REE	metals, alloys (La, Ce, Pr) mining and construction tools (Nd) mechanical equipment & industrial motors (Dy) wind turbines (Pr, Dy) polishing/pickling & etching (La, Ce, Pr)	scrap
		autocatalysts (La, Ce, Nd) ceramics (La, Ce, Pr, Nd)	

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Name	Symbol	Applications	Identified products (potential recyclables)
		glass (La, Ce, Nd, Er)	
		fibre-optics (Er) lasers (Er) audio-systems (Dy)Computers (Pr, Dy) plasma (Eu) permanent magnets in hybrid and electrical vehicles (electric motors) (Ce, Nd, Sm, Dy, Tb, Gd) and in MRI (Nd, Dy) semiconductor: capacitors (Dy), integrated circuits (Pr) NiMH batteries (where M=La, Ce, Nd, Pr up till 5%) phosphors: light convertors (Tb and Eu in CFL; Y in SSL), LEDs (Y, Ce, Eu)	WEEE: desktop computers, laptop computers, lamps, flat panel displays ELV: Electric vehicles, Hybrid electric vehicles batteries
Scandium	Sc	solid oxide fuel cells Sc-Al alloys	
Silicon Metal	Si	silicon wafers: capacitors and integrated circuits photovoltaic modules chemical products	WEEE
		aluminium alloys	scrap

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Name	Symbol	Applications	Identified products (potential recyclables)
Tantalum	Ta	superalloys (turbine blades)	turbine blades
		capacitors surface acoustic wave filters sputtering targets	WEEE: cellular and wireless telephones, television sets, video recorders, tire pressure control and keyless entry systems
		cemented carbides	scrap
Tungsten	W	alloys: high speed steel hard materials (tungsten carbides): milling&cutting tools, mining&construction tools, other wear tools aircrafts/defence	scrap cemented carbide scrap
		chemical applications: catalysts, lubricants, X-ray shielding (medical equipment), fluorescent lighting, scintillation detectors	spent Ni-W catalysts
		electrical and electronic equipment: light bulb, electrodes for welding, cathode-ray tube, and vacuum tube filaments, heating elements	WEEE: burnt-out bulbs, electric contacts/devices, electrodes, bullets
Vanadium	V	alloys	steel scrap
		catalysts	spent chemical process catalysts
		fossil fuel processing	ash, slag, residues

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3. CHALLENGES FOR EU CRM SUPPLY FROM INDIGENOUS SOURCES

3.1. PRIMARY RESOURCES

The main challenges for sustainable supply of primary CRM in Europe are:

- Development of innovative technologies addressing exploration of CRM to discover new potential deposits on land and off shore.
- Development of new primary CRM production in Europe will decrease import dependence and make sure that exploitation takes place under sustainable conditions. This includes the necessity for exploration of deep-seated deposits in brownfield areas across the EU where potential CRM resources may occur in genetic associations with common industrial and other high-tech metals.
- Adapting technology, economical constraints and mind-set to allow for the exploitation of smaller and lower-grade deposits.
- Mining technologies adapted to the treatment of primary mineral resources with increasing complexity and decreasing grade.
- To refine low grade ores and materials containing CRM while reducing energy consumption and environmental impact.
- The need to develop methods for extracting all valuable metals from currently-mined ores and recycled materials, including minor elements that are commonly now rejected.
- Development of the technologies adjusted to the properties of the processed CRMs to increase extraction efficiency and metal recoveries.

To fully meet future CRM needs, metals and mineral products from primary sources will still be needed in the future. Most of them will continue to be imported from sources outside Europe; but others can, for political and economical reasons, be produced domestically.

The detailed analysis of primary CRM resources is presented in D3.1.

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3.2. MINERAL-BASED WASTES

The main challenges related to supply of secondary CRM from mineral-based wastes, e.g. mining waste, processing tailings, in Europe are:

- Insufficient information about CRM compositions and volume characteristics in the mineral resources from primary ore deposits.
- Insufficient information about CRM compositions and volumes in mineral-based wastes like for example mining waste such as dumps and tailings.
- Insufficient knowledge about mineralogical and geochemical behaviour of CRM during mining and processing using physical and chemical methods.
- Insufficient information about the mineral-based character of residues, and their physical and chemical properties.
- Insufficient information about overall availability and resource potential of historic mining sites.
- Insufficient information about historical smelter locations and metallurgical wastes.
- High losses of CRM during pre-processing, impurities degrading product/residue quality.
- Lack of systematic identification/mapping of mining waste sites for future CRM extraction.
- Lack of a unified system for classification of CRM (e.g. UNECE/UNCF system) in various types of mining waste.
- Lack of specific methods of extracting metals and other valuable products from secondary, often heterogeneous sources.
- Overall lack of a full inventory and range of metals to anticipate future demand.

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3.3. NON-MINERAL-BASED SECONDARY RESOURCES

A sustainable supply of mineral products and metals for European industry requires more efficient and rational consumption, enhanced substitution and improved recycling. Recycling is mandatory to secure the access to raw materials, now and in the future. Metals are in principle infinitely recyclable without a degradation of their pristine quality. However, recycling becomes much more difficult with increasing product complexity. Many metals are dissipated during product use, and contamination and dilution both lead to ecomic challenges in recycling.

In general, recycling of manufacturing waste (e.g. new scrap) is in many cases less complicated than that of post-consumer waste (e.g. EoL products). Nowadays, recycling is mainly managed by private companies and there are usually no requirements to publish detailed information on the quality and composition of recycled materials. Therefore, improved recycling rates should revolutionise a supply of secondary CRM.

Recycling from scrap to raw materials has been rapidly growing over the last years (see Table 5). However, continuous reuse cannot provide alone the necessary quantities of CRM. The main factors are:

- Recycling loss;
- The growing demand for CRM is higher than the rate of primary supply, recycled CRM production and finding new CRM sources and substitutions;
- Main challenges today are so called ‘metallurgical challenges’’ and they are related to finding a product and material groups with the highest potential for high-grade recovery of the CRM that are largely lost today (e.g. indium, gallium, germanium, tantalum, rare earth elements).

It is technically relatively easy to recycle base metals from simple products, but with increasing product complexity, metal heterogeneity, and recycling of trace components such as CRM, recycling becomes much more difficult. Innovative recycling technologies for CRM from complex products have to be developed in order to improve the efficiency of material

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production and used throughout the whole supply chain up to the moment when waste becomes the resource needed by another process (e.g. redesign for recycling, collection and disassembly). In this field, the main challenges are:

- Product manufacturing;
- Product distribution and use;
- End-of-life collection and logistics;
- End-of-life pre-processing;

The development of a circular economy incorporating a maximum level of recycling, substitution and optimised use of resources has become a top priority for the EU CRM supply.

Table 5. CRMs and their potential non-mineral-based secondary sources.

CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Antimony	Lead-acid batteries	28%		
Antimony	Lead-alloys	?		
Antimony	Cables and wires, WEEE	?		

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Antimony	Bottom ash	0%		Not economically viable
Baryte	Weighting agent	1%		Only recovery at the drill site
Baryte	Filler, additive in rubber, paint, ceramics and glass, high density concrete and plaster	0%		Baryte is not recovered and cannot be recycled
Beryllium	Post-consumer recycling (old scrap)	0%		The recuperation of pure metal of beryllium from end finished products is extremely difficult because of the small size of components and the tiny fraction of Beryllium contained in appliances
Beryllium	Industrial recycling (new scrap)	-	94-100%	Beryllium can be recovered from new scrap generated during the manufacture of beryllium products and from old scrap. Quite all the new scrap (between 94% and 100%) is sent back to the producer and recycled

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Bismuth	Solder alloys in electronic equipment	1%		
Bismuth	Pigments and pharmaceuticals	0%		Dissipative uses
Borates	Borosilicate glass	0%		Non-functional recycling. It is recycled to new glass but it does not replace primary boron
Cobalt	Pigments	0%		Dissipative uses
Cobalt	Old scrap (turbine blades, parts of jet engines, cutting tools, spent rechargeable batteries, magnets, spent catalyst)	0%		Recycling rate depends on the efficiency of collection systems and the economics of recovery process (estimated as 68%). However, most cobalt containing alloys are recycled into stainless steel so Co is not recovered.
Cobalt	New or processing scrap	-	32%	The recycled content of fabricated metal is 32% (UNEP, 2011), i.e. the total scrap, both 'old scrap' and 'new scrap', contained within the total

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
				quantity of cobalt metal used by manufacturers
Fluorspar	Uranium enrichment, stainless steel pickling and petroleum alkylation	1%		Not recyclable. Few thousand tons of synthetic fluorspar are recovered during uranium enrichment. HF and fluorides are recovered from aluminium smelting operations. Fluorochemicals are recycled (60-70%) from refrigeration sector
Gallium	Semiconductor devices: Integrated circuits (ICs) and light emitting diodes (LEDs)	0%		Highly dispersed, current recycling processes of WEEE do not favour gallium recovery, ending up as impurity in recycled materials or waste slags
Gallium	Industrial scrap	-	30-60%	In the manufacture processes of gallium arsenide and gallium nitride wafers, scrap is generated and recycled in a closed loop (60%). In thin film photovoltaic production

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
				material is also recovered (30-60%)
Germanium	New scrap	-	30%	Scrap generated during the manufacture of fibre-optic cables and infrared optics
Germanium	Old scrap	2%		Few EoL are collected separately (e.g. IR optics such as mobile phones), no functional recycling takes place as Germanium is present in trace amounts
Hafnium	Metal alloys and superalloys	1%		Little post-use recycling as by product of titanium and zirconium. Potential contamination in the nuclear industry and low percentage content in super alloys
Helium	Scientific R&D and industrial applications	1%		Helium used in large-volume applications is seldom recycled

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Indium	New scrap: mostly spent ITO (tin-doped indium oxide) sputtering targets to produce thin films	-	70%	Secondary indium recovered from scrap exceed virgin indium production (70% indium from the starting targets is recovered)
Indium	Old scrap: end-of-life products	1%		Minor indium concentrations in final products
Magnesium	New scrap	-	50%	Secondary magnesium is an important component in magnesium supply. EU recycling capacity is 75,000 tons/y
Magnesium	Aluminium scrap	9%		Most of end-of-life magnesium scrap is recycled as part of aluminium value stream
Natural graphite	Material containing natural graphite	3%		A significant amount of material containing natural graphite is lost during use (lubricants, friction materials, and to some extent refractories) and therefore cannot be recycled. Only some

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
				recycling of used refractory material.
Niobium	End-of-life scrap	0.3%		Niobium is recycled as constituent of ferrous scrap (>50%). Functional recycling is negligible (0.3%)
Iridium	Consumer applications	14%		End of life recycling rate varies considerably by country and by application
Iridium	Industrial applications		40-50%	
Palladium	Autocatalysts			
Palladium	WEEE	10%		The end of life recycling rate varies considerably by country and by application. The supply of palladium from secondary materials was 38% of total supply, of which 75% came from autocatalysts and 17% from WEEE

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Palladium	Intermediate products and wastes from mineral beneficiation, smelting, refining and manufacturing processes.		?	There is believed to be significant international trade in palladium-bearing waste and scrap, but Eurostat data are not available to ascertain the volumes involved.
Platinum	End-of-life products jewellery		26%	The end of life recycling rate varies considerably by country and by application. The supply of platinum from secondary materials was 26% of total supply, of which 61% came from autocatalysts and 37% from jewellery (BRGM, 2015).
Platinum	Autocatalysts	11%		
Platinum	Intermediate products and wastes from mineral beneficiation, smelting, refining and manufacturing processes.	-	?	There is significant international trade in platinum-bearing waste and scrap

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Rhodium	End-of-life products (autocatalysts, industrial catalysts and equipment for glass manufacture)	24%		The end of life recycling rate varies considerably by country and by application.
Rhodium	Intermediate products and wastes from mineral processing, smelting, refining and manufacturing processes	-	?	
Ruthenium	Electrical applications	11%	5%	The end of life recycling rate varies considerably by country and by application.
Ruthenium	Industrial applications (catalysts, manufacturing waste and by-products)		40-50%	

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Phosphate rock and white phosphorus	Applications in agriculture (biogenic waste flows)	17% (phosphate rock) 0% (white phosphorus)		For its applications in agriculture, phosphate rock can be replaced by secondary sources of phosphorous.
Phosphate rock and white phosphorus	Sewage sludge incineration ash or meat and bone meal ash	0%		Only at the pilot scale and no industrial installation is yet under construction
Cerium	Polishing powders	1%		Cerium can be re-used in the form of mishmetal
Dysprosium	EoL permanent magnets	0%		
Erbium	EoL optical applications, lighting	1%		
Europium	EoL lamps	38%		Solvay plant in La Rochelle closed in 2016 because prices of europium dropped significantly, thus the recycling process was less competitive

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Gadolinium	EoL permanent magnets, lighting and metallurgy	1%		
Holmium, Lutetium, Yterbium, Thulium	Optical applications	1%		
Lanthanum	Fluid cracking catalysts, glass and ceramics, batteries	1%		
Neodymium	EoL magnets, metallurgical alloys and ceramics	1%		
Praseodymiun	EoL magnets, ceramics and batteries	10%		
Samarium	Magnets	1%		
Terbium	EoL lamps	6%		Solvay plant in La Rochelle closed in 2016 because prices of terbium dropped

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
				significantly, thus the recycling process was less competitive
Ytrium	EoL fluorscent lamps	31%		Solvay plant in La Rochelle closed in 2016 because prices of ytrium dropped significantly, thus the recycling process was less competitive
Ytrium	Oxygen sensors in ELVs			
Scandium	Solid oxide fuel cells and Sc-Al alloys	0%		No recycling circuit is known for scandium in end-of-life products nor at the stage of 'new scrap'
Silicon metal	Post-consumer waste	0%		Dispersive applications
Silicon metal	Silicon wafers	0%		There is research on recycling of silicon wafers, however it has not yet materialised in marketable solutions. There is no functional recycling of silicon metal in aluminium alloys.

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
Silicon metal	Silicon waste streams from metallurgical grade silicon		?	Very little material is sold back into the market by metallurgical silicon users
Silicon metal	Slicon scrap for the production of electronic applications		?	As silicon metal used in electronic industry is of hig quality, silicon obtained from scrap can be used in the photovoltaic industry
Tantalum	Turbine blades		?	
Tantalum	Scrap from electronics industry (capacitors, sputtering targets, etc.)		30%	
Tantalum	EoL tantalum products	1%		
Tungsten	Contaminated cemented carbide scrap, turnings,	42%		Secondary tungsten is processed to ATP

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
	grindings and power scrap			
Tungsten	Clean cemented carbide and compacts			Converted to power
Tungsten	Tungsten containing scrap and residues			
Tungsten	High speed steel		60-70%	
Tungsten	Lamp filaments, welding electrodes and chemical uses	0%		Concentration is low so not economic to recycle
Vanadium	Steel scrap	44%		Scrap is matched and melted into a product having the desired chemistry
Vanadium	Spent chemical process catalysts			Recovery from spent catalyst, fly-ask, uranium and stone coal mining incur the highest cost.
Vanadium	Fossil fuel processing (vanadium bearing			

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CRMs	Potential secondary resources	End of life recycling input rate - EoL-RIR	Industrial (new) scrap recycling rates	Challenges/comments
	ash, slag, spent catalyst or residue)			

3.4. RECYCLING FROM EOL PRODUCTS

Recently published review about REE recovery from permannet magnet scrap (Yang et al. 2017) summarized the main challenges in the recycling industry:

- During the next decade, recycling is unlikely to substantially contribute to the global REE supply (see Fig. 2).
- In general, efficient metallurgical separation and refining processes remain the main challenges.
- It is estimated that an approximate time period of 5–10 years is required to set up a recycling practice.

Although recycling is unlikely to close the wide gap between future demand and supply by 2050, in the long term, secondary supply from recycling can potentially meet almost 50 % of the demand, i.e., by 2100.

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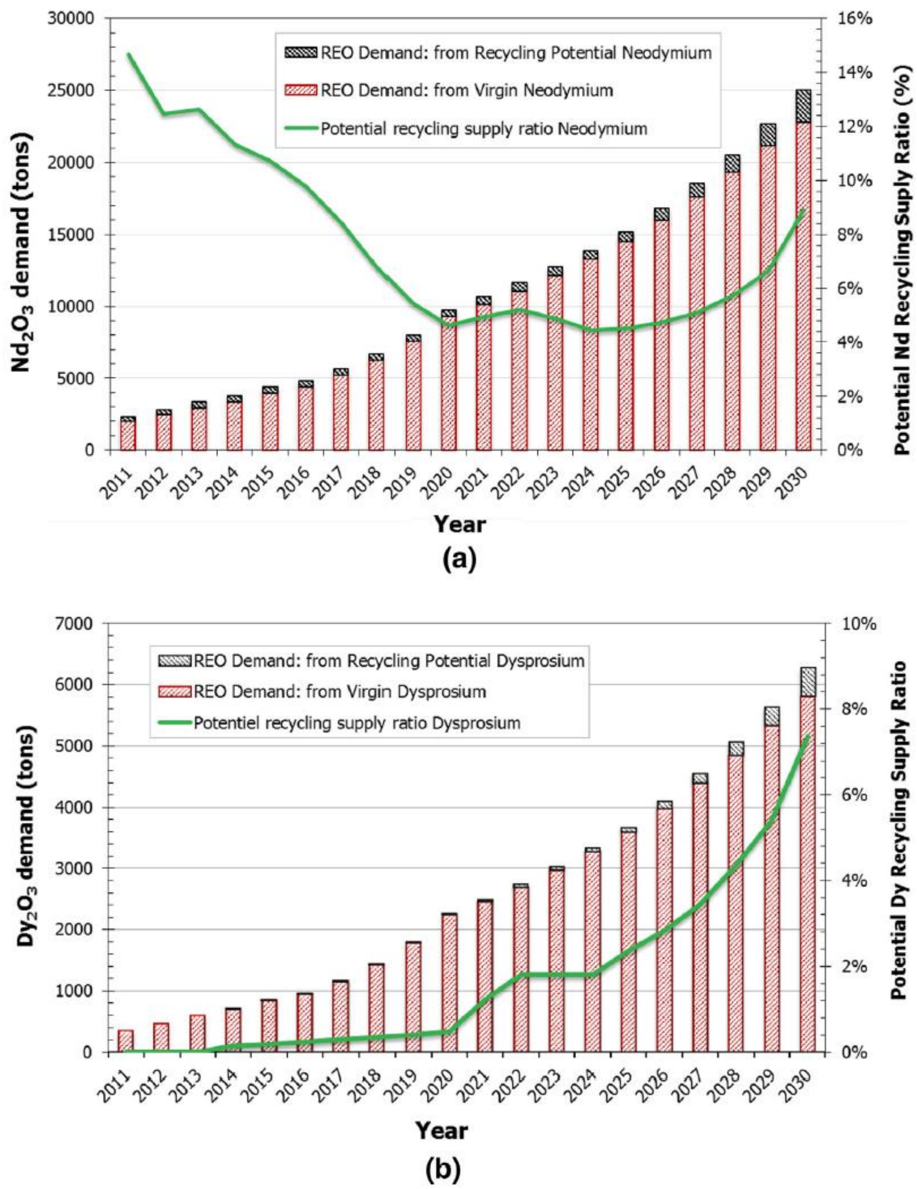

Figure 2. Predicted recycling potentials of (a) Nd and (b) Dy from EOL permanent magnets for all the 3 sectors (computer hard disk drives, wind turbines, and automotive industry).

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4. CRM STRATEGIC GOVERNANCE IN MEMBER STATES

4.1. GOOD EXAMPLE CRITERIA (POLICY) WITH RESPECT TO MINERAL-BASED SECONDARY RESOURCES

Mineral policies are built into a framework of legislation permitting and supporting structures. The supporting structures contain what we can call infrastructural parts with basic information about placements of mining wastes and their content. These mining wastes were and are to a large part unknown to their exact resource value particularly with regards to their content of critical raw materials (CRM). Due to the need for supply of CRM, specifically identified secondary sources make resource potential targets, in terms of feasible extraction of critical minerals and metals, including also any policy-related challenges involved.

Policies and various rules applied to mining waste are listed on the Minventory/EU website. The current list on the Competent Authorities responsible for collecting and publishing sets of data on mining waste of EU countries can be found using the following link: https://ec.europa.eu/jrc/en/scientific-tool/minventory. Relevant information on totally 40 European countries listed is available and downloadable, e.g. on the authorities having any kind of legal or policy-related responsibility for mining wastes.

4.1.1. GOOD PRACTICE EXAMPLE ON MINERAL-BASED WASTE IN SWEDEN

In Sweden, the Swedish Environmental Protection Agency enforces Regulation (2013:319) on Extractive Waste. National legislation /policy do not require collection of data. However, data is collected and published by the Environmental Protection Agency. With respect to operating mines, data is made available to site level to the public and relates to: Location,

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Type of facility, Waste characterisation and Waste source (http://utslappisiffror.naturvardsverket.se/en/Search/).

Environmental reports from all active mines and concentrators required to have permits, including controls and imputations made possible by using data on single mines in the annual "Bergverksstatistik" record from the Geological Survey of Sweden (SGU).

With regards to closed and abandoned facilities, data is collected, but it is not available generally to the public, only to local and regional authorities via online access. This database contains all condemned sites, not only mines. Types of data collected include: Location, Type of facility, Waste characterisation, Waste source and other information (risk classification, whether investigated, whether treated etc.).

The overall needs for mineral raw materials and the growing demand of CRM, both from primary and secondary sources (e.g. mineral-based wastes) have been addressed in the Swedish Mineral Strategy (http://www.government.se/49b757/contentassets/78bb6c6324bf43158d7c153ebf2a4611/swedens-minerals-strategy.-for-sustainable-use-of-swedens-mineral-resources-that-creates-growth-throughout-the-country-complete-version), which was launched with specific tasks commissioned by the government to expert authorities, like the Geological Survey of Sweden(SGU). These tasks are integrated in such a way that an overall geological investigation of both primary and secondary raw materials are being undertaken in all important mining districts of Sweden, such as the Bergslagen region. One of the reasons for integrating knowledge about primary and secondary resources is to understand and trace any commodities from the mined primary resources that end up in the mineral-based waste flows produced. This is done as an effort to support and encourage the mining industry to develop routines and technologies for extraction of both primary and secondary resources. Apart from supporting infrastructure information, such as datasets of drill cores, intelligence upon known deposits and geological knowledge, the exploration of secondary sources, in terms mainly of mineral-based wastes, is also in focus as a challenging exploitation target. Current tasks are:

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1. Assessment of CRM content in selected mineral-based wastes. This part consists of several steps. The first step is to create a data base of existing mineral-based wastes which has partly been initiated by the Geological Survey of Sweden, the Swedish Environmental Protection Agency and the Regional County Boards. Next steps include sampling of the recorded wastes and determination of their mineralogical and geochemical compositions. The Geological Survey of Sweden has been given a specific task from the government regarding mapping and characterizing the mining wastes, with special focus on recovery potential of the CRM and related CRM prospectivity (Hallberg and Reginiussen, 2018; http://resource.sgu.se/produkter/regeringsrapporter/2018/RR1801.pdf). This work is on-going and is planned to be finished during 2018 (Fig. 3). Even though all mineral-based wastes of the country are not included, the potential value in relation to some CRM is clearly indicated and documented. A preliminary conclusion is that CRM is to be found both within the old known mining districts, along with extensively exposed brownfields, but also beyond and outside them. From the information collected and evaluated it is obvious that there is a significant potential for CRM secondary resources in Sweden.
2. Detailed assessment of primary mineral deposits where advanced knowledge on the mineralogical composition is available. Special attention is paid to the CRM (e.g. lithium, cobalt, graphite) needed for manufacturing of Li-ion batteries required by the electric vehicle industry. The Geological Survey of Sweden has currently been granted 10 MSEK by the government for investigating and mapping these CRM within Sweden.

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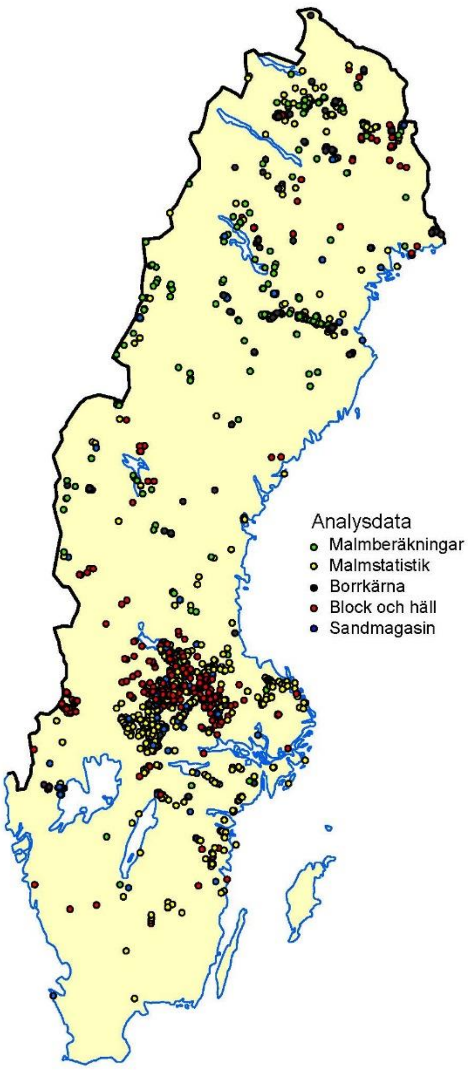

Figure 3. Locations of sites sampled in Sweden in order to create a chemical database for mineral resources including mineral-based waste (source: Hallberg and Reiginiussen 2018).

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4.2. GOOD PRACTICE CASES WITH RESPECT TO NON-MINERAL-BASED SECONDARY RESOURCES

As previously mentioned, the main challenges for the recovery of CRM from secondary resources are:

- Non-sufficient research and technical development of new metal extracting technologies and recycling methods in order to improve the efficiency of material production and use throughout the whole supply chain.
- Lack of extensive datasets, both in the individual states and overall, on the presence and nature of CRM in industrial waste.
- Particularly in the case of EoL products, the redesign for recycling, collection and disassembly.

The following cases show examples of the secondary resources potential for the supply of CRM with different degrees of success.

4.2.1. RECOVERY OF REES FROM END-OF-LIFE PRODUCTS AND INDUSTRIAL RESIDUES

Introduction

During the last years, there has been an intensification of research activities for the development of effective recycling routes for rare earths. Recycling is often difficult because of the way that REE are incorporated as small components in complex items, or are part of complex materials. The processes required are energy intensive and complex. Nevertheless, new scraps generated during the manufacture of alloys are an important secondary source, mainly in a closed loop (30% of magnet alloys end up in scraps during manufacture). Although the concentrations of rare earths in such streams are low - typically less than 1% rare-earth oxides - since the available waste volumes are huge, the total amount of rare

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earths in these waste fractions is very substantial, so that they can represent a potentially relevant alternative source of rare earths.

End-of-Life recycling rates of the rare earths are very low, mainly because of the lack of efficient collecting systems and prohibitive costs of building REE recycling plants.

Process/Technology

Presently, only limited information is available with respect to the mineralogy of the different rare-earth rich phases in bauxite residue, phosphogypsum and metallurgical slag.

Knowledge of these phases could aid the development of new more efficient leaching processes. There is also a need for methods that allow efficient recovery of rare-earth ions from dilute aqueous solutions, not only from waste water streams, but especially from the dilute leachates. Since the concentrations of rare earths in industrial waste residues are low compared to primary rare-earth ores and reclaimed End-of-Life consumer goods (WEEE), tailored, zero-waste processes dedicated to the recovery of rare earths from these dilute waste streams must be developed.

Most of the REE recycling research has been directed towards the chemical processing of the collected REE recyclates, in a way that is reminiscent of the processing of rare-earth primary resources (REE ores). However, an efficient recycling of rare earths requires the development of environmentally-friendly, fully integrated and logistically sound recycling flow sheets, including dismantling, sorting, pre-processing, and pyro-, hydro- and/or electrometallurgical processing steps to recover the REEs from magnets, batteries, lamp phosphors and other products/components.

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Recycling potential

According to ERECON project final recommendations (ERECON, 2015), the priority streams for REE recycling are as follows:

Permanent magnets – Nd, Pr, Dy, Tb, Sm

Phosphors – Eu, Tb, Y, Ce, Gd, La

Batteries – La, Ce, Nd, Pr

Polishing compounds – Ce

Catalysts – La, Ce, Pr, Nd, Y

Since each PRODCOM list code (http://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM&StrGroupCode=CLASSIFIC&StrLanguageCode=EN&IntFamilyCode=&TxtSearch=prodcom&IntCurrentPage=1) embrace a variety of products and thus different REEs and amounts contained on them, quantitative recycling potential of REEs for the above categories of EoL products was not possible to estimate.

Case study (Solvay in France)

Solvay, one of the main REE-based phosphor producers in the EU developed a recycling unit together with Umicore in France in 2012 but had to stop operations by January 2016 because it had become uneconomic (https://www.usinenouvelle.com/article/solvay-renonce-au-recyclage-des-terres-rares.N375935).

When Solvay decided to go into the industrial phase of its innovative recycling process for rare earths contained in low-energy light bulbs, the tightening of Chinese exports gave rise to fears of supply difficulties. The price increase that followed justified the higher cost of

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recycling and the € 15 million invested in the project. Four years later, rare earth prices have returned to pre-crisis levels, and the process has lost its competitiveness.

The profitability of the REEs recycling is mostly dependent on REE prices and in the current situation of low prices the economics are difficult.

4.2.2. RECOVERY OF REES FROM PHOSPHOGYPSUM

Introduction

Phosphate rocks (mainly in the form of mineral apatite) are mined and either solubilized (acid leach) to produce wet-process phosphoric acid, or smelted to produce elemental phosphorus. The phosphate rock production in the world was 260 Mt in 2016, and most (82% of P_2O_5) was used for fertilizer. Phosphorites usually contain significant amount of rare earth elements (REE), approximately an average of 460 ppm.

Phosphogypsum (PG) is a by-product of the phosphoric acid wet-process and the main component is calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$) but may also contain other minor solid phases as reaction products of the acid wet process (e.g. alkali fluorosilicates and fluorides), unreacted phosphate rock and gangue mineral particles (e.g. quartz and feldspars). The manufacturing of phosphoric acid is a highly waste generating activity; around 5 tons of PG are produced for every ton of phosphoric acid manufactured. The huge production of these unwanted by-products, i.e. over 100e280 Mt/yr of PG worldwide, has promoted the searching of new recycling alternatives.

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Process/Technology

As the phases hosting REE in PG are complex, being carried by monazite and REE mineral mixtures or intergrowths, and in the form of REE substituting for Ca in gypsum, as well as in the form of surface-adsorbed components, enrichment by physical methods is difficult.

Direct leaching with mineral acids or some organic agents for extraction of REE from PG has been studied and indicated that it is technically feasible, but also that further research is needed prior to any industrial implementation. The main challenges are as follows:

- Some other trace elements such as strontium (Sr), barium (Ba), silicon (Si), phosphorus (P), iron (Fe), aluminium (Al), titanium (Ti), uranium (U), and thorium (Th) etc. are contained in PG, which leads to one of the main environmental concerns. For safe disposal or utilization of PG the removal of these impurities needs to be considered.
- Tailored processes for the recovery of rare earths from dilute waste streams must be developed.
- Economically attractive if (heavy) rare earth prices increase.

Integration of production of phosphoric acid and the recovery of REE into the process is recommended to enhance economic feasibility. In addition, this could potentially also lead to improved final recovery of phosphorous.

Recycling potential

Data on sold production of phosphoric acid and polyphosphoric acids (20132455) have been collected from PRODCOM list (NACE Rev. 2) - annual data.

Due to confidentiality reasons, some EU countries did not report individual data, however the figure for total EU28 production corresponding to 2016 has been extracted.

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Based on the average quantity of PG produced for every ton of phosphoric acid manufactured and the concentrations of HREE and LREE in PG reported by Cánovas (2016), Table 6 shows estimates of the potential recyclability of HREE and LREE from the PG generated by the production of phosphoric acid at EU level (in t) for the year 2016 (Table 6).

Table 6. Potential recyclability of HREE and LREE from the phosphogypsum (PG).

	EU 28 TOTAL, 2016 (in t)			
PRODCOM list	PRODUCTION (t)	PHOSPHOGYPSUM (4.9 t/t)	HREEs (123 g/t)	LREEs (160 g/t)
20132455 - Phosphoric acid and polyphosphoric acids	360,718	1,767,521	217.4	282.8

Case study (Huelva PG stack in Spain):

Phosphate fertilizer plants operated in Huelva city (SW Spain) since 1968 and have led to the stockpiling of around 100 Mt of PG over approximately 1,200 ha of surface of estuarine marshland, less than 300 m from the city.

The dumping of these wastes directly on bare marshland soils over 40 years has left an appalling environmental legacy; i.e. many edge outflows with a high content of toxic metals and radionuclides reach the estuary. The restoration plan consists on the removal of process

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water ponds and the cover of PG stacks with impermeable materials. However, the growing social and political pressure urges to explore more sustainable solutions to the management of these wastes, which could contain high concentrations of elements of economic interest whose recovery could help offset treatment costs. For instance, the presence of rare earth elements is especially significant. The recovery of these elements could constitute a promising economic and environmental friendly solution for the management of these wastes.

- Estimated amounts enclosed in PG: 30,400 t of B; 16,000 t of LREE and Zn; 12,000 t of HREE; 1,400t of Cr.
- Estimated amounts contained in process water: 630 t U and Cr; 110 t HREE.
- Lesser amounts of Sc, Co, Ga, Sb

4.2.3. RECOVERY OF ANTIMONY FROM LEAD-ACID BATTERIES AND INDUSTRIAL RESIDUES

Introduction

Antimony is connected to secondary lead production because it occurs in the lead alloys. Due to the large production volumes of lead (11,000,000 t/year in 2014), compared to antimony (160,000 t/year in 2014), lead production residues are considered as important secondary feedstocks of antimony.

Indeed, secondary antimony is chiefly recovered from lead-acid batteries so the availability of secondary antimony is almost entirely dependent on the extent of lead recycling and the market conditions for lead and lead-acid battery scrap. However, antimony could potentially be recovered from other industrial residues and EoL products.

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Process/Technology

Currently, secondary production of antimony is mainly restricted to the recycling of antimony-containing lead alloys from lead acid battery recycling plants.

The process of the lead recovery from automotive or industrial scrap batteries for further refining to get minimum 99.97% purity, or making lead alloy, or to use in the production of lead oxides, or in the casting of grids/terminals to reuse again in the production of lead acid batteries; involves the following basic operations:

1. Collection and safe storage of dry / wet scrap batteries
2. Battery cutting / crushing and separation of lead contents / material and other component along with neutralization of acid / electrolyte
3. Smelting in closed compact furnace
4. Refining and alloying process
5. Pollution control equipment for effective control of the fumes and gases generated during operation of above furnaces

Antimony can be recovered in the residues from the lead refining process, indeed, efforts are being made to recover antimony from secondary lead, e.g.:

- Antimonial drosses are used to produce antimonial lead.
- Efforts have also started to upgrade the process in order to produce pure Sb_2O_3 from these secondary lead residues.
- Residues with low antimony contents such as the slags and matte are less interesting when it comes to antimony recycling, but can have other applications.
- Lead refiners are highly interested in valorizing the valuable Sb containing waste streams both from an economic and environmental standpoint.

Schematic overview of secondary lead production from spent lead-acid (LA) batteries and the composition of the different process residues are shown in Fig. 4.

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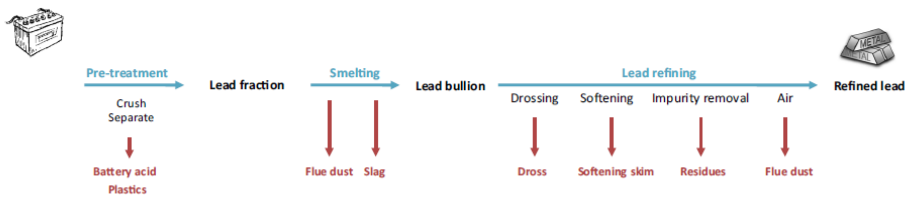

Residue	Sb	Pb	Cu	As	Fe	Ni	Zn	Ag	Sn	Bi
Slag [77]		2.8	0.1		37.1		11.2			
Harris dross [78]	8.2	67.0			0.8		0.7			
Speiss [7]	3.3	14.8	43.5	12.2	1.7	1.4	0.9	0.9	0.5	
Matte [80]	0.9	41.1	45.3	0.6	0.3	0.3	0.4			
Softening skim [7]	31.7	52.9		3.3						
Sb dust [76]	42.4	7.5	0.12	10.4						0.6
Slime [79]	63.6	12.6	1.47	4.0				1.1		3.3

Figure 4. Schematic overview of secondary lead production from spent lead-acid (LA) batteries (source: Dupont 2016).

As well as secondary production of antimony from the recycling of lead acid battery, the only antimony secondary resource recycled on a large scale, interesting future secondary sources could include industrial residues (e.g., mine tailings, process residues, manufacturing scrap) from the production of lead, copper and gold; and antimony containing end-of-life products such as plastics with antimony- containing flame retardants, antimony-containing glass, and phosphor powders from spent fluorescent lamps.

Dupont (2016) gives an overview of existing waste streams which could be of importance as secondary sources of antimony, including incineration ashes from concentrated fractions such as textiles or flame retardant plastics. Sufficient technologies are available to make antimony recycling a success and current recycling rates of approximately 20 % are expected to rise.

However, one of the remaining obstacles for the implementation of antimony recycling in the industry is the upscaling from laboratory methods to industrial processes.

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Recycling potential

Data on sales, imports and exports of lead-acid accumulators (27202100, 27202200) have been collected from PRODCOM list (NACE Rev. 2) - annual data.

Due to confidentiality reasons, some EU countries did not report individual data, however the figure for total EU28 production corresponding to 2016 has been extracted.

Based on the average weight of lead-acid accumulators (15kg), the content of lead alloy (25% w/w) and the average content of Sb in lead alloy (1.5% w/w), an estimation of the potential recyclable antimony from lead-acid batteries has been calculated (Table 7).

Table 7. The content (in kg) of lead alloy and the average content of antimony in lead alloy calculated from lead-acid accumulators.

EU 28 TOTAL, 2016							
PRODCOM code	Export (u)	Import (u)	Production (u)	Consumption (u)	Consumption (t)	Lead alloy (kg)	Antimony (kg)
27202100 - Lead-acid accumulators for starting piston engines	17.757.385	23.406.746	86.748.723	92.398.084	1.385.971	346.493	5.197
27202200 - Lead-acid accumulators, excluding for starting piston engines	16.164.524	103.300.630	23.367.074	110.503.180	1.657.548	414.387	6.216

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Antimony potentially recyclable from other industrial residues was not possible to estimate because waste categories reported statistically (e.g. Eurostat) classifies the residues by type but not for their particular content.

Case study

Lead battery recycling process is a consolidated technology which is supplied by different providers all over the world e.g. Gravita, Retriev, etc. (http://www.gravitatechnomech.com/Battery-Recycling/battery-recycling-plant.html). Regarding other waste streams which could be of importance as secondary sources of antimony, such as incineration ashes from concentrated fractions such as textiles or flame retardant plastics, sufficient technologies are available to make antimony recycling a success and current recycling rates of approximately 20 % are expected to rise.

However, further work needs to be carried out on pilot scale to see which methods are sufficiently robust and flexible. Economic feasibility studies and life cycle assessments need to be carried out to determine which techniques are the most promising for industrial upscaling.

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5. PREVIOUS/ONGOING CRM ADDRESSING PROJECTS

5.1. EU LEVEL

So, far several EU projects addressed the CRM issues at the various levels of details (see Table 8 and 9). The information available from their websites vary a lot. So far, the only digital data service on CRMs from mining waste is provided by the completed ProMine project, however, the data has not been updated since the project was finished. Some updated aggregated information was published in the Minerals Yearbook drafted during the Minerals4EU project. A new digital database platform about secondary CRM - First Urban Mine Knowledge Data Platform - is under construction through PROSUM project and is planned to be delivered in 2018, and hosted and operated by the Minerals4EUpermanent body. This new service will provide data and information on arisings, stocks, flows and treatment of waste electrical and electronic equipment (WEEE), end-of-life vehicles (ELVs) and batteries, as well as mining wastes.

However, as already mentioned in section 2.1, relevant projects addressing non mining CRM secondary sources such as ProSUM and MSP REFRAM show that basic information concerning the distribution of the use of CRM among the applications exists but there are still significant gaps concerning the information on CRM content in end-of-life waste.

Most of the projects listed in Table 9 are focused on the recovery of critical raw materials with the most added value, this is REEs, PGMs, gallium, tantalum etc. The most relevant for the overall scope of SCRREEN project are briefly described below.

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Table 8. EU projects (completed and on-going projects addressing the CRM from mineral-based waste).

Project	Full name	Status	Links	CRM relevance	Digital data platform
PROMINE	Nano-particle products from new mineral resources in Europé	closed project	http://promine.gtk.fi/	yes	yes
MINERALS4EU	Minerals Intelligence Network for Europé	closed project	http://www.minerals4eu.eu/, http://minerals4eu.brgm-rec.fr/	yes	yes (incomplete, not all countries represented)
EuroGeoSource	EuroGeoSource	closed project	http://www.eurogeosource.eu	possibly	not operational for the moment
EURARE	EURARE (Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits')	closed project	http://www.eurare.eu/	yes (though focused on primary resources)	Portal "IKMS"; map and data portal on primary REE) works, but data need quite some corrections and additions.
Min-Guide	Minerals Policy Guide	on-going	http://www.min-guide.eu/about/overview	yes	no
EGDI-Scope	European Geological Data Infrastructure	closed project	http://www.egdi-scope.eu/	yes	no

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Project	Full name	Status	Links	CRM relevance	Digital data platform
EGDI	European Geological Data Infrastructure	on-going	http://www.europe-geology.eu/	yes	yes
MINVENTORY	The Minventory metadata portal	closed project	http://www.minventory.eu/ https://ec.europa.eu/jrc/en/scientific-tool/minventory	possibly	no
MINEPEP	Establishing of a novel technology platform for bio-based mineral processing: Development of peptides as agents for the separation of rare earth minerals via bio-flotation	closed project	http://cordis.europa.eu/project/rcn/185962_en.html; https://www.hzdr.de/db/Cms?pNid=619	yes	no
ERA-MIN	ERA-NET Cofund on Raw Materials (ERA-MIN 2)	on-going	https://www.era-min.eu/	yes	no
MINATURA2020	Mineral Deposits of Public Importance	on-going	http://minatura2020.eu/	possibly	no

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Project	Full name	Status	Links	CRM relevance	Digital data platform
I2MINE	Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future	closed project	http://www.etpsmr.org/?post_projects=i2mine	possibly	no
PROSUM	ProSUM – Prospecting Secondary raw materials from the Urban Mine and Mining waste	closed project	http://www.prosumproject.eu/	yes	yes
MICA	Mineral Intelligence Capacity Analysis	on-going	http://www.mica-project.eu/	yes	yes (under construction)
METGrow+	Metal Recovery from Low Grade Ores and Wastes	on-going	http://metgrowplus.eu/	yes	no
MSP REFRAM	Multi-Stakeholder Platform for a Secure Supply of Refractory Metals	closed project	http://prometia.eu/msp-refram/	yes	no

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Project	Full name	Status	Links	CRM relevance	Digital data platform
Smart Ground	Smart data collection and intergration platform to enhance availability and accessibility of data and information in the EU territory on secondary raw materials.	on-going	http://www.smart-ground.eu/	yes	yes (under construction)

Table 9. A list of CRM EU projects addressing non mineral-based secondary resources.

Project	Full name	status	links	CRM relevance	digital data platform
ADIR	Next generation urban mining - Automated disassembly, separation and recovery of valuable materials from electronic equipment	on-going	http://www.adir.eu/	Yes (REE, tantalum, germanium, cobalt, palladium, gallium and tungsten)	no
AVAR	Added Value Alumina Refining	on-going?	https://eitrawmaterials.eu/project/avar/	Yes (Gallium, Vanadium)	no

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Project	Full name	status	links	CRM relevance	digital data platform
CloseWEEE	Integrated solutions for pre-processing electronic equipment, closing the loop of post-consumer high-grade plastics, and advanced recovery of critical raw materials antimony and graphite	on-going	http://closeweee.eu/	Yes (critical minerals and metals)	no
CYCLED	Cycling resources embedded in systems containing Light Emitting Diodes		http://www.cyc-led.eu/	Yes (Ga, In, REE (Ce, Eu, Lu, Y), Au, Ag, Sn)	no
ERECON	European Rare Earths Competency Network	closed project	https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/erecon_es	Yes (Rare Earth Metals)	no
HOPE-4-0	From iron and manganese oxides wastes to valuable metal alloys using novel carbon sources materials	on-going	https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/iron-and-manganese-oxides-wastes-valuable-metal-alloys-using-novel-carbon-sources-materials	Possibly	
MINERALS 4EU	Minerals Intelligence Network for Europe	closed project	http://www.minerals4eu.eu/,	yes	yes (incompl

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Project	Full name	status	links	CRM relevance	digital data platform
			http://minerals4eu.brgm-rec.fr/		ete, not all countries represented)
MSP REFRAM	Multi stakeholder platform for a secure supply of refractory metals	closed project	http://prometia.eu/msp-refram/	Yes (niobium, tungsten, tantalum)	no
NewEco	Towards a New European industrial ecosystem for strategic metals production	on-going	https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/towards-new-european-industrial-ecosystem-strategic-metals-production	Possibly	no
NEW_InnoNet	The Near-zero European Waste Innovation Network	Should be closed	http://www.newinnonet.eu/	Possibly	no
PLATIRUS	PLATInum group metals Recovery Using Secondary raw materials	on-going	http://www.platirus.eu/	yes (Platinum Group Metals)	no
PROSUM	ProSUM – Prospecting Secondary raw materials from the Urban Mine and Mining waste	on-going	http://www.prosumproject.eu/	yes	yes (not ready, in prep)

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Project	Full name	status	links	CRM relevance	digital data platform
RECLAIM	Reclamation from secondary resources (photovoltaics, solid-state lighting and electronic waste)	closed project	http://www.re-claim.eu/	Yes (indium, gallium, yttrium and europium)	no
RECYVAL-NANO	Development of recovery processes for recycling of valuable components from FPDs (In, Y, Nd) for the production of high added value NPs	closed project	http://www.recyval-nano.eu/	Yes (indium, ytrium and neodinium)	no
REE Value Chain	Rare Earth Supply Chain and Industrial Ecosystem: A Material Flow Assessment of European Union	on-going	https://www.universiteitleiden.nl/onderzoek/onderzoeksprojecten/wiskunde-en-natuurwetenschappen/cmlrare-earth-supply-chain-and-industrial-ecosystem-a-material-flow-assessment-of-european-union	yes (REEs)	no
REE4EU	Integrated high temperature electrolysis (HTE) and Ion Liquid Extraction (ILE) for a strong and independent European	on-going	http://www.ree4eu.eu/	yes (REEs)	no

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Project	Full name	status	links	CRM relevance	digital data platform
	Rare Earth Elements Supply Chain				
REECOVER	Recovery of Rare Earth Elements from magnetic waste in the WEEE recycling industry and tailings from the iron ore industry	closed project	http://www.reecover.eu/	yes (Rare Earth Elements Y, Nd, Tb and Dy)	no
REE-CYCLE	Rare Earth Element reCYCLing with Low harmful Emissions	closed project	https://reecycle-erc.blogspot.com.es/p/about.html	yes (REEs)	no
REMAGHIC	New Recovery Processes to produce Rare Earth - Magnesium Alloys of High Performance and Low Cost	on-going	http://www.remaghic-project.eu/	yes (REEs)	no
ResCoM	Resource Conservative Manufacturing - transforming waste into high value resource through closed-loop product systems	on-going	http://www.rescoms.eu/	possibly	yes (not public)
RIGaT	Recovery of indium, germanium and tin from lead bearing alloys	?	https://eitrawmaterials.eu/project/rigat/	Yes (indium, germanium)	no

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Project	Full name	status	links	CRM relevance	digital data platform
	generated in zinc refinement for direct implementation in industrial practice				
Smart Ground	Smart Data Collection and integration platform to enhance availability and accessability of data and information in the EU territory on secondary raw materials	on-going	http://www.smart-ground.eu/index.php?ln=en	possibly	yes (available March 2018)

5.1.1. PROMINE (COMPLETED)

http://promine.gtk.fi/; http://ptrarc.gtk.fi/ProMine/default.aspx

The purpose of the ProMine project (2009-2013) was to enhance overall production chain of minerals and metals in Europe. A major objective of the ProMine was to stimulate the extractive industry to deliver new products to manufacturing industry. ProMine produced a pan-European GIS based resources and modelling system for all potential metallic and non-metallic mineral resources (known and predicted) within the EU. The project produced INSPIRE compliant data, a geospatial data portal, web map services, a web feature service and reports. ProMine geospatial data portal with the map viewer provides point data with the description of the CRM concentrations in various types of materials including mining waste, smelter waste, surface storage etc. (data from the PROMINE portal is also accessible via EGDI portal) (Fig. 5).
The ProMine delivered a database containing the known and predicted metalliferous and non-metalliferous resources, which together define the strategic reserves (including

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secondary resources and CRMs) of the EU. Among other tasks, the authors tried to calculate the volumes of potentially strategic metals (e.g. cobalt, niobium, vanadium, antimony, platinum group elements and REE) and minerals that are currently not extracted in Europe. As a matter of fact**,** it was the first ever delivery of the occurrences of Critical Raw Minerals in Europe, at the request of the Commission, thus demonstrating the usefulness of a European wide mineral resource assessment. The ProMine investigated geological mineral resource potential modelling across Europe, where some of the CRMs were included, e.g. new strategic and 'green‘ commodities such as Ga, Ge, In, Li, Nb, Ti, Ta, PGE and REE. Assessment of secondary minerals and resources in combination with metalliferous ores, assessment of valuable mining and metallurgical residues were some of the tasks.

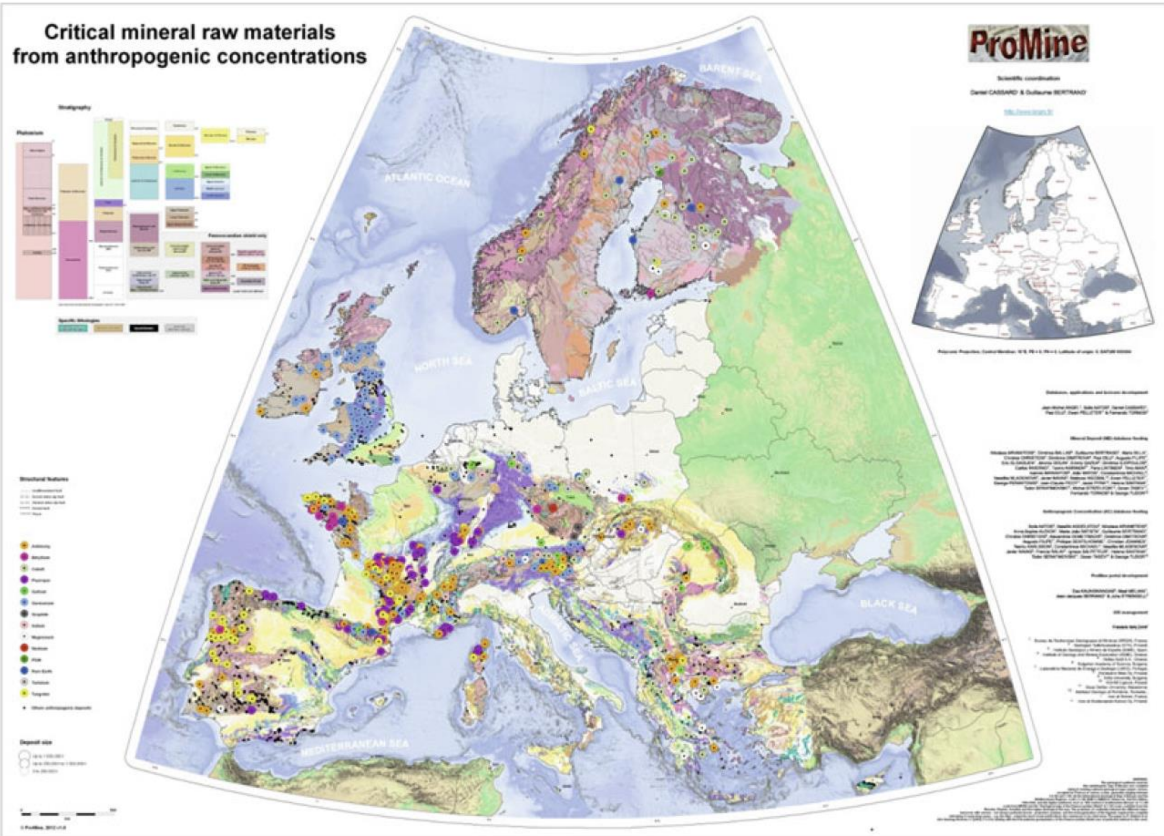

Figure 5. Geological map of Europe showing CRM occurences hosted by anthropogenic concentrations (ProMine).

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Additionally, the ProMine promoted some concepts for (bio)hydrometallurgy technologies on European resources, e.g. to optimize the recovery of metals by developing innovative routes for treatment of wastes and secondary resources (tailings, contaminated process water).

The ProMine Anthropogenic Database (AC) stores all the information on anthropogenic concentrations related to the mining and metallurgical industries such as mine wastes and unprocessed products (e.g. run-of-mine ore, unprocessed ore stockpiles, mine waste dumps, barren overburden), ore processing wastes (e.g. cobbing wastes, wash tailings, flotation tailings, leach residues, magnetic-separation tailings) and treatment wastes (e.g. smelter wastes, flue dusts, roasting residues, chemical treatment wastes, leach tailings, ashes, cocking plant residues, etc.)

The ProMine project focused on the largest anthropogenic concentrations and on those of greatest interest in terms of volume/tonnage and content (i.e. possible presence of critical commodities). The aim was to have an inventory, as complete as possible, of concentrations which could be processed for the recovery of strategic/high-tech/critical commodities, and to avoid overlap between the ProMine project and the work done by the member states under the Mining Wastes Directive (MWD). The ProMine approach targeted those sites with the greatest potential for the recovery of strategic commodities, with emphasis on establishing links with the primary concentration(s). It was beyond the scope of ProMine to compile a comprehensive inventory of wastes throughout Europe. Such a very detailed and systematic inventory was done by Member States in the frame of the Mining Wastes Directives (notably, the directives 2006/21/EC http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0021 and 2008/98/EC, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098). This inventory, though, was more focused on environmental impact than on the characterization of secondary resources and, as such, does not overlap with the work done in the ProMine.

The definition of the size of wastes (surface occupied, volume or tonnage) and the grade of the contained commodities was a common problem. In many cases, it was impossible to fill these fields in the AC database because of the lack of data. As a result the information

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collected in the ProMine AC database is essentially qualitative, rather than quantitative, and does not permit the calculation of aggregated resource potential or its spatial distribution. On the other hand, the inventory compiled for the Mining Wastes directive brought useful data on volume and tonnage of wastes in European countries. Despite the data shortcomings, the aggregated potential from a limited number of sites for critical commodities has been calculated and is presented in Table 10. It is important to stress that these values are indicative and provide minimum estimates of the potential tonnages available in selected European wastes. It should also be noted that these estimates are much lower than those calculated as potentially available from primary resources.

Table 10. CRM statistics and related resource estimates from anthropogenic concentrations (ProMine).

Commodity	Total no. of sites	Number of sites with calculated potential	∑ potential (t)
Be	36	9	41
Co	131	62	39.656
Ga	59	28	8.82
Ge	157	18	408
In	36	7	4.273
Mg	42	27	17,147,091
Nb	18	8	379
Pt	5	1	0.6
REE	13	5	13.755
Sb	198	37	78.299
W	124	23	15.137

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The example of CRM from mining waste in Greece

CRM data and metadata information of 127 mining sites from all over the country were provided to the ProMine anthropogenic database. Totally 173 wastes from 18 different types were studied and assessed with respect to their CRM exploration potential and exploitation feasibility (Table 11). Based on the information collected and the evaluation approach undertaken, a map of mining waste deposits in Greece was created and delivered using the ProMine classification in relation to potential concentrations of CRM commodities (Fig. 6).

Table 11. Classification and related statistics of mining wastes in Greece.

TYPE OF WASTE	NUMBER
"Red muds" from bauxite processing (Bayer)	2
Barren overburden	12
Cobbing waste	1
Flotation tailings	15
Flue dust (pyrometallurgical, electrochemical processes)	1
Magnetic-separation tailings (heavy minerals from glass sand)	2
Matte (intermediate product)	3
Mine products and waste	10
Mine waste dump	57
Ore processing wastes	8
Ore stockpiles unprocessed	5
Refining plant tailings	1
Roasting residues (pyrometallurgy)	2
Run-of-mine ore	8
Slag	38
Smelter waste	1
Treatment waste (metallurgical residues & slags, etc.)	2
Wash tailings	5
Total	173

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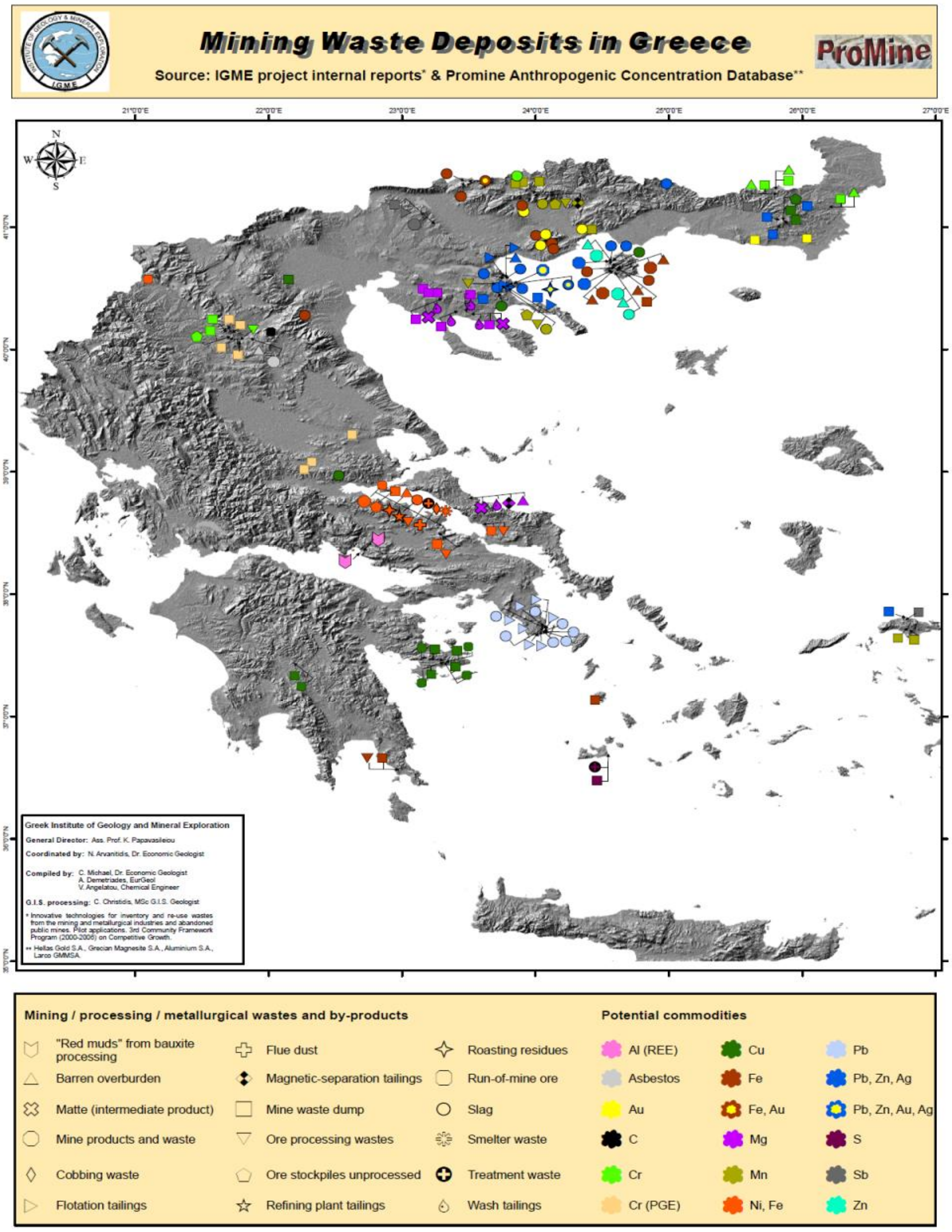

Figure 6. Map showing the types of mining wastes and expected concentrations of potential metal commodities.

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5.1.2. MINERALS4EU (COMPLETED)

http://www.minerals4eu.eu/

The Minerals4EU project was designed to meet the recommendations of the Raw Materials Initiative and tried to develop an EU Mineral intelligence network structure in a form of a web portal, a European Minerals Yearbook and foresight studies. The Minerals4EU project was built around an INSPIRE compatible infrastructure that enables EU geological surveys and other partners to share mineral information and knowledge, and stakeholders to find, view and acquire standardized and harmonized georesource and related data.

The main task of the project was to provide a minerals information and intelligence provision service, incorporating links to existing projects, relevant databases and auxiliary datasets of Geological Surveys and other relevant institutions consisting of mineral data from primary and secondary resources on land and the sea-floor.

Information about mines, mining activity and mining wastes are stored in a structured manner in the M4EU relational database which is based on the INSPIRE Mineral Resources core for the characterisation of mining wastes, mines and mining activities. The present version of the Mining Waste table in the M4EU/INSPIRE database only stores and provides information about the amount, grade and density of waste material. It does not include data on the presence of CRMs and consequently on the CRM amounts. This was the task of the recently finished PROSUM project. The availability of data relating to secondary raw materials was known to be an issue at the commencement of the project. However, data relating to waste generation, treatment and trade flows have been brought together and presented in the Yearbook, alongside the data for primary minerals for the first time. The resolution of the presented data is, unfortunately, not comparable to the statistics for primary minerals because the existing statistical classification systems report data by category not individual commodity.

The classification of mining waste is based on several categories, e.g.: wastes from mineral excavation, waste from mineral metalliferous excavation, waste from mineral non-

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metalliferous excavation, wastes from mineral dressing, wastes from the dressing of metalliferous minerals, cobbing waste, magnetic-separation tailings, wash tailings, flotation tailings, leach residues, wastes from the dressing on non-metalliferous minerals, dusty and powdery waste, red mud from alumina production, sludge, mud and chemical liquid products, waste gravel and crushed rocks, waste sand and clays, waste from washing and cleaning of minerals, drilling muds and other drilling wastes. The Table 12 shows the mineral-based waste categories used in the project.

Table 12. Mineral-based waste categories according to the European Waste Classification for statistical purposes (EWC-Stat).

C & D waste	concrete, bricks, ceramic tiles, track ballast, road surfacing waste
Metallic waste ferrous	mill scales, discarded moulds, filings and turnings, ferrous metal, iron and steel
Metallic waste non-ferrous	aluminium, copper, brass, bronze, zinc, tin, lead and other non-ferrous waste
Metallic waste mixed	metallic packaging, mixed metallic wastes
Other mineral waste	waste with asbestos, waste of naturally occurring minerals, artificial mineral waste, waste refractory materials
Combustion waste	flue gas purification waste, slags and ashes
Dredging spoil	dredging spoil (hazardous and non-hazardous)

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Mineral waste from waste treatment and stabilised waste	waste treatment waste (i.e. ashes), solidified or stabilised waste, vitrified waste
Discarded vehicles	end-of life vehicles
Discarded equipment	discarded electrical and electronic equipment, other discarded machines and equipment components
Batteries and accumulators	alkaline batteries, lead batteries, Ni-Cd batteries, mercury containing batteries, other batteries and accumulators
Glass waste	glass packaging waste, other glass waste

Minerals Yearbook

The Yearbook is the most comprehensive compilation of publically-available European minerals information. Almost all CRMs are listed in the Yearbook if searched after Commodity for primary minerals. However, when the Category for waste flows is chosen, no detailed information about CRM can be found other than general statistics for produced metal waste (total and from Mining and quarrying), ferrous and non-ferrous one. This information is based on the Eurostat waste statistics for 34 out of 40 countries included in this study. The geographical coverage of data on waste generation and treatment has improved considerably over the years. All EU Members States report data on waste generation and treatment and they are publicly available through Eurostat.

More useful information about CRM primary sources and waste flows can be deduced when separate countries are searched. The following categories can be seen: production import, export, resource, reserve, exploration and waste flow. Mining waste is not described here as

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separate category. Indirect information about possibility of CRM production from mining waste can be deducted from the primary production and resources (+reserves).

Map viewer

http://minerals4eu.brgm-rec.fr/minerals4EU/

This map viewer provides similar information as the Minerals Yearbook. Mining waste is not described here as separate category. However, primary mineral occurrences are shown on the map and indirect information about possibility of CRM production from mining waste can be deducted from the primary production of major ore.

Unfortunately, the location of historical and active mines is incomplete and not all European countries can be viewed. The mine locations are provided for: Finland, Denmark (Greenland), Slovakia, Hungary, Slovenia, Belgium, The Netherlands, Switzerland, France, Spain, Portugal, Ireland, Cyprus. Mineral occurrences for CRM are listed in the viewer separately, but the location of them is incomplete and can be seen only for: Sweden, Norway, Finland, Greece, Cyprus, Ireland, Portugal, France, Denmark (Greenland), Switzerland. In case of overlapping mine (for primary ore) and CRM mineralisation locations (often accompanied by other primary mineralisation), deduction of possibility of CRM mining can be done. Unfortunately, some point markings seem to be not active to access additional information about the site.

Minerals Knowledge Data Platform

The EU-MKDP (Minerals Knowledge Data Platform) is supposed to provide a simplified and user-friendly access to all available and new data related to mineral resources from national geological surveys, scientific institutes and universities, relevant industries and professional organizations, as well as from former European projects such as ProMine (information on both mineral deposits and anthropogenic concentrations resulting from mining and downstream activities) and EuroGeoSource (information on energy and mineral resources, extraction locations, production, reserves). The system is also designed to accommodate and

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manage semi- and non-structured data (e.g., syntheses and statistics in the form of graph charts, time-series related to exploration and primary reserves and resources, secondary resources, exploitation technologies including ore beneficiation, extraction technologies, end product development and waste management practices, European market survey and raw material demand). These data, semantically harmonized using common terminology are delivered through INSPIRE/OGC compliant web services. New data and information delivered during the project by other work packages (statistics analyses, analyses of supply and demand in the EU, stocks, flows, including trends in what products are put on the market and their composition, analyses of the composition of waste products and wastes arising from pre-processing and their geographic location in EU) in various formats will be accessible through the portal.

The access of direct information about the CRM is not possible at the moment. Indirect and partial information can be accessed from the case studies and from a selection of saved publications.

5.1.3. EUROGEOSOURCE (COMPLETED)

http://www.eurogeosource.eu/

EuroGeoSource is supposed to be a data portal, which allows Internet access to the aggregated geographical information on geo-energy (oil, gas, coal etc.) and mineral resources (metallic and non-metallic minerals, industrial minerals and construction materials: gravel, sand, ornamental stone etc.). The information is coming from a wide range of sources for 12 European countries: Poland, Denmark, Estonia, Belgium, the Netherland, Italy, Slovenia, Hungary, Romania, Bulgaria, Portugal and Spain.

The aim of the project was to provide information on oil and gas fields, including prospects and mineral deposits, in order to stimulate investment in new prospects for geo-energy

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resources, as well as in renewing production at mines undergoing economic decline or closure, contributing this way to the independence of the EU having to import valuable minerals from outside resources.

5.1.4. EURARE (COMPLETED)

http://www.eurare.eu/

EURARE is a project, funded within the FP7 framework by the European Commission, for the 'Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits'. EURARE is thus entirely focused on the so-called rare earth elements (REE), this particular group of metals considered very critical for the present and future industry, and for which Europe is wholly dependent on imports. The main goal of the EURARE project is to set the basis for the development of a European REE industry that will safeguard the uninterrupted supply of REE raw materials and products crucial for the EU economy industrial sectors, such as automotive, electronics, machinery and chemicals, in a sustainable, economically viable and environmentally friendly way.

A task of the EURARE project is to develop an “Integrated Knowledge Management System” (IKMS; Fig. 7) that will give access to all available data related to mineral resources containing rare earth elements. As described by Cassard et al. (2014), it is developed as a data management system, based on high-level interoperability standards, which has integrated advances made in several former EU-FP7 projects such as OneGeology-Europe, ProMine and EuroGeoSource, ongoing projects like Minerals4EU in terms of database structure, harvesting systems, web services, metadata management, and integration of nonstructured information, and InGeoCloudS project in terms of cloud computing. Through this system EURARE will contribute to implement the standards of a European geoscientific data infrastructure defined in the EU-FP7 EGDI-Scope project. This IKMS can be accessed through the portal at http://eurare.brgm-rec.fr/. Thus, the role of the IKMS is to provide end-users with a seamless access to the whole value chain from REE deposit exploration,

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mining and extraction of ore, beneficiation and extraction technologies to treatment of end-of-life products and the generation of "new" materials, with the ability to combine all spatial and non-spatial pertinent information in a single reference system.

Figure 7. The EURARE project, its partners, and components.

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This project includes the whole chain, from rare earth element resources and their classification and distribution, via mining and beneficiation, extraction and separation, to regulation and regulatory frameworks in relation to the REEs. At the most fundamental level are the REE resources the most basic component of an intra-European supply chain. These have been outlined through mapping, characterization and technological and economic evaluation.

The focus of resource studies within EURARE has been on primary, geological occurrences, a task that has been performed primarily by the national geological surveys involved (Britain, Denmark-Greenland, Finland, France, Greece, Norway and Sweden). Thus, direct information about secondary resources was not part of the EURARE project, but the collection and database management (the IKMS; see above) of information on primary deposits which contain quite many occurrences, deposits and mineralisations that have been mined over time, and hence also important information regarding potential sites with secondary (mining waste) resources.

5.1.5. MIN-GUIDE (ON-GOING)

http://www.min-guide.eu/

The MIN-GUIDE project addresses the need for a secure and sustainable supply of minerals in Europe by developing a ‘Minerals Policy Guide’. To secure minerals supply in Europe, we would need a policy framework promoting innovative and sustainable approaches to tackle challenges in the mining value chain. An online knowledge repository-based Mineral Policy Guide has been developed seeking to achieve greater transparency of European and national minerals policies and outline the innovation potential of those policies and to highlight good practice examples along the whole chain of mining activities. This online knowledge repository is based on up-to-date and comparable information on minerals policy and related policy areas at EU level and in the 28 EU Member States.

Generally speaking the MIN-GUIDE project delivers :

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- Deeper understanding on good practice policies and practical experiences for policy implementation and transferability.
- Increased policy knowledge and understanding of policy impacts on innovation.
- Insights into the projects results on policies in all EU Member States that foster innovation in exploration, mining, processing and waste management.
- Training and guidance (online and onsite) to use the Minerals Policy Guide in professional environment.
- Knowledge exchange that supports networking and mutual learning among different stakeholders.
- Targeted and wide-spread dissemination and promotion of latest scientific results on minerals policy issues and industrial innovation.

5.1.6. EGDI-SCOPE (COMPLETED)

http://www.egdi-scope.eu/

The objective of the EGDI-Scope project is to deliver an implementation plan for the concrete realization of a pan-European Geological Data Infrastructure (EGDI). This Infrastructure should enable European geological surveys to serve and maintain INSPIRE-compliant, interoperable geological data and information reflecting our understanding of the subsurface. Another important objective is to create a framework to sustain results from past, on-going and future European projects (e.g. OneGeology Europe, EuroGeoSource, PanGeo, eMODNet, etc.).
Inventory includes detailed analysis of the data available (type, format), how it was created, and portals currently in use to access the data. The necessary development needed in order to make the data interoperable and suitable for EGDI.
An inventory of 80 previous and current European geological projects has been compiled (see EGDI-Scope D 3.1: Detailed Review of previous and ongoing projects; K A Lee, R W Armstrong, December 2012). Of these, 27 (34%) are classed as Natural Risk/Geohazard, 11 (14%) are developing Data Infrastructures, 10 (12%) and 7 (10%) are Economic resources/Energy and Geochemistry respectively.

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It seems that WP3 was responsible for preparation of the list of data which should be developed where mining hazard potential and mineral resources are included. However, for now it is not possible to find out whether CRM are practically part of it as a separate category.

5.1.7. PAN-EUROPEAN GEOLOGICAL DATA INFRASTRUCTURE (EGDI) (ON-GOING)

http://www.europe-geology.eu/

EGDI is EuroGeoSurveys' European Geological Data Infrastructure. It provides access to Pan-European and national geological datasets and services from the Geological Survey Organizations of Europe.

EGDI features:

- Central database systems for storing pan-European geological datasets
- Mechanisms for populating these databases with data from National Geological Survey Organisations (NGSOs)
- A metadatabase containing a large amount of information about pan-European, national and cross border geological datasets
- A website including a GIS enabling the user to find and show data related to a number of topics, search for all datasets avaiable, combine data from different topics, show metadata, etc.

EGDI gives access to datasets and services from a number of pan-European data harmonisation and infrastructure projects, either entirely funded by EGS members or co-funded by the EU, including OneGeology-Europe (geological mapping), EuroGeoSource (energy and minerals), ProMine (minerals), PanGeo (Earth Observation and geohazards), TerraFirma (Earth Observation and geohazards), GeoMind (geophysics), GEMAS (soils and geochemistry) and EMODNet (seabed mapping). For this first version of EGDI a new digital

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geological map of Europe, developed according to the EC INSPIRE Directive specifications, has been prepared to replace the previous OneGeology-Europe map.

CRMs can be viewed as:

- Presented in the ProMine database, some CRMs are listed as associated mineralisations and possibly have potential to be extracted from mining waste in case the mine is or was in operation.
- Under category ''Anthropogenic concentrations'' from ProMine database the following CRMs can be viewed (CRMs in bold): Precious Metals (gold, silver, platinoids), Iron and ferro-alloy metals (iron, chrome, manganese, vanadium, wolfram, molybdenum, nickel, cobalt, niobium), Speciality and rare metals (lithium, beryllium, tantalum, rare earth elements, cesium, rubidium, scandium, zirconium and hafnium, germanium, gallium, indium, cadmium, selenium and rhenium, bismuth, tellurium and mercury, antimony, titanium), Energy commodities (uranium and thorium, coal, lignite and peat, bituminous rocks, petroleum and gas, geothermal energy), and Critical mineral raw materials as a separate category.
- Some of the CRMs are plotted on the ProMine map viewer with information about the waste and storage types, e.g for Be, Co, Sc, Ga, Ge, W, In and REE, etc. So far this is the second best place online with secondary CRMs after a primary ProMine website.
- CRMS are part of the Minerals4EU data platform, but only primary CRMs can be viewed e.g. prospects, commodities, deposits etc.

5.1.8. MINVENTORY (COMPLETED)

http://www.minventory.eu/
https://ec.europa.eu/jrc/en/scientific-tool/minventory

The Minventory metadata portal which contains general statistical data and their characteristics for primary raw materials, mining waste, landfill stocks and waste. It covers the EU28 and a number of neighbouring countries. The project provides information on the

Competent Authorities responsible for collecting and publishing sets of data on mining waste (https://ec.europa.eu/assets/jrc/minventory/mining-waste-liste.html).

Material stocks are analysed and described not only by statistics. The portal provides links to other related initiatives and portals which cover these complementary aspects.

The aim of this project was to assess the possibility of implementing a pan-European statistical database on mineral resources and reserves in raw materials deposits. As such, it had three main objectives:
• to create a comprehensive directory of where information may be located within the EU28 (and neighbouring) countries;
• to build a web-site so that users may access this listing and find resource data more quickly and easily;
• to develop an action plan for harmonisation of European mineral resources data where this is useful and feasible up to 2020.

There is general information about treatment of mining waste in EU countries but no separate information about CRM from these sources. Minventory is producing a metadata portal with export functions (MS Excel tables) but no web services.

5.1.9. MINEPEP (COMPLETED)

https://www.hzdr.de/db/Cms?pNid=619
http://cordis.europa.eu/project/rcn/185962_en.html

Full name of the project is 'Establishing of a novel technology platform for bio-based mineral processing: Development of peptides as agents for the separation of rare earth minerals via bio-flotation'.

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The MinePep project was addressing the development of an innovative, clean process for the recovery of raw materials (REEs) from primary and secondary sources.

MinePep target the development and application of specific peptides that can be used as agents in flotation processes. The focus was on the recovery of rare earth elements (REEs) from electronic scrap.

5.1.10. ERA-MIN (ON-GOING)

https://www.era-min.eu/node/3

ERA-NET Cofund on Raw Materials (ERA-MIN 2) is public-public partnerships funded under Horizon 2020. ERA-MIN 2 aims to implement a European-wide coordination of research and innovation programmes on raw materials to strengthen the industry, competitiveness and the shift to a circular economy. In order to secure a sustainable and responsible supply of raw materials to the economy and industry, the current ERA-MIN Joint Call 2017 addresses three segments of the non-energy, non-agricultural raw materials: Metallic, Construction, and Industrial minerals.

The call topics of the ERA-MIN Joint Call 2017 are based on challenges and priorities identified in the ERA-MIN Research Agenda. They are in line with the integrated strategy proposed in the EU Raw Materials Initiative, the Strategic Implementation Plan of the European Innovation Partnership on Raw Materials, as well as with the national and regional priorities. ERA-MIN 2 is supporting the EU's transition to a Circular Economy by addressing topics which are aiming at retaining the value of the raw materials we use in products and returning them into the product cycle at the end of their use, keeping in mind the need for a sustainable and responsible industrial supply of primary resources to feed the circular economy.

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The main thematic areas which are potentially relevant for CRM are:

- Supply of raw materials from exploration and mining
- Design
- Processing, Production and Remanufacturing
- Recycling of End-of-Life Products
- Cross-cutting topics:
- New business models,
- Improvement of methods or data for environmental impact assessment,
- Social acceptance and trust/public perception of raw materials.

So far, ERA-MIN funded several projects which deal with secondary mineral resources and CRMs, within topic areas such as Recycling of mining and smelting residues (including historical dumps and tailings), and extraction, minerals processing, mine closure and rehabilitation e.g.:

AMDREY: Extraction of Earth Elements from Acid Mine Drainage

ENVIREE: ENVIronmentally friendly and efficient methods for extraction of Rare Earth Elements from secondary sources

EXTRAVAN: Innovative extraction and management of vanadium from high vanadium iron concentrate and steel slags

NewOres: Development of New models for the genesis of Rare Metal (W, Nb, Ta, Li) Ore deposits from the European Variscan Belt and valorization of low grade and fine grained ore and mine tailings

RAREASH: Assessment of Possible Recycling Directions of Heavy & Rare Metals Discovered from Combustion Waste Products

REMinE: Improve Resource Efficiency and Minimize Environmental Footprint

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5.1.11. MINATURA2020 (ON-GOING)

http://minatura2020.eu/

The project develops a concept for a European minerals deposit framework, funded within the European Commission's Horizon 2020 Programme. The overall objective of this project is to develop a concept and methodology for the definition and subsequent protection of "Mineral Deposits of Public Importance" (MDoPI) in order to ensure their best use in the future with a view to being included in a harmonised European regulatory, guidance or policy framework. The society needs must be met to ensure effective exploration and exploitation of mineral deposits, without compromising the needs of current or future generations. The potential of exploitable mineral deposits (including abandoned and historic mining sites) needs to be evaluated specifically and in relation to other land use and environmental objectives.

The main objectives of the project are development of the concept behind "mineral deposits of public importance". Development of an appropriate mapping framework based on detailed qualifying conditions for classifying "mineral deposits of public importance" must be in agreement with the definition of "deposits of special interest by and importance for" the EU Member States, regional or local administration, criticality of minerals (as assessed by the Raw Materials Initiative (RMI) and subject to protection for cultural/historical/Heritage, etc.

Although, the focus of the project is on primary mineral resources, there is a possibility that secondary sources from mining waste can be discussed in this project in the context of the future mining and the land-use issues.

''Accordingly exploitable mineral deposits (known deposits, abandoned mines and historical mining sites) need to be assessed against other land uses, taking into account criteria such as habitats, other environmental concerns, priorities for settlements, etc. Access to mineral deposits, on the other hand, also meets public interests such as raw materials security.''

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5.1.12. I2MINE (COMPLETED)

http://www.etpsmr.org/?post_projects=i2mine

The I^{2}Mine (Innovative Technologies and Concepts for the Intelligent Deep Mine of the Future) project carried out a number of activities designed to realise the concept of an invisible, zero-impact mine. It will concentrate on the development of technologies suitable for deep mining activities. The I^{2}Mine project tried to develop the innovative methods, technologies, machines and equipment necessary for the efficient exploitation of minerals and disposal of waste, all of which will be carried out underground. This should dramatically reduce the volume of surface transportation of both ore and waste, minimising the above ground installations and reducing the environmental impact. Mining processes that decrease the volume of waste rock would reduce cost both based on volume but also for long-term maintenance. The authors stated that the challenges for the minerals extractive industry are so large that comprehensive international cooperation is needed in order to succeed. In this sense, the project might be relevant for secondary CRMs extraction which is friendly with the environment and accepted by the local societies.

5.1.13. PROSUM (COMPLETED)

http://www.prosumproject.eu

The ProSUM project is establishing a European network of expertise on secondary sources of critical raw materials (CRMs), vital to today's high-tech society. ProSUM directly supports the European Innovation Partnership (EIP) on Raw Materials and its Strategic Implementation

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Plan calling for the creation of a European raw materials knowledge base. The aim of the ProSUM project was to provide a state of the art knowledge base, using best available data in a harmonised and updateable format, which allows the recycling industry and policymakers to make more informed investment and policy decisions to increase the supply and recycling of secondary raw materials. The ProSUM project has created an inventory for waste streams with a high potential to serve as a source of secondary raw materials (Huisman et al. 2017).

Data on primary and secondary raw materials are available in Europe, but scattered amongst a variety of institutions including government agencies, universities, non-governmental organisations and industry. By establishing an EU Information Network (EUIN), the project coordinates efforts to collect secondary CRM data and collate maps of stocks and flows for materials and products of the "urban mine". Relevant sources for secondary CRMs are electrical and electronic equipment, vehicles, batteries and mining tailings. The project is constructing a comprehensive inventory identifying, quantifying and mapping CRM stocks and flows at national and regional levels across Europe. The availability of primary and secondary raw materials data, easily accessible in one platform, will provide the foundation for improving Europe's position on raw material supply, with the ability to accommodate more wastes and resources in future. Standardised classification methods are needed to bring together dispersed information on mining wastes from several countries into a common database and to compare the metal and mineral potential of mining wastes with the urban mine.

Via a user-friendly, open-access Urban Mine Platform (UMP, http://www.urbanmineplatform.eu/homepage), the results are communicated online combining them at the same time with primary raw materials data via the existing EU Minerals Knowledge Data Platform (generated by Minerals4EU). To maintain and expand the UMP in the future, the ProSUM provides update protocols, standards and recommendations for additional statistics and improved reporting on CRM's in waste flows required.

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Mining wastes

Part of the PROSUM project was to collect data on amount and composition of stocks of mining waste (called mineral-based wastes in the present report D3.2) and to create a dataset from which deposits with high levels of CRM could be identified. In the ProSUM project, mining waste is divided into two groups: the mining waste generated at the mine during the mining activity, commonly described as waste rock, and the waste generated by the processing of ore at a concentrator, dressing plant or similar in the form of tailings or sludge. Location- wise the waste rock is reported together with the mine whose location is given in Minerals4EU database. These data, which also contain other information about the mining waste such as location, type of waste and origin, will be stored in an extension of the database for primary raw materials, the Minerals4EU database. This database, accessible via http://minerals4eu.brgm-rec.fr, makes up an important part of the European Minerals Knowledge Data Platform (MKDP).

In mining countries, the mining wastes constitute the largest part of society's total waste flow and make up the largest waste stocks but also in countries with historic mining, the mining waste stocks can be significant. The metal grade of mining wastes is low in comparison with some products in the urban mine.

The status of knowledge on mining waste with special reference to critical raw material in each of the participating countries (mostly geological surveys) is summarized in the table below (Table 13). It is obvious that few countries (green) have any quality and quantity data on the three waste types defined.

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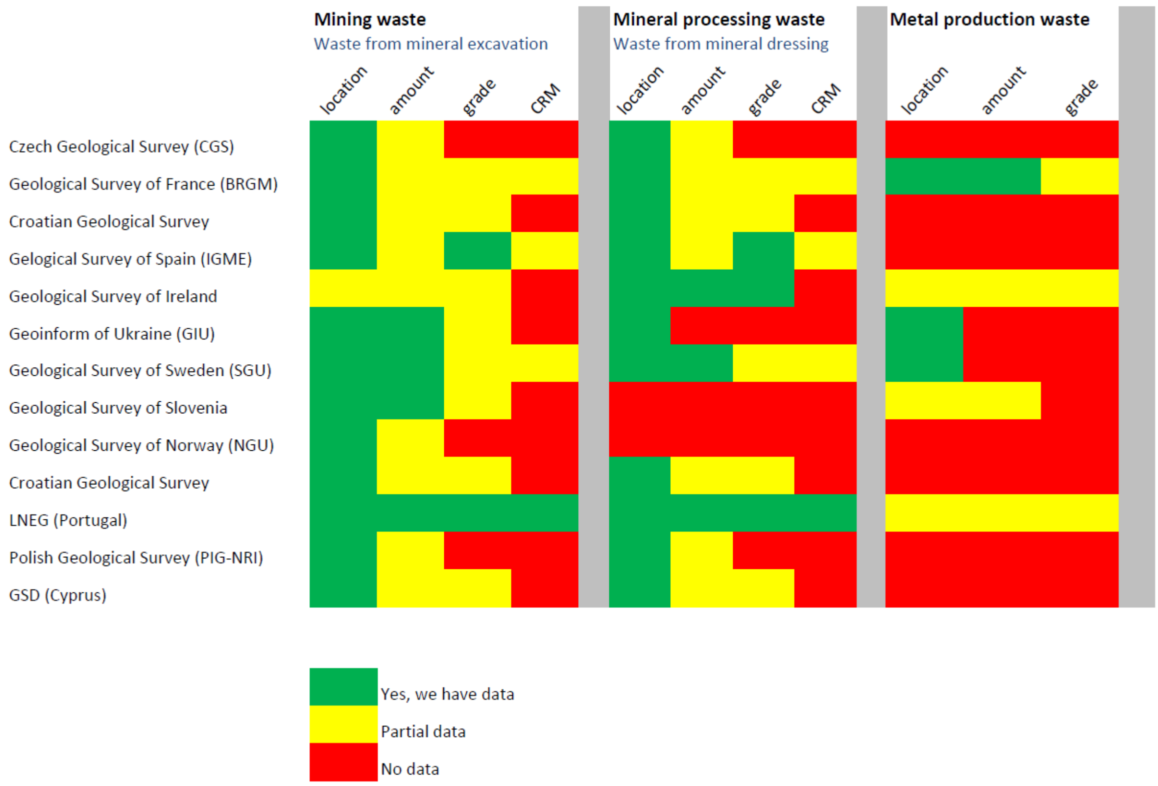
Table 13. Current state of resource and compositional data on CRM in mining, mineral processing and production wastes among some EU member states.



Selected flows and deposits for mining wastes

Every mining, quarrying and mineral processing operation generates mining waste. Figure 8 shows the location of more than 1600 mines for which the amounts of waste rock have been roughly calculated.

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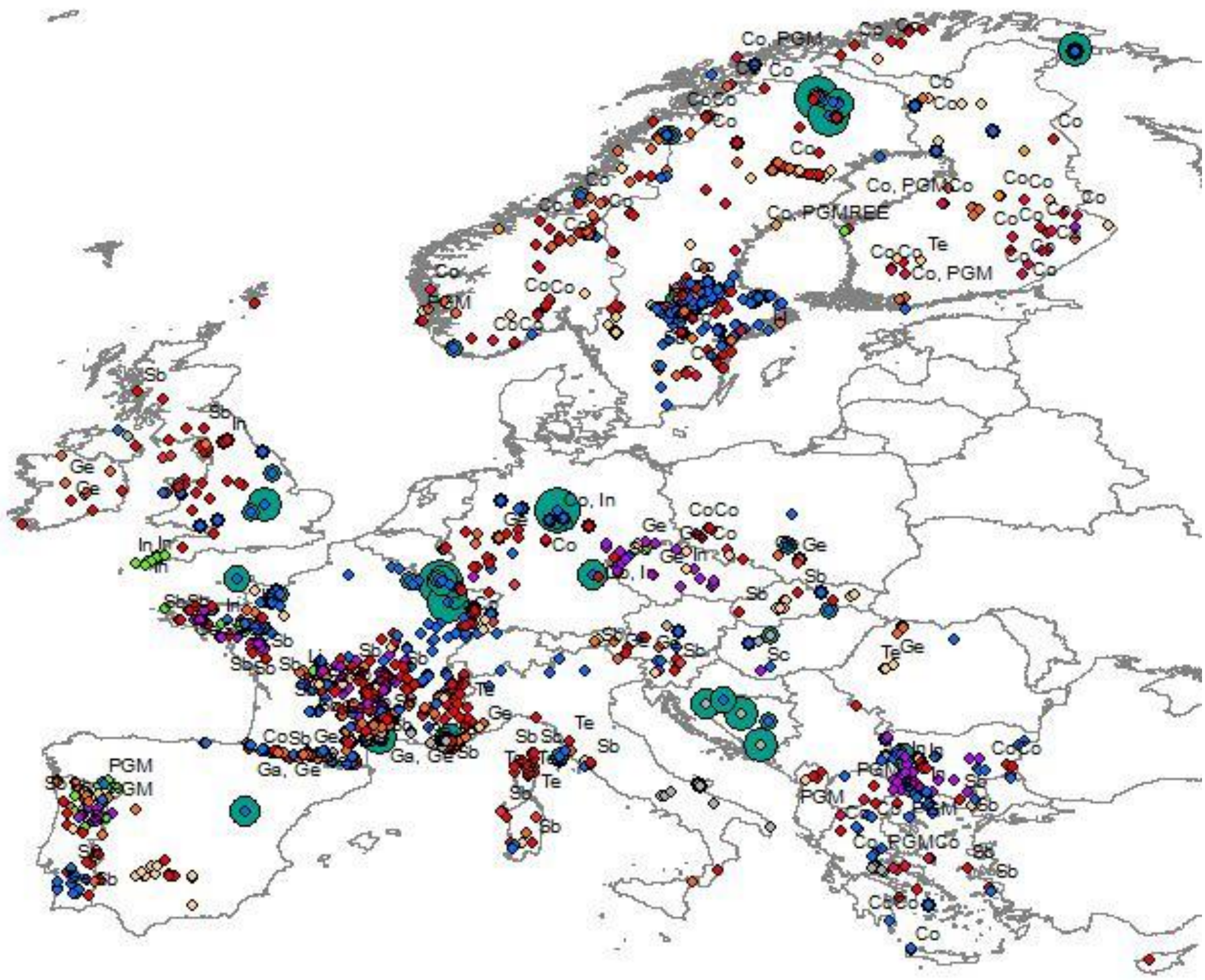

Figure 8. Map of Europe showing closed and operating mines. The green circles represent the calculated amount of waste rock where the largest circles represent more than 500 Mt of waste rock. Diamonds represents smaller mines and the colors represents type of ore; blue for iron and iron-alloy metals, yellow for precious metals, red for base metals, grey for bauxite, violet for energy metals (U) and green for special metals (data from ProMine (http://promine.gtk.fi/)and FODD (http://en.gtk.fi/informationservices/databases/fodd/)).

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Mining waste does not follow the same legislation as other product groups in ProSUM. There is no EU legislation that requires recycling of mining waste, there is no major recycling industry, there are sparse Eurostat statistics on mining waste and only at a country level.

The PROSUM project has gathered data and conducted sampling and analysis of mining waste in order to present complete characterizations of this waste group, including CRMs. The main focus in the data gathering have been locations of mines (already available in Minerals4EU) and mineral processing plants, types of processes that produced the waste, types of wastes and amount and composition of the waste. This data is stored in a ProSUM extension to the Minerals4EU database.

One of the main goals in ProSUM for mining wastes was to create a common framework for the collection and storage of data on mining waste including location, amount and composition. The target was to gather data on the most important waste deposits with respect to the critical raw materials (CRM) as well as the common commodities. Collection of data on mining waste from the participating countries was based on the data model and code lists for mining wastes completed in ProSUM. The selection was determined, in order of priority, by:

- Size of waste deposit
- Metal and/or mineral content
- Critical raw materials content
- Active mines and processing plants
- Small mining waste deposits

The reason why CRM were not given a top priority is that most of the data available are limited to those commodities (e.g. iron and alloy metals, base and precious metals) that gave economic viability to the mine or processing plant. Rare metals and minerals with lower economic or environmental importance, including several of the CRM, were seldom analyzed and reported.

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Assessment of existing data quality for mining wastes

The bulk of the available data on ore, mineral processing and mining waste come nowadays from the extractive industry, and can be found in annual reports or environmental reports. Their data are based on several thousand of analyses taken during the operations and it is assumed that these data are correct and representative. For other data sources, i.e. environmental investigations made by government authorities, research reports etc. the analytical methods are, in most cases, reported and can be used to evaluate the analytical quality.

Data gaps for mining wastes

Mining waste, as also notified above, has mostly been regarded as an environmental problem; it is only in recent years that the economic potential has been recognized. The previous lack of economic interest means that there are limited data on the amounts of mining waste (waste rock, tailings, waste sludge etc.) produced and accumulated in stocks (waste rock landfills, tailing and sludge dams).

Mining of metallic ores is an extractive industry which results in waste rocks which, due to its low economic value, in most cases are deposited close to the mine. Some of the rock is used as backfill in mines, for dam construction or for other infrastructure purpose, at the mine site or in the vicinity of the mine. The remaining waste rock is deposited in a waste rock deposit.

The proportion of the ore to the concentrator that becomes waste is highly dependent on type of ore. For example, for gold ores and low-grade base metals ore almost all the processed ore becomes waste while around 30% of the iron ore becomes waste. Table 13 shows some well documented cases where the proportion of ore that become waste is given.

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Table 13. Preliminary approach showing the portion of the ore that becomes waste during mineral processing of different types of ore in Sweden.

Type of deposit	Waste (%)	Examples (Sweden)
Low grade ore (porphyry copper, gold ore)	99	Aitik, Björkdal, Åkerberg
Disseminated ore (skarn deposits, sandstone hosted)	94	Laisvall, Yxsjöberg
Massive sulphides	75	Kristineberg, Boliden, Zinkgruvan
Iron ore	30	Kiruna, Grängesberg

Several of the critical raw materials have never been extracted on a large scale in the EU and therefore the amount of available analytical data is limited, especially compared to the data on primary resources.

Alternative sources to mining waste data include environmental reports and mine site remediation reports conducted by environmental authorities and mining companies, data from work by national surveys in accordance with the Mining Waste Directive and scientific reports dealing with various aspects of mining waste. However, as mentioned above, the research made on the national inventories of mining wastes related to the implementation of the MWD showed that any compositional information provided is very limited and of uncertain quality.

Urban Mine: electrical and electronic equipment, vehicles and batteries

In ProSUM, the Urban Mine includes spent batteries, waste electrical and electronic equipment (WEEE), end-of-life vehicles (ELV) and mining wastes. Apart from historic mine deposits and wastes from active mining, these product groups are relatively rich in CRM (Huisman et al., 2016 and 2017). For these three product groups in the Urban Mine, a

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detailed inventory of available data has been created (Urban Mine Platform, UMP) which describes products placed on the market, the stock of them in use or hibernated at homes or businesses, and the waste generated when discarded. In detail, this means to provide the mass, number, mass fraction of components, materials, and elements as they occur in products, allowing the calculation of the CRM content in the product. It is the world's first regional database of secondary raw materials with consolidated data collection and reporting from scrap vehicles, spent batteries, and waste electronic and electrical equipment.

The UMP has several services and applications that allow the user to access and explore the data, e.g. bar charts, metadata descriptions and data downloads (http://www.urbanmineplatform.eu/homepage). The number of composition data available varies significantly between the different product groups: around 800 data were collected for batteries, 1,800 for vehicles and 27,000 for EEE. The datasets rely on published information, which in some cases is too scarce to make reliable estimates of relevant parameters. Until now, data on CRMs has been produced by a variety of institutions including government agencies, universities, NGOs, and industry, scattered across various databases in different formats difficult to compare or aggregate.

The centralized database such as UMP documents the flows of secondary raw materials, such as gold, silver, CRM and rare minerals needed to make electronics, throughout their journey from the "urban mine" until their end of life — millions of tonnes of accumulated end-of-life vehicles, discarded appliances, batteries, and high tech gadgets.

Every year in Europe, around 9.45 million tonnes of waste electrical and electronic equipment (WEEE) are generated and over 1 million tonnes of batteries are sold. In addition, some 7 to 8 million tonnes of vehicles reach their end-of-life (ELV). All represent a rich source of secondary CRMs. The goal is to promote mining of € billions worth of materials from discarded vehicles, e-waste and batteries to recover valuable critical raw materials (CRMs) for securing ongoing supplies for manufacturing, and to ending European Union dependence on non-EU suppliers.

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A smartphone alone contains around 40 different CRMs. The parts per million concentration of gold alone in a mobile phone is 25 to 30 times that of the richest ores. Other recoverable precious resources include gallium, vital to making integrated circuits and optical electronic devices, consuming virtually all (99%) of world supplies, indium, 74% of which is used in flat panel displays, and cobalt, with rechargeable batteries consuming 27% of world production.

According to the ProSUM consortium mining waste to recover valuable critical raw materials (CRMs) is vital for securing growing production of variety of products, and to ending European Union dependence on non-EU suppliers.

5.1.14. MICA (ON-GOING)

http://www.mica-project.eu/

MICA (Mineral Intelligence Capacity Analysis) project does not generate new data, but reviews existing datasets and develops metadata records related to raw material intelligence.
The MICA plans to create an online data inventory e.g. from other project libraries e.g. Minerals4EU, EURare.
One of the targets of the MICA project are anthropogenic stocks and recycling including:

- Abandoned mining waste deposits and tailings;
- Abandoned mines for future land use (contamination, geological safety, etc.);
- Above ground infrastructure stock of commodities (buildings, railways, etc.);
- Subsurface infrastructure stock of commodities (water pipes, underground energy cables, etc.);
- Material flows for the recovery of commodities (demolition waste, industrial residues, etc.);
- Landfill mining for the recovery of commodities.

Data gathering has initiated and there are currently approximately 180 metadata records produced which comprise the draft data inventory. The metadata template and subsequent

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records are linked to the MICA Online Platform. An online data portal is currently under development, which will allow access to all the metadata records being produced.
A total of 408 records now form part of the MICA metadata inventory. Out of the 408 records identified, 370 metadata records have been fully prepared and the remaining 38 are in the pipeline and will be delivered shortly. Online metadata inventory is under construction. A beta-version of the online metadata MICA inventory has become publicly available, which contains a first batch of 101 records (http://metadata.bgs.ac.uk/mica/srv/eng/catalog.search#/home). The content of the MICA metadata inventory varies considerably. It includes datasets, but also scientific articles, reports, websites (e.g. for trade associations), maps, project information, information about relevant legal documents etc.

5.1.15. METGROW (ON-GOING)

http://metgrowplus.eu/

The project Metal Recovery from Low Grade Ores and Wastes addresses the issues related to bottlenecks in the European raw materials supply by developing innovative metallurgical technologies for unlocking the use of potential domestic raw materials. Both primary and secondary materials are studied as potential metal resources e.g., economically important nickel-cobalt deposits, low grade polymetallic wastes and iron containing sludges. METGROW+ targets innovative processes to extract important metals including Ni, Cu, Zn, Co, In, Ga, Ge in a cost-effective way. Four low-grade resource families were selected in the project:

(1) Primary nickel-cobalt laterite deposits,

(2) Iron-rich sludges from the zinc industry,

(3) Chromium-rich sludges from the stainless steel industry and

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(4) Fayalitic slags from non-ferrous metallurgy.

The metals valorised from these sources include both economically important metals (Ni, Zn, Cu) and critical metals (In, Ga, Ge, Sb, Co and Cr).

5.1.16. MSP REFRAM (COMPLETED)

http://prometia.eu/msp-refram/

The MSP-REFRAM project was a EU funded initiative that aims at providing the expertise required to cover the entire refractory metals (niobium, tantalum, rhenium, tungsten and molybdenum) value chain. The main goal of the project was to facilitate strategic knowledge-based decisions by policy-makers and industrialists. Thus, by fostering the collaboration of a wide panel of experts in the MSP-REFRAM Committees (along the value chains and among stakeholders, public authorities and civil society organisations), MSP-REFRAM has coordinated a global overview on the refractory metal value chain by:

- Establishing state-of-the-art refractory metals value chains including mining, processing and recycling applications.
- Analysing the innovation potential all along these value chains, including, technology, market and society/policy issues. Substitution opportunities will be proposed as well.
- Proposing new value chains including environmental regulations and standards evolutions needed as well as policy and society related issues and considering the new circular economy in sustainable development.

Since the demand for refractory metals in the EU remains high, MSP REFRAM has identified several challenges and problematic issues in refractory metals panorama that must be addressed in the coming years if Europe is to strengthen its position in the worldwide refractory metals value chain.

As for secondary sources, scrap is imported into the UK and Germany and then is subsequently used in recycling efforts throughout Europe, which underscores the need for better collection systems for secondary sources. By implementing the right incentive policies and strategies, Europe could avoid having to import secondary sources and boost self-

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sufficiency. Another challenge is the lack of proper systems for the identification of the metals contained in EoL products, which makes a well-targeted and tailored sorting and processing industrial process difficult.
Lastly, the wide array of data available on refractory metals is often conflicting. Some discrepancies have been found for example concerning Niobium information from Comtrade and EUROSTAT. Rhenium data are also hard to analyse as products and wastes are often reported together and at times even with other refractory metals such as niobium. Hence, more transparency is needed in order to be able to accurately assess the current status of European markets.

5.1.17. SMART GROUND (ON-GOING)

http://www.smart-ground.eu/

SMART GROUND aims at improving the availability and accessibility of data and information on SRM (Secondary Raw Materials), particularly in landfills and dumps, in the EU territory, while creating collaborations and synergies among the different stakeholders involved in the SRM value chain.
To do so, the consortium carries out a set of activities to integrate all the data from existing sources and new information retrieved with time progress, in a single EU database:

- To collect quantitative and structural knowledge from existing SRM resources and to identify critical points and bottlenecks that hinder the effective use of SRM from landfills and dumps
- To take stock of existing standards for RM (Raw Materials) and waste inventory and develop new ones for SRM, with the aim of validating them on selected pilot sites
- To Integrate and harmonize the data and information collected by gathering them in a single EU database
- To identify the most promising markets for the SRM
- To evaluate and to analyze the environmental, economic and social impacts triggered by different processes
- To analyze the existing legislation at EU and national level on waste management and diffusion of best practices
- To facilitate the access to information on available SRM for end-users
- To raise awareness among policy makers and public opinion to support the social recognisability of the positive impact of dumps exploitation to obtain SRM

5.2. NATIONAL PROJECTS

The Mineral Resources Expert Group (MREG) of EuroGeoSurveys has a task team with the functional role to register the project activities carried out by European Geological Surveys at national level. This task team has the mandate to hold a record, give a brief description and monitor the progress of ongoing national projects addressing mineral resources and any other topics and issues of relevance. The data included are all provided by each country's Geological Survey and listed in an excel format. The information delivered is available to the public and is updated annually.

The last update is from April 2017 and includes contributions from 27 countries, namely, Albania, Austria, Belgium, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Federation of Bosnia and Herzegovina, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom. A total number of 472 finalised and ongoing projects was reported (Fig. 9), corresponding to 725 fields of multi-disciplinary activities (Fig. 10) approaching issues and topics related to mineral resources. An impressive number of 1372 commodities (Fig. 11) was addressed, with metallic and industrial minerals, and construction materials dominating. Going back to the 725 thematic fields of project activities, an analysis of the information provided shows that less than 100 deal with mining wastes (Fig. 12), whereas country wise 20 of the 27 reporting countries have CRM related projects (Fig. 13).

It is obvious that majority of the countries have incorporated mining wastes and CRM economic geology and exploration activities into their project planning. This is a finding that's becoming a clear trend among the group of ongoing and recent projects.

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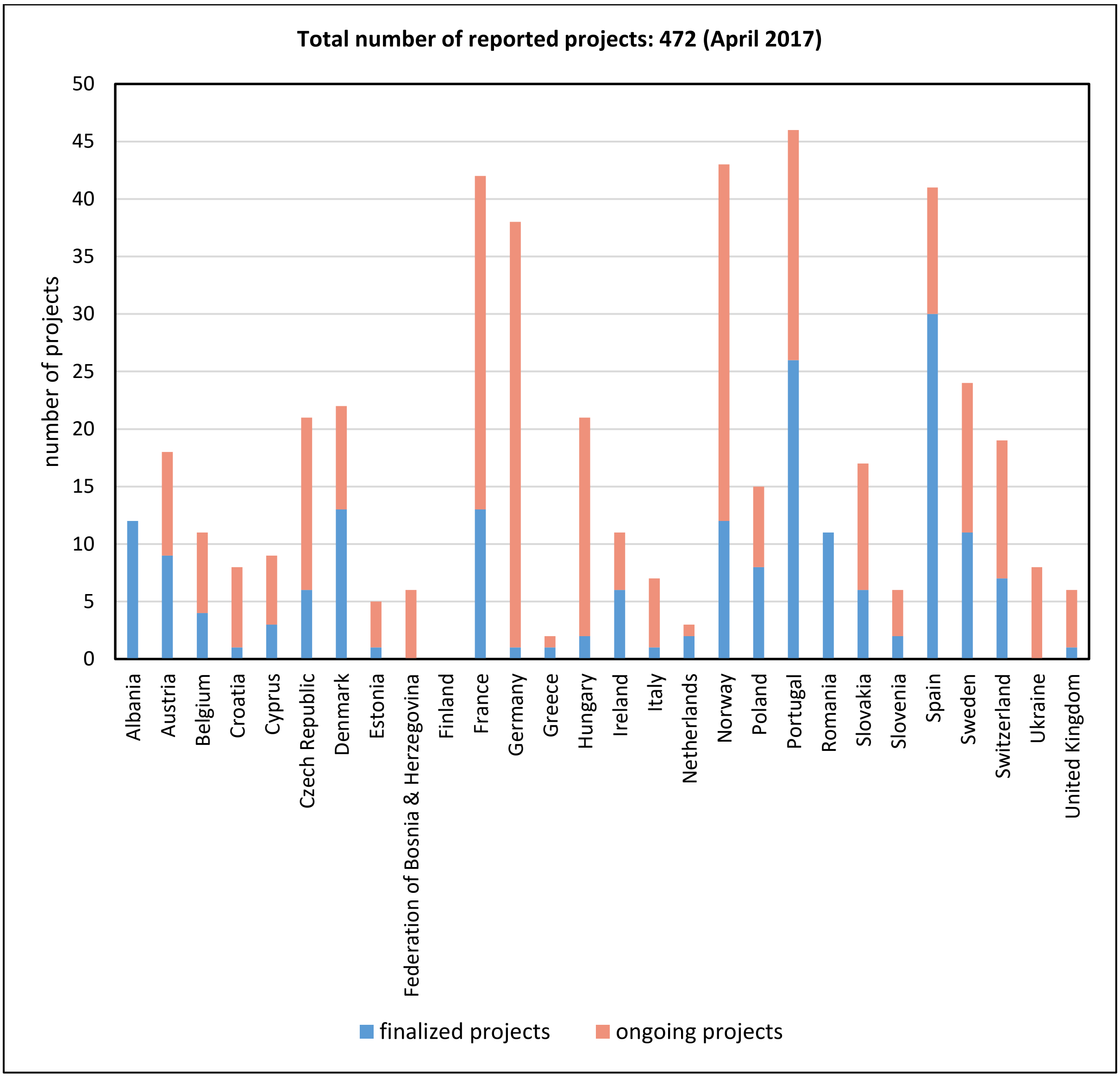

Figure 9. Finalised and on-going national projects carried out by European geological surveys (last update from April 2017).

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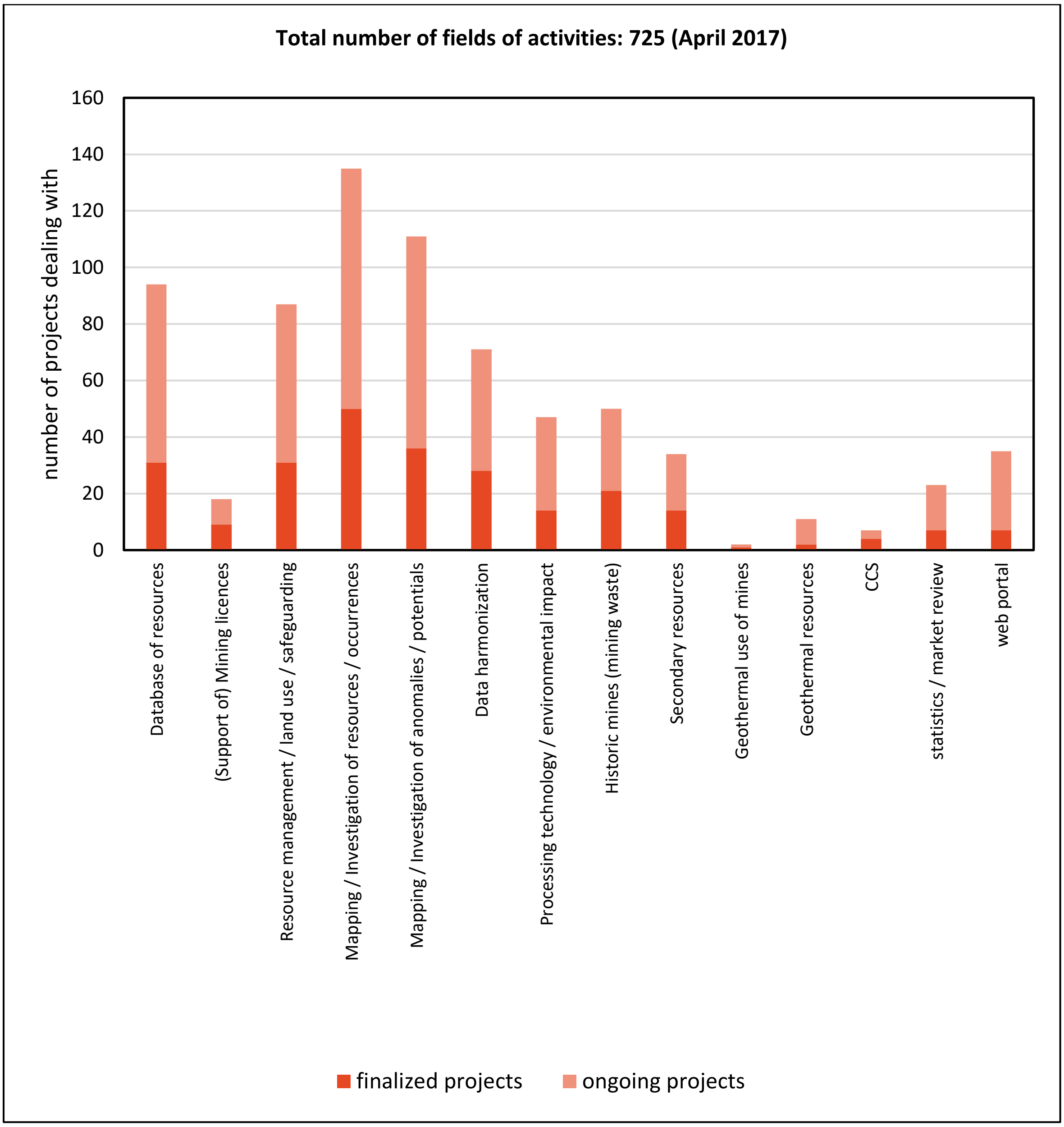

Figure 10. Geo-thematic topics addressed by national projects undertaken by European geological surveys.

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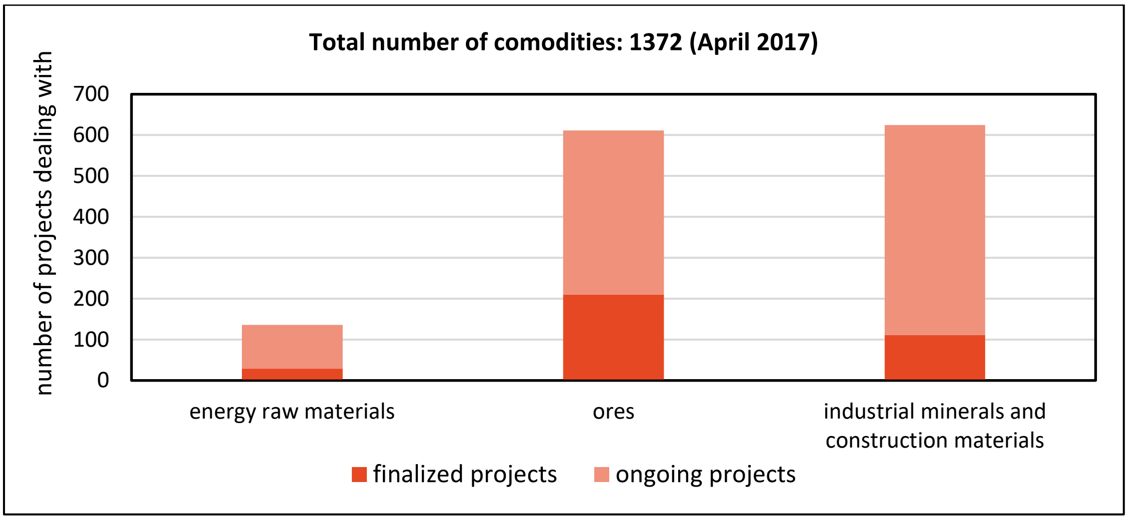

Figure 11. Most of the European geological surveys´ national projects deal equally with metallic and industrial minerals.

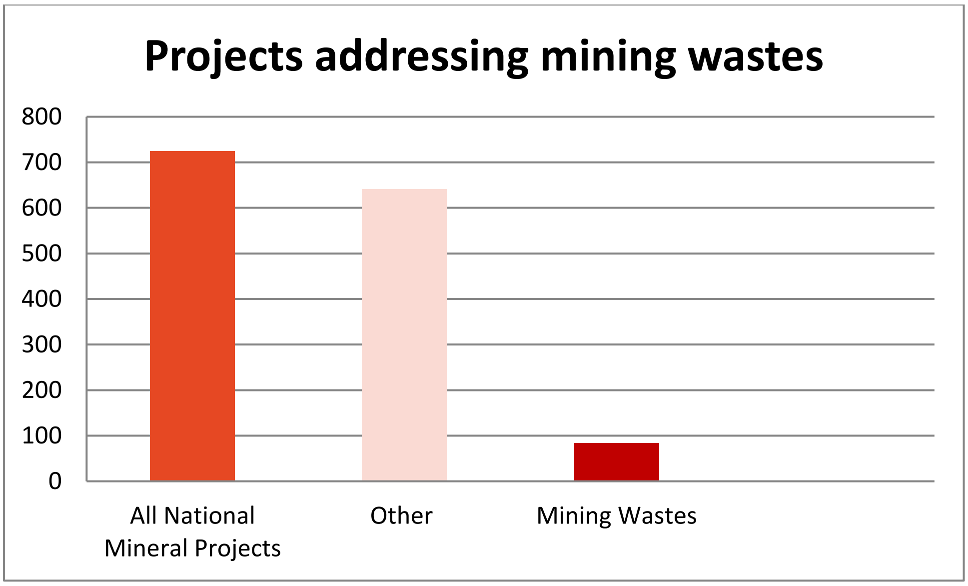

Figure 12. During last years, mining wastes related issues have become major project targets.

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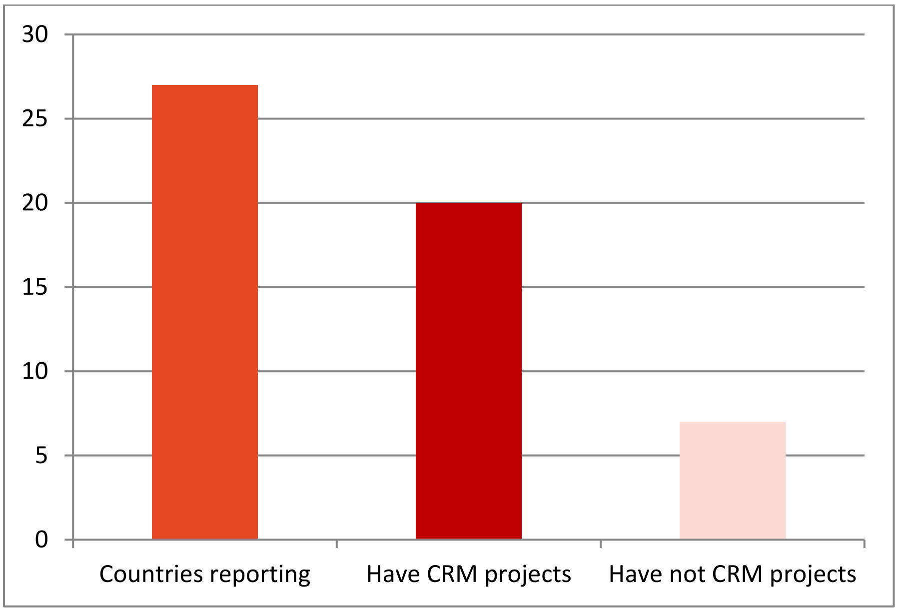

Figure 13. The CRM are central in national projects of most European countries.

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6. ANALYSIS AND EVALUATION OF GAPS AND NEEDS

6.1. SUMMARY FROM THE QUESTIONNAIRE ABOUT CRM IN MINING WASTE

The questionnaire (Table 14) has been used for the info gathering survey and it was sent out to capture the general overview of the knowledge about CRM in national geological surveys. The questions targeted the general policy issues with responsible authorities and carried out projects with CRM topics. The main focus was on CRM from mineral-based (mining) waste. 18 countries had responded by 20th November 2017: Austria, Croatia, Cyprus, Denmark, Finland, France, Germany, Ireland, Italy, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and Ukraine.

The main results of the query are:

- Many surveys have partial information about CRM from mining waste (Table 15).
- There is a large grey zone, where information is not known or hard to find.
- Information about CRM in mineral-based waste is not collected systematically but rather occasionally, and often as a result of "personal interest".
- Majority of the national geological surveys are not responsible for collecting and storing of information about CRM from waste (in a broad sense, both mineral-based and non-mineral waste).
- There is uncertainty about the answers 'no' and 'I do not know' which is interpreted as individuals attitude to the question. To some degree high frequency of answers 'I do not know' might indicate that not the right person has been contacted about answering the question and relevant knowledge might exist elsewhere. This part is difficult to verify.
- A small amount of questions remained unanswered, which can potentially be considered equal to the answer 'I do not know'.
- The participation in previous EU projects related to various geo-topics has increased the knowledge about available information about CRM.
- The countries which have best confidence about their CRM status are (most 'yes' answers): Sweden, France, Finland and Romania (Fig.14 and Fig. 15, Table 15).

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- The countries which have lowest confidence about their CRM status (most 'no' and 'do not know' answers) are: Croatia, Germany, Portugal, Denmark and Italy (Fig.14 and Fig. 15, Table 15).

Table 14. Questions included in the questionnaire and summary of positive and negative answers in the questionnaire (only questions which can be simply answered 'yes' or 'no' are taken into account here).

nr	question	yes	no	do not know	comment
1	Does your organisation collect and keep information about mining wastes?	14	4	0	partial information is interpreted as "yes" in this table
2	If not, which organisation in your country is responsible for collecting and keeping such information?				descriptive
3	In which way do you classify mining wastes in your country? E.g. waste rocks, mine dumps, processing tailings, metallurgy residues, etc. Do you use a classification developed by PROSUM/INSPIRE projects?				descriptive
4	Does your organisation conduct any projects aiming at estimating the resources and determing the composition of mining wastes? In other words, projects on mining wastes characterisation.	9	8	1	
5	Does your institution collect information about secondary Critical Raw Materials (CRM), i.e. from mining waste?	7	9	2	
6	Does your organisation or any other organisation in your country manage a database or any other knowledge platform on mining wastes?	10	4	4	

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nr	question	yes	no	do not know	comment
7	Are listed CRM from the primary sources (rock, soil, water) part of your database? (if yes, mark given CRM with the cross X)	8	7	3	
8	Do you have any compositional data concerning concentrations/grades of any of the listed CRM in mining wastes in your country?	4	13	1	
9	Do you know of any datasets/databases on mining wastes, and in particular with reference to CRM, held by private companies?	1	15	2	only Ukraine gave 'yes'
10	Do you have any information about the CRM production from mining wastes?	1	15	2	only Poland gave 'yes'
11	Has your organisation delivered any kind of mining wastes data to previous or ongoing EU projects? If yes, please name them.	11	5	2	references to PROSUM, MINERALS4EU, PROMINE, EUROGEOSOURCE, SUSMIN
12	Has your organisation published any national and/or international reports on mining wastes, particularly on any included CRM?	5	11	2	
13	Does your organisation, or any other organisation in your country publish annual aggregated information on mining waste?	4	13	1	
14	If yes, is this information provided to any EU institution, e.g. EUROSTAT?	2	2	14	
15	Are mining wastes included as a secondary resource option in your national mineral policy/strategy?	5	9	4	
16	Are mining wastes considered as potential sources for CRM in your national mineral policy/strategy?	5	11	2	

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nr	question	yes	no	do not know	comment
17	Is your country a CRM producing country? If yes, can you mark the relevant CRM in the list?	6	11	1	relatively many 'yes' answers indicating the importantce of CRM industry for EU countries
18	Do you plan any specific, near-future national projects or activities on exploring the CRM potential in mining wastes?	7	9	2	
19	Do you plan any raw materials commitments or EU projects addressing characterisation of mining wastes? If no, would you be interested to join such an initiative? If yes, do you already participate in such a consortium?	9	8	1	
20	Which are, in your opinion, the biggest challenges for EU CRM supply from non-mining (industrial/EoL) secondary resources?				descriptive

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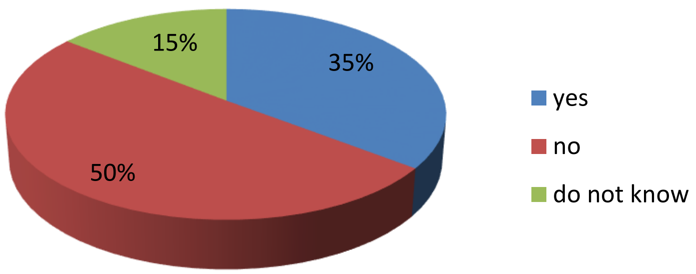

Figure 14. Percent distribution of all answers from all participants to the questions (excluding descriptive questions 2, 3 and 20).

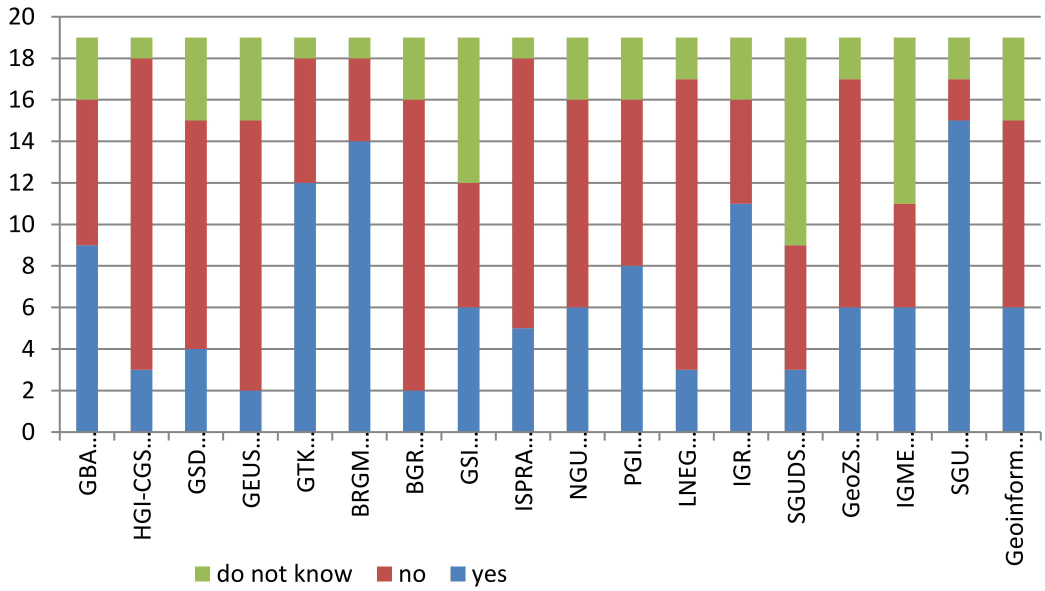

Figure 15. Summary of all answers to questions 1-19 from the questionnaire organised according to the participating surveys (countries).

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Table 15. Sorted answers for all participating countries.

country	answer	country	answer	country	answer
	yes		no		do not know
Sweden	15	Croatia	15	Slovakia	10
France	14	Germany	14	Spain	8
Finland	12	Portugal	14	Ireland	7
Romania	11	Denmark	13	Cyprus	4
Austria	9	Italy	13	Denmark	4
Poland	8	Cyprus	11	Ukraine	4
Ireland	6	Slovenia	11	Austria	3
Norway	6	Norway	10	Germany	3
Slovenia	6	Ukraine	9	Norway	3
Spain	6	Poland	8	Poland	3
Ukraine	6	Austria	7	Romania	3
Italy	5	Finland	6	Portugal	2
Cyprus	4	Ireland	6	Slovenia	2
Croatia	3	Slovakia	6	Sweden	2
Portugal	3	Romania	5	Croatia	1
Slovakia	3	Spain	5	Finland	1
Denmark	2	France	4	France	1
Germany	2	Sweden	2	Italy	1

6.2. ASSESSMENT OF THE SURVEY

The questionnaire revealed that only a few European geological surveys have relatively good insight into their CRM market situation (from mining to recycling). Interestingly, in countries which have minor CRM production, the information quality at the governmental level varies significantly. For example, among six countries which produce selected CRMs (Austria: tungsten, Finland: cobalt, germanium, PGM, phosphate rock, Norway: cobalt, magnesium, natural graphite, PGM, silicon metal as quartz, Poland: PGM, coking coal, helium, Portugal: indium, Ukraine: barite, germanium, magnesium, natural graphite, phosphate rock, tantalum, vanadium), the status of knowledge about national CRM varies from good

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(Finland, Austria) to rather poor (Portugal). This includes the existing or non-existing policies and authorities responsible for gathering of such information. The gaps between information available to, and collected by the governmental organisations and private industrial actors and research institutions tend to be a common phenomenon.

The balance between positive and negative answers to the survey can be a direct reflection of current policies and the roles of respective institutions in EU countries. A good example here is France which, although it does not have any operational mines in the country, has relatively good knowledge about their CRM resources (information collected by the French Geological Survey). Another example, Germany, with many known deposits containing CRM, has a surprisingly high frequency of negative answers. In general, the mining countries in the EU such as Sweden, Finland, Romania appear to have a rather good control on country's CRM current exploitatatin scheme.

6.3. IDENTIFICATION OF NEEDS AND GAPS

Regularly updated and reliable information about CRM production from primary and secondary sources is necessary to assess real consumption needs of CRM within the European Union, the potential of secondary resources, the need for substitution products and technologies which take into account complex supply chains and the environmental and sustainability implications, including policies.

Current knowledge about global primary and secondary CRM mining and industry resources is limited in practice to some data on resource estimates and production. Global production data is available as well as national data (for some countries) or for some producing companies but usually only for a limited selection of CRM. Data on many minerals and metals produced in, relatively speaking, small quantities such as the CRM is scarce or unavailable.

Open source trade data available from UN COMTRADE (global trade), EUROSTAT and national statistical authorities are difficult to process and analyse. This data only allows an assessment of the EU or national consumptions as, for instance, metals and minerals

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contents are hidden in traded manufactured or semi-manufactured goods, in alloys, in concentrates, in waste, in scrap or in end-of life products. However, they are not individually identified and recorded in trade statistics.

There are many gaps in data availability on CRM in Europe. The main ones are:

- Lack of consequent and detailed reporting of CRM from/in primary resources.
- Lack of any consequent reporting of CRM in secondary resources from mineral-based waste.
- No diversification of CRM contents in relation to the waste types.
- High losses of secondary raw materials before and within the recycling chain with existing recycling technology.
- Insufficient knowledge about current and future potential availabilities of EoL products, about their flows through the recycling chain, and about final destinations.
- Neglecting exploration efforts which address specifically CRM mineral systems and resources.

The main needs for long-term CRM management are:

- The availability of public data on global primary and secondary resources and reserves data on the diverse metals and minerals required by the EU economy remains too limited to efficiently guide public policy making and investment decisions. Data acquisition and EU information systems are needed to support EU level policy-making in fields such as competitiveness, development, environment, marine policy, research, trade. These information systems should also include information on the ownership and legal accessibility of these resources and reserves.
- Method standardisation to collect analytical data on CRM in mining waste and non-mining waste.
- Developing appropriate sampling technologies including non-destructive metal identification technologies for heterogeneous landfills.

- The general understanding where and how CRM end up in various types of waste.
- Better understanding of natural properties of CRM in relation to their host deposit.
- Detailed knowledge of the mineralogy, textures, grain sizes and similar properties of CRM-hosting minerals in both primary and secondary mining-related deposits.
- A comprehensive database on current and historic residue streams from EU mining and smelting activities.
- Characterisation of CRM from mining and smelter wastes taking into account the diverse origin of these residues.
- Planning of waste management at an early stage of characterisation of a new deposit. This will require full documentation, including the nature of primary (ore) minerals and barren rock/overburden.
- Waste flow data that are commodity based.
- Waste should be categorised upon its resource potential
- Examination of available data on CRM for mineral-based waste in greater detail.
- Extracted CRMs must be used as efficiently and economically as possible during manufacturing and throughout their entire life cycle and their dissipation during use should be minimised.
- Development of criteria for appropriate grouping of EoL-product types into collection categories to improve pre-processing performance.
- Process development for liberation and sorting of CRM for new requirements. This can be tested with complex products such as cars or IT electronics.
- Policy regarding collecting waste for recycling from various sources, from single households to company level.

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7. RECOMMENDATIONS FOR FUTURE ACTIONS

Data related to raw materials, including CRM, primary and from mineral-based wastes (mining and industrial) are only partially available in Europe. The limited data available are, however, often dispersed amongst a variety of institutions, including governmental agencies, universities, non-governmental organisations and industries. In the case of the latter, now defunct or historical industries and mines may have had documentation lost altogether since the cessation of production. When available, these data are often stored in databases or in analogue form, with their own non-standardised architecture and vocabulary, making any attempt of a compilation difficult and time consuming, besides potential problems in recognition as well as primary access. The problems regarding availability, quality, organization, accessibility and sharing of data are common. Solving these problems requires measures that address exchange, sharing, access and use of interoperable spatial data and services both at national and European levels. This is the aim of the INSPIRE Directive (2007, "Establishing an Infrastructure for Spatial Information in the European Community"), but its implementation in the Member States has just started and achieving those objectives represents a major challenge.

EU sustainable value chain and supply of CRM from primary and secondary resources needs:

- New geological, geophysical and geochemical data focused on raw materials including the CRM are needed. Such new, in-depth data are lacking for most of Europe; in this context, it seems that exploration in the EU is hindered in comparison with most developed countries, mainly due to political reasons. These are very costly activities which are necessary to have a CRM situation ‘under control’, and which need to be jointly covered by government and private companies, but with a common system.
- More detailed evaluations of resource potential in underexplored regions of Europe and revisiting of historic mining regions (brownfields and historical wastes) with new technology and concepts.

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- Enhance the accessibility to existing data on both primary and secondary resources to achieve high potential and new mineral deposits (e.g. CRM) taking also into account competing land-use.
- There is still much work to be done in the field of waste reuse and recycling R&D&I. For European Geological Surveys, the major interest is primarily on mineral-based wastes related to the so called mining life cycle. One important issue is the pan-EU standardised and harmonised compositional and mineralogical characterisation of waste rocks, mining wastes, processing tailings, by-products, and metallurgical residues. Using modern analytical technologies it is possible to deliver accurate grades with respect to CRM. There is no meaning in discussion the potential of the secondary resources component if your compositional ground is uncertain. Along with grades, there is of course a need for detailed mapping of all stocks in brownfields of abandoned mining areas, as well as in operating mines, to be able to consider resource estimation and classifications issues.
- Development of eco-friendly extracting technologies of CRM from waste can satisfy goals like waste reduction and reduced land use and they should become inherent objectives of the ecological part of every future mining/quarrying related activities. This can be actively incorporated into the remediation of historical mining sites and other inactive industrial facilities.
- A functional EU data base on CRM material flow analysis approaching real minerals and metals used by the EU.
- The practical life cycle database for all economically important minerals and metals containing CRM.
- Development of long-term supply of CRM and the analysis of industrial supply chains linking geological data to industrial products.
- Waste flow data that are commodity based.
- Waste should be categorised upon its resource potential.
- Examination of available data on CRM for mine waste in greater detail.

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- Mapping and prioritisation of most relevant manufacturing areas such as product designers and metallurgists/recyclers.
- Identification of the production residues containing CRMs for improved recycling, a selection of the most relevant residue streams for CRM recycling.

Although there has been increasing attention on CRM recycling from the political and legislative sides, current recycling grades are far away from ''efficient'' to fulfil the vision of a "circular economy". This is particularly valid for most of the critical metals as shown in the UNEP report on Recycling Rates of Metals (2011). Extracted CRM must be used as efficiently and economically as possible during manufacturing and throughout their entire life cycle and their dissipation during their use should be minimised.
One of the urgent issues is a need for intra-European infrastructures and tools necessary to process geological data in relation to CRM resources and reserves in a harmonised manner. As long as the recycling efficiency for most of CRM is very low, the primary sources and recycling of mineral-based waste will play the main role in CRM supply in the nearest future.

Optimised and sustainable production of CRM requires (following the ERA-MIN research strategy):
• Reduction of the loss of critical elements within residues and waste products during the entire life cycle.
• Reduction of the energy, water and aggressive compounds used during mining, refining and processing.
• Reduction of the need for CRM and fostering end-of-life recycling of such materials due to innovative new technologies.
• CRM substitution development at the various levels of production chain, e.g. original product design, replacements by more available materials with adequate properties and functionality.

Recommendations to improve knowledge on the reserves of CRM in end-of-life waste are:

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- Adaptation of the waste and product statistics: the individual statistical categories usually include both products containing and not containing CRM. In many cases the percentages of CRM may vary even in the same kind of products, e.g. tantalum in capacitors.
- Publicly available studies including reliable data on concentrations of CRM in end-of-life products.
- Track changes in the use of components and metals caused by product development, for example use of electronics in cars.
- Recycling of manufacturing waste: require recyclers to publish detailed information on the quality and composition of recycled materials.

8. EXPECTED IMPACTS AT EU LEVEL

There are numerous reasons for supporting an active mining and mineral-processing and recycling industry in Europe. Most of them are purely economic, to assure a sustainable supply of raw materials for European industry. Other arguments come from environmental and societal concerns. The general idea is that food and other materials should be sought close to sites of consumption so as to reduce transport costs (both financial and environmental) and to support the local economy. On this basis, it can be argued that metals should also be produced locally and not imported from far-flung sources. Likewise, there are strong reasons to argue that mining and mineral processing should be conducted in Europe under the control of stringent European environmental and societal norms and regulations, rather than in an uncontrolled manner in politically unstable and commonly corrupt foreign countries.

A major barrier for domestic metals production is the generally negative public opinion of the minerals industry. Although today's state-of-the art technologies are very different from methods used in the past, memories of a 'dirty' mineral industry stem from the period when local mines closed, before modern techniques were employed. It follows that most citizens

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have very negative image of the minerals and metals industries, leading politicians to oppose their development in many European countries.

Taking into account that CRM recycling is still at the technical cradle stage, the vast majority of ‘green energy’ metals must be provided by mining and ore processing in order to satisfy the current demand. Therefore, efforts need to taken to promote their primary production at the same time developing the recycling efficiency and other substitutions.

An efficient and safe waste management should be done by improving its transportation and tailings management, preventing any environmental contamination, and reusing waste as possible. In this respect, waste should be always considered as a potential secondary resource. Mining should aim to recover all valuable metals and minimize waste.

Promotion of energy savings and increasing use of renewable energy sources such as solar panels and wind is necessary to reduce carbon dioxide emissions. As mining has high energy consupmtion, it needs to develop new technologies to improve its energy efficiency. Essentially, many of the minerals and metals are components of the new ‘green’ technologies and therefore critical to fast energy transition towards a low-carbon society.

The establishment of a sustainable and efficient CRM value chains will also make a policy challenge for related current and future socio-economic, such as job creation, and environmental issues and activities, such as the transformation towards low-emission transport and the production and storage of electricity from renewable energy sources.

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