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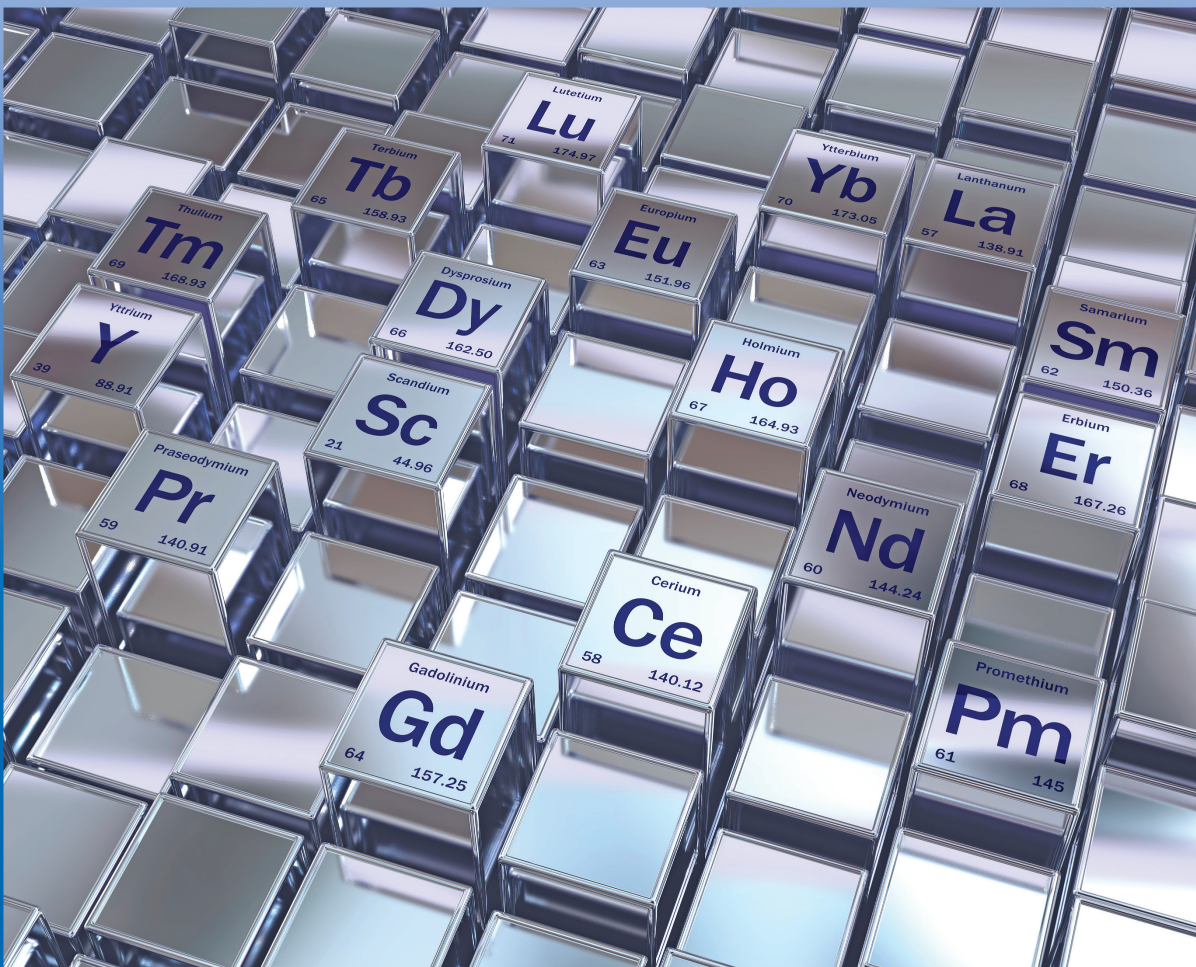
Priorities for critical materials for a circular economy



EASAC policy report 29

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building science into EU policy

EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. EASAC was founded in 2001 at the Royal Swedish Academy of Sciences.

Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union. It is funded by the member academies and by contracts with interested bodies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 29 individual members – highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway and Switzerland are also represented. The Council is supported by a professional Secretariat based at the Leopoldina, the German National Academy of Sciences, in Halle (Saale) and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

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Foreword

EASAC, which celebrated its 15th anniversary in 2016, brought together the collective resources of Europe's academies of science to primarily address policy-relevant scientific issues, and since 2001 we have worked on a very wide range of issues within the broad categories of environment, energy and biosciences. Since our creation, however, it has becoming increasingly obvious that key science-based issues with major policy ramifications may also include important aspects that are best addressed from the perspective of the social sciences, particularly economics. It has long been a topic for discussion in our Council to what extent we should extend our activities to recognise this and include the social sciences in relevant projects.

With the intensive debate that took place during 2013 to 2014 within the European Commission and Parliament on the circular economy, an issue emerged that is very much an inseparable combination of science, technology and social sciences which cannot easily be compartmentalised into one or the other. With a strong wish in the Council to contribute to this debate, we took EASAC's first decision to actively engage social scientists in a major project. Member Academies were invited to nominate experts for the Circular Economy Working Group across all fields of natural and social sciences, and we were pleasantly surprised to find that our membership responded very positively and provided a rich resource of experts in social as well as the natural sciences.

The result of that original project was a statement we released in November 2015 addressing some of the circular economy issues from the perspective of the natural and social sciences. Given the limited time available to that initial project, we were unable to address in sufficient detail some of the issues that arose, and the Working Group suggested additional projects that EASAC could undertake to contribute to the Commission's declared follow-up actions in its 2015 circular economy statement.

One of those important issues is the identification of which materials are critical to the European Union, on what basis their criticality should be assessed, and what are the implications of a material being identified as critical. To address these key points, members of the original Working Group on the circular economy with a particular interest in this subject worked together with our programme director to compile the detailed analyses in this report. We have timed its completion and publication to be consistent with the schedule of the Commission, which is planning to review and update its list of critical materials during 2017. We hope that our analysis of this issue will be useful to all the stakeholders involved in this process.

Jos WM van der Meer
EASAC President

Summary

The European Commission is in the process of preparing a report on critical raw materials in the circular economy. This was one of the issues identified in EASAC's earlier commentary on the implications of natural and social sciences for the circular economy, and this report follows up the issue in more detail.

This report reviews briefly the historical criteria for critical raw materials currently under review by the Commission and the Joint Research Centre (JRC), and notes that many critical materials still have very low recycling rates which increases the demand for virgin materials and therefore reduces lifetime of supply. EASAC is in broad agreement with the criteria that the Commission proposes to apply in selecting critical materials for the new list in 2017 but notes that environmental impacts of extraction of raw materials are substantial and should be considered in the criticality assessment. EASAC recognises limitations on available data that would allow the Commission to measure environmental impacts and risks related to extraction and processing, but encourages the Commission to continue work on developing a methodology to consider environmental and social considerations outside the European Union (EU). The report compares the energy and water consumption requirements for production of metals from primary ores with those for recycling, and shows the major reductions in environmental impact that can be achieved through increased recycling.

The Commission considers substitution and recycling rates as factors in its criticality assessments but EASAC cautions against relying too much on substitution as a solution to anticipated supply constraints. Insufficient attention is given to the basic geological distribution of critical elements, and EASAC offers some potential approaches to analysing scarcity and identifying which elements are likely to be at risk of future scarcity. We also note that the Commission is already addressing some of the issues raised in this report including forecasting future reserves and supply, and extending the coverage to non-metals including helium.

The report considers securing the future supply of critical materials from two angles. Firstly, measures that can be taken to increase supply, where a fundamental point is that many of the anticipated critical elements are associated in nature with 'attractor' or 'carrier' base metals and therefore can be co-products of a primary metal smelter. Increasing supply in Europe is part of the EU Raw Materials Initiative but the strategy needs to take into account this complex interrelationship. Producers of base metals are key sources of critical elements so that supply is dependent on taking a systems-integrated metal production approach. By improving the extent to which these critical materials are separated from their carrier base metals, it is possible to significantly increase their supply within the EU.

The second approach is to improve recycling rates for critical materials, some of which are very low. Consumer goods are an important source but the elements are distributed at low concentrations over a wide range of products which have to be collected for recycle. The report analyses some of the logistical and technological challenges to this and concludes that there is substantial potential for improving recycling. However, ensuring efficient use and recovery of critical materials requires a different approach from the broad targets previously applied to recovery rates of bulk materials. Specific points include the following:

- Effective recycling requires sophisticated knowledge of the components present in the end-of-life (EoL) products stream and this cannot be achieved with mixed recycling in broad categories. EASAC is satisfied that the case for moving towards a product-centric approach to collection and recycling is strong and should feature in the development of future EU policy.

- A more product-centric approach could improve on current low levels of recovery by encouraging recovery at end of life to be built in to dedicated collection schemes providing feedstock for specialised recycling. Options include deposit schemes, including return and recycling costs in the purchase price, trade-in which offers a financial reward for return, or contractual obligation. The current situation whereby much of Europe's e-waste leaves the EU (in many cases for informal and inefficient recycling in Asia or Africa) comprises a significant leakage of critical metals requiring attention. A level playing field is needed so that low-quality recycling or avoiding recycling through legal loopholes does not continue to offer the cheapest option. The current proposals to amend the Extended Producer Responsibility requirements provide a mechanism to incorporate special emphasis and priority on products containing economically significant quantities of critical materials.

- Supply of critical metals requires a baseline technology infrastructure that can recover metals from complex mixtures, thus extending the concept of criticality from that of the individual elements to the infrastructure necessary for their cyclical use. The EU should evaluate the adequacy of the EU's 'Critical Metallurgical Infrastructure' for the critical metals decided and consider measures to strengthen it.

- Product design should consider the complexity of recycling and avoid incompatible metal mixtures, or joints between product parts that hinder recycling. EASAC notes, however, that trends driven by consumer convenience and demand continue to introduce additional burdens rather than facilitate recycling. The Commission should seek to engage consumer groups as well as manufacturers in a dialogue on ways of reducing or eliminating such inherent conflicts, so that 'design for resource efficiency' becomes standard practice.

- Developing effective recycling technology can require considerable investment. Particularly with critical materials, the circular economy policy needs to provide market signals which incentivise all companies to work towards a circular economy. The Horizon 2020 programme should also support research and development on critical materials recovery and recycling ranging from the basic science underpinning the behaviour of metals and their mixtures to novel separation and purification processes.

1 Introduction

The European Commission (EC), in its document 'Closing the loop - An EU action plan for the Circular Economy' (EC, 2015), refers to critical raw materials as both of high economic importance for the EU and vulnerable to supply disruption; in certain cases, their extraction also causes significant environmental impacts. It undertook to **prepare a report on critical raw materials in the circular economy**. EASAC's earlier commentary on the implications of natural and social sciences for the design and implementation of a circular economy (EASAC, 2015) had also observed *inter alia* that setting criteria for critical raw materials may need to take into account several factors in addition to security of supply, and thus EASAC Council decided to explore this in further detail. This EASAC project has been guided by the Project Group listed in Annex 1. The focus of this report is critical chemical elements (particularly but not exclusively metals and metalloids).

2 Current EU policy and actions on critical materials

To achieve the basic goals in sustainable development (both of intra- and inter-generational equity), access to and security of supply of mineral and energy resources have to be ensured (Wellmer and Hagelüken, 2015). The supply of resources has thus attracted much attention globally, and the concept of very important or 'critical' resources or materials has emerged in several studies in the EU, USA, Japan and elsewhere.

The EC regards critical materials as economically important raw materials which are subject to a high risk of supply interruption. Most of the chemical elements involved (but not all, e.g. phosphorus, helium) are metals where Europe consumes 25–30% of the world's production; in contrast only 3% of global metal production is in Europe, and many important metals and other elements are not produced in Europe at all (Nurmi *et al.,* 2010; Sverdrup and Ragnarsdottir, 2014). As technological innovation has led to increasingly complex mixtures of elements to achieve specific purposes, various industries (including the energy technologies of hybrid and electric vehicles, wind turbines and photovoltaic panels) have become dependent on such technology-critical elements. Providing a stable and affordable supply is thus an important issue, especially since some of the reserves are concentrated in a very small number of countries.

In this respect, the EC launched the Raw Materials Initiative in 2008 (EC, 2008, 2011) which includes the three pillars of actions in Box 1[1].

Initial steps (EC, 2008) were to identify materials considered critical on the basis of 'supply risk' (how concentrated is production, the political and economic stability of the producing countries, the potential for substitution and recycling rate); and an 'environmental country risk' (where producing countries might place regulations on the supply of raw materials to Europe to reduce their environmental impact). Forty-one materials were assessed for criticality and 14 initially identified as critical. These were antimony (Sb), beryllium (Be), fluorspar, graphite, germanium (Ge), indium (In), magnesium (Mg), rare earth elements (REEs), tungsten (W), cobalt (Co), tantalum (Ta), platinum group metals (PGMs), niobium (Nb) and gallium (Ga). Subsequently, the EC recommended (EC, 2010) *'… policy actions to ensure that recycling of raw materials and products containing them becomes more efficient through promoting collections, stopping illegal exports of end of life (EoL) products and promoting research on system optimisation and on tackling technical challenges'*. The third pillar in Box 1 has also been integrated into the circular economy approach in the Commission's 2015's package (EC, 2015).

The Commission also charged the Joint Research Centre (JRC) with investigating potential bottlenecks associated with the use of metals in six energy technologies: nuclear, solar, wind, bio-energy, carbon capture and storage, and electricity grids (but not energy storage), each identified as strategic in the Strategic Energy Technologies Plan (SET-Plan)[2] (Moss *et al*., 2011; JRC,

1 It should be noted that this EASAC report is most relevant to Pillar 3 and does not address aspects in Pillars 1 and 2.
2 The SET is the technology pillar of the EU's energy and climate policy. C(2015) 6317 final.

Box 1 The main elements of the raw materials initiative

Pillar 1: Secure access to raw materials by ensuring undistorted world market conditions:

- through diplomacy with resource-rich countries such as China and resource-dependent countries such as the US and Japan for cooperation;
- through international cooperation via fora such as G8, OECD, etc. to raise awareness about the issues and create dialogue;
- by making access to primary and secondary raw materials a priority for the EU trade and regulatory policy, to ensure that measures that distort open market trade such as restrictions of exports and dual pricing are eliminated.

Pillar 2: Foster sustainable supply of raw materials from European countries, by:

- making sure the right framework conditions are in place to prevent delays in permitting that can inhibit new projects;
- improving the European knowledge base on mineral deposits. The long-term access to these deposits should be considered during land use planning;
- better exchange of information between countries through networking between the national geological surveys;
- promoting research projects with a focus on extraction and processing (7th Framework Programme and continued in Horizon 2020) and making funding available for projects;
- increasing the amount of skilled personnel by cooperating with universities and increasing public awareness of the importance of domestic materials.

Pillar 3: Reduce the EU's consumption of primary raw material, through:

- improving resource efficiency such as by improving product design, for example through the Eco-Design Directive;
- decreasing the amount of materials lost through illegal exporting to secure secondary raw materials. This will also require good relations with third countries to ensure the enforcement of Waste Shipment Regulations;
- increasing reuse and recycling through legislation, standards and labelling, financing, knowledge sharing, etc.

Table 2.1 Elements regarded as critical and technologies (JRC, 2013)

Element	Rating	Associated Technology
Rare Earths: Dy, Pr, Nd	High	vehicles, wind
Rare Earths: Eu, Tb, Y	High	lighting
Gallium	High	lighting, solar
Tellurium	High	solar
Graphite	Medium-High	vehicles
Rhenium	Medium-High	fossil fuels
Hafnium	Medium-High	nuclear
Germanium	Medium-High	lighting
Platinum	Medium-High	fuel cells
Indium	Medium-High	solar, lighting, nuclear
Rare Earths: La, Ce, Sm	Medium	vehicles
Rare Earths: Gd	Medium	lighting
Cobalt	Medium	vehicles, fossil fuels
Tantalum	Medium	geothermal, fossil fuels
Niobium	Medium	CCS
Vanadium	Medium	CCS
Tin	Medium	solar
Chromium	Medium	desalination

2013). JRC assessed criticality against risk criteria of supply constraints, demand growth rate, political risk and geographical concentration and summarised the most critical elements as in Table 2.1.

The Commission updated its earlier list of critical raw materials (CRM) in 2014 after analysing 54 materials using the criteria of economic importance and supply risk. This led to 20 CRM taken from a 'criticality zone' of high supply risk and economic importance, which were antimony, beryllium, borates, chromium, cobalt, coking coal, fluorspar, gallium, germanium, indium, magnesite, magnesium, natural graphite, niobium, PGMs, phosphate rock, REEs (heavy), REEs (light), silicon metal and tungsten. Following the 2015 policy package, the Commission plans to publish a new list during 2017 and the JRC has already published a revised analysis of the methodology on which that selection will be based (JRC, 2016).

3 Recycling of critical materials

Recycling reduces the amount of material lost in the product's life cycle and reduces the environmental impact associated with the extraction phase by reducing demand for virgin material. Recycling is also an integral part of the green economy (ETC/SCP, 2011). Recycling alone, however, cannot cover all demand for raw materials and primary and secondary raw material supply will still be needed for two main reasons. Firstly, capture of material for recycle at EoL will inevitably include some losses; moreover, in a global market of growing demands, supplies of EoL material will be from historical stocks at much lower levels than current demands[3]. Secondly, an ultimate limit to the potential of recycling of metals is that most applications require both high-quality grades and the absence of specific impurities. The mixed sources that emerge from EoL waste cause carryover of impurities during recycling which affects the specification of the target metal or alloy (Verhoef *et al.*, 2004). As a result, the range of suitable applications is restricted and such realities need to be factored into recycling policy and technology.

Recycling associated with EoL treatment (i.e. post-consumer) recovers useful materials, but metals may also be recovered during processing and manufacturing from waste produced at these stages. However, UNEP found in its review of recycling around the world for 60 metals, that EoL recycling rates for many of the rarer elements are currently very low (Figure 3.1) owing to the difficulties of collection and technological separation of critical materials from the product. The recycling rates for the elements in the EU-20 list of CRM are in Table 3.1. More recent figures relevant to the EU are available in a raw materials system analysis (Deloitte, 2015) which confirms the low rates of recovery for several of the current EU CRM list elements, as well as suggesting some have been assigned unjustifiably high recycle rates in the UNEP survey[4].

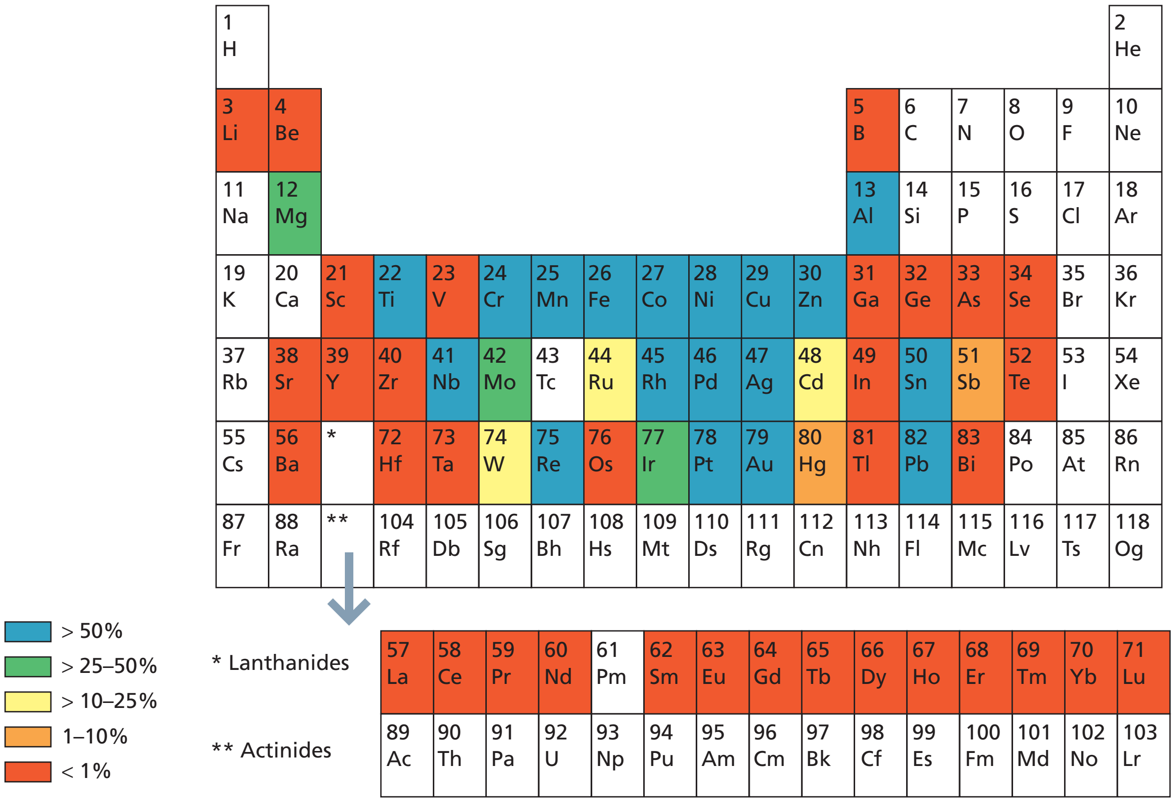

Figure 3.1 Recycling rates for critical materials (UNEP, 2011).

3 Even though near 90% of all ferrous scrap is recycled, this is only enough to meet about one-third of the global demand. For more information on recycling's contribution to meeting materials demand, see EIP (2016).

4 For instance Deloitte (2015) estimate that the 14 tonnes of platinum recycled is just ~20% of the input in processing, while approximately 4.7 tonnes go to landfill (in contrast to UNEP's estimate that more than 50% are recycled).

Table 3.1 Recycling rates in EU-20 CRM LIST (Wellmer and Hagelüken, 2015)

Recycling rate (according to UNEP)	Critical material on EU list
<1%	Beryllium, gallium, germanium, indium, osmium, rare earths
1–10%	Antimony
>10–25%	Ruthenium, tungsten
>25–50%	Magnesium, iridium
>50%	Cobalt, niobium, platinum, palladium, rhodium, chromium

The figures in Table 3.1 for some metals have been enhanced by including the near-100% recycling rates in jewellery, and overall efficiency of recycling from specific waste streams can be much lower than the average: for instance, the overall efficiency of gold and palladium recycling from WEEE in Europe is estimated to be below 20%. Such low rates of recycling have important implications for the longer-term supply situation for many metals since, as illustrated in Table 3.2, anticipated lifetimes of supply are highly dependent on improving recycling rates.

Table 3.2 Potential for extending the lifetime of supply through recycling (Sverdrup and Ragnarsdottir, 2014)

Element	Business-as-usual burn-off time* (years from 2011)	50% recycle (years from 2011)	70% recycle (years from 2011)
Nickel	42	**	209
Copper	31	**	157
Zinc	20	37	61
Manganese	29	46	229
Indium	19	38	190
Lithium	25	49	245
Tin	20	30	150
Molybdenum	48	72	358
Lead	23	23	90
Niobium	45	72	360
Helium	9	17	87
Arsenic	31	62	309
Antimony	25	35	175
Gold	48	48	71
Silver	14	**	43
Rhodium	44	**	132

*Burn-off time is defined as the estimated extractable resources divided by the present net extraction rate.
**Current recycle rate already 50% or above.

4 Factors to be considered in defining critical materials

The purpose of the current EC criticality exercise underway is to identify critical raw materials from a macro-economic perspective rather than from a more holistic sustainable development perspective. The basic criteria for a 'critical' material are firstly, a relatively high supply risk due to worldwide production being concentrated in only a few countries with potential geopolitical constraints (compounded by low substitution and low recycling rates), and secondly its economic importance (proportion of each material associated with industrial mega-sectors in the EU). The most recent review of the methodology (JRC, 2016) maintains these two basic criteria but updates them and provides a more detailed methodology for calculating material rankings and a more detailed analysis of the reasons for including and excluding certain factors. Thus the economic importance of the material is now calculated from a more detailed assessment of the use of the material in specific industrial sectors as well as a raw material-specific substitution index. Supply risk is now assessed by combining the level of governance in the country, and the risk of trade-related restrictions (such as export quotas). Supply risk can be reduced by allowing for EoL recycling rates and for substitution.

The JRC also considered five additional influences on supply risk and offer potential ways of integrating these into the criticality calculation. These are (1) land use competition, (2) mining governance, (3) by-production dynamics, (4) supply chain approach and (5) environmental and social considerations (which may influence the long-term supply risk). EASAC considers the current basis for analysis sound but would offer the following comments for consideration in the final assessment of criticality in 2017.

4.1 Environmental impacts of extraction and processing criticality

In its earlier criticality assessments, the Commission considered environmental impacts in producing countries as a factor to be considered through its potential regulatory impact on European industry rather than the environmental impact on the producing country itself. Environmental impacts are also part of the consideration in some of the five additional influences on supply risk itemised above (1, 2 and 5). For these reasons and from the point of view of global environmental protection, such environmental impacts warrant further consideration. Sources of data are however limited. While the environmental impacts of extracting some major elements have been characterised (e.g. iron and aluminium), those of others are less well quantified. In addition many elements are extracted in combination with others, or as subsidiary processes, so that assigning environmental impact to a single element can be difficult. Nevertheless impacts can be considerable, as illustrated by Schuler *et al*. (2011)'s qualitative discussion of rare earth environmental impacts and risks (Figure 4.1).

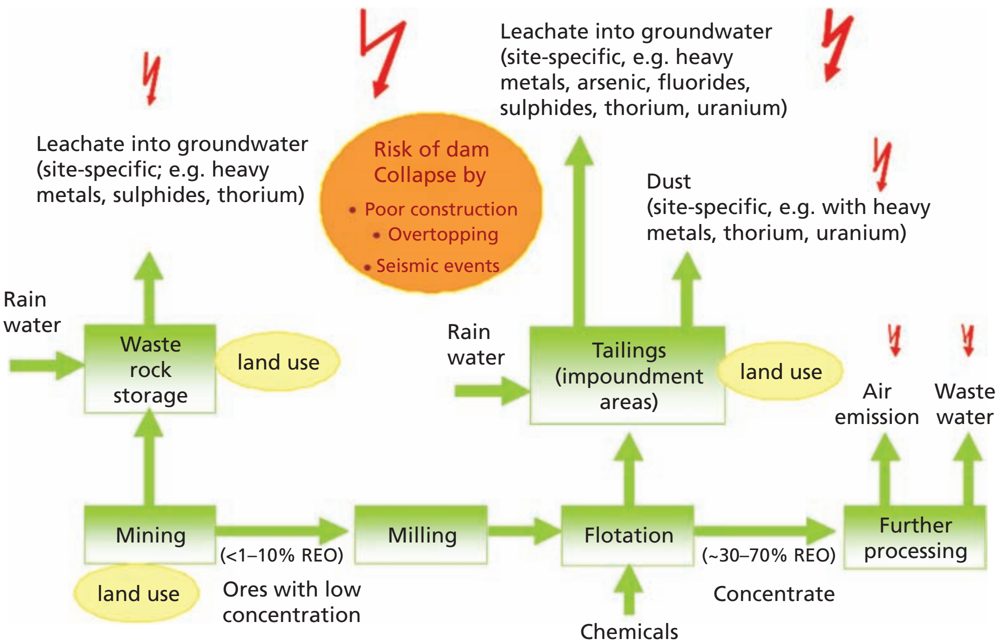

Figure 4.1 Rare earth environmental impacts, risks (Schuler et al. 2011).

Table 4.1 Energy and water consumption in production of metals from scrap and ores (range given is high to low grade) (Sverdrup and Koca, 2016)

Metal	Energy use in metal extraction (MJ/kg)		Water use (m^3/ton)	
	Scrap	Ores	Scrap	Ores
Iron	6	20–100	12–16	50–600
Aluminium	10	238–925	2	11–320
Magnesium	10	165–230	2	2–15
Copper	14	31–2,040	15	40–200
Zinc	11	32–63	20	75–100
Lead	9	32–45	40	50–75
Chromium	6	22–51	12	52–92
Nickel	20	130–370	20	60–320
Cobalt	20–140	140–2100	30–100	40–2,000
PGM	1,400–3,400	18,860–254,860	3,000–6,000	100,000–1,200,000
Zirconium	230	1,320–1,500	260	12,600–13,000
Gold	140–230	13,300–52,300	30	120,000–420,000
Silver	80–180	480–4,280	20–40	60–200
Tin	15	480–2,180	5	75–130
Rare Earths	1,000–5,000	5,500–7,200	250–1,250	1,275–1,800

Moreover, environmental impact of extraction and processing is also relevant within the EU. In this context, JRC (2016) includes a comparison of the location of protected areas (such as Natura 2000) and mining activities which show that more than 10% of the mapped mines in EU28 are located within a Natura 2000 site and about 72% of mining locations are in close proximity (within a 5 kilometre radius) of natural protected areas. Especially given the emphasis in Pillar 2 of the EU Raw Materials Initiative in increasing domestic supply, the potential exists for future conflicts between increasing supply of minerals from domestic sources and maintaining the protection under Natura 2000.

Graedel *et al*. (2012) have developed a methodology to quantify the criticality of metals which includes environmental implications (as well as supply risk and vulnerability to supply restriction). The environmental burden is calculated considering toxicity, the use of energy and water in processing, emissions to air, water or land using the Ecoinvent database as its data source. More recently, Sverdrup and Koca (2016) provide data on the energy and water demands for different metals obtained from scrap sources and naturally available ores. Some examples are given in Table 4.1. However, other sources of environmental impact are less readily available (for instance, impacts on the biosphere such as in rainforests, Arctic regions, ocean floors) from excavation, and waste produced per tonne of material extracted[5]).

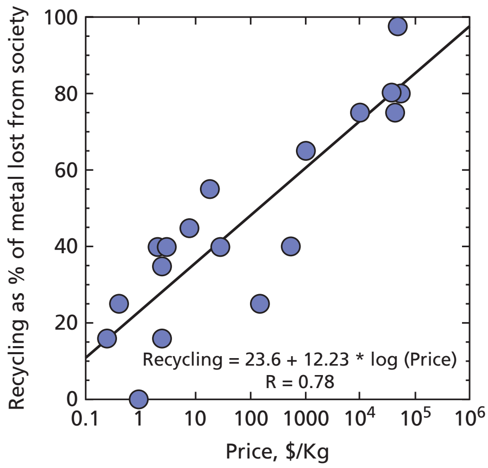

Figure 4.2 Recycling rate of metals relative to price (Sverdrup and Ragnarsdottir, 2014).

The Commission's Raw Material Supply Advisory Group (EC, 2014) considered the Environmental Performance Index (see EASAC, 2016) as a possible basis for assessing environmental impacts and risks but concluded that it did not provide a reliable basis for such assessments. Moreover, there are no reliable European data available and the Commission thus lacks the data on which to base a reliable assessment of environmental impacts and risks related to extracting and processing. While EASAC recognises the limitations on available data, we nevertheless encourage the Commission to continue work on developing a methodology to

5 As pointed out in EASAC (2016), wastes from mining and processing are substantial; for example, in aluminium production, each tonne of metal is associated with 150–250 tonnes of waste (red mud).

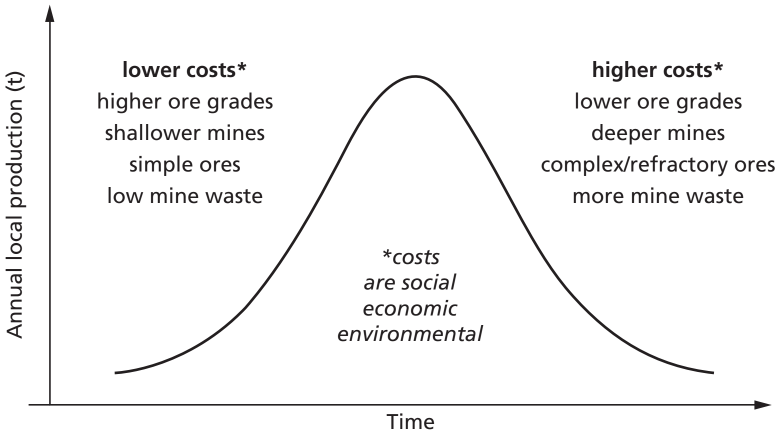

Figure 4.3 Conceptual model of peak production of metals (ISF, 2010).

consider environmental and social considerations outside the EU.

Even on the basis of the limited data in Table 4.1, it is clear that there are major differences in the environmental impact both between metals and between scrap and ore sources, particularly when the richest ores have been used up and lower-grade sources are used. There are several metals where the energy and water required for recovering the metal from scrap is less than 10% of that required for production from ore. Improving recycling rates thus contributes directly to reducing such environmental burdens.

4.2 Substitution and recycling rates

These two factors are included in the current methodology as potential moderators of supply risk. As already pointed out, many of the metals already identified as critical have low recycling rates (Figure 3.1) which means that supply remains dependent on virgin material. There are many factors which influence the recycling rate. While (Table 4.1) the very large savings in the energy required to recycle compared with that required to produce virgin material may encourage recycling, some elements are difficult to separate from the low concentrations found in recyclable materials so that energy costs can be prohibitive. Supply of the scrap (particularly electronic scrap) in sufficient quantities and quality is a major factor, as well as the technological possibilities (see Chapter 5). In general, higher prices will encourage higher recycling rates: for instance the high price of gold is associated with a 95% recycling rate. A broad correlation between price and recycling rate was found by Sverdrup and Ragnarsdottir (2014) as shown in Figure 4.2.

Substitution is often mentioned as a solution to supply scarcity: indeed as some elements have been restricted for environmental or health reasons (e.g. mercury, cadmium, lead) substitutes have been identified and implemented over a period of years. However, it is important to recognise that there are limitations to substitution. It is clearly impractical to substitute an element with a high rate of demand with one currently produced in much lower quantities. Hagelüken and Meskers (2010) also point out that substitutes are often similarly critical elements and reduction in demand for one critical material may merely lead to increased demand for another (as with the case of substituting platinum with palladium in autocatalysts). Legislation requiring substitution may also lead to perverse outcomes- for example banning lead in solders increased demand for tin, silver and bismuth which are partly produced as a by-product from lead production, thereby squeezing supply at the same time as increasing demand (Verhoef *et al*., 2004). Assessing potential for substitution ahead of actual supply constraints which generate innovation to provide the substitute, is also difficult and often relies on expert judgements which can be arbitrary and qualitative. Incorporating substitution effectively into the supply risk assessment thus remains a significant challenge.

4.3 Impending scarcity

Using supply risk as one of the basic criteria for criticality is not the same as implying an actual shortage of material. The likely impact of supply risks may be greater price volatility which can create an incentive to increase supply and avoid physical scarcity. Rather than be determined by the quantities present in the geosphere, shortages may reflect the effort companies and countries put into verifying reserves and how this depends on prices and rates of extraction. It may be only profitable to invest in prospecting and proving resource deposits to cover the near-term, in which case projected shortages may not be a reflection of scarcity *sensu stricto*.

The literature on scarcity of natural resources is extensive in resource economics and empirical evidence does not indicate a significant increase in the scarcity of natural resource commodities in the past (Krautkraemer, 2005), through

Table 4.2 Peak estimates, and ranges considering the lowest and highest possible reserves (Sverdrup and Ragnarsdottir, 2014)

Metal	Peak production year; average (range of upper/lower estimates)	Comments
Mercury	1962	Phased out by political action
Tellurium	1984	Depends on copper and zinc mining
Zirconium	1994	Phased
Cadmium	1998	Phased out by political action
Thallium	1995	Dependent on copper
Tantalum	1995	Partly dependent on Congo mining
Platinum	2015 (2010–2025)	Partly dependent on nickel
Palladium	2015 (2010–2025)	Partly dependent on nickel
Rhodium	2015 (2010–2025)	Partly dependent on nickel and platinum mining
Gold	2013 (2012–2017)	Partly dependent on silver, copper and platinum
Lead	2018 (2013–2023)	Reduced by political action
Niobium	2018 (2014–2023)	
Indium	2020 (2018–2025)	Dependent on copper-zinc mining
Manganese	2021 (2018–2025)	
Gallium	2020 (2018–2022)	Dependent on bauxite/aluminium
Selenium	2025 (2022–2035)	Dependent on zinc and copper
Chromium	2025 (2022–2035)	
Zinc	2025 (2018–2028)	
Cobalt	2025 (2020–2030)	Dependent on copper, nickel and platinum mining
Nickel	2026 (2022–2028)	
Silver	2034 (2028–2040)	Partly dependent on copper and lead
Rhenium	2035 (2030–2040)	Dependent on molybdenum
Copper	2038 (2032–2042)	
Iron	2040 (2025–2080)	
Phosphorus	2040 (2025–2100)	

increased mining/metallurgical extraction, technological progress leading to greater efficiencies in use, substitution, recycling and other mechanisms. However, economic assessments have yet to account for actual geological distribution data for specific elements, and the increased evidence of physical limits to a global environment capable of sustaining current society[6]. Moreover, even though few metals are currently facing physical depletion, they are becoming harder to obtain, and the energy, environmental and social cost of acquiring them could constrain future production and lead to a peak in production (Figure 4.3).

Sverdrup and Ragnarsdottir (2014) applied the concept of peak production in Figure 4.3 and evaluated how long resources for specific elements may last under business-as-usual scenarios, applied a technique developed in the oil industry for estimating peak production (Hubbert curves[7]), as well as a systems-based dynamic model. Their model simulations are able to reconstruct historical extraction rates and declining ore grades, and the authors conclude that Hubbert's model can be applied to other non-renewable resources to indicate future trends. Using this approach, it is estimated that physical scarcities may occur for several materials within the next few decades. Table 4.2 summarises those which have already peaked in production, and are expected to peak in the next 10–30 years.

Table 4.2 includes several elements where production has already peaked and indicates that current consumption rates are not sustainable. While some uses have been curtailed through political decisions related to toxicity (mercury, cadmium, lead) others such as the platinum group metals (PGMs) have critical roles in important sectors of the economy so that demand is increasing. Limits to the supply of tantalum may also impact some areas of high tech industry. Such trends increase pressure to increase recycling rates and/or technological substitution. Some future potential shortages would have substantial impacts on society; for instance, how would the infrastructure of cities evolve if iron production reaches a peak around the middle of this century. Furthermore, critical materials are not just metals—for instance, phosphorus and helium are also important (Box 2).

[6] As referred to in EASAC (2015), growth in the use of natural resources may lead to various planetary boundaries being exceeded that are critical to providing an environment capable of supporting current and future populations and society (Steffen *et al*., 2015).

[7] Hubbert modelling is a method based on statistics rather than physics. In the original Hubbert model, oil production data were fitted to a type of mathematical curve called a logistic curve. Hubbert modelling assumes that the rate of oil production will be maximal when half of the oil reserves have been produced. This has also been applied to non-oil resources by Sverdrup and Ragnarsdottir (2014).

Box 2 Examples of non-metal possible critical materials

(a) Phosphorus

Phosphorus is one of the most important resources for agricultural food production and the chemical industry. High-grade phosphate ore supplies are limited currently to USA, China and Morocco, and increasing demand for fertilisers worldwide is anticipated to deplete high-grade phosphate ore resources by the end of this century. The phosphate material flow and potential for recycle have been discussed by various authors (e.g. Liu *et al*., 2008; Matsubae and Nagasaka, 2014). Sverdrup and Ragnarsdottir (2014) applied their world systems model to demands for phosphorus against global population and noted that at present, with a world population of over 7 billion, per capita consumption of phosphate rock is 29 kilograms per year, from a total of 147 million to 157 million tonnes per year of phosphate rock taken from mines. Their model suggests that production from high-grade ore is near its peak and will start declining around 2030–2040, running out after 2100, with low-grade ore also running out after 2200. Since phosphorus is such a critical element for agriculture and there is no substitution option available, models suggest its supply may ultimately limit the size of the global population which can be sustained.

Potential recycling technologies include recovery from poultry manure, waste water and from the ash following the incineration of sewage sludge (see, for example, Matsubae and Nagasaka, 2014). Recent methods include direct recovery from urine and faeces (Mihelcic *et al.* 2011) or black water (Fernandes *et al*., 2015). The Commission issued a consultation on the sustainable use of phosphorus (EC, 2013) and has also supported research on recycling (EC, 2015a) via several nutrient recycling research and demonstration projects. Review of progress in 2015 suggested that some processes are already at a commercial production scale (e.g. struvite recovery or EcoPhos process using sludge ash). Numerous other approaches investigated by research institutes or industry are also being pursued.

(b) Helium

Helium has some critically important usages in cryogenics where it is essential for superconducting magnets (used in medical equipment, particle accelerators such as CERN, etc.). Other important uses include welding, detectors used in security systems, weather balloons, blimps, etc. Expanding usage combined with limited supply led the 'business-as-usual' scenario to give a burn-off rate of 9 years (Table 3.2). Natural gas contains about 5 parts per million of helium and can be extracted by cooling below 90 kelvin (Nuttall *et al*., 2012), but because of the low price of helium resulting from the large quantities offloaded from the US stockpile since 2000, it is not economically attractive to extract from all gas fields. Supply has been improved by increased extraction in Qatar and Russia but remains highly concentrated in a few countries. Because of the difficulty of recycling, the main option to safeguard this critical material would be through requiring or encouraging extraction from more natural gas fields or by prioritising uses (Daxbock *et al*., 2013). Recently, concentrations found in shallow gas deposits in Tanzania may offer an additional source.

The validity of the basic assumptions of the Hubbert model and its relevance outside of the oil resource are not however accepted by some economists[8], and the calculations in Table 4.2 remain dependent on the authors' hypothesis (on the basis of historical trends analysis) that the empirical Hubbert model can be applied to other resources to indicate future production peaks. Nevertheless, a similar approach has been used by other authors: for instance the risks associated with future peaks in production of minerals within Australia (ISF, 2010) and a global peak for copper production independently estimated for around 2040 by Kerr (2014). The German economy's future demand for materials critical to emerging technologies has also been estimated and compared with likely future production, indicating several potential shortages in supply (Marscheider-Weidemann *et al*., 2016)[9]. Angrick *et al*. (2014) also predict scarcities of non-renewable materials such as metals, limited availability of ecological capacities and shortages arising from geographic concentrations of materials. Even though debate continues in the economics and resource literature on the aspect of scarcity and peak production, it is appropriate for the Commission to consider this aspect in assessing critical materials priorities. It is worth noting therefore that the current studies in preparation for 2017's anticipated policy package include a 5–10–20 year forecast of reserves and supply, and that helium will also be included in the 2017 assessments.

[8] For a review of the arguments on the applicability of the Hubbert model, see Fisher (2008).

[9] Lithium, dysprosium, terbium, rhenium, germanium, cobalt, scandium, tantalum, neodymium and praseodymium.

5 Securing future critical materials

Two important factors in addressing criticality relate to the extraction and supply stage and the extent to which materials can be recovered and recycled at end of life.

5.1 Critical materials supply

Projected peak production years were already given in Table 4.2 for several elements, and further information on the ratio between current global production rates, available reserves and recycling rates are given in Table 5.1. These data indicate that peak production has either passed or will occur before the middle of this century for several metals, that current reserves for some metals are sufficient only to supply current consumption rates for a few decades, and that recycling rates vary considerably between materials[10].

Table 5.1 Production rates, recoverable amounts, recycling rates, years remaining in supply in current reserves (Sverdrup and Ragnarsdottir, 2014)

Metal	Global production 2012 (tonnes per year)	Recoverable reserves (tonnes)	Recycling rate (%)	Reserves to production ratio (years)
Iron	1,400,000,000	340,000,000,000	60	242
Aluminium	44,000,000	22,400,000,000	75	436
Manganese	18,000,000	1,030,000,000	45	57
Chromium	16,000,000	437,000,000	22	27
Copper	16,000,000	558,000,000	60	35
Zinc	11,000,000	1,110,000,000	20	101
Lead	4,000,000	693,000,000	65	173
Nickel	1,700,000	96,000,000	60	56
Titanium	1,500,000	600,000,000	20	400
Zirconium	900,000	60,000,000	10	67
Magnesium	750,000	200,000,000,000	40	260,000
Strontium	400,000	1,000,000,000	0	2,500
Tin	300,000	76,200,000	20	254
Molybdenum	280,000	22,500,000	40	80
Vanadium	260,000	19,400,000	40	75
Lithium	200,000	40,000,000	10	200
Antimony	180,000	7,000,000	15	39
Rare earths	130,000	100,000,000	15	770
Cobalt	110,000	11,600,000	40	105
Tungsten	90,000	2,900,000	40	32
Niobium	68,000	3,972,000	60	58
Silver	23,000	1,308,000	80	57
Yttrium	8,900	540,000	10	61
Bismuth	7,000	360,000	15	51
Gold	2,600	135,000	95	52
Selenium	2,200	171,000	0	78
Caesium	900	200,000,000	0	220,000
Indium	670	47,100	40	70
Tantalum	600	58,500	25	97
Gallium	280	5,200	15	19
Beryllium	250	80,000	20	320
Palladium	200	36,000	60	180
Platinum	180	44,100	70	245
Germanium	150	12,500	30	83
Tellurium	120	11,080	0	92
Rhenium	55	4,190	85	84
Rubidium	22	5,000,000	0	227,000
Thallium	10	380,000	0	38,000

[10] Recoverable reserves will of course change, so such estimates are only indicative of trends based on data available at the time the study.

Many of the rarer elements are associated with 'attractor' or 'carrier' base metals (iron, aluminium, copper, lead, nickel, zinc, tin) and therefore can be co-products of a primary metal smelter (see Table 4.2). However, whether they are extracted depends on whether it is economically feasible to mine the main product and whether the co-product value is sufficient to influence the processing design for the base metal. For these reasons, response to increased demand may be unpredictable or slow. Examples of elements associated with these 'carrier' metals are shown in Figure 5.1. These relationships are also critical to the design of processes for recycling metals from EoL products.

Increasing supply in Europe is Pillar 2 of the EU Raw Materials Initiative but, whether increasing supply from primary refining or metals recycling, the strategy needs to take into account these complex interrelationships in the supply of base and rarer metals- what has been called the 'Web of Metals (WoM)' (Reuter *et al.*, 2015) or 'Metal wheel' (Verhoef *et al.*, 2004; UNEP, 2013; Hagelüken, 2014). These summarise the chemical and physical linkages between metals and the set of metallurgical processes that has been developed to accommodate these linkages. Producers of base metals which are potential sources of critical materials essential for a circular economy need to be seen as part of a systems-integrated metal production (SIMP) approach. Supply of critical metals requires a baseline technology infrastructure that can recover metals from complex mixtures, thus extending the concept of criticality from that of the individual elements to the infrastructure necessary for their cyclical use—what Reuter *et al.* (2015) call a 'Critical Metallurgical Infrastructure'. Recycling now commonly has to deal with as many as 50 elements, which makes recovery of the metals and materials increasingly difficult if no such metallurgical infrastructure is available for the economic production of high-purity metals and materials from a mix of incompatible elements (UNEP, 2013). Criticality assessments of the base metals should thus also take into account their importance as sources of the rarer elements essential for many of the technologies underpinning a sustainable economy.

In this context, Ayres and Peiró (2013) point to several strategies to increase production of rarer elements from their 'carrier' base metals and quantify potential supplies from this approach (Table 5.2) focusing on iron (rare earths), aluminium (gallium), copper (cobalt, rhenium, molybdenum, tellurium and selenium), zinc (germanium and indium), nickel (cobalt and PGM) and tin (niobium and tantalum).

5.2 Improving recycle rates

A fundamental strategy in securing the supply of critical materials is ensuring that their use is as efficient and as cyclical as possible. The amount of some critical metals present in consumer goods sold during a year is significant (quantities can range from 4% to 20% of the annual mine production of the metal (Hagelüken, 2014)). However, this is distributed across a wide range of consumer products and a pre-condition for recycling is for sufficient quantities of these dispersed products to be collected. There is also a lag between the input of the material into the consumer goods 'technosphere' and availability for recycling. For instance, the use of PGM in automotive catalysts started in the mid-1990s and as a result of the relatively long lifetime of cars, 1,100 tonnes of PGM are in use within Europe (Hagelüken, 2014) and amounts available for recycling will be increasing as post-catalyst era cars are scrapped. In the absence of an effective recycling system (for instance due to lack of removal from all cars before shredding), these valuable elements will be lost. Other sources of high demand for critical materials relate to renewable

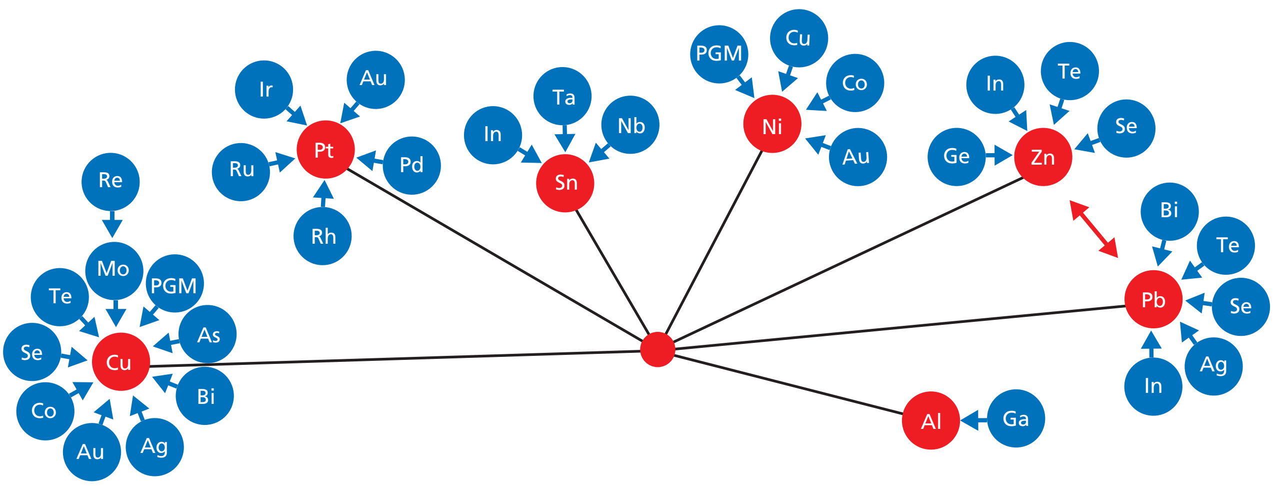

Figure 5.1 Sources of critical materials and their associated base metal (based on Hagelüken and Meskers, 2010).

Table 5.2 Potential sources of critical metals from base metal attractors (Ayres and Peiró, 2013)

Base metal 'attractor'	Production (10^6 tonnes)	Critical metal	Current mine production (tonnes)	Potential mine production (tonnes)
Iron ore	24	Rare earth oxides	54,000	4,114,000
		Niobium	63,000	89,140
Aluminium[11]	28.15	Gallium	106	10,550
Copper	16.2	Cobalt	31,000	408,800
		Rhenium	46	9,370
		Molybdenum	133,000	281,050
		Tellurium	475	1,050
		Selenium	3,250	4,210
Zinc	8.4	Germanium	84	600
		Indium	574	600
		Gallium	—	420
Nickel	1.45	Cobalt	44,000	44,600
		PGMs	11	17
Tin	0.26	Niobium	2	370
		Tantalum	102	750

energy technologies (e.g. wind generators, solar panels) and will remain in operation for many years before they are available for recycling in large quantities. Recycling infrastructure needs to anticipate these future trends.

Despite this lag in supply of EoL products from some sectors, substantial amounts of smaller and shorter-lived applications using critical materials already enter the waste stream, yet have very low rates of circularity. Quantities are already strategically and economically important if appropriate recycling methods and technologies can be applied. For instance, Du and Graedel (2011) estimate globally that in 2007 between 1,000 and 3,000 tonnes of praseodymium, neodymium and yttrium went to landfill. Some countries are focusing attention on specific elements and their material flows: for instance Japan introduced a rare earths strategy in 2009 (Box 3).

Owing to many critical materials being used in separate applications at low concentrations, separation from EoL products presents many challenges. Recycling has to be seen as an advanced logistical and technological process and very different from the main waste management infrastructure which has evolved from a system designed to deal with the diversity of post-consumer waste in one process (landfill, incineration, etc.). For instance, from the point of view of critical metals recovery, a vehicle at the end of its life should firstly be dismantled to remove batteries containing lead, electronic items and wiring, window glass, plastic, copper or aluminium body parts and trim, stainless steel items, catalytic exhausts, tyres and other rubber items (Ayres and Peiró, 2013). In the process, potentially re-usable or re-conditionable components (such as electric motors, pumps, transformers, engines or axles) should be recovered intact. Currently, metal scrap generally goes to an electric arc furnace, so that rarer critical metals present are not separated. Extending recovery to rarer metals requires additional measures. The many small electric motors in the car contain neodymium-based magnets. Motor-generators contain neodymium, dysprosium, praseodymium and terbium. Sensors and displays contain yttrium (also cerium and europium). A hybrid car's nickel–metal hydride (NiMH) battery contains lanthanum, cerium, praseodymium, neodymium and samarium, as well as cobalt. Catalytic convertors contain palladium, platinum and rhodium as well as rare earths. Targeting the recovery of these elements requires a much more detailed separation process as well as links with sophisticated metallurgy processes.

Electronic waste is a key source of critical metals but there remain technological barriers: for instance there is no technology for the recovery of gallium, germanium or tantalum. Moreover, while copper, gold, silver, platinum and palladium may be recycled, despite their high prices, rarer metals tend not to be recovered.

11 The residues from aluminium processing (red mud) can also be a source of iron, titanium and rare earths as well as of aluminium not extracted in the first round of processing (European Training Network for Zero-waste Valorisation of Bauxite Residue Project under Horizon 2020)

Box 3 Japan and rare earths in permanent magnets

Faced with supply risks triggered by Chinese restrictions on exports of rare earths, Japan introduced a 'strategy for ensuring stable supplies of rare metals' in 2009. Enhancing recycling was one of the four pillars with a budget allocated for research into recycling technologies for rare earths (via NEDO). One of the most important uses is in permanent magnets. Methods for recycling rare earth magnets are long established (although have only recently become cost effective), using a process involving molten magnesium to extract the rare earths. The recycled metals are suitable for the manufacture of new magnets with only a small degradation in performance compared with new magnets. Organisations supported by research funding (e.g. Japan Rare Earths) have also developed new methods for the extraction of rare earths from recyclable magnets using proprietary processes which are simpler than previous methods, and which allow the rare earths recovered to retain more of their functional properties. Hitachi has developed equipment which greatly improves the efficiency of extracting magnets. Toyota also received the Prime Minister's prize for achievements in 3R (reduce, reuse and recycle) for its technology which enable rare metals in hybrid vehicles to be recovered for use in new motor magnets. Mitsubishi Materials has developed new technology to recycle rare earth magnets from compressors in air conditioners and washing machine motors. Japan Metals and Chemicals Company and Honda have developed a recycling facility capable of recovering rare earths from batteries. Such government initiatives offer options for improving the recycling rate and avoiding scrap materials ending up in generic scrap metal waste streams.

Batteries containing lithium, cobalt and manganese could be recycled but are not (yet) recycled due to prices being low.

Recycling for critical metals needs to be seen as a system which begins with collecting, sorting and dismantling, pre-processing to separate components containing valuable metals, and upgrading relevant fractions before final metallurgical processing. This requires integration of the roles of the key stakeholders at all stages of the cradle to cradle cycle:

- primary metals producers of both base and rarer metals;
- product designers to optimise critical material use and recyclability into the design phase[12];
- retailers and local government to provide the facilities for collection and separation to provide the raw materials for recycling;
- consumers to cooperate in separation and return programmes for EoL goods;
- governments to provide an appropriate societal and legislative framework to deliver high rates of recycling (e.g. Extended Producer Responsibility schemes, effective collection and sorting and public education);
- recyclers applying best available techniques (BAT) to recover critical materials from separated waste streams.

In this process, Hagelüken (2014) sets out seven conditions for effective recycling:

1. Technical recyclability from the source.
2. Accessibility of the source components (e.g. automotive catalysts, car battery, personal computer, mobile phone, motors).
3. Economic viability, whether by the inherent value of the extractive material or the fiscal environment established by regulation.
4. Collection mechanisms to ensure the product is available for recycling.
5. Entry into the recycling chain rather than loss due to export or improper disposal (for instance mislabelling of electronic goods as for reuse and export thereby bypassing waste export regulations).
6. Optimal technical and organisational set-up adapted to the particular product type.
7. Sufficient capacity to handle the potential supply.

The pre-condition is to ensure secure and sufficient volumes of waste, collected (or sorted) in ways that are compatible with its metallurgical processing. The major barrier remains the supply of EoL goods which provide the raw material for recovery processing. The current collection rate of multifunctional mobile phones is only about 3%, despite the fact that they contain many likely critical metals (OECD (2009) and (Figure 5.2)) and that smelting and refining is capable of recovering about 95 per cent of the rare metals contained within them (Hagelüken, 2012). The 'Countering WEEE illegal trade' study (CWIT, 2015) reports that for EU countries

[12] Modern electronic goods are highly complex, containing sometimes more than 40 elements, and product design should consider the complexity of recycling such products by avoiding incompatible metal mixtures, or joints between product parts that hinder recycling. Policy should reinforce this point. This 'design for resource efficiency' will recognise the inherent relationship between different critical materials and their carrier metals.

Figure 5.2 Metals contained in mobile phones (Geological Survey of Ireland (2016), Department of Communications, Energy & Natural Resources).

(plus Norway and Switzerland), 9.46 million tons of WEEE was generated in 2012, but only 35% entered official collection and recycling systems. The other 65% (6.15 million tons) was either exported (1.5 million tons), scavenged for valuable parts (750,000 tons), simply thrown in waste bins (750,000 tons) or recycled under unknown conditions in Europe (3.15 million tons).

The complexity of the challenge of strengthening EoL collection can be illustrated by the example of printed circuit boards. Figure 5.3 shows the stages from EoL to recovered critical material on the basis of European experience (Wellmer and Hagelüken, 2015). The overall efficiency is the product of the efficiencies at each stage (right hand column in Figure 5.3), where the first collection stage has the lowest efficiency and needs to involve many participants. Intermediate disassembly and beneficiation can be performed on a regional basis but the final high-tech recycling of the metals requires technology which is available in only a handful of global centres.

Overcoming the barriers to recycling arising from the low levels of collection of consumer goods and their inefficient handling within the recycling chain requires the current 'open' system of consumer products to apply the lessons learnt in industrial recycling of precious metals (Hagelüken and Meskers, 2010). In industry, the components containing valuable metals (e.g. platinum in catalysts) are owned by the industry; changes in ownership or location are documented and material flows transparent. Stakeholders in the life cycle work closely together and this 'closed loop' system is inherently efficient. In contrast, ownership of consumer items shifts frequently, the owner will be unaware of the value of the metals contained, changes in ownership and location makes it impossible to trace and ensure recovery. Recycling is thus not given a priority and may not be handled by agents with appropriate expertise or facilities.

Changing the current leaky 'open' system of consumer goods to a more 'closed system' is a precondition for more effective recycling of critical materials. So-called 'urban mining' requires the return of electronic goods at end of life to become a routine part of consumer and retailer behaviour to ensure that the vast majority of electronic goods are returned to points where they can enter the recycle chain. At present, however, this is far from the situation. Of the over 40 million tonnes of electronic waste generated globally, much of developed countries' e-waste is exported to India, China and Africa where informal recycling leads to substantial adverse environmental and health impacts. While this is not in conformity with the Basel Convention (which calls for

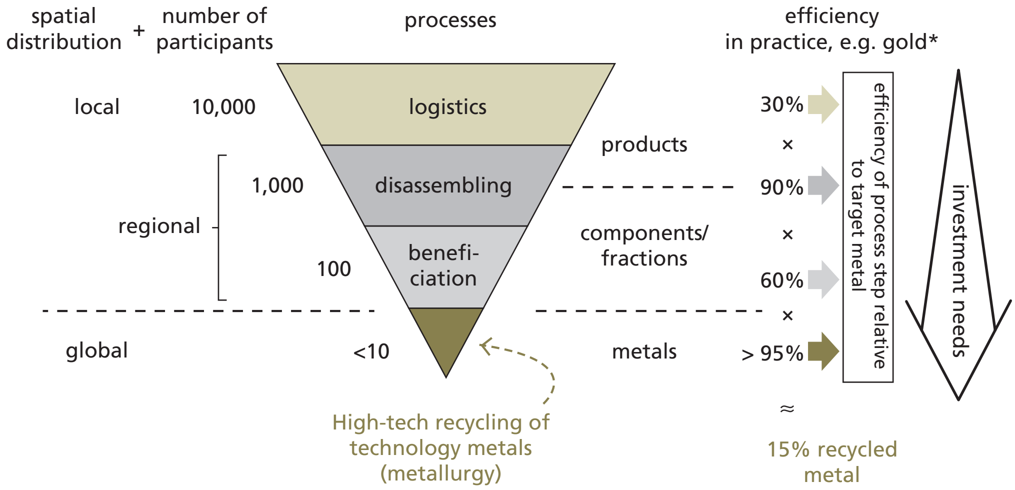

Figure 5.3 Recycling stages for printed circuit boards (Wellmer and Hagelüken, 2015).

countries to treat and dispose of e-waste as close to the origin as possible), this is easily avoided through classifying e-waste as working equipment. Addressing this fundamental problem needs to be part of the strategy to ensure future supplies of critical materials. Since, despite the adverse environmental and health effects, export and informal recycling provide income to large numbers of low-income households, the preferred approach could be to bring the informal sector into a more formal system for urban mining whereby European providers of e-waste can use low-cost countries for separation of retrieved parts, but seek centralised and certified processing either through re-import or appropriate facilities in the country to which the waste has been exported. By creating incentives for smaller operators to deliver retrieved parts to central processing units deploying appropriate technologies, health and environmental issues could be mitigated and metal yields improved.[13]

Encouraging recovery of critical materials within Europe requires an efficient collection and return of EoL products to recycling supply chains with the necessary recycling infrastructure. Deposit funding systems can incentivise consumers to hand back their own devices, while leasing models allow manufacturers or retailers to retain ownership and therefore recycle at the end of life. As pointed out in our report on indicators (EASAC, 2016), Japan achieves high levels of metal recycling through comprehensive and consumer-friendly return systems which include prepayment for return and recycling at the point of purchase, and collaboration between manufacturers in recycling larger electrical appliances. Similar takeback schemes and advance recycling fees are also applied in Switzerland[14]. Legislative support may also be justified because recycling of some critical metals has macroeconomic benefits independently of the economic viability of the recycle process.

In contrast to the low efficiency of the collection and separation processes, the metallurgical processing stage has much higher efficiency. Umicore's integrated smelter–refinery facility in Belgium can treat up to 350,000 tonnes per annum of secondary materials (Umicore, 2007). The plant recovers gold, PGMs, silver, indium, antimony, copper, nickel, lead and other metals (17 in all). Even so, several important metals are not included. However, there are only five such rare-metal recovery complexes in the world at the present time (of which three are in Europe). The World Economic Forum's Risk Response Network (WEF/RRN, 2011) concludes that these capacities will not be sufficient in the future, for example for PGMs in automotive catalysts, indium in LCDs, and tellurium in photovoltaic applications.

Many technical challenges remain even if collection rates can be improved. As already mentioned, permanent magnets used in small electrical items are already reaching waste streams but their recovery is a challenge, due to their small size and because they are often glued to other components. TNO estimates that there are about 2 million tonnes of WEEE containing permanent magnets (out of 12 million tonnes arising), with a rare earth content of less than 0.1% (TNO, 2012). Simpler to recover are the permanent magnets contained within hard disc drives because these are already separately collected on a significant scale for data destruction, but there is no evidence that the magnets are currently recovered for

[13] General guidance is under development by Roundtable of the Sustainable Recycling Industry (http://sustainable-recycling.org/sri-roundtable-overview). In India, one new recycling company relies on the informal sector for its supply and has established central collection points which feed a certified metallurgical refinery. (http://www.attero.in/)
[14] www.swicorecycling.ch/en/home
[15] http://cordis.europa.eu/result/rcn/155713_en.html

recycling. However, industry trends to miniaturisation involving gluing rather than screws or other fasteners are making recycling even more difficult. Such trends present challenges in harmonising the forces driving consumer innovation with the needs of a circular economy.

As for rare earth phosphors, collection and processing systems are already in place because of the hazardous waste (mercury) content. Estimates suggest that 1,000–1,500 tonnes of phosphor powder are available for recycling each year in Europe, of which 100–300 tonnes might contain rare earths (REconserve, 2012). To overcome the problem of rare earths being widely dispersed, Hydro WEEE has developed a mobile hydrometallurgical plant that can be transported site-to-site inside a lorry to treat batches of waste that have accumulated at WEEE treatment centres[15]. WEF/RRN (2011) also emphasises the importance of new recycling technologies, for example for tantalum in applications such as cell phones, rare earths and lithium.

Research and development are clearly important in delivering improved technologies and processes. For instance, Hitachi has reduced the costs of dismantling neodymium magnets from hard discs and compressors. Birmingham University's Magnetic Materials Group has developed a process for removing permanent magnets from HDDs. A FP7 project (CycLED; 2012–2015) focuses on optimising the resource flows for LED products, including the recycling of scarce metals in LED production and opportunities for reduced resource losses in production, use and recycling. Any critical materials strategy of the Commission thus needs to include promotion and support of research and development on technologies for critical materials recovery (e.g. through Horizon 2020). Requirements range from basic science (e.g. thermodynamic studies of critical metal compounds and mixtures) to upscaling from pilot plants to production plants.

Even in committed companies, incorporating recycled materials in products is not straightforward and may require substantial investment in research and development. For instance, used batteries are classified as hazardous waste due to their including several potentially harmful toxic metals (nickel, cadmium, cobalt, lead, etc.). However, recovering these potentially valuable chemicals is not easy and one company researched for 8 years[16] before being able to accommodate up to 4% of recycled product in new batteries. New methods for refining recycled materials to make them as pure as possible had to be developed to equal the purity of virgin materials. The logistical infrastructure for the recovery of used batteries also had to be developed, together with communication strategies to encourage consumers to participate in recovery efforts. Hurdles also existed in recycled raw materials being classified as waste with the associated regulatory burdens. Finally, consumers needed to be assured that recycled batteries had no performance loss, while recycled batteries should be seen as added value for consumers who were becoming conscious of recycling trends. This illustrates the many barriers which exist: not just in the basic chemistry of recovery and reuse but logistical, regulatory and communication challenges.

A key final question related to the selection of critical metals is what implications for policy result from an element being assigned the CRM label. Most of those selected to date have been metals and a comprehensive global review of the current status, opportunities and inherent limits on metal recycling (UNEP, 2013; Deloitte, 2015) highlights the significant differences in approach which are necessary to ensure effective critical metals recycling relative to the bulk material recycling model which underpins EU directives. As pointed out by Hagelüken and Meskers (2010) and Hagelüken (2014), current recycling systems and regulations have focused on recycling common materials (plastics, metals, paper, glass, etc.), whereas effective recovery of rarer and critical elements needs to focus on the effectiveness with which smaller quantities of high value products are recovered. The 'carrier' metals included in these categories (iron, aluminium, copper, lead, zinc) have historically considered the rarer elements as a problem rather than an asset to be extracted. Indeed, the mass-based or percentage recycling targets of current waste legislation may lead to the loss of critical materials present in only small quantities. In contrast to this inherited situation, the above reviews recommend that recycling and associated incentives should be repositioned around a product-centric approach, where appropriate recycling technologies are adapted to different product streams according to their critical element composition, and would optimise the recovery of the several metals present in complex products. Current Commission proposals to strengthen Extended Producer Requirement measures provide an opportunity to apply this product-centric approach to a range of products containing economically significant amounts of critical materials.[17]

16 https://www.greenbiz.com/article/how-energizer-taking-holy-grail-e-waste.

17 The Commission's circular economy package includes setting minimum operating standards for Extended Producer Responsibility by amending Article 8 of the Waste Directive 2008/98.

6 Conclusions

We have considered two aspects of the critical materials issue: firstly the selection process for a material to be assessed as critical; secondly the measures that need to follow from a material being assigned to that category, with a particular focus on recycling.

On the first of these, EASAC generally supports the Commission's approach to the evaluation process and guidelines for the selection of critical materials. However, we consider that environmental factors outside the boundaries of the EU should also be included and that the Commission should include the issue of scarcity in future critical material assessments.

In responding to the challenges of maintaining a future secure and economic supply of critical materials, EASAC sees several important aspects emerging from the circular economy approach which should be considered in future EU policy. Ensuring efficient use and recovery of critical materials requires a different approach from the broad targets previously applied to recovery rates of bulk materials. Current recovery rates of EoL products containing the likely critical elements are still low and many potential opportunities are yet to be grasped. Fundamental amongst these is the collection of the materials for recycle. The complex interrelationships between metals means that effective recycling requires sophisticated knowledge of the components present in the EoL products stream, which cannot be achieved with mixed recycling in broad categories. EASAC is satisfied that the case for moving towards a product-centric approach to collection and recycling is strong and should feature in the development of future EU policy.

A more product-centric approach could improve on current low levels of recovery by encouraging recovery to be built in to dedicated collection schemes providing feedstock for specialised recycling. Options include deposit schemes, including return and recycling costs in the purchase price, trade-in which offers a financial reward for return, or contractual obligation. The current situation whereby much of Europe's e- waste leaves the EU (in many cases for informal and inefficient recycling in Asia or Africa) comprises a significant leakage of critical metals requiring attention. A level playing field is needed so that low quality recycling or avoiding recycling through legal loopholes does not continue to offer the cheapest option. For particularly critical materials, the viability of labelling schemes to trace metals from the mine to the market should be evaluated. The current proposals to amend the Extended Producer Responsibility requirements provide a mechanism to incorporate special emphasis and priority on products containing economically significant quantities of critical materials.

Supply of critical metals requires a baseline technology infrastructure that can recover metals from complex mixtures, thus extending the concept of criticality from that of the individual elements to the infrastructure necessary for their cyclical use. The EU should evaluate the adequacy of the EU's 'Critical Metallurgical Infrastructure' for the critical metals decided and consider measures to strengthen it.

Modern electronic goods are highly complex, containing sometimes more than 40 elements. Product design should thus consider the complexity of recycling such products by avoiding incompatible metal mixtures, or joints between product parts that hinder recycling. EASAC notes however that even though design is given considerable emphasis in many of the Commission's statements on the circular economy, trends driven by consumer convenience and demand continue to introduce additional burdens rather than facilitate the process. For instance, the continued trend towards miniaturisation of computers and other electronic equipment depending on gluing rather than detachable fixtures only adds to the difficulty of reusing or recovering materials or parts by any other means than shredding. The Commission is already looking at developing generic standards (EC, 2015b) which cover eco-design requirements related to material efficiency aspects (such as recyclability, recoverability and reusability, durability, reversible disassembly and EoL extraction time) but competition between manufacturers for consumer convenience is a powerful trend. The Commission could thus consider seeking the support of consumer groups and the major manufacturers through a dialogue on ways of reducing or eliminating inherent conflicts, to encourage 'design for resource efficiency' to become standard practice. To this end, EASAC supports the Commission's proposal to strengthen EPR schemes to incorporate EoL costs into product prices and provide incentives for producers to take better into account recyclability and reusability when designing their products.

Developing effective recycling technology can require considerable investment. Companies with a particularly strong commitment to a circular economy approach may be prepared to invest over the substantial period required, but this cannot be assumed for all companies. Particularly with critical materials, the circular economy policy needs to provide market signals which incentivise all companies to work towards a circular economy rather than relying on individual leaders. The Horizon 2020 programme should also support research and development on critical materials recovery and recycling, ranging from the basic science underpinning the behaviour of metals and their mixtures to novel separation and purification processes.

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Glossary

BAT	Best available techniques
CCS	Carbon capture and storage
CRM	Critical raw materials
EASAC	European Academies' Science Advisory Council
EPR	Extended producer responsibility
EoL	End-of-life
HDD	Hard disc drive
JRC	Joint Research Centre
LED	Light-emitting diode
NEDO	New Energy & Industrial Technology Development Organization
NiMH	Nickel–metal hydride
PGM	Platinum group metals
REE	Rare earth elements
SET	Strategic energy technologies
SIMP	Systems-integrated metal production
TNO	Netherlands Organisation for Applied Scientific Research
UNEP	United Nations Environment Programme
WEEE	Waste electrical and electronic equipment
WOM	Web of metals

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