



DIRECTORATE-GENERAL FOR INTERNAL POLICIES
POLICY DEPARTMENT
ECONOMIC AND SCIENTIFIC POLICY **A**



Recovery of Rare Earths from Electronic Wastes: An Opportunity for High-Tech SMEs

Study for the ITRE Committee

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DIRECTORATE GENERAL FOR INTERNAL POLICIES
POLICY DEPARTMENT A: ECONOMIC AND SCIENTIFIC POLICY

Recovery of Rare Earths from Electronic wastes: An opportunity for High-Tech SMEs

STUDY

Abstract

This document was prepared on behalf of Policy Department A at the request of the Committee on Industry, Research and Energy. It reviews the current level of technology development for the recovery of rare earths from electronic waste and examines the elements that affect its development at the industrial scale and the opportunities arising for high tech SMEs. It also reviews the existing policy framework and provides a set of recommendations for improved implementation of existing actions and new policy measures.

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

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LIST OF ABBREVIATIONS

- EIP-RM** European Innovation Partnership on Raw Materials
- ERECON** European Rare Earths Competency Network
- HREEs** Heavy Rare Earth Elements
- LED** Light Emitting Diodes
- LREEs** Light Rare Earth Elements
- MREEs** Medium Rare Earth Elements
- REEs** Rare Earth Elements
- RMI** Raw Materials Initiative
- SMEs** Small and Medium Enterprises
- WEEE** Waste Electrical and Electronic Equipment

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EXECUTIVE SUMMARY

Background

Critical raw materials, such as rare earths, have a high economic importance for the EU, combined with a high risk associated with their supply. It is expected that in the coming years, demand for rare earths will grow as consumer preferences shift towards hi-tech and green products. Therefore, the recovery of the RE elements from electronics scrap is extremely important for both economic and environmental reasons.

Scope of the Study

The objective of the study is to describe the potential of innovative technologies for recovery of rare earths from electronic waste and to evaluate how they could be implemented in industry, in particular in hitech SMEs.

Main findings

Rare earth elements (REEs) are critical due to their importance in a number of applications, including a number of green technologies, but, primarily, because of the high supply risks arising from the dependence on a single source (China).

At a global level, the demand for rare earth oxides in 2008 was estimated at around 120 000 tonnes, expected to increase up to around 170 000 – 200 000 tonnes in 2014. The EU is a net importer of REEs and accounted for less than 8% of the total in 2012. However, most REEs that enter the EU are already embodied in components manufactured outside the EU.

Since the 1990s China has been producing roughly 90% of the world's supply of REEs, exceeding 95% in 2011. The increase in the price of REEs during the period 2009-2011 following China's decision to tighten its export quotas increased interest in REEs and led to new mining projects outside of China, research into the substitution and recycling of REEs and related policy initiatives. Prices for many REEs have dropped significantly since 2013 as a result of decreased demand following the financial crisis but also the opening of a few new mines outside China and efforts to substitute rare earths. Still, prices for some REEs are 2-3 times higher than the 2009 levels.

In the medium to long term, supply of REEs is expected to exceed demand with the notable exception of a few key REEs (Europium, Terbium, Yttrium, Dysprosium) which are used in the production of permanent magnets and phosphors.

In terms of the volume of waste electrical and electronic equipment (WEEE), the amount of WEEE generated in Europe is about 12 million tonnes per year and the European WEEE recycling market is estimated to be worth around EUR 1 billion (2013). However, the current level of recycling (urban mining) is still very limited (<1%) and there are only few firms in Europe that are actively involved in REE recovery. Furthermore, this recycling mainly concerns pre-consumer scrap (mainly permanent magnets or polishing compounds) and there is very limited activity in the post consumer recycling of WEEE.

The literature on existing recovery technologies of REEs from WEEE suggests that – while there has been a significant level of R&D – very little activity has moved to an industrial scale. Generally, since the chemistry of metallurgical extraction is well-known, the challenge usually lies with dealing with the impurities that accompany the typical recyclates. The recovery of REEs from lamp phosphors is the most mature in terms of industrial scale applications.

The prime determinant of any move towards industrial scale recycling of REEs does not appear to be the development of new technologies. More important are the economics of REE recycling – linked to the costs of the process, the need to achieve economies of scale and REE prices- and the absence of a supply chain structure geared towards the pre-processing of WEEE with focus on REEs. An effective supply chain is necessary to ensure availability of suitable recyclates from which REEs can be economically recovered based on existing technologies. Thus, while the further development of both pre-processing and refining technologies is important, most experts agree that the priority should be addressing existing gaps in the supply chain. Furthermore, each application of REEs within complex products has its own specific characteristics and poses different challenges to the recycling process. As a result, product-specific solutions are necessary in most cases.

Within this context, future opportunities for SMEs primarily arise in the area of sorting and pre-processing of WEEE streams - where large scale investment and achieving economies of scale may not be critical. However, it is important that SMEs have access to relevant WEEE streams. Another area is the provision of engineering/technical services since there is a significant number of SMEs and research organisations with high levels of technical expertise. This expertise can be used to support the development of various parts of the recycling supply chain within Europe, but also be exported to other countries where most of the processing of REEs and manufacturing of components containing REEs take place.

There has been significant EU level support for R&D in the recycling of REEs including for some pilot projects, mainly through the EU Framework Programmes for Research and Technological Development and to a lesser degree the Eco-innovation and Life programmes. The EIP on Raw Materials is expected to contribute further to the development of research and technology, while also integrating relevant non-technological aspects (changes to the legal framework, development of standards for information exchange and development of the supply chain). The EIP does bring together most of the relevant actors; however, it is too early to assess the effectiveness of these initiatives.

The Raw Materials Initiative has also played an important role in setting the direction for policy making in relation to critical raw materials and it has been followed by action in a number of Member States (national strategic plans, support for R&D, investment in increasing knowledge and understanding of raw materials flows). The private sector has also contributed, mainly through participation in R&D projects but also through involvement and sharing of knowledge in the groups established through the RMI.

The level of formal coordination between Member States in the area is rather limited and none at all for managing the demand for rare earths at the European or national level. The main mechanisms for information and experience exchange among Member States and the industry are those established in the context of the RMI.

Recommendations

On the basis of the analysis, a set of recommendations for enhanced or additional actions have been formulated. They are directed to different actors.

For the EU and Member States:

- increase the financial support available through existing European and national schemes with greater more product-specific solutions and giving priority to the later stages of technology development, supporting establishment of pilot plants

and demonstration projects and consideration of all steps of the recycling process;

- build on the work and expertise developed in the ad-hoc group on critical raw materials and the ERECON network to maintain a high level of understanding of the potential of REE recycling and how developments in technology and the markets may affect its viability;
- expedite existing work on the development of methodologies and data collection in the context of the Ecodesign Directive so that requirements for submission of information on raw material content and design for recycling can eventually become mandatory;
- support development of standards relating to the information on the presence of raw materials in complex products (e.g. environmental product declarations) and for sorting, pre-processing and recycling activities covering critical raw materials;
- examine the feasibility and effectiveness of instruments, adopted at EU or national level, aiming to influence the economics of REE recycling. These may include subsidies for the pre-processing and recycling of critical raw materials and ensuring that critical raw materials are part of extended producer responsibility schemes.

For industry :

- organise networking activities among the different actors in the supply chain to increase the level of interaction between product designers, producers, waste management and recycling firms and develop a common understanding of the challenges arising for end-of-life recycling.

1. INTRODUCTION

1.1. Assignment Aims

The European Parliament's Committee on Industry, Research and Energy has requested a research study on 'Recovery of Rare Earths from electronic wastes: An opportunity for High-tech SMEs'.

The purpose of this assignment is to identify and analyse the potential of innovative technologies for recovery of rare earths from electronic waste and to evaluate how they could be implemented, in particular by high-tech SMEs. It should enable Members of the ITRE Committee to establish their own view on the subject, and in particular as to whether existing EU policies are sufficient and have been effectively implemented and the extent to which additional initiatives and actions may be needed. More specifically, the study intends to provide answers to the following questions:

- To what extent do the EU and Member States recognise the central importance of the Raw Materials Initiative? What is the contribution of the private sector?
- What does criticality mean?
- What is a high tech SME?
- What are the drivers for a rapid industrial exploitation of rare earth recycling from electronic waste streams?
- What is the state of play in international cooperation in Research and Innovation in this field?
- Which refining technologies are mature? What could be the environmental footprint of these new technologies?
- How is the coordination between member states organised?
- How efficient is the European Innovation Partnership on Raw Materials?
- How to anticipate and facilitate the emergence of value chain based on recycling of rare earths?
- How effective are the measures to support the development of new business models based on eco-innovation?

1.2. Methodological approach

The note is developed on the basis of a combination of desk research to review relevant material, and an interview programme with key decision-makers and stakeholders at the EU and Member State levels.

1.2.1. Literature review

We reviewed key literature EU policy documents relating to the Raw Materials initiative (with a focus on rare earths, recycling, etc.), existing academic literature and other studies reviewing the technology of rare earths recycling, online articles concerning developments in rare earths recycling and market reports. The complete list of references is provided in Appendix 1.

1.2.2. Interview programme

The information from existing studies and data sources was complemented by 16 interviews with stakeholders representing industry, the research community, public authorities and environmental groups. The objective of the interviews was to provide an

up-to-date picture concerning developments in relation to research and technological development in the field of rare earth recycling, views concerning the drivers and obstacles for industrial exploitation of rare earths' recycling, opportunities for SMEs and the role of EU and national policies. Table 1.2 lists the organisations interviewed.

Table 1: List of stakeholders interviewed

Type of stakeholder	Proposed interview targets
European Commission officials	DG ENTR – Unit F3 (Raw materials, Metals, Minerals and Forest-based industries) DG ENV – Unit A1 (Eco-Innovation and Circular Economy)
National authorities, institutions/agencies	German Mineral Resources Agency – DERA (DE) French Geological survey (FR) TNO (NL)
Environmental groups	European Environmental Bureau WEEE - Forum
Industry associations	European Metal Trade and Recycling Association European Electronic Recyclers Association
Firms active in EEE waste management, recycling and recovery	Rhodia-Solvay (FR), Outotec (FI), Comet (FR) , Less Common Metals (UK) – SME, ALR Innovations limited (IE) – SME
Researchers and experts	VITO (NL), WRAP (UK), ENEA (IT)

1.2.3. Reporting

The study includes a brief background and policy context section (Chapter 2) followed by a section addressing the questions set in the specification (Chapter 3). Chapter 4 presents the key conclusions from the analysis and a set of recommendations.

2. BACKGROUND AND POLICY CONTEXT

2.1. What are rare earths?

The International Union of Pure and Applied Chemistry (IUPAC) defines the rare earth metals as a group of 17 elements consisting of the 15 lanthanoids¹ plus Scandium (Sc) and Yttrium (Y)².

¹ Lanthanum (La), Cerium (Ce), Praseodymium (Pr), Neodymium (Nd), Promethium (Pm), Samarium (Sm), Europium (Eu), Gadolinium (Gd), Terbium (Tb), Dysprosium (Dy), Holmium (Ho), Erbium (Er), Thulium (Tm), Ytterbium (Yb) and Lutetium (Lu).

Rare earths (REEs) tend to be analysed as a single group due to their generally similar properties. However, within the rare earth groups various distinctions are often made. The most common division made is between Light Rare Earth Elements (LREEs) and Heavy Rare Earth Elements (HREEs)³ reflecting differences in chemical properties and geological availability. This classification has also been followed in the most recent (2014) report on Critical raw materials for the EU⁴. A further distinction sometimes made (e.g. UNEP 2013 report on metal recycling⁵) includes an additional grouping, the medium REEs (MREEs) defined in a way that is based on which groups of elements are processed. HREEs are generally scarcer than LREEs. The majority of mineral deposits are dominated, in tonnage terms, by the presence of LREEs. However, given that HREE are more valuable, mineral deposits are generally designated on the basis of the potential value of that deposit by virtue of the presence of HREEs and not their overall tonnage (Innovation metals, nd)⁶.

2.2. Supply and demand trends of rare earths

REEs are essential raw materials for a wide range of applications, including metallurgy (metal refining and metal alloying), as catalysts in the automotive and the petrochemical industry, for colouring glass/ceramics, phosphors (LEDs, compact fluorescent lamps, flat panel displays), lasers, rechargeable solid state batteries, fibre optics and others. REEs are also vital elements in solid state fuel cells, superconductors, magnetic cooling, hydrogen storage and high performance permanent magnets. Permanent magnets play a crucial role in a number of high-tech and green energy applications including wind-turbines, hybrid cars, hard disk drives, mobile phone speakers and microphones. The table below summarises the various uses of REEs and the share in demand in 2010.

Table 2: Uses of REEs

Category of application	Specific rare earth elements	Category of products	Share in total demand for REEs (economic value)
Magnets	Nd, Pr, Tb, Dy	Hard disc, optical drives, speakers, smartphones, wind turbines, electric /hybrid vehicles	37%
Phosphors and luminescence	Eu, Y, Ce, Gd, Tb, La,	Displays, LED, lamps	32%

² Alonso,E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.F., Roth, R., and Kirchain, R.E., (2012), Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies, Environ. Sci. Technol., 2012, 46 (6), pp 3406–3414.

³ In most studies LREEs include: lanthanum, cerium, praseodymium, neodymium, samarium, europium. HREEs: gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium and yttrium. However, there is no worldwide accepted definition for which REE belongs to the HREE or the LREE group.

⁴ European Commission (2014), Report on critical raw materials for the EU - Report of the Ad hoc Working Group on defining critical raw materials, May 2014.

⁵ UNEP (2013) Metal Recycling: Opportunities, Limits, Infrastructure, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M. A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C.

⁶ Innovation metals (n.d.), Introduction to rare earths, Retrieved from <http://www.innovationmetals.com/introduction-to-the-rare-earths> on 15/10/2014.

Category of application	Specific rare earth elements	Category of products	Share in total demand for REEs (economic value)
Metal alloys/batteries	La, Ce, Pr, Nd	NiMH batteries, fuel cells,	14%
Glass, polishing and ceramics	Ce, La, Y,	Colouring and decolouring agents in glass	9%
Catalysts	Ce, La	Automotive & chemical processes catalysts	5%

Source: Own elaboration on the basis of Öko Institut (2011)

At a global level, the demand for rare earth oxides⁷ in 2008 was estimated at around 120,000 tonnes, which is expected to increase up to around 170 000 – 200 000 tonnes in 2014 (Oakdene Hollins cited in Öko Institut, 2011)⁸. The EU is a net importer of REEs importing in 2012 around 8 000 tonnes, which accounts for less than 8%⁹. These figures do not take into account the amount of REEs already embedded in electrical products which is far larger. The EU has very limited processing capacity of REEs and imports most of the batteries, magnets or compact fluorescent lamps that are used in electrical products¹⁰.

In terms of supply of REEs, since the 1990s China has been producing roughly 90% of the world's supply of REEs, and this exceeded 95% in 2011. This has been recently reduced (85% in 2013) following the reopening of two mines in the US and Australia¹¹.

For most of the last 40 years average rare earth prices had been stable at around EUR 4-EUR 8/kg. However, China tightened its REE export quota from 50 145 tons in 2009 to only 31 130 tons in 2012. This led to a significant increase of prices for most REEs in 2011, up to 20 times their 2009 values¹². However, since 2013 prices for many REEs have dropped significantly, in some case to almost pre-2009 levels (see Table 3), as a result of decreased demand following the financial crisis but also the opening of a few new mines outside China and efforts to substitute rare earths¹³. Still, prices for some REEs are 2-3 times higher than the 2009 levels. Prices in 2014 have stabilised and have shown resistance to further decline.

⁷ REEs are frequently separated and sold in their oxide form and thus it is customary to render mineral-deposit data in terms of rare-earth oxide (REO) equivalents.

⁸ Öko Institut(2011), Study on rare earths and their recycling – A report for the Greens/EFA Group in the European parliament.

⁹ EC (2014), Report on critical raw materials for the EU – Critical raw materials profiles, http://ec.europa.eu/enterprise/policies/raw-materials/files/crm-critical-material-profiles_en.pdf

¹⁰ European Commission(2014), Report on critical raw materials for the EU - critical raw materials profiles.

¹¹ Ibid.

¹² <http://www.arultd.com/rare-earths/pricing>.

¹³ Topf,A., (2013), Rare Earths Outlook: Prices to Rise, Western Producers Cutting Into Chinese Monopoly, Rare earths investing news, retrieved from <http://rareearthinvestingnews.com/19313-rare-earths-outlook-prices-to-rise-western-producers-cutting-into-chinese-monopoly.html>, Accessed on 18/11/2014.

Table 3: Evolution of prices of selected rare earth oxides (EUR /kg)

	2007	2009	2011	2013
Lanthanum oxide	2.5	4.7	84.4	6.0
Cerium oxide	2.0	3.4	82.5	6.3
Neodymium oxide	23.3	12.1	188.3	56.3
Terbium oxide	445.9	283.3	1921.3	753.4
Dysprosium oxide	66.8	83.7	1184.0	429.8
Yttrium oxide	5.6	11.3	109.5	20.1

Source: Arafura Resources limited (2014) - Prices in EUROS converted from US Dollars on the basis of a 0.8 USD/EUR conversion rate

The price spike that followed the tightening of the export quota and the strategic decision of a number of countries to reduce dependence from a single source of supply led to a renewed interest in rare-earth exploration and development projects underway around the world. As of July 2012, the market analysis firm Technology Metals Research (TMR) has been monitoring over 440 rare-earth exploration projects outside of China and India, located in 37 different countries⁸.

This increase in mining activity suggests that in the medium to long term supply is expected to meet demand for most REE elements. Certain HREEs are still expected to experience shortages such as Dysprosium. In the short term shortages are expected for neodymium, dysprosium, europium and terbium that are required for Rare Earth magnets and phosphors¹⁴.

2.3. Level of recycling and recovery of rare earths from WEEE

At the global level the volume of waste electrical and electronic equipment (WEEE) is enormous, estimated to be between around 50 million tonnes per annum. In Europe, the amount of WEEE generated is about 12 million tonnes per year. This is expected to increase in the coming decades at a rate of at least 4 % per annum (UNEP,2013). According to data from the European Electronic Recycles Association, its 38 members and over 100 subsidiaries had a total turnover of around EUR 900 million and treat around 2.2 million tonnes of WEEE per year¹⁵. Frost& Sullivan¹⁶ put the WEEE recycling market revenue in Europe at around EUR 1 billion, expecting it to reach EUR 1.5 b by 2020. The WEEE recycling industry is characterised by a pyramid structure, with a very small number (<10) of very large companies focusing on the refining and smelting of metals, a larger number (100s or 1000s) in the dismantling and pre-processing and a much larger in the initial collection.

¹⁴ European Commission(2014), Report on critical raw materials for the EU - critical raw materials profiles.

¹⁵ Norbert Zonnenfeld (2014), Circular economy-saving resources creating jobs – How to increase WEEE recycling rates, Presentation during the Green week, retrieved from http://www.greenweek2014.eu/docs/presentations/parallel-side-sessions-2/2-4/zonneveld_2.4.pdf on 27.10.2014

¹⁶ Frost & Sullivan (2013), European waste electrical and electronics equipment recycling market, <http://www.endseurope.com/docs/131001c.pdf>, Accessed on 26.10.2014.

However, in the case of recycling of REEs, data from the most recent UNEP report (2011)¹⁷ suggest that the current level of recycling (urban mining) is still very limited (<1%) and there are only few firms across the supply chain in Europe that are actively involved in REE recovery. Furthermore, this recycling mainly concerns pre-consumer scrap (mainly permanent magnets scrap or polishing compounds) and there is very limited activity in terms of post consumer recycling of WEEE.

It is also important to note that recycling and recovery of rare earths represents only part of a broader approach towards addressing a possible REE supply challenge. Binnemans et al (2013)¹⁸ propose that a threefold approach should be adopted including substitution of critical rare earths by less critical metals when possible, investment in sustainable primary mining from old or new REE deposits and, thirdly, so called "technospheric mining". This includes the recovery and recycling of postconsumer multi-material End-of-Life products (urban mining) such as EEE, direct recycling of pre-consumer manufacturing REE scrap/residues and landfill mining of historic (and future) urban and industrial waste residues.

Looking into the future, on the basis of the analysis of existing technologies and levels of recycling Binnemans et al. (2013) provided an estimate of the potential level of recycling of REEs by 2020. The figures are based on certain estimates of stocks of REE, different scenarios concerning the collection rates of respective components and efficiency of recycling processes that are discussed in Chapter 3. The total estimated global recycling potential is 5.6-10.7 thousand tonnes¹⁹, similar to the annual usage of REEs in Europe.

Table 4: Global recycling potentials for REEs from magnets, nickel-metal-hydride batteries and phosphors

REE application	Expected REE stocks in 2020 (tons)	Recycling process efficiency	Recycled REE in 2020 (tons) – Different scenarios	
			Pessimistic	Optimistic
Lamp phosphors	25,000	80%	3 300	6 600
Magnets	300,000	55%	1 333	2 333
NiMH Batteries	50,000	50%	1 000	1 750
Total	29,167		5 633	10 683

Source: Binnemans et al. (2013)

2.4. Policy context

At the EU level, the policy on raw materials is primarily built on the Raw Materials Initiative (RMI) that was launched in 2008²⁰ and further developed in 2011²¹. Within the

¹⁷ UNEP International Resource Panel (2011), Recycling Rates of Metals: A Status Report.

¹⁸ Binnemans, K., Jones,P.T., Blanpain,B., VanGerven,T., Yang,Y., Walton,A., Buchert, M., (2013), Recycling of rare earths – a critical review, Journal of cleaner production 51 : 1-22.

¹⁹ For individual REEs the estimates of the authors are 2390- 4755 tons of Nd, 805 -- 1600 tons of Pr, 610- 1070 tons of La, 480-840 tons of Ce, 920-1615 tons of Y, 165-330 tons of Dy, 68- 121 tons of Tb and 65- 115 tons of Eu.

²⁰ COM(2008) 699 Communication “The raw materials initiative - meeting our critical needs for growth and jobs in Europe”.

third pillar of the RMI, the Commission stated its intention to promote measures aiming to improve how the recycling markets work. This included the development of best practice in the collection and treatment of waste, improving the availability of certain statistics on waste and materials flows, reduction of illegal waste dumping, reviewing²² key pieces of legislation (EU waste²³ and Ecodesign legislation), support for research and innovation and the promotion of economic incentives for recycling.

In parallel, the Commission Communication "Towards a circular economy: A zero waste programme for Europe"²⁴ identifies actions aiming to turn waste into a resource. This includes measures for the development of markets for high quality secondary raw materials and recommendations towards Member States to adopt measures regarding collection and recycling of waste containing significant amounts of critical raw materials in their national waste management plans.

2.5. Support for Research and Development in the area

At the EU level, research and technological development in relation to the recycling of REEs have been supported through the 7th Framework Programme for Research & Technological Development with the implementation of a few focused projects. In the case of the Horizon 2020 programme, around EUR 14.5 m has been allocated for the period 2014-2015 for projects focusing on the recycling of raw materials from products and buildings. The objectives reflect the targets set in the context of the European Innovation Partnership on Raw Materials (EIP-RM)²⁵. The EIP-RM promotes technological and non-technological innovation along the entire value chain of raw materials (i.e. exploration, extraction, processing, refining, re-use, recycling and substitution). Under the technology pillar it focuses on developing and demonstrating cost-effective, resource and energy efficient and environmentally sound solutions including the recycling and recovery of valuable raw materials from complex products and other other waste streams. Furthermore, under the non-technology pillar of the EIP there are actions envisaged reflecting the issues and obstacles related to the development of REE recycling. Finally, the International Cooperation pillar envisages actions to develop an exchange of information on recycling technologies and the promotion of existing recycling technologies.

²¹ Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: 'Tackling the Challenges in Commodity Markets and on Raw Materials', COM(2011) 25, 2.2.2011.

²² COM(2014) 397 final, Proposal for a Directive of the European Parliament and of the Council amending Directives 2008/98/EC on waste, 94/62/EC on packaging and packaging waste, 1999/31/EC on the landfill of waste, 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment.

²³ Waste Electrical and Electronic Equipment Directive (WEEE), the EU End of Life Vehicles Directive (ELV) and the EU Battery Directive.

²⁴ [http://ec.europa.eu/environment/circular-economy/pdf/Annex-COM\(2014\)398.pdf](http://ec.europa.eu/environment/circular-economy/pdf/Annex-COM(2014)398.pdf).

²⁵ See http://ec.europa.eu/enterprise/policies/raw-materials/innovation-partnership/index_en.htm.

3. ASSESSMENT OF KEY ISSUES

3.1. To what extent does the EU and the Member States recognise the central importance of the Raw Materials Initiative? What contribution has the private sector made in this direction?

The Raw Materials Initiative is the key initiative in relation to raw materials. The 2013 and 2014 implementation reports point to a number of actions that have taken place in the last few years in relation to all three pillars of the RMI. This includes the allocation of funds for relevant R&D projects under FP7 and Horizon 2020, establishment of the European Innovation Partnership on Raw Materials, review of the relevant legal framework and work towards the development of standards. According to the EU officers the RMI provides the overarching policy context and it has clearly driven recent developments in the sector.

At the national level, our discussions with representatives of the German Minerals Resource Agency and the French geological survey suggest that the RMI – and particularly the discussion around critical raw materials - has not only raised awareness at the national level but has led to actions at the national level that reflect the priorities of the RMI. This includes the development of national raw materials strategies – or further developing the pre-existing strategy in the case of Germany. The review of the national strategies developed by a number of Member States²⁶ aim to safeguard the availability of critical raw materials and mitigate any risks^{27 28}. While there are differences in the focus and priorities a review of these documents suggests that there are a few key strategic directions that indicate that key elements of the RMI have been taken on board at the national level:

- Development of a better understanding of the needs of national industries for critical raw materials through studies and a closer coordination with industry;
- supporting the diversification of supply sources for various CRMs including investments in new exploration to reduce dependence from a single source; and
- promotion of resource efficiency, material recovery and recycling, including investments in R&D in order to reduce demand for REEs and critical raw materials more generally.

The involvement of the private sector has come mainly through its active engagement in various discussion forums (such as the Raw Materials Supply Group) and networks (e.g. the ERECON network on Rare Earths²⁹). The involvement of industry is considered to be important for sharing the knowledge and understanding of the sector and the operation of the supply chain and information policy recommendations and actions.

At the same time, there is an increasing level of investment in R&D either on the basis of own resources or through national and EU programmes. In the context of the European Innovation partnership on raw materials there was a total of 80 long terms projects (commitments) approved. We have identified 3 (HydroWEEE³⁰, WEEE 2020³¹ and EARTH

²⁶ See documents in : http://ec.europa.eu/enterprise/policies/raw-materials/documents/index_en.htm#h2-8

²⁷ European Commission (2014), Report on critical raw materials for the EU - Report of the Ad hoc Working Group on defining critical raw materials, May 2014.

²⁸ DEFRA(2012), A Review of National Resource Strategies and Research, retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69526/pb13722-national-resource-strategies-review.pdf on 25.10.2014.

²⁹ http://ec.europa.eu/enterprise/policies/raw-materials/erecon/index_en.htm.

³⁰ EC (2014), EIP commitments: Innovative Hydrometallurgical processes to recover precious and critical metals from WEEE and other High-tech products <https://ec.europa.eu/eip/raw->

2020³²) that are related to the recycling and recovery of rare earths from WEEE that bring together individual firms and industry associations.

3.2. What does criticality and critical raw materials mean?

Against the background of the expected growth of demand for REEs and possible supply restrictions, a number of approaches and classification systems have been developed to characterise the "criticality" of raw materials and metals, including rare earths. A recent study (Hartfield et al., 2014)³³ identified a total of 17 critical resources/materials assessments, or projects with characteristics similar to a criticality assessment. The common features of all approaches are:

- the extent of criticality of one material is measured in relative terms against the criticality of others within the same scope and scale.
- the form of a risk analysis - these include two or three dimensions (generally supply risk and vulnerability or possibly environmental risk). Thus, a material with a high level of supply risk may be termed 'critical', but within the concept of a criticality assessment it is not strictly a 'critical resource'.

It is also important that in each case criticality is assessed within a specific context and having also in mind the specific end-user (e.g. policy maker, business). While some studies may focus on a specific economic zone or a country (such as the 2010 report "Critical raw materials for the EU"), others may focus on a specific area of technology or sector (such as the study from the department of energy) or a specific company.

Concerning the analysis at the EU level, the 2010 report "Critical raw materials for the EU" (EC 2010)³⁴ identified materials as critical on the basis of two key criteria:

- The relative economic importance of each material for the EU on the basis of its association (level of use and application) in industrial sectors with the different shares in EU GDP;
- the risks of supply shortages as a result of concentrated primary production in a few or even a single country with poor governance (as indicated by the World governance indicator). The capacity to substitute the specific material and the end-of life recycling rate both reduce the level of risk for the supply of a specific material.

The EU criticality assessment provides a snapshot and does not address the fact that conditions can change. Other studies have aimed to incorporate future supply and demand criteria although there are important uncertainties included in such projections. The EU approach does also not consider the market size (e.g. scale of problem),

[materials/en/content/innovative-hydrometallurgical-processes-recover-precious-and-critical-metals-weee-and-other](https://ec.europa.eu/eip/raw-materials/en/content/innovative-hydrometallurgical-processes-recover-precious-and-critical-metals-weee-and-other), Accessed on 25.10.2014.

³¹ EC (2014), EIP commitments: WEEE 2020 Raw Material Partnership – Delivering advancements across the WEEE value chain to improve the environment, help meet EU material demand and drive a resource efficient, green economy. <https://ec.europa.eu/eip/raw-materials/en/content/weee-2020-raw-material-partnership-%E2%80%93-delivering-advancements-across-weee-value-chain-improve>, Accessed on 25.10.2014.

³² EC (2014), EIP commitments: Environmentally sound Advanced Recycling Technologies for Hi Tech products: An innovative technology framework for the development of advanced recycling systems of critical and precious raw materials from hi tech products, <https://ec.europa.eu/eip/raw-materials/en/content/environmentally-sound-advanced-recycling-technologies-hi-tech-products-innovative-technology>, Accessed on 25.10.2014.

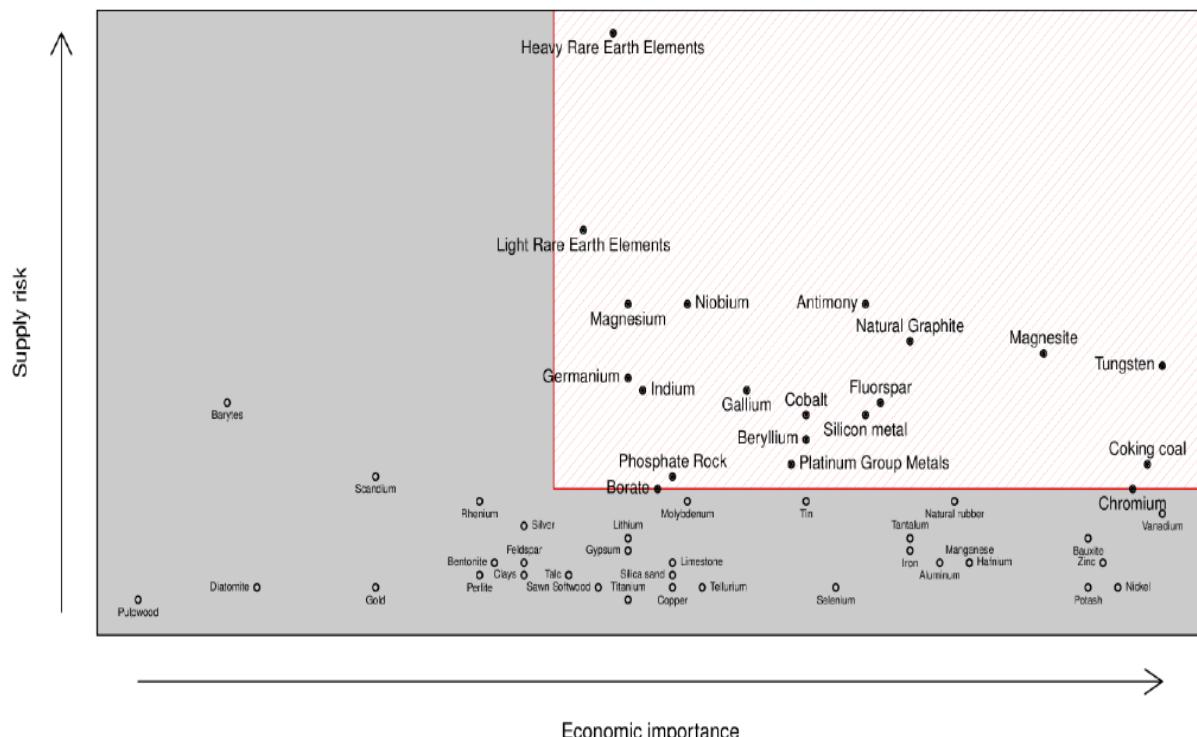
³³ Harfield, P., Christopher, H., Sanders C., EcoDesign Centre, (2014), Mapping Critical Resources for Wales

³⁴ European Commission, (2010). Critical raw materials for the EU, Report of the Ad-hoc Working Group on defining critical raw materials.

or the interdependence between different metal markets (both on the supply and the demand side).

The initial analysis was performed in 2010, and was subsequently updated in 2013 on the basis of better data. It was also extended to additional materials and this led to the characterization of raw materials as critical on the basis that they exceeded a minimum threshold value for each criterion. These threshold values were set on the basis of expert judgments. Figure 3 presents the result of 2014 analysis, where REEs – both heavy and light – were identified as exceeding the minimum threshold, particularly in relation to the supply risk criterion. This is driven by the high level of dependence on supply from a single country (China) and the poor governance score.

Figure 1: Criticality assessment for the EU



Source: European Commission, (2014).

In the initial EU definition of supply risk, environmental performance aspects – measured through an Environmental Performance Index - were also considered, reflecting the danger that countries may take measures to reduce impacts from mining. This was subsequently removed on the basis that it did not reflect the reality in the mining sector of certain countries. Alternative approaches to the definition of criticality – such as the study of behalf of the UN Environmental programme (Öko-Institut, 2009)³⁵ - have used the impact on the environment as an additional criterion³⁶. Greadel et al. (2012) used a three axis (criteria) approach to assess criticality. A study for the U.S. Department of Energy used as a criterion the importance of specific REEs to the development of clean energy technologies.

³⁵ Öko-Institut (2009), Critical metals for future sustainable technologies and their recycling potential.

³⁶ Harfield, P., Christopher, H., Sanders C., EcoDesign Centre, (2014), Mapping Critical Resources for Wales.

It should be noted that rare earth elements have been identified as critical in most – but not all - criticality assessment studies where they were considered. Neodymium, Dysprosium and Europium are the three REEs that are identified as most critical.

3.3. What is a high tech SME?

According to the European Commission review of High-tech SMEs (2002)³⁷, a clear, detailed and consolidated definition does not exist. There is in fact a diversity of terms with often rather similar or related meanings such as new technology-based firms (NTBFs), innovative SMEs, knowledge-based firms, R&D intensive companies. According to the Oslo Manual³⁸ a technological product and process innovating firm is one that has implemented technologically new or significantly technologically improved products or processes. Another common approach focuses on the R&D intensity of a specific firm or a sector (i.e. the ratio of annual R&D expenditures to sales) although, in the case of SMEs, it can often be the case that they can be innovative without conducting R&D. Furthermore, when it comes to firms in the services sector, so called Knowledge Intensive Services (KIS) firms may be primarily identified on the basis of the high level of their human capital and the reliance on professional knowledge.

Within the context of rare earths recycling, high-tech SMEs in this sector would be either firms involved in the development of innovative recycling processes and technologies in relation to either the recovery process or the earlier parts of the supply chain or firms which – on the basis of their knowledge and R&D activities³⁹ - provide R&D, engineering or other technical support services to firms in the sector with the aim of improving technology and process development.

3.4. Which refining technologies are mature?

The REE recycling process includes a number of key steps before reaching the refining stage. It typically includes an initial sorting process to identify products that contain REEs, a dismantling and separation process to extract the specific components with REEs and a final recovery/refining of the REE material.

The review of the literature points to a number of REEs refining technologies at different stages of development. A number of studies (Binnemans et al., 2013⁴⁰; Oeko Institut (2012)⁴¹, Oakdene Hollins (2011)⁴², UNEP(2013)⁴³) refer to existing refining technologies as well as a few WEEE pro-processing technologies. A recent report by the WIPO⁴⁴ also point to an increasing level of patenting activity linked to the recovery of rare earth

³⁷ European Commission (2002), Observatory of European SMEs - No 6 High-tech SMEs in Europe.

³⁸ OECD/Eurostat: The measurement of scientific and technological activities. Proposed guidelines for collecting and interpreting technological innovation data - Oslo Manual, Organisation for Economic Co-operation and Development (OECD) Paris: OECD, 1997.

³⁹ Here definition of product and process innovation are taken from OECD/Eurostat: The measurement of scientific and technological activities. Proposed guidelines for collecting and interpreting technological innovation data - Oslo Manual, Organisation for Economic Co-operation and Development (OECD) Paris: OECD, 1997.

⁴⁰ Binnemans, K., Jones,P.T., Blanpain,B., VanGerven,T., Yang,Y., Walton,A., Buchert, M., (2013), Recycling of rare earths : a critical review, Journal of Cleaner Production, 51,1-22.

⁴¹ Öko Institut (2012), Recycling critical raw materials from waste electronic equipment, Study Commissioned by the North Rhine- Westphalia State Agency for Nature, Environment and Consumer Protection, February 2012.

⁴² Oakdene Hollins (2011), European Pathway to Zero Waste - Study into the feasibility of protecting and recovering critical raw materials through infrastructure development in the south east of England.

⁴³ UNEP (2013), Metal Recycling – opportunities, limits, infrastructure – A report of the working group on the global metal flows to the international resource panel, Reuter, M.A., Hudson, C., van Schaik,A., Heiskanen, K., Meskers, C., Hageluchen, C.

⁴⁴ WIPO (2013), Patent Landscape Report on E-Waste Recycling Technologies.

metals from electronic waste streams. Between 2005 and 2010, patenting activity in this specific thematic area increased from 10 patent families per year to over 35. Japan-based entities are the pre-eminent source of new patent applications followed by the United States, China, Germany and France. In a recent study examining possible pilot plants by TNO (2013)⁴⁵, a total of 14 pilots aiming to achieve improved recovery of materials from end-of-life products were identified. Of these, 7 were considered to be at a high level of technological readiness (between 6 and 7 in the TRL scale) while the remaining were still at lab scale.

In general, most recent developments towards industrial scale have concentrated in the areas where relatively REE-rich scrap can be obtained and where the rare earths in the scrap are highly valued. These include the recycling of permanent magnets, lamp phosphors, and nickel metal hydride batteries (Golev et al, 2014).

In the following paragraphs we provide a brief description of a number of technologies and methods for the recovery of REEs from magnets, lamp phosphors and batteries providing available information on the presence of industrial scale development.

3.4.1. REEs from permanent magnets

The most common REE magnets included in hard disk drives, air conditioning units or cars are based upon neodymium-iron-boron (NdFeB) alloys. Dysprosium is also often added to magnets to increase their temperature stability against demagnetization and its content in NdFeB magnets varies widely, depending on the application. A second, less prevalent type of rare earth magnets (<2% of market) are based upon samarium-cobalt alloys. It should be noted though that there are different types of magnets in different products and it is often difficult to know what type of magnet is being used even within one specific application. Furthermore, in many cases protective coatings (e.g Nikel) is used that make the recovery process more complicated.

Currently, most scrap from HDDs is shredded, a key reason being the need to destroy the data on the disk for security reasons. However, as the magnets are brittle they break up into granules which are still permanently magnetic. This powder then sticks to the other ferrous waste contained in the electronics and/or to the shredder, making it very difficult to effectively separate it. There are two main approaches followed. The first is based on the direct smelting of the shredded residues that containing a mixture of metals with the aim of extracting various metals – including REEs. The second includes an initial stage of extraction of the permanent magnets from the EEE before shredding, aiming for a higher level of concentration. The recovered magnets can in a few cases be re-used after further processing (e.g. magnets from wind turbines but nor from hard disk drives), or, in most cases, be fed into a smelting process for extraction of REEs.

There are various well established separation methods used for metals in general but these are often not appropriate for REEs in magnets due to their properties and the use of coatings. The literature refers to a dismantling technology developed by Hitachi to recover NdFeB magnets from HDDs and compressors of air conditioners. It is based on a combination of vibration, demagnetization and manual collection. The process expected to be implemented at industrial scale by 2013 covering about 10% of the entire Hitachi Group's REE needs. Another recently developed technology by the University of Birmingham uses hydrogen at atmospheric pressure to separate sintered REE magnets from computer HDDs, leading to hydrogenated NdFeB powder which can be directly

⁴⁵ Elewaut,E., Bastein, T., (2013),Raw Materials: Study on Innovative Technologies and Possible Pilot Plants – Draft final report, Retrieved from http://ec.europa.eu/eip/raw-materials/en/system/files/qed/80%20RAMINTECH%202013_Final_report_16-03-2013.pdf on 20.10.2014.

reprocessed from the alloy into new magnets with magnetic properties approaching the performance of the original magnets or into cheaper bonded magnets of a lower magnetic performance. In both cases, a subsequent metallurgical process may be used to recover REEs.

Existing technologies for processing of shredded or pre-processed residues in order to extract precious and other metals are based on smelting operations, (hydrometallurgic/pyrometallurgic) using lead, copper and nickel as collectors for valuable metals. Hydrometallurgy has been the traditional route. It was used in the 1990s for the recovery of Samarium which was economically justifiable at that time but it is much less effective and more costly in the case of current End of Life WEEE (e.g. HDD), which contain NdFeB, dysprosium but often also protective coatings. Researchers in China and Japan – primarily – have published a number of studies on possible alternative approaches but these are all at lab-scale level.

Rhodia-Solvay have developed a relevant process for REEs – although not at an industrial scale – while recent R&D in the University of Leuven in cooperation with Rhodia has focused on making the process more efficient. This is still at the laboratory stage. Pyrometallurgical routes (high-temperature routes) have also been developed as an alternative for the hydrometallurgical routes allowing remelting of the REE alloys or extraction of the REEs from transition metals in the metallic state (liquid metal extraction). Other pyrometallurgical routes are more suitable for recycling of REEs of partly oxidized REE magnet alloys (electroslag refining or the glass slag method). However, according to Binnemans et al. (2013)⁴⁶ the relevant flow sheets for these processes have not yet been developed.

3.4.2. REEs from lamp phosphors

Lamp phosphors in fluorescent lamps are a rich source of the heavy rare earths elements, including europium, terbium, and yttrium. Existing technology development for extracting rare earths from lamp phosphors is restricted to large fluorescent lamps, compact fluorescent lamps and cathode ray tubes. There has been no research yet on the recovery of rare earths from small fluorescent lamps used in LCD backlights or from phosphors used in white LEDs (Buchert et al., 2012)⁴⁷.

There are three different approaches possible in relation to the recovery of REEs. The first includes a direct re-use of lamp phosphors in new lamps, the second recycling of the individual phosphor components by physicochemical separation methods and, a third, chemical attack on the phosphors to recover their REE content.

Direct re-use is the most simple but is only applicable to one type of fluorescent lamp, because different lamps make use of different phosphor mixtures and phosphors deteriorate over the lifetime of the lamp. Re-use of the separate phosphors for new lamps is often problematic unless lamp producers can recycle the phosphors from their own End-of-Life fluorescent lamps. This has been the case for the process developed by the Belgian waste-processing company Indaver in close collaboration with Philips Lighting for the recycling of phosphors from Philips' linear fluorescent tube lamps which established such a facility in 2000 in the Netherlands⁴⁸.

⁴⁶ Binnemans, K., Jones, P.T., Blanpain, B., VanGerven, T., Yang, Y., Walton, A., Buchert, M., (2013), Recycling of rare earths : a critical review, Journal of Cleaner Production, 51, 1–22.

⁴⁷ Buchert, M., Manhart, A., Bleher, D., Pingel, D., 2012. Recycling Critical Raw Materials from Waste Electronic Equipment. Oeko-Institut e.V, Darmstadt, Germany.

⁴⁸ Binnemans, K., Jones, P.T., Blanpain, B., VanGerven, T., Yang, Y., Walton, A., Buchert, M., (2013), Recycling of rare earths : a critical review, Journal of Cleaner Production, 51, 1–22.

Physicochemical separation methods can also be used for the pre-treatment of the phosphor mixture before recycling of its REE content, to remove the halophosphate phosphor fraction from the rare-earth phosphors⁴⁹. For the recovery of REE, the phosphor mixtures are chemically attacked and the REEs are recovered from the solution by precipitation or solvent extraction, similar to the process used for the processing of REE ores. A number of researchers, mainly in China and Japan, have developed alternative methods and chemicals for the extraction of REEs. OSRAM (owned by Siemens) has also patented a process to recover all REEs from used phosphors while Rhodia-Solvay has already established two dedicated facilities in France that have been in operation since 2012.

A key advantage of the recycling of REE from fluorescent lamps is that they are collected in many countries due to their mercury content. After their collection, the lamps are typically being processed to recycle their glass, metal, plastics, phosphor powder and mercury. Thus, a fully developed supply chain that ensures the collection of the phosphorus is already in place, in contrast to the recycling from other REEs sources.

3.4.3. REEs from batteries

Nickel metal hydride (NiMH) batteries contain lanthanum cerium, praseodymium and neodymium. Until recently, the industrial recycling of NiMH batteries consisted of the smelting of whole battery focusing on the extraction of nickel for use in stainless steel production. The rare earths were lost in the smelter slags. Recently research has led to the development of metallurgical methods for the recovery of nickel, cobalt and rare earths from NiMH batteries. In 2011, Umicore and Rhodia announced that they have developed a process for recycling rare earths from nickel metal hydride rechargeable batteries.

Besides these three key areas, recovery of REEs from optical glass and glass polishing powder that are used in WEEE has also been researched using various methods for the extraction of metals and REEs. However, all are still at the lab-scale with no information on any possible moves to industrial scale.

In conclusion, there have been are a few industrial scale recycling activities currently implemented or examined for rare earths. However, may more recycling technologies remain at a laboratory scale.

Table 5: Review of existing REEs recovery technologies

Source of REEs	Technology/ method	Stage of technology	Existing at industrial scale
Lamp phosphors (Ey, Terbium, Yt)	Chemical attack of phosphors and recovery of REEs from the solution by precipitation or solvent extraction	Mature (but still developing)	Yes (Rhodia)
Cathode Ray Tube phosphors (Ey)	Chemical attack and solvent extraction	Limited research (declining interest)	NO
Permanent Magnets	Hydrometallurgy	Mature generally but still in lab scale	Investment project

⁴⁹ Ibid.

Source of REEs	Technology/ method	Stage of technology	Existing at industrial scale
(Neodymium, Dysprosium, Samarium)		in relation to REE	(Rhodia)
	Pyrometallurgy	Mature generally but not in relation to REE	NO
	Gas-phase extraction	Lab scale	NO
	Reprocessing of alloys to magnets after hydrogen decrepitation	Lab scale	NO
	Biometallurgical method	Lab scale	Planned pilot in 2014
Nickel metal-hydride batteries (lanthanum cerium, praseodymium and neodymium)	Combination of Ultra High Temperature smelting and hydrometallurgy/pyrometallurgy	Mature	Yes (Umicore & Rhodia)
Optical glass (Lanthanum)	Hydrometallurgy process	Lab scale	NO
Glass polishing powder (Cerium)	Chemical process	Lab scale	NO

Source : Binnemans et al. (2013) and own elaboration

3.5. What could be the environmental footprint of these technologies?

In general, REE recycling has significant advantages over the mining of rare earths including savings in energy, water and chemicals consumption, along with a significant reduction of emissions, effluents and solid waste generation resulting from the extraction and processing of rare earth ores. REE recyclates do not contain radioactive thorium and uranium, unlike the primary mined rare-earth ores. Therefore, radioactive tailing stockpiles and mining health problems can be, at least partially, avoided. There are also possible benefits from avoiding land allocation for the mine and for radioactive waste streams and transportation.⁵⁰ Furthermore, recycling helps address the so called "balance problem"⁵¹, namely the fact that certain REEs with high level of demand (e.g. Europium, Dysprosium) are present in small quantities in REE ores along with other REEs that have low demand. This means that in order to meet the demand for the former, the latter are produced in excess and are stockpiled.

Nonetheless, the environmental footprint of some recycling methods for REEs may itself be significant. Most of the processes described above require high levels of energy use, consumption of large amounts of chemicals and generation of waste chemicals and water. Hydrometallurgical processes are comparable to those used for the extraction of

⁵⁰ A. Golev, M. Scott, P.D. Erskine, S.H. Ali, G.R. Ballantyne, (2014), "Rare earths supply chains: Current status, constraints and opportunities", Resources Policy, 41, 52-59.

⁵¹ Binnemans,K.,Jones,P.T.,Acker,K.,Blanpain,B.,Mishra,B.,Apelian,D., (2013), Rare-earth economics: the balance problem, Journal of Management, 65, 846-848.

REEs from minerals, large amounts of strong acids and non recyclable chemicals (NaOH, HF) are required for the recycling of REE magnets where alloys first have to be converted into oxides (or chlorides or fluorides) and then reduced back to the metal. They also generate large quantities of waste water. The removal of mercury from lamp phosphors which contain europium, terbium and yttrium, requires complicated, energy intensive equipment (Buchert et al., 2012). The fact that REE in electronic waste is often present in very small concentrations may lead to high levels of inputs used per amount of REE recovered. At the same time though, developments in REE mining processes lead to reductions in the environmental impacts. A few experts have suggested that some of the processes developed may even be comparable to recycling in terms of their overall environmental footprint.

A recent study by Sprecher et al. (2014)⁵² examined the recycling of neodymium from hard disk drives in comparison to the extraction route concludes that, especially in the case of manual dismantling, recycling is preferable to primary production with 88% less energy use and 98% lower Human Toxicity than primary production process. In the case of shredded HDD the benefits are still significant (58% less energy and 81% lower Human Toxicity). There are also differences between the two processes. Manual disassembly allows for all magnetic material to be recovered while shredding leads to very low recovery rates (<10%). Similar work takes place in the context of RARE³ project funded by KU Leuven and industry focusing on rare earths in magnets and lamp phosphors assessing the environmental footprint of these technologies (Binemmans et al., 2013)⁵³. No results are currently available⁵⁴.

Concluding, the overall environmental footprint of certain parts of the recycling process can still be significant and the extent of improvement, against mining and processing of ores, depend on the specific element concerned and the process used.

3.6. What are the main drivers for a rapid industrial exploitation of rare earth recycling from electronic waste streams?

The review of the literature and the discussions with experts in the sector point to a number of key drivers and critical parameters that can determine a rapid industrial exploitation of rare earth recycling and recovery.

From the positive side, TNO (2013)⁵⁵ concludes that there is supportive political and regulatory context and societal support for the development of recycling in general, together with the presence of large and increasing amounts of WEEE and a number of firms with significant technological capacity. In addition, there is expectation of increasing demand for certain REEs used in some electronic devices particularly for the rare earths used in magnets and new energy technologies together with concerns about the future availability (UNEP, 2013). However, there are also a few key parameters which, on the basis of the discussions and review of relevant studies, are seen as barriers. The first concerns the economics of REE recycling determined by the prices of REEs - as determined by the current and future demand and supply for REEs – and the costs of existing recycling and recovery processes. The second is the absence - in

⁵² Sprecher,B., Xiao,Y., Walton,A., Speight,J., Harris,R., Kleijn,R., Visser,G., Jan Kramer,G., (2014), Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets, Environmental science and technology, 48 :3951-3958.

⁵³ Binemmans,K., Jones,P.T., Acker,K., Blanpain,B., Mishra,B., Apelian,D., (2013), Rare-earth economics: the balance problem, Journal of Management, 65, 846-848.

⁵⁴ KU Leuven (2014), RARE³ – Research platform for the advanced recycling and reuse of rare earth – Focus teams, <http://www.kuleuven.rare3.eu/focus.php>, Accessed on 23.10.2014.

⁵⁵ Elewaut,E., Bastein, T., (2013), Raw Materials: Study on Innovative Technologies and Possible Pilot Plants – Draft final report.

general - of an effective supply chain concerning the collection and pre-treatment of WEEE in relation to critical raw materials.

3.6.1. The Economics of rare earth recycling

The sharp increase in the price of most rare earth elements since 2009 played an important role in the increased level of research – and in some cases investments – in REE recycling over recent last years. However, prices have gradually returned to almost pre-2009 levels even if with variations depending on the specific element⁵⁶ – and this is clearly seen as a major consideration for any future investment in REEs. The existing volatility in the market and the uncertainty that this creates is also not supportive for investments in large scale recovery.

The discussions with experts and industry suggest that, at the current price levels, the recycling of rare earths is in most cases not economically viable. However, a moderate increase in the prices could change the picture. The representative of one firm that has been in relevant projects considers, at this point, that a business case could be made if prices for recycled material were at least 10 times higher. One of the large scale manufacturers already involved in the recovery of REE suggested that even a 50% increase in prices (1.5 times higher) would make some of the existing processes profitable.

From the costs side, bringing refining/recovery processes to an industrial scale often require sizeable investments⁵⁷, although this may not be the case for sorting and dismantling. The European Electronic Recyclers Association suggests that increasing complexity of EEE, miniaturisation and shorter life cycles of products pose technical and economic challenges that have led to reduced recovery rates and lower returns⁵⁸. Thus, ensuring economies of scale is important for the viability of the overall process. The involvement of large enterprises with significant financial resources to invest in new facilities or to adapt existing processing units is most probably necessary. Even then, the value of the recycled material will need to be able to cover the costs for the whole process of collection and recycling. Currently, this does not seem to be the case for most areas of REE recycling.

3.6.2. Effective collection and pre-treatment system

Existing collection, sorting and pre-treatment systems for WEEE are generally not focused on critical raw materials – and particularly REEs – which are often present in very small quantities within complex EEEs. Shredding of WEEE is the dominant approach in Europe and this leads to the loss of REEs in dust and ferrous fractions. The low concentration of rare earths in the waste streams before the final recovery process poses important questions as to whether recycling can be made economically viable in the absence of sorting processes that will ensure higher level of concentration and standard quality before the recovery process.

Thus, there is a need for the development of targeted collection systems including dismantling, sorting and pre-processing. Currently, only in the case of lamps is the supply chain geared towards the recovery phosphors, a result of the existing

⁵⁶ TRU (2013), Rare Earth Elements price bottoms out – China monthly data update?, <http://trugroup.com/rare-earth-conference> (page accessed on 27.10.2014).

⁵⁷ Figures for pilot plants provided in TNO study indicate capital investment costs in the range of EUR 5-50 million depending on the specific process.

⁵⁸ Norbert Zonneveld (2014), Circular economy-saving resources creating jobs – How to increase WEEE recycling rates, Presentation during the Green week, retrieved from http://www.greenweek2014.eu/docs/presentations/parallel-side-sessions-2/2-4/zonneveld_2.4.pdf.

requirements for the recovery of mercury in accordance to the WEEE Directive. Despite possible issues with the effectiveness of the technology used in the case of lamp phosphors, the recovery of REE from phosphorus is at this stage the one that is closest to reaching full scale industrial development.

It is also within this part of the overall recycling process cycle – the sorting and pre-processing – where most opportunities for SMEs are identified from almost all stakeholders. In contrast to the costly recycling and recovery processes that require sizeable investment, SMEs can find significant opportunities, if they are able to develop and implement innovative technologies and processes for the dismantling and sorting of WEEE that will lead to a high concentration of REEs in waste streams and make their recycling processes more effective. In this context it is important that access to WEEE stream is open to all firms in equal terms. They may also be involved in the provision of technical/engineering expertise across the supply chain providing R&D and technical support services to firms – within and outside EU - involved in the processing of REEs and manufacturing of components containing REEs.

3.6.3. Substitution of REEs

Demand for REEs is generally expected to increase, but this will also be affected by possible substitution in certain applications, driven either by scarcity or innovation. The analysis of possible substitutes for some REEs by the Öko Institute⁵⁹ concluded that direct substitution of an REE compound by another compound is a rare case and that in most cases substitution requires a totally new product design. In certain technological applications experts consider that the use of REE is key to ensuring the required functionality but there are also examples where REE may not be used in the future. For example, Li-ion batteries are gaining market share against NiMH in the case of portable devices. Furthermore, further development of solid state drives may lead to the replacement of hard disk drives. According to the study of the US Department of Energy (cited in the Oko Institute report)⁶⁰, LEDs might eliminate the need for lanthanum and terbium phosphors while continuing the use of cerium and europium. Future generations of organic LEDs might even be free of rare earths.

Even if substitution were to reduce the demand for REE in the future, the accumulation of WEEE containing REEs is expected to continue in the short to medium term given the long life of a number of products currently in the market. Thus, the availability of material and the opportunities for increasing the size of urban mining will continue.

3.7. What is the state of play with regard to international cooperation in research and innovation in this field?

At the EU level cooperation is mainly driven by the R&D projects supported within the context of the 7th Framework programme and Horizon 2020. Additional support mechanisms are the Life Programme and the Eco-innovation initiative. We have been able to identify nine (9) projects with a total budget of over EUR 35 million that are currently running or recently completed. They include development and demonstration of new recovery and recycling processes (e.g. REMANENCE, RECYVAL-NANO, REE Cover, Hydro WEEE) and sorting technologies (e.g. RECLAIM). In addition, the FP7 funded European Rare Earth Recycling Network⁶¹ focuses on training young researchers in the

⁵⁹ Öko Institut(2011), Study on rare earths and their recycling – A report for the Greens/EFA Group in the European parliament.

⁶⁰ Ibid.

⁶¹ <http://erean.eu/>

science and technology of rare earths, with emphasis on the recycling of these elements from permanent magnets.

Looking into the future, in the context of the European Innovation partnership the 3 approved long terms projects commitments (HydroWEEE, WEEE 2020 and EARTH 2020) which were recently approved bring together a large number of actors across the industry. Approvals of proposals for funding under Horizon 2020 are not available at this point.

Moving beyond the EU programmes, the Research Platform for the Advanced Recycling and Reuse of Rare Earths (RARE³) represents a long term project funded by KU Leuven and brings together industry (27 firms) and researchers from a number of disciplines. It focuses on developing breakthrough recycling processes based on non-aqueous technology for the two main applications of rare earths: permanent magnets and lamp phosphors, which represent >70% of the rare earths market by value. The broader objective is to create fully integrated, closed-loop recycling flow sheets for rare-earth magnets and phosphors while, in parallel, the project activities include a life cycle analysis of the recycling of rare earths in magnets and lamp phosphors.

Table 6: EU funded research and innovation projects in the REE recycling thematic area

	Project name Duration	Programme Budget	Key Project Objectives
1.	RECLAIM 1/2013-12/2016	FP7 EUR 7.0 m	Develop technological solutions that relieve bottlenecks in the recycling of gallium, indium, REEs Demonstrate their application potential by means of a pilot implementation in an industrial setting.
2.	RECYVAL NANO 12/2012-11/2016	FP7 EUR 4.4m	Develop an innovative recycling process for recovery and reuse of indium, yttrium and neodymium metals from Flat Panels Displays
3.	RECLAIM 1/2013-12/2016	FP7 EUR 7.0 m	Develop technological solutions that relieve bottlenecks in the recycling of gallium, indium, REEs Demonstrate their application potential by means of a pilot implementation in an industrial setting.
4.	REEcover 12/2013-11/2016	FP7 EUR 8.0 m	Improve European supply of REEs (Y, Nd, Tb, Dy) Strengthen SME position in REE production and recovery value chain Research routes for metallurgical recovery of REEs Demonstrate viability and potential of different types of deposited industrial wastes including magnetic waste material from the WEEE recycling industry
5.	Hydro-WEEE 10/2012-9/2016	FP7 EUR 3.8 m	Develop innovative plant technology that uses liquid solvents to extract metals including REEs in high purity from electronic waste Accommodate the needs of (SMEs) in the process of adopting new technologies and processes.

	Project name Duration	Programme Budget	Key Project Objectives
6.	Biolix 10/2012- 09/2015	Eco-innovation initiative EUR 2.1 m	Develop bacterially-catalyzed process for the selective recovery of purified metals out of low grade polymetallic materials. Develop first bio-hydrometallurgical unit by 2014
7.	REWARD 08/2009- 07/2012	Eco-innovation initiative EUR 1.3 m	Present a design for a new prototype facility for the generation of recyclable products from WEEE to substitute virgin primary materials and to decrease dependency on imports.
8.	LOOP 6/2012/- 11/2014	Life programme EUR 2.5 m	Validate the potential of innovative, environmentally friendly recycling of REEs contained in phosphorescent powders of fluorescent lamps.

Sources: CORDIS database, Eco-innovation, Life programme

Outside Europe, the Centre for Resource Recovery & Recycling (CR3)⁶² was jointly set up by KU Leuven in Belgium, Worcester Polytechnic Institute (WPI) and the Colorado School of Mines (CSM) but also involves key firms like Umicore and Veolia. Their research focuses on development of cost-effective technologies to recover HREEs from lamp phosphor dust and Nd from waste magnets, but also the development of sorting and REEs separation methods.

The recent reports on patenting activity from the WIPO⁶³ suggest an increasing level of patenting activity in the last 5-10 years and Japan-based entities are the pre-eminent source of new patent applications followed by the United States, China, Germany and France.

Finally, it is worth referring to the trilateral workshops on critical raw materials that brings together policy makers, experts and industry from the EU, United States and Japan focusing on information exchange, promotion of collaborative research as well as collaboration on regulation⁶⁴.

3.8. How is coordination between the Member States organised?

On the basis of our research and discussion with experts and authorities, there appear to be no formal mechanisms of coordination among Member States in relation to rare earths policy.

Concerning the demand for rare earths, Member States authorities themselves do not have any active role in the management of industrial demand – or any other critical raw materials. The general view is that this is primarily the responsibility of industry and the focus of national governments and the EU concentrates on ensuring free trade terms and access to resources. In that respect, the Market Access Advisory Committee - composed of Member State representatives who identify and analyse market access barriers in

⁶² WPI (2014), Centre for Resource Recovery & Recycling <http://wp.wpi.edu/cr3/>.

⁶³ WIPO (2013), Patent Landscape Report on E-Waste Recycling Technologies.

⁶⁴ EC (2013), US-Japan-EU trilateral workshop on Critical Raw Materials 2 December 2013: workshop report, <http://ec.europa.eu/DocsRoom/documents/5663/attachments/1/translations/en/renditions/native>.

non-EU countries - represents the tool to monitor possible restrictions affecting trade in raw materials.

At the broader level, the ad-hoc working group on critical raw materials, the cooperation project in the context of the EU research programmes and the EIP Raw Materials High Level steering group represent mechanisms to facilitate cooperation. However, it is not possible to refer to the formal coordination structures among Member States.

3.9. How effective are the existing measures to support the development of new business models based on eco-innovation?

There are a number of policy measures that are available to support the development of new business models based on eco-innovation. These include:

- Creating and strengthening green innovation opportunities through supply side measures such as support of R&D and technology development and market replication and demand in the form of procurement, development of standards or environmental labels;
- providing an enabling market environment through regulatory framework and market institutions;
- facilitating the interaction and co-operation between different kinds of organizations.

There has been limited information and studies available directly addressing the role of existing measures to the promotion of eco-innovation based models. One of the relevant financial support programmes has been the Eco-innovation Initiative that has been running since 2008. So far it has funded four⁶⁵ projects focusing on the recycling of electronic waste and one project (Biolix⁶⁶) focusing on the rare earths. The recent review of the Eco-innovation initiative⁶⁷ concluded that, in general, the programme has helped shorten the time to market of eco-innovation and the time taken to secure a payback on the investments made in the projects. The programme has also allowed smaller companies to collaborate on equal terms with larger ones and to be involved in international collaboration which otherwise would have been very difficult.

Turning to the legal framework, waste legislation (including WEEE Directive) and the Ecodesign Directive are, potentially, relevant. However, at this stage the WEEE Directive – even after its recent revision – focuses on weight and volume targets and has had a rather limited role to play in promoting the recycling of critical raw materials and rare earths that are present in small quantities. Furthermore, there have been different effectiveness and efficiency levels in terms of meeting the recycling targets set.

In the case of the Ecodesign Directive, the recent evaluation⁶⁸ pointed to a supportive role of the Directive in promoting innovation, even though the priority of the Directive is mainly to remove the worst performing products from the market. In addition, beyond energy efficiency aspects the role of the Ecodesign Directive in addressing other environmental consideration has been very limited. A number of stakeholders point to the potential for promoting of product design that will take in consideration recycling

⁶⁵ WEEE TRACE, BIOLIX, REWARD, E-AIMS.

⁶⁶ Eco-innovation (2014), Biolix project information sheet, <http://ec.europa.eu/environment/eco-innovation/projects/sites/eco-innovation-projects/files/projects/documents/vb - biolix.pdf>.

⁶⁷ EACI (2013), Analysing and reporting on the results achieved by CIP Eco-Innovation market replication projects, Report prepared for EACI by ICF GHK in association with VITO and UNU-MERIT.

⁶⁸ CSES (2012), Evaluation of the Ecodesign Directive (2009/125/EC) - Final Report.

requirements⁶⁹ (e.g. design for dismantling/recovery/recycling) through the introduction of relevant requirements. At this stage, such requirements are missing from the Directive the reason being, among others, the absence of appropriate methodologies and relevant data.

Extended Producer Responsibility schemes can also play a role in support raw materials recycling if pre-paid fees can contribute towards investments for sorting and recycling facilities. However, so far the efficiency and effectiveness of EPR schemes vary considerably among EU Member States.

3.10. How efficient is the European Innovation Partnership on Raw Materials?

The European Innovation Partnership on Raw Materials (EIP-RM) has set an overall objective of reducing Europe's import dependency on the raw materials that are critical to Europe's industries. The recently developed Strategic Implementation Plan of the EIP of Raw Materials (2013) identified priority areas and sets relevant targets. A number of them are directly or indirectly linked with issues relating to rare earths discussed earlier.

However, the EIP-RM does not provide additional sources of funding. Its role is to ensure coordination among the various financial support tools at the European (e.g. Horizon 2020, Life programme, Structural funds) and the national level and also to ensure coherence with the goals of the EU 2020 strategy and the Innovation union flagship initiatives.

At this stage it is too early to refer to specific results and assess efficiency and effectiveness of the EIP. Implementation started in 2013 and has a timeframe up to 2020. The Commission is intending to publish annual monitoring reports and also conduct a first mid-term evaluation in 2015⁷⁰. So far a couple of studies have been commissioned – including the 2013 revision of the study on Critical Raw materials. Furthermore, a total of 80 commitments by partners to activities aimed at achieving the EIP objectives were approved in 2013. The input from stakeholders involved in the process suggests that the EIP has helped develop a more coherent and consistent structure.

3.11. How can the emergence of value chains based on the recovery and recycling of rare earths be anticipated and facilitated?

The picture illustrated suggests that, under the current circumstances of low rare earth prices, high costs for technology untested at an industrial scale and the absence of effective collection and sorting schemes, the emergence of a value chain is not imminent for the majority of products. The industry is looking into the opportunities arising – in many respects motivated by concerns for future supply constraints and, to some extent, by the increasing level of public support available – but actual investments at an industrial scale are still limited. Only a few firms are currently actively involved in the recycling of rare earths although a significantly greater number is involved in relevant technologies and processes and has relevant technical expertise.

Market driven developments that may lead to the emergence of a value chain include:

- possible future constraints in the availability of rare earths (particularly HREEs) and subsequent prices;

⁶⁹ UNEP (2013), Metal Recycling – opportunities, limits, infrastructure – A report of the working group on the global metal flows to the international resource panel, Reuter, M.A., Hudson, C., van Schaik,A., Heiskanen, K., Meskers, C., Hageluken, C.

⁷⁰ EC (2014), Monitoring and evaluation scheme for the European Innovation Partnership strategic implementation plan on raw materials.

- developments leading to significant reduction in costs as a result of new recycling technology or, more probably, in the sorting and pre-processing parts that will lead to reliable high levels of REE concentrations of rare earths in the processed waste streams.

Turning to the question of facilitating the development of value chains based on the recovery and recycling of rare earths, a recent study by Technopolis group⁷¹ examined various eco-innovation business models – including those related to waste regeneration and recycling - and assessed the possible role of available policy measures. The conclusion of their analysis in the case of waste regeneration systems is that the most relevant measures include the introduction of some type of environmental taxes/fees in combination with regulation and development of standards and labels. These are seen as particularly relevant for developing a firm foundation for the introduction of new eco-innovation based business models. In parallel, instruments including funding for R&D, testing, pilot plant development and commercialisation are also relevant to specific solutions such as development of new products and technologies.

Focusing on the specifics of the rare earths recycling and recovery, the review of the literature and the discussions with expert points to the following possible mechanisms to facilitate the development of a recovery/recycling value chain:

- Introduce changes to the legal framework: this will include possible changes to the WEEE Directive introducing more sophisticated waste recovery targets going beyond existing weight targets and motivating separation on the basis of material content. It should be noted though that setting targets for the recycling of specific REEs could be ineffective and costly if it does not recognise the fact that REEs are present in different forms in different products and the extraction costs and effectiveness can vary greatly. As such, a product specific approach – including design requirements through the Ecodesign Directive - taking into consideration recycling requirements is probably more appropriate in the case of REEs⁷². At the initial stage, information requirements on the presence of critical raw materials could be introduced to facilitate recycling process while, at a later stage, the adoption of specific design principles (e.g. design for dismantling/recovery/recycling) could be introduced;
- promote the development of standards in relation to design of products, reporting on raw materials content and sorting and dismantling taking into account critical raw materials that will facilitate the exchange of information along the supply chain concerning the presence of REEs and lead to recyclates with levels of REE concentration;
- further support R&D and innovation activities for development of refining technologies but also for the collection, sorting and pre-processing processes geared towards critical raw materials and rare earths;
- provide financial support to demonstrate the viability of the recycling of rare earths through pilot plants based on existing mature technologies, possibly in the context of the Eco-innovation initiative;
- adoption of economic instruments such as extension of producer responsibility schemes to cover the costs of collection and recycling or targeted financial support for critical raw materials recycling.

⁷¹ Technopolis (2012), Business Models for Systemic Eco-innovations - Final Report, http://www.technopolis-group.com/wp-content/uploads/2014/04/1524_EcoBM-Eco-Innovation-Business-Models-assessment.pdf.

⁷² UNEP (2013), Metal Recycling – opportunities, limits, infrastructure – A report of the working group on the global metal flows to the international resource panel, Reuter, M.A., Hudson, C., van Schaik,A., Heiskanen, K., Meskers, C., Hagelukken, C.

4. CONCLUSIONS AND RECOMMENDATIONS

In this section we summarise the key conclusions arising from the analysis and propose recommendations for improvements of existing actions or adoption of new policies.

4.1. Conclusions

Rare earth elements are critical due to their importance for a number of applications, including a number of green technologies, but, primarily, because of the high supply risks arising from the dependence on a single source (China). In the medium to long term, supply of REEs is expected to exceed demand with the notable exception of a few key REEs (Europium, Terbium, Yttrium, Dysprosium) which are used in the production of permanent magnets and phosphors.

The increase in the price of REEs during the period 2009-2011 following China's decision to significantly tighten its export quotas increased interest in REEs and led to new mining projects outside of China, research into the substitution and recycling of REEs and related policy initiatives. Prices for some REEs have since returned to pre-2009 levels and this has had a cooling effect in terms of investments in recycling.

It is important to appreciate that currently there is only restricted capacity within Europe to manufacture the goods and components that make use of REEs directly. Most use of REEs is in a form where they are already embodied in components manufactured outside the EU.

The review of the literature on existing recovery technologies of REEs from WEEE suggest that – while there has been significant level of research – very few of them have moved to industrial scale. Generally, while metallurgical extraction chemistry is well-known, the challenge usually lies with dealing with the impurities that accompany the typical recyclates. To this point, the recovery of REEs from lamp phosphors is the most mature in terms of industrial scale application.

The prime determinant towards industrial scale recycling of REEs does not appear to be the need for further development of technologies. The key parameters are, on the one hand, the economics of the REE recycling -determined by the costs of the process and the need to achieve economies of scale and the REE prices- and, on the other, the absence of a supply chain structure geared towards the pre-processing of WEEE with focus on REEs. An effective supply chain is necessary to ensure availability of suitable recyclates with high REEs concentration from which REEs can be economically recovered based on existing technologies. Thus, while further development of both pre-processing and refining technologies is still important, most experts agree that priority should be in addressing existing gaps in the supply chain. Furthermore, each application of REEs within complex products has its own specific characteristics and poses different challenges to the recycling process. As a result, product-specific solutions are in most cases necessary.

Within this context, future opportunities for small and medium enterprises arise primarily in the area of sorting and pre-processing of WEEE streams - where large scale investment and achieving economies of scale may not be critical. In that respect, it is also important that SMEs have access to relevant WEEE streams. Another area is the provision of engineering/technical services. There is an important number of SMEs and research organisations involved in R&D with high level of technical expertise. This expertise can be used to support the development of various parts of the recycling supply within Europe, but also exported to other countries where most of the processing of REEs and manufacturing of components containing REEs take place.

There has been significant level of support for R&D in the recycling of REE as well as some pilot projects, mainly through the Framework Programme for Research and, at a lesser degree the Eco-innovation and Life programme. The EIP on Raw Materials is expected to contribute further to the development of research and technology in the specific area, but it also integrates relevant non-technological aspects (changes to the existing legal framework, development of standards that can contribute to effective information exchange and development of the supply chain). The existing commitments in the context of the EIP bring together most relevant actors. However, it is too early to assess the effectiveness of these initiatives.

The Raw Materials Initiative has played an important role in terms of setting the direction for policy making in relation to critical raw materials and it has been followed by action in a number of Member States (development of national strategic plans, support for R&D, investment in increasing knowledge and understanding of raw materials flows). The private sector has also contributed, mainly through participation in R&D projects but also through involvement and sharing of knowledge in the relevant groups established through the RMI.

The level of formal coordination among Member States in the area is rather limited. There are no coordination structures for managing the demand for rare earths at the European or national level. This is considered to be a responsibility of industry. The main mechanisms for information and experience exchange among Member States and the industry are those established in the context of the RMI.

4.2. Recommendations

On the basis of the analysis, there are a few areas where enhanced or additional action is merited. The following set of recommendations is directed towards different actors.

For the EU and Member States:

- increase available financial support through existing European and national schemes with greater focus on product-specific solutions, giving priority to the later stages of technology development, establishment of pilot plants and demonstration projects and consideration of all steps of the recycling process;
- sustain and extend the work and expertise developed in the context of the ad-hoc group on critical raw materials and the ERECON network to maintain a high level of understanding of the potential of REEs recycling and how developments in technology and the markets may affect the viability of REE recycling;
- expedite existing work for the development of methodologies and data collection in the context of the Ecodesign Directive so that requirements for submission of information on raw material content and design for recycling can eventually become mandatory;
- support development of standards concerning the information on the presence of raw materials in complex products (e.g. through environmental product declarations) and for sorting, pre-processing and recycling activities that will cover critical raw materials;
- examine the feasibility and possible effectiveness of economic instruments adopted at EU or national level aiming to influence the economics of REE recycling. These may include subsidies for pre-processing and recycling of critical raw materials and ensuring that critical raw materials are part of extended producer responsibility schemes.

For industry:

- organise networking activities among the different actors in the supply chain to increase the level of interaction between product designers, producers, waste management and recycling firms and develop a common understanding of the challenges arising for end-of-life recycling.

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NOTES

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