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CICERONE
Circular economy platform for European priorities strategic agenda

Overview report on definition and concept of the Circular Economy in a European Perspective

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Summary

On the basis of a literature research, this subtask develops a conceptional framework for a common understanding of CE within the project team and for the following work packages and tasks. After a brief introduction into the objectives and the context of a circular economy, a more elaborated look into the necessity of an explicit understanding of CE, the objectives, the spatial perspective of CE and the specific challenges within the CICERONE context will be done, in order to develop a basis for a common understanding within the project context. Circular economy can and has to be understood as an (eco-)innovation agenda. Therefore, the paper investigates the role policy has to play to support innovation for a CE transition, for creating the framework conditions and why CE has also to be build from the ground up. Finally, the paper looks from two perspectives at emerging trends and business models in a CE to sketch next steps towards the transition in a selection of central sectors. Conclusions are drawn on the basis of the insights gained by the preceding chapters.

Approval

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EXECUTIVE SUMMARY

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After a brief introduction into the objectives and the context of a circular economy, a more elaborated look into the necessity of an explicit understanding of CE, the objectives, the spatial perspective of CE and the specific challenges within the CICERONE context will be done, in order to develop a basis for a common understanding within the project context.

Circular economy can and has to be understood as an (eco-)innovation agenda. Therefore, the paper investigates the role policy has to play to support innovation for a CE transition, for creating the framework conditions and why CE has also to be build from the ground up.

Finally, the paper looks from two perspectives at emerging trends and business models in a CE to sketch next steps towards the transition in a selection of central sectors.

Conclusions are drawn on the basis of the insights gained by the preceding chapters.

KEYWORDS

Circular economy, eco-innovation, circular business models, objectives, critical raw materials

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1 INTRODUCTION, OBJECTIVES AND CONTEXT

The CICERONE project brings together programme owners, research organizations and other stakeholders to create a platform for efficient Circular Economy programming. The priority setting and the organization of the future platform is driven by Programme Owners (POs), involved either as project partners, or via a stakeholder network.

Within the project, WP 1 aims to generate an understanding for CE in terms of its societal challenge, industrial relevance, R&I policy, and trends in technology developments using as far as possible relevant available reports (e. g. from various EU-funded projects Circular Impacts, SCREEN, MIREU, CRESTING, FUTURING, SCRREEN, and others). It compiles and analyses the status quo regarding the emergence of circular economy and affiliated strategies and policy making in a European Union context.

The key objective is to assess how CE is being implemented at regional level, e.g. via the RIS3 strategy and Structural Funds. As such it sets the scope for the project and provides the background against, which programmes and measures can be understood, assessed, developed and recommended in succinct tasks and work packages.

Against this background, this first deliverable is a short overview paper on CE in a European context. It provides a common conceptional understanding of circular economy and highlights trends in technology and business field developments.

Based on this common understanding, WP 1 will continue to carry out an initial benchmarking exercise for a deeper understanding of the state of the art, mapping stakeholders, existing RDI priorities as well as funding and legal mechanisms. A prioritisation methodology will be developed to support an analysis of the current performance: synergies, gaps and duplications will be characterised, and pathways for improvements will be formulated. Identified best practices will drive the definition of policy recommendations.

Once the state of the art has been clearly mapped out, the actual prioritisation work will be carried out. This includes building a Strategic Research and Innovation Agenda (SRIA), performing an ex-ante impact assessment of joint programming on circular economy R&I, and developing a policy toolkit to promote the priorities and foster adoption by policy-makers. The project will also set the grounds for the future PO platform, starting with defining its strategic role in the existing landscape. The next step will be to specify governance and possible legal frameworks, as well as creating a financially sustainable model. It is a key objective that the platform be sustained after the end of the project.

This specific deliverable is structured as follows: Chapter 2 will discuss the relevance of a shared understanding what is actually meant by a circular economy and how this is addressed within CICERONE. Chapter 3 focuses on CE in the context of innovation processes in different business fields, the final chapter draws preliminary conclusions for the further work in CICERONE.

2 UNDERSTANDIG CIRCULAR ECONOMY

2.1 Necessity of an explicit conceptional understanding of CE

Despite the growing academic literature on the circular economy, the theoretical foundations for a shared ground of knowledge or a set conceptional model have not been established yet (see e.g. Kalmykova et al., 2018; Prendeville et al., 2018). It is generally accepted that this area of research is still in a consolidation phase in terms of definition, boundaries, principles and associated practices

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(Korhonen et al., 2018b, Merli et al., 2018). This also holds for the understanding of how complex socio-economic systems and sub-systems may affect and be affected by the so-called 'circular-economy transitions' (Korhonen et al., 2018a). A recent publication highlighted that in the scientific literature alone more than 100 definitions of a circular economy can be differentiated (Kirchherr et al., 2017).

It is important to take into account that this broad variety of definitions – from very academic, complex models to often simple and pragmatic visualisations – is linked to an frequently very diverging understanding of the objectives of becoming circular. Against that background, measuring progress towards circularity requires as a crucial first step an explicit understanding of the objectives and the rationality of a circular economy – otherwise the development of indicators as well as the monitoring of these indicators might completely overlook the actual relevant trends and developments. The overview on existing indicator frameworks by Kirchherr et al. (2017) very clearly highlighted that the robustness or accuracy of specific indicators can only be assessed with a clear conceptional understanding of a circular economy and its objectives that also allows to develop a specific hierarchy of targets and indicators, e.g. in the case of trade-offs. The aspired transformation of our patterns of consumption and productions will require a complex systemic change that will have to take into account all sorts of intended or un-intended side effects, variables and causal links as illustrated in Figure 1. Success or failure of this change process will depend on a clear and shared idea of its overall objectives.

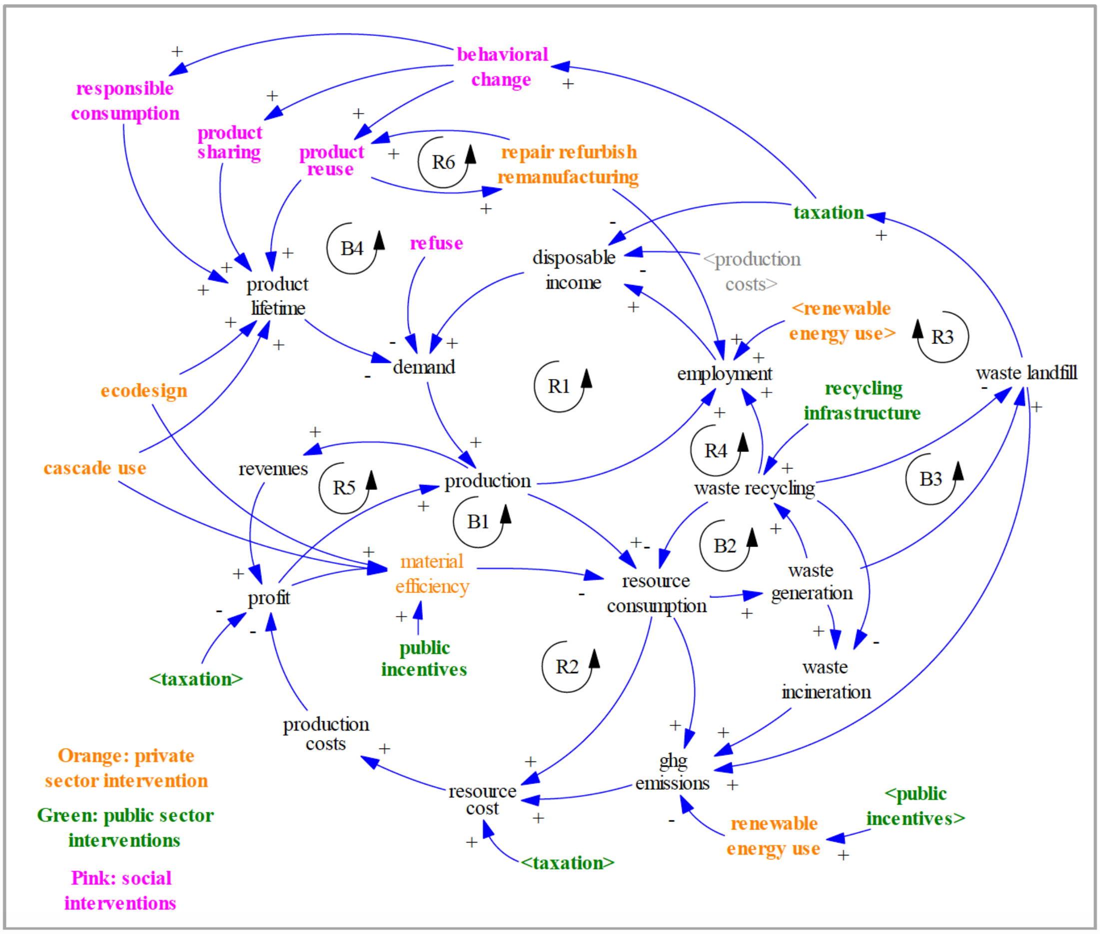

Figure 1: Causal loop diagram for the circular economy and its interlinkages (ESPON, 2018).

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2.2 Objectives of a CE

Following the different definitions and conceptionalisations of a circular economy, different analytical categories have to be differentiated in order to gain an explicit understanding of the objectives to be achieved in a more circular – or if that´s even possible – completely circular economy.

Most importantly it has to be noted that the overall strategic objectives can but does not have to include aspects of environmental, economic and social objectives. The starting point for most definitions is an environmental rationale to protect natural resources, to avoid environmental burdens to ecosystems, species and thus indirectly also to avoid negative impacts on human health. Most concepts focus on the output-side of the socio-economic metabolism – the waste streams and their disposal and recovery – as well as on the input-side, measured e.g. by material-flow based indicators like domestic material consumption. Increasingly also the potential contributions to climate change mitigation by circularity are seen as a strategic objective (Material Economics, n.d.).

Despite this focus on the environmental benefits of the circular economy, it should be noted that e.g. the Circular Economy Action Plan by the European Commission has been initiated primarily by DG Grow and has a clear focus on the cost savings, job creation and competitiveness potentials (European Commission, 2015):

"The circular economy will boost the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices, helping to create new business opportunities and innovative, more efficient ways of producing and consuming. It will create local jobs at all skills levels and opportunities for social integration and cohesion. At the same time, it will save energy and help avoid the irreversible damages caused by using up resources at a rate that exceeds the Earth's capacity to renew them in terms of climate and biodiversity, air, soil and water pollution. (...) Action on the circular economy therefore ties in closely with key EU priorities, including jobs and growth, the investment agenda, climate and energy, the social agenda and industrial innovation, and with global efforts on sustainable development."

Obviously environmental objectives on the one hand and economic objectives on the other can be very well aligned – this is the unique opportunity of the circular economy as e.g. illustrated by the assessments published by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2017). Nevertheless it has to be stated that these co-synergies are not an automatic and necessary must – but have to be ensured by an appropriate regulatory framework! Trade-offs can be imaginable on many different levels, e.g. lowering the technical thresholds for pollutants in recycled plastics could definitely lead to new business opportunities but at the same time pose severe risks to the health of consumers. From a more conceptional point of view the circular economy often has a clear emphasis on the consistency of our socio-economic metabolism – neglecting the need for an absolute reduction of the natural resource requirements of our industry (UNEP, 2017). Looking at the mostly positively connoted image of the "circle", its overall long-term sustainability will depend not only on its closure but also on the total amount of resources that will be necessary to keep it floating. CE indicator frameworks from the global down to the urban level will have to ensure that these aspects are comprehensively covered, e.g. by not only focussing on recycling rates and neglecting waste generation.

Other important analytical dimensions e.g. include the temporal perspective with a majority of indicators focussing on current data, looking at improvements of the status quo compared to the past. A very different set of indicators in contrast has a focus on future developments, measuring e.g.

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eco-innovation potentials in terms of R&D expenditures or based on patent analysis (O'Brien et al., 2018).

2.3 Spatial perspective

Starting point of the CIRCTER project have been the specific challenges of a spatial perspective on the circular economy: the regulation of local circuits and the relational logic of geographical norms and scales as factors for circular economy development remain very little discussed for the moment (Barles, 2009). In our view, three key analytical challenges need to be sorted out to characterise the circular economy under a territorial perspective, namely: (1) the scales of operation of circular economic systems and sub-systems; (2) the territorial factors that may affect the development of closed material and energy loops, and; (3) the territorial outcomes that might derive from the penetration of Circular Business Models (CBM) at various levels.

Regarding the first challenge, we argue that the circular economy can be characterised and studied at different scales depending on the specific sub-systems that are considered, which are also tightly linked with the notion of 'organizational width'. The circular economy clearly has a multi-scalar expression that should be analysed beyond the borders of single companies, cities, regions or countries. At national and global levels (macro scale), this can be done by e.g. focusing on the geographies of international supply chains and globalised waste flows (Clapp, 2001, Velis, 2015). Some argue that intermediate regional areas (meso-scale) may be the most suitable level for closing material loops and creating sustainable industrial ecosystems (Sterr & Ott, 2004). But the circular economy also has an expression at the urban and local levels (micro-scale). Here is where the circular economy can be materialised in very tangible initiatives, for instance in the form of local food systems or closed circuits of secondary materials of the lowest value (e.g. demolition materials or organic wastes). In any case, the debate on the territorial definition of a circular economy goes well beyond the delimitation of scales of operation based on administrative-unit boundaries. In fact, the identification of the scales of operation ultimately links to the definition of appropriate system boundaries for the characterization of circular economies at various territorial levels.

These somehow theoretical considerations become very concrete when it comes to the assessment of imports and exports of materials as well as waste streams: The circular economy is often conceptionalised as a self-sufficiency approach where the reliance on raw material imports is reduced, as e.g. illustrated in the following schematic CE figure by the European Environment Agency that explicitly states that for a circular system material imports and waste exports should be minimized.

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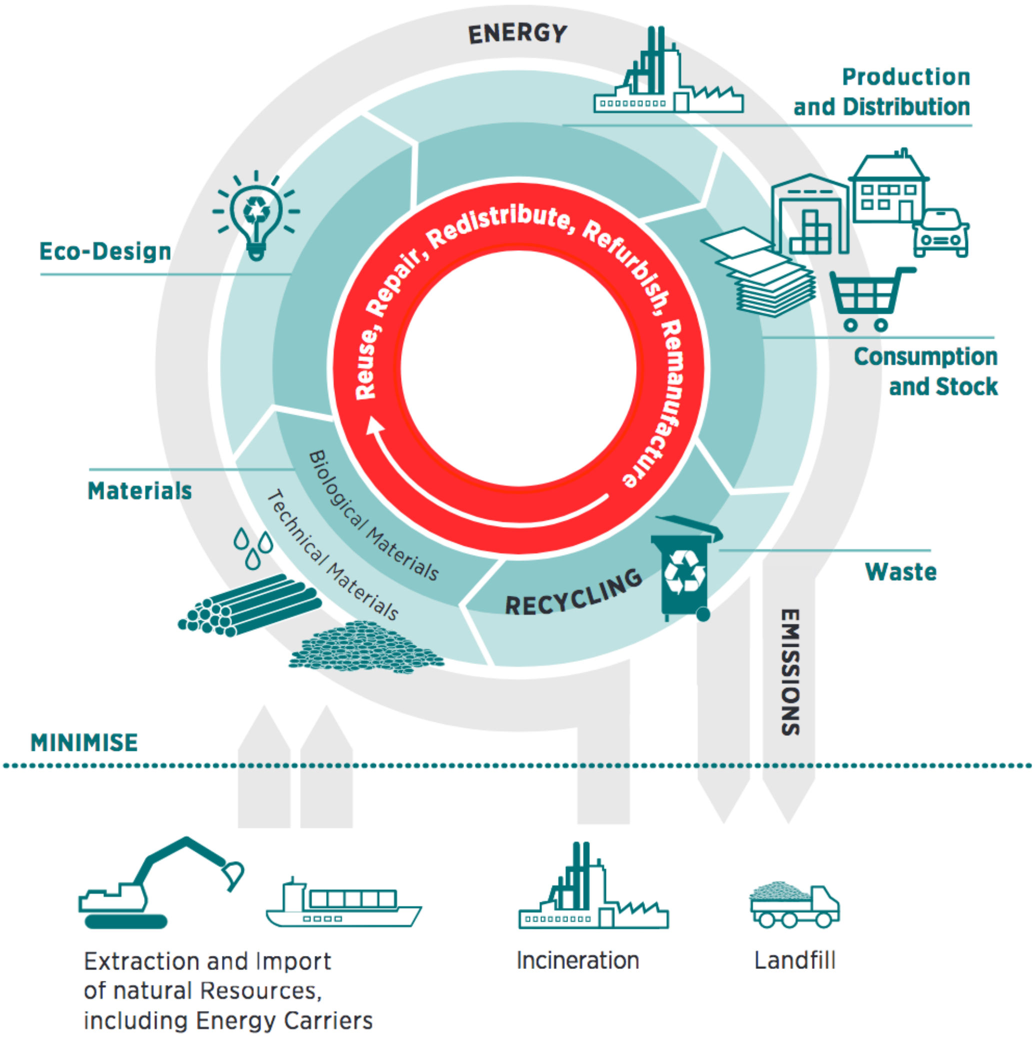

Figure 2: The Concept of Circular Economy (Wilts & Berg, 2017)

From an environmental point of view such approach aims of course to reduce a simple shifting of burdens to other regions of the world, e.g. by disposing residual waste in countries with lower environmental standards as highlighted by the Chinese ban of low quality waste imports.

At the same time the strict self-sufficiency approach also bears the risk of neglecting relevant territorial factors as outlined above: If one region has established high quality waste treatment infrastructures – why shouldn´t it import waste from regions without appropriate technology where waste would e.g. just landfilled.

The second important aspect is of course the spatial scale chosen for the closing of material cycles: The assessment of recovery rates for example for municipal solid waste would be completely different if calculated on a city level, on an average national level or in contrast on a city quarter level – and despite the completely different results for the same indicator just on different spatial levels, the environmental performance of the system could be exactly the same.

2.4 Specific CE challenges in the CICERONE context

When addressing circular economy, the CICERONE partners refer to a comprehensive scope, in line with the European Commission. This is illustrated in the schematic below.

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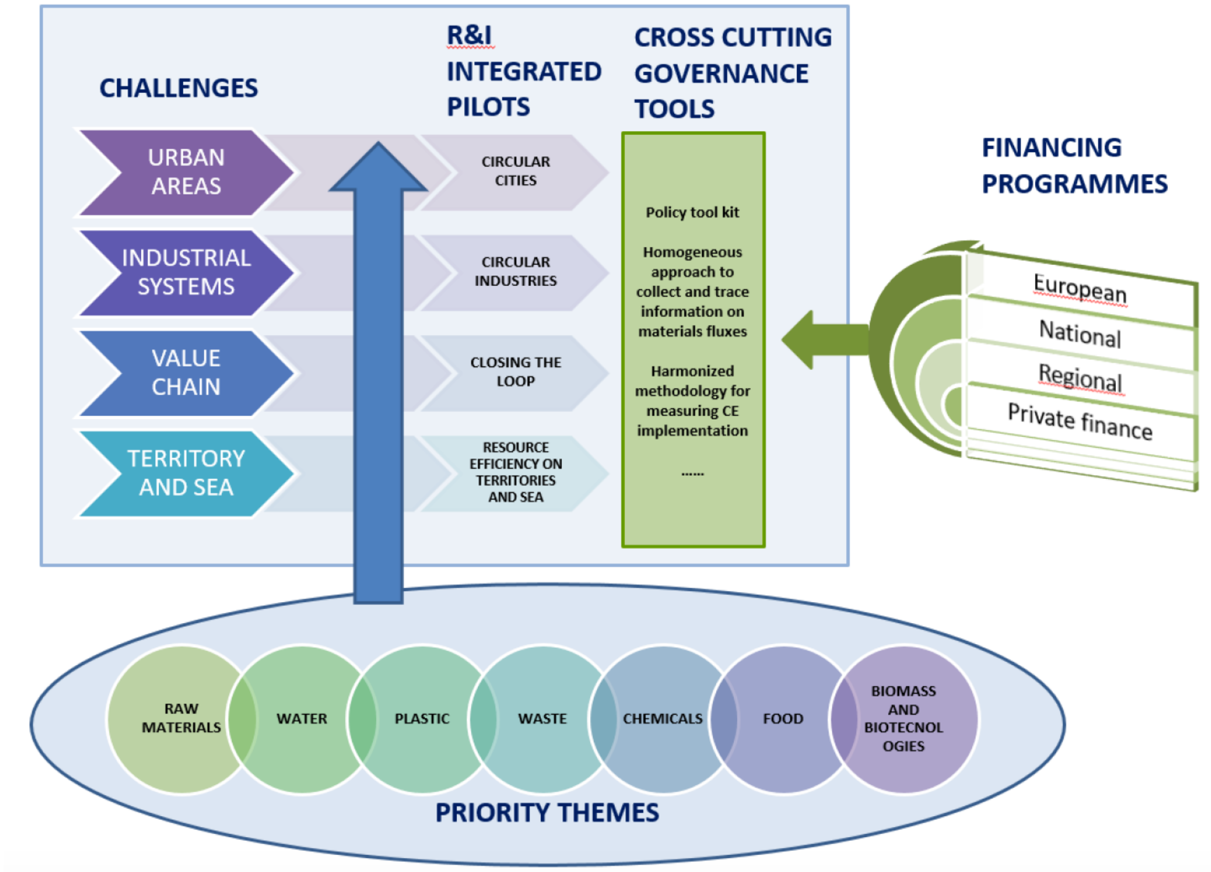

Figure 3: Addressing Circular Economy on CICERONE

The project will address as first priority the definition of joint national and regional funding programmes, complementary to European private finance funding programmes. The following matrix details the main topics of these challenges.

Table 1: Thematic focus of the CICERONE project

Challenges	Addressed topics
Urban areas	Waste prevention and management; Urban water management and reuse; Urban mining; Sharing economy; Prolongation of products life - products reuse; Building; Food waste prevention and valorisation; Citizen awareness
Industrial systems	Eco-design; Product and process eco-innovation; Water cycle; Agroindustry; Metallurgy; Manufacturing; Lean and clean technologies; Chemicals; Industrial Symbiosis, Business models;
Value chains	Eco-design and Product eco-innovation; Value chain traceability; Sustainable consumption; Reuse; Collection; Recycling; Sharing economy
Territory & sea	Marine litter; Material flows; Landfill mining; Sustainable tourism

For these challenges, it aims to develop an innovation-oriented CE approach; with the transition from a linear to a circular economy at its core. Thus the project will go beyond closing the loops of material flows. Circular economy in this context will be aligned with the focus of the European Commission´s

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CE Action Plan as it includes comprehensive commitments on ecodesign, the development of strategic approaches for specific materials. CIRECONE will specifically focus on horizontal enabling measures in areas such as innovation and investment that are included to stimulate the transition to a circular economy: "The proposed actions support the circular economy in each step of the value chain – from production to consumption, repair and remanufacturing, waste management, and secondary raw materials that are fed back into the economy" (European Commission, 2015).

Taking these different aspects and issues into account, the following figure shows an analytical CE framework that goes beyond the rather static perspective of flows but focuses on circular activities, business models and innovations instead.

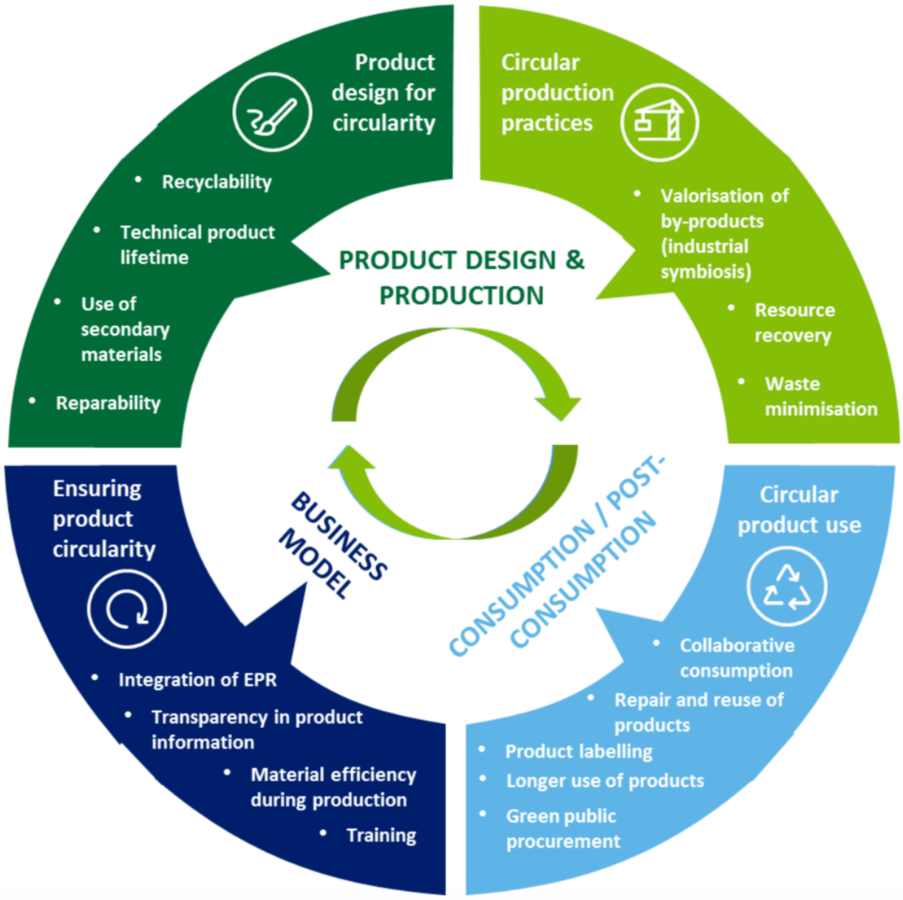

Figure 4: Framework for monitoring and evaluation of product eco-innovation for the circular economy (O'Brien et al., 2018, p. 20)

The framework encompasses three main areas (business model, product design/production and use/post-consumption) and associated indicators that effect the circularity of the system:

- Business model: factors applied in business models to ensure the full circularity potential of a product, e.g. establishment of take back schemes, application of extended producer responsibility (EPR), integration of circular product design and production into business models, etc.
- Product design and production: product design and manufacturing elements that influence the circularity potential of the product from a technical perspective, e.g. durability, reparability, recyclability, type of materials used, efficient production processes in terms of less resources used and waste produced, etc.

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- Use and post-consumption: consumer behaviour elements that contribute towards close-looped product cycles, e.g. innovative consumption models, longer use of products, recycling, etc.

3 THE CIRCULAR ECONOMY AS AN INNOVATION AGENDA

3.1 Introduction

The pace of innovation and technological change is unprecedented today. While many innovations and technological achievements are expected to be helpful in order to strive for the reduction of environmental pressures and progress towards circularity, there is much uncertainty and risk, and many innovations doubtlessly still contribute to accelerating resource use and wastage due to rebound effects.

The current system of production and consumption can be characterised as a predominately linear system – as outlined above as key starting point of the CICERONE project. Resources are extracted, processed, used and disposed as waste. At the end of a products' life cycle wastes are typically incinerated (thermal recovery) or landfilled. In both cases, materials are withdrawn from or eliminated within the economic system, even if some energy is regained through thermal utilisation. Such a linear economic model is able to persist as long as resources are abundant within a world of infinite needs. However, the global demand for resources is still increasing and both non-renewables and also renewables are limited. In the long term, a linear economic model must reach its limits (Wilts 2016).

However, there are a multitude of alternatives approaches to break up the linear path-dependent economy, reduce its resource use, increase its resource efficiency and minimise its generation of hazardous substances and wastes. These are known as the 3 R's: reduce (i.e., decrease the demand and the use of raw materials, intermediates and products); reuse (i.e., reutilisation of products or components of products); and recycle (i.e., feed back substances and materials into the system). All those approaches support a circular economy as a fundamental alternative to the linear economic model (EEA 2015, p. 9, EEA 2016).

Besides the famous 3 R's, further essential elements of a circular economy have been brought onto the agenda as innovative circular business models. These include: refurbish, sharing/leasing, remanufacture, recovery, and repair while reduce (in the sense of waste prevention and minimisation of hazardous substances) plays also a prominent role (European Commission 2014).

The vision is to deploy eco-innovation as a means to reach a resource-efficient circular economy in Europe.

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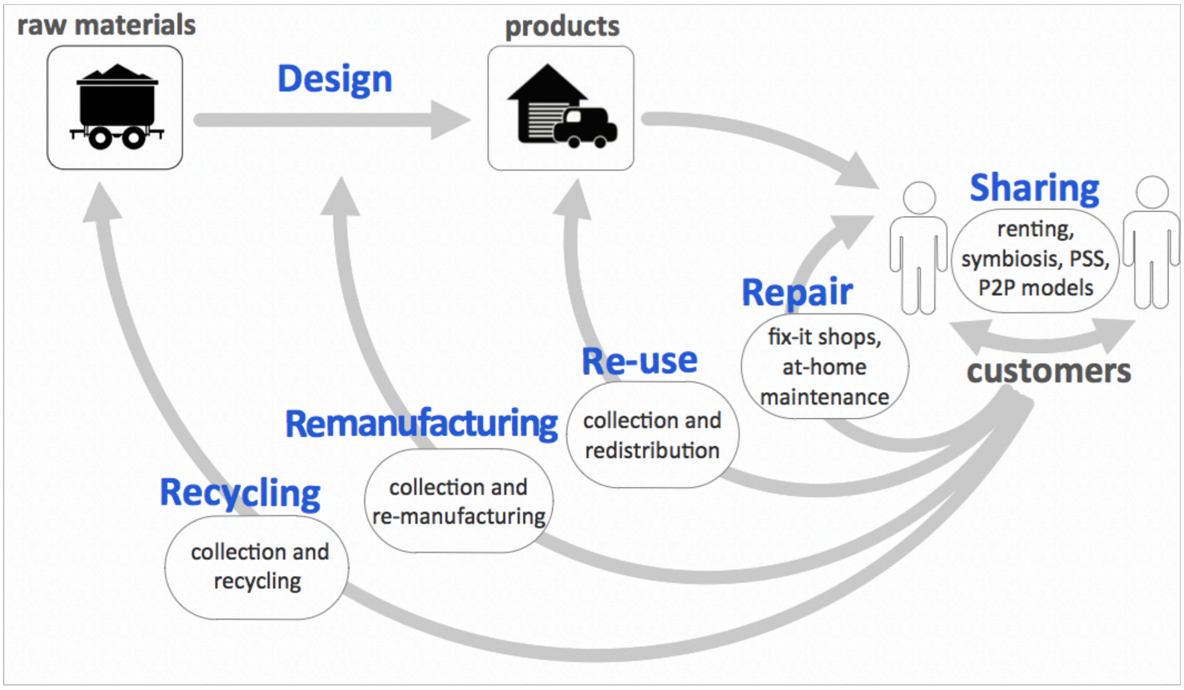

Figure 5: A simplified illustration of a circular economy (Based on EIO 2014, p.4)

The goal of a sustainable resource and waste management must be to ultimately achieve a transition to a fully fledged circular economy within this century (WBGU 2016, p. 85), i.e. to preserve the value of the resources and materials as long as possible, to reuse them as often as possible and, ideally, to generate no or as little as possible waste. The concept includes all sectors of the economy, from resource extraction over the production, storage and consumption, as well as the disposal or recycling. Through the closing of loops waste shall become a resource again (so-called "second-sourcing"). But to implement this idea as extensively as possible, the consideration of reuse, repair, remanufacturing, sharing and recycling is necessary as well as eco-innovation and circular economy aspects in the product design (Wilts 2016). Stronger eco-innovation efforts are needed for each option.

Eco-innovation is a vital element of all circular economy efforts and has been defined as any innovation that reduces the use of natural resources and decreases the release of harmful substances across the whole lifecycle (EIO 2010). Eco-innovations with the potential to enable the transition to a resource-efficient circular economy model span efforts to change dominant business models (from novel product and service design to reconfigured value chains), transform the way citizens interact with products and services (ownership, leasing, sharing, etc.) and develop improved systems for delivering value (sustainable cities, green mobility, smart energy systems, etc.) (EIO 2014, p.8).

Table 2 presents the scope of different types of eco-innovation related to the circular economy. It portrays the wide array of avenues to eco-innovation that may play a role in different aspects of the transformation: for example from changing behaviours to adapting technologies.

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Table 2: Types of eco-innovation for a circular economy

Type	Brief descriptions, examples & keywords
Process eco-innovation	**Material use, emissions and hazardous substances are reduced, risks are lowered and costs are saved in production processes** Advancing remanufacturing, such as - Refurbishment by replacing or repairing components that are defective, including the update of products - Disassembly and recovery at the component, material and substance level - Upcycling, functional recycling, downcycling → Zero waste production, zero emissions, cleaner production
Organisational eco-innovation	**Methods and management systems reorganisation pushing for closing the loops and increasing resource efficiency** New business models e.g. industrial symbiosis, new collection and recovery schemes for valuable resources (incl. Extended Producer Responsibility/Individual Producer Responsibility), → From products to functional services (product-service systems)
Marketing eco-innovation	**Product and service design, placement, promotion, pricing** Promotion of the reuse for the same purpose (e.g. bottles, appliances), promotion of the reuse for different purposes (e.g. tyres as boat fenders, for play grounds) → Eco-labelling, green branding
Social eco-innovation	**Behavioural and lifestyle changes, user-led innovation** Sharing (e.g. domestic appliances, books, textiles), collaborative consumption (e.g. flats, garden tools) sufficiency (e.g. plastic bag bans) → Smart consumption, responsible shopping, use rather than own schemes
System eco-innovation	**Entirely new systems are created with completely new functions reducing the overall environmental impact** Leading to a substantial dematerialisation of the industrial society → New urban governance, smart cities, permaculture

Source: Adapted on the basis of EIO 2014.

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3.2 The role of policy in the circular economy transition: how change can be driven

3.2.1 Framework conditions for fostering the CE

3.2.1.1 CE in a wider policy context

The concept of a circular economy is relatively new at the European level, but the term has been in use for some years, e.g. in China, Japan, and Germany, notwithstanding that those countries have not implemented a fully-fledged circular economy already. In Europe, the circular economy concept has been embedded in a wider policy context referring to the green economy and the strive for a resource-efficient and low-carbon society (see Figure 6 below) (European Commission 2015). As yet, circular economy activities at the Member State level are still overwhelmingly regarded as waste management measures (EEA 2016), which indicates a lack of knowledge and general uncertainty in the transformation to a circular resource management and neglects the eco-innovation efforts in the stage of product design.

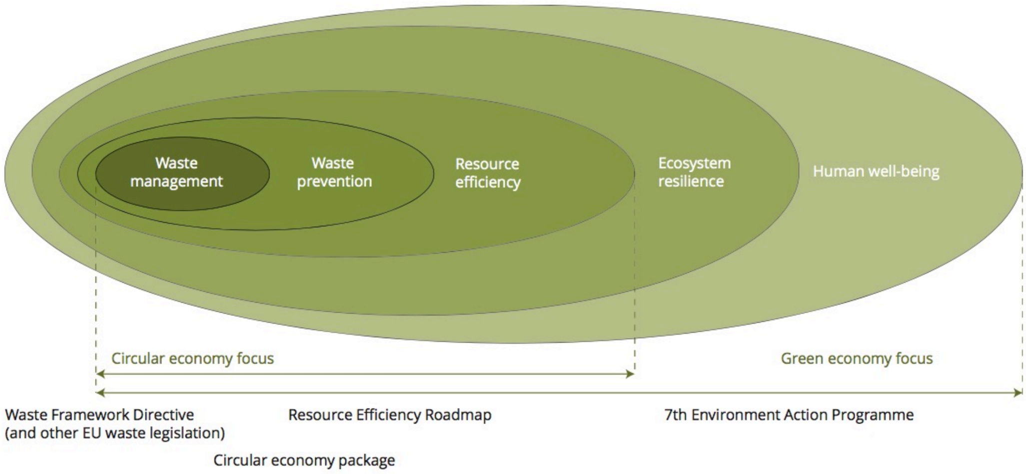

Figure 6: Circular Economy in the Wider Polcy Context (EEA 2016, p.31)

However, eco-innovation and circular economy concepts and activities need to be more closely linked – especially when it comes to R&D programmes. The Waste Framework Directive provides for technical requirements and regulations (e.g. mandatory recycling quota for several waste streams) but, as yet, the institutional settings and the country-specific planning for circular economy issues vary significantly from country to country with regard to contents, ambitions, targets and choice of policy instruments and it mainly focuses on waste management (Bahn-Walkowiak et al. 2014). The following Figure 7 shows where the current policy framework has direct and indirect impacts on the different options and phases of a circular economy.

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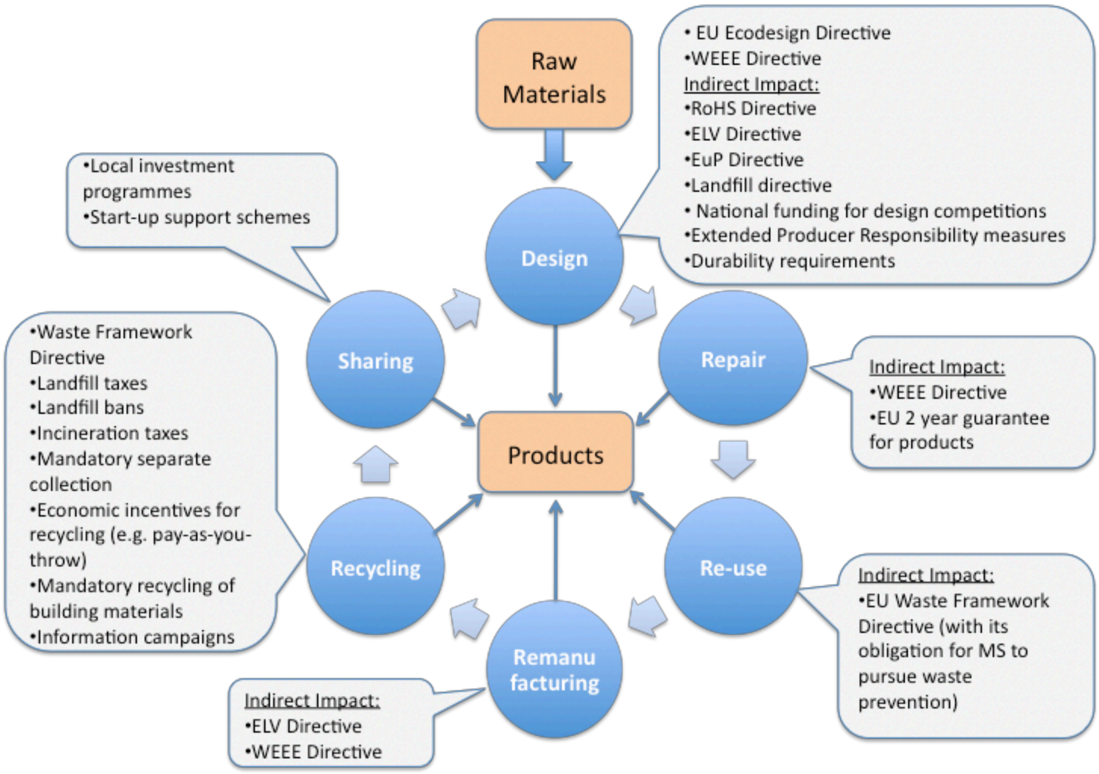

Figure 7: Overview of existing instruments and approaches for a circular economy in EU (Doranova and Gigli 2014)

The EU MS also often lack an integrated infrastructure planning for waste infrastructures, with corresponding counter and side effects on resource efficiency and circular economy. For example, regional waste incineration over-capacities act as an incentive to use those usually capital-intensive incineration plants at full capacity but they do not drive a circular economy. The current diverging country performances concerning waste recycling rates, infrastructures and waste prevention measures in place indicate that—as long as waste is still looked at as a cost factor instead of as a "resource"—regulatory instruments are often more effective than economic instruments (Bahn-Walkowiak et al. 2014).

Policy approaches are frequently not sufficiently considering the waste hierarchy and circular necessities and thus lead to unwanted effects. A policy for diverting waste from landfill without considering an alternative and eco-innovative treatment for a pathway further up the waste hierarchy, which might be environmentally and economically appropriate in the specific context, can lead to results, which:

- are ineffective (e.g. recycling focus on less resource-intensive waste fractions instead of the resource-intensive ones),
- induce unwanted pathways (e.g. investment in capital-intensive incineration capacities without taking account of future shifts such as recycling) or
- have a completely counterproductive effect (e.g. illegal dumping).

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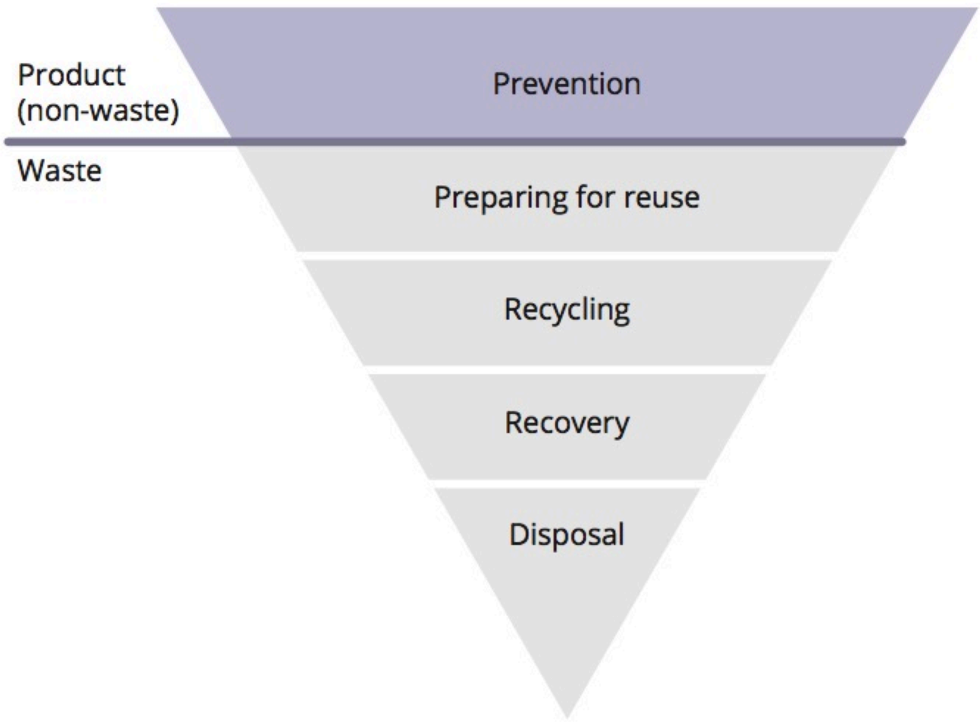

Figure 8: Waste Hierarchy (The European Parliament and the Council of the European Union 2008).

3.2.1.2 Barriers to a better circular performance

While the benefits are increasingly recognised, there are many barriers to the transition to a circular economy indicating investment in a series of necessary measures at the same time:

- Insufficient **investment** in recycling and recovery infrastructure, and eco-innovation and eco-technologies for closing the loops;
- Insufficient **skills and investment** in circular product ecodesign and production which could facilitate greater re-use, remanufacture, repair and recycling;
- Challenges in obtaining **suitable finance** for eco-investment;
- Current levels of **resource pricing** create economic signals that do not encourage efficient resource use, pollution mitigiation or innovation;
- Limited **consumer and business acceptance of potentially more efficient service oriented buisness models**, e.g. leasing rather than owing, performance-based payment models;
- Insufficient **waste separation at source** (e.g. for food waste, packaging);
- Lack of incentives due tot he insufficient **internalisation of externalites** through policy or other measures;
- Limited **information, know-how and economic incentives for key elements in the supply and maintenance chain**, e.g. for repair and reuse, on chemical composition of certain products such as substances in electronic devices;

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- Limited **sustainable public procurement** incentives in most public agenices (i.e. Green Public Procurement);
- Non-**alignment of power and incentives between actors within and across value chains** (e.g. between producers and recyclers) to imrpove cross-cycle and cross-sector performance;
- Shortfalls in **consumer awareness** (e.g. perishability of food products);
- Weaknesses in **policy coherence at different levels** (e.g. bioenergy and waste policies) (adapted from European Union 2014)

A circular economy will need to address all stakeholders for such fundamental transition: businesses, citizens, civil society, and governments (EEA 2016) as well as take different action at the EU, national, regional and local levels.

3.2.1.3 Key actors in building a CE

Implementing policies towards building a circular economy model requires the participation of many different types of stakeholders. This is particularly true for implementing a coherent strategy, when a wide range of actors should be involved, including national/regional/local governments, local businesses, NGOs, social enterprises, consumers/citizens, academic and research centres. Diverse roles and potential inputs by diverse stakeholders are summarised below.

Table 3: Key actors to be involved and their role in promoting circular economy

National, regional, local authorities and agencies dealing with industrial development and waste • Ensuring policy, regulatory support, introduction of support measures, as well as technical and financial support • Facilitating the dialogue with, and between, research organisations, businesses and civil society organisations • Leading, or involvement in, project development, implementation, monitoring of project activities and the financial allocation • Supporting awareness raising and education amongst the population and promoting more sustainable lifestyle, sharing, re-use, recycling
Businesses and industries • Developing and investing in new sustainable businesses, business models, products and services based on circularity principles, symbiosis • Cooperating with authorities in implementing initiatives and helping to scope visions for the greening and circularity in regions, cities and communities • Cooperating with research organisations in developing new eco-innovative and circular solutions
National, regional or local innovation agencies and intermediaries • Advising SMEs and organisations on innovation measures • Advising or playing an active role in the development and implementation of projects and monitoring project activities, outcomes and impacts

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• Cooperating with authorities in implementing eco-innovation initiatives and scoping visions for the greening of regions, cities and communities • Promoting or lobbying for specific regulations or policy decisions
Research organisations, cluster organisations and universities • Cooperating with authorities in implementing sustainable initiatives and helping to scope visions for the greening and circularity of regions, cities and communities • Cooperating with SMEs and industries in developing new solutions • Facilitating or taking an active role in project development and implementation, and the monitoring of project activities, outcomes and impacts
NGOs, citizens, user groups • Participating in priority setting for eco-innovation initiative planning • Educating and raising awareness amongst the population and promoting social innovations in areas such as lifestyle and mobility • Supporting project planning, implementation and monitoring • Creating networks and mobilising local efforts • Lobbying for specific regulations or policy decisions • Co-creating and co-testing of new eco-innovations by users, NGOs, citizens, user groups • Supporting the dissemination of eco-innovations towards a circular economy • Supporting eco-innovative or sustainable systems such as recycling, eco-mobility and sustainable lifestyle

Source: Based on Doronova and Gigli 2014.

For all those stakeholders, circular economy will have different meanings and involve different approaches and responsibilities. This requires a systemic approach that "makes use of a wide toolkit of policies and measures, across different points of value changes and affecting the full set of private and public stakeholders. Given the multi-level governance approach needed, options can be structured across different actors (e.g. EU, Member State, regional and local authorities, private sector, civil society, citizens), levels and timeframes, keeping in mind that in some areas circular economy benefits will materialise as a result of own initiatives by the private sector, while in other areas support (including public intervention) will be needed to encourage transitions" (European Union 2014, p. 54).

3.2.2 Building a CE from the ground up

Grounded on the idea that the circular economy transition will be powered by a combination of bottom-up and top-down changes, eco-innovation can transform individual behaviour and also create new forms of interactions between people or change peoples' relationship with products.

The transformative potential of cities and urban regions, for example, is important at different levels by contributing to a sustainable development and in practice by a multitude of circular economy relevant approaches, like initiating and running repair cafés, sharing, reuse and refurbish initiatives,

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and promoting waste prevention approaches, etc. which are, first and foremost, implementable at local levels (Maschkowski and Wanner 2014). At present, this is a niche development mentioned here in order to illustrate the ideas of bottom-up initiatives. As an organisational innovation in businesses re-manufacturing, repair, maintenance, recycling and eco-design can however create business opportunities for SMEs and "have a great potential to become drivers of economic growth and job creation while, at the same time, making a significant contribution to addressing environmental challenges" (European Commission 2014).

This section briefly shows different types of eco-innovation that play a role within a circular economy for future citizens *and* businesses and provides good practice examples from the country reports. A social (and sometimes user-led niche innovation) can induce behavioural and lifestyle changes that are more sustainable than existing solutions and thus "reduce impacts on the environment, but also re-structure social relations in one form or the other" (EIO 2013).

3.2.2.1 Re-use, sharing and collaborative consumption

Re-use is a critical part of the 3R waste management strategy (reduce, reuse, recycle) and eco-innovation can play a central role in enabling re-use, sharing and collaborative consumption. From the product perspective, re-use relates to aspects like longevity, durability, and reparability, and thus closely links to product design. Social eco-innovation such as sharing and collaborative consumption, often induced by user-led social eco-innovation and new business models, emerge as particularly relevant. Re-use is linked to social enterprises as well as citizen movements and relates to changes in consumption and disposal behaviour. This can play an important role notably in eco-innovative business models based on service provision and is instrumental in models based on sharing, leasing and product-service systems, which require extensive use of goods by multiple users and increase the need for regular maintenance and repair, be it commercial or non-commercial.

3.2.2.2 Repair and maintenance

Repair[1], maintenance[2] and remanufacturing[3] can be characterised as service innovation activities prolonging the lifetime of products which allow avoiding buying new replacements, thus preventing pollution, dispensable material use and waste arising. There is significant potential to develop innovative approaches to providing maintenance and repair services in the EU. However, the role of repair and maintenance has not been explored sufficiently in relation to eco-innovation, nevertheless their role in service based eco-innovative business models (based on sharing, rental, product-service systems) can be significant.

Integrating repair services in the product can provide a competitive advantage for a company and repair based business models can offer extended business opportunities for product suppliers. There are also some practices where producers provide lifetime guarantees and repair services for their product, which can be seen as a part of the business model. These products are normally "high end" products, however there are also examples relevant to "average consumers". There is a close link to eco-design that has to allow for repair and maintenance.

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[1] Repair (refurbish, reconditioning) is defined as a correction of a specified fault in a product/component and returning it to

[2] Maintenance has a wider scope than 'repair' and it is defined as a critical activity carried out in the use phase of the product life cycle to prolong system availability. Maintenance offerings can include repairs, servicing, diagnostics (onsite and remote), technical support (documentation and personal), installation, warranty, courtesy replacement product whilst product is being repaired, cleaning/valeting (http://circulareconomytoolkit.org/about.html).

[3] refers to used product that after the remanufacturing process is as good as a new one; so includes even upgrading.

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3.2.2.3 User-led eco-design

The concept of eco-design has a focus on the environmental impacts of products during their whole life cycle and aims to offer new solutions that are profitable and attractive but lead to an overall reduction in the consumption of materials and energy at the same time (EIO 2014). In addition to that, user-led eco-innovation is driven by customer demands for new goods and services or developed with stakeholders, thereby minimising the risk of superfluous product features or functionality.

The concept of eco-design has been evolving from a focus on single aspects of the product, like energy consumption, to a more holistic, life-cycle approach. This is a clear link to the circular economy model as it means that each phase of the product life cycle—including raw materials, production, distribution, use, re-use, re-manufacturing, recycling and disposal—is taken into consideration in the design of a product. In practice, however, the application of the concept is still rather narrow: while energy performance has become a standard element of a wide range of products (home appliances, vehicles, etc.), life-cycle thinking has only been applied to a limited number of examples and has not, yet, broken out of niche markets (EIO 2014).

3.2.2.4 Mix of policy measures to support circular economy on national and local level

Introducing rightly chosen and designed policy measures can motivate or regulate resource efficiency, waste reduction, recycling, re-use, and remanufacturing, and create demand for sustainably designed products as well as resource saving services. There is a need to directly support resource saving and eco-innovation in SMEs, as underlined by the Green Action Plan for SMEs “thus supporting green business developments across all European regions, notably in view of the fact that, at this stage, significant differences in resource efficiency exist between sectors and Member States” (European Commission 2014).

The scope of policy measures to support eco-innovations for circular economy, resource saving, and sustainable design can be quite wide. Many traditional innovation support measures can be adapted to support eco-innovations based on circularity. The figure below presents policy measures that can be adopted to support circular economy objectives.

Table 4: Examples of national and local policy measures to support circular economy

Categories of policy measures	Examples of policy measures
Regulatory instruments	• Regulations (e.g. on waste recycling, extended producers responsibility, eco-design, take-back, transparency in material chain and responsibilities, etc.) • Quality and other mandatory targets (e.g. waste recycling, re-use) • Codes, standards, certification for products, recycled material content, packaging, emissions, as well as the ones triggering innovation prior to setting new minimum performance limits
Economic instruments	• Fiscal/financial instruments and incentives, including, charges and taxes for waste, incineration, landfill, subsidies and tax reliefs, pay as you throw • Direct investment/funding (e.g. infrastructure, programme, etc.) • Demand pull instruments, including public procurement • Market based instruments, etc.

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Research, development and deployment	• Funding for R&D in CE related themes (e.g. direct or competitive grants) • Pre-commercial /R&D procurement for products and services with sustainable design • Providing R&D infrastructure • Innovation vouchers schemes for SME on CE related innovations • Support to innovation incubators focusing on CE related areas • Support programmes and incentives for R&D personnel
Information, capacity building and networking support	• Advisory services & information provision (to companies, start-ups, customers, technology adopters, etc.) • Professional training and qualification and skills enhancement courses, i.e. in material chain management • Support networking via matchmaking, technology platforms
Voluntary measures	• Performance label for products and services • Guarantee for product durability, repair, • Negotiated agreements (public-private sector) • Public or unilateral voluntary commitments (by private sector)

Source: Doranova and Gigli 2014.

4 TOWARDS THE CIRCULAR ECONOMY

The circular economy aims to boost the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices by helping to create new business opportunities and innovative more efficient ways of producing and consuming (European Commission 2015, p.2). Policy frameworks like the European Commission's Circular Economy Action Plan or similar national initiatives aim to initiate eco-innovations that would enable fulfilling these ambitious objectives. For the circular economy to go from an attractive concept towards business reality, pioneers along the whole value chain are challenged to develop alternatives to the traditional "make-use-dispose" approach.

Already today new technologies, design concepts, services, and innovative forms of co-operation are contributing to the circular economy across the EU.

4.1 The "hardware" perspective

Becoming a circular economy will require radical eco-innovations that enable completely transforming the linear patterns of production and consumption that developed over the last two centuries and became an obviously wasteful but stable regime of over-consuming natural resources. The circular economy will thus require eco-innovations in two very different fields that could be labelled as circular economy "hardware" and "software": The technologies and technical infrastructures that would allow to turn waste (like glass, see the following good practice example) into resources (hardware) and at the same time the skills, expertise and business models that would turn this transformation into a business case (software).

The broad field of waste, waste collection and waste management forms a great part of the circular economy approach. With regard to the rising publicity of the concept of a circular economy as analogous to highly efficient waste treatment one might expect an increase of patents in the waste sector as an indication of technological innovation. However, a study conducted by Francesco Nicolli in 2013 suggests otherwise. This study took into account 28 countries (including e.g. UK, US,

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Germany, Japan, New Zealand, Mexico) and all patents in the waste sector filed under the Patent Cooperation Treaty (PCT) for over 25 years. These numbers were then compared to the total patent applications. It shows, that unlike the total patent applications, the number of patent applications in the field of waste is stagnating and at times (e.g. 1997, 2002 and 2005) even decreased. If divided into five categories (waste management, material recycling, solid waste collection, incineration and recovery, fertilizers from waste) in order to gain better insights into this trend, the two most the most dynamic categories for a circular economy with the most patent applications (waste management and material recycling) follow this stagnating and at times decreasing trend.

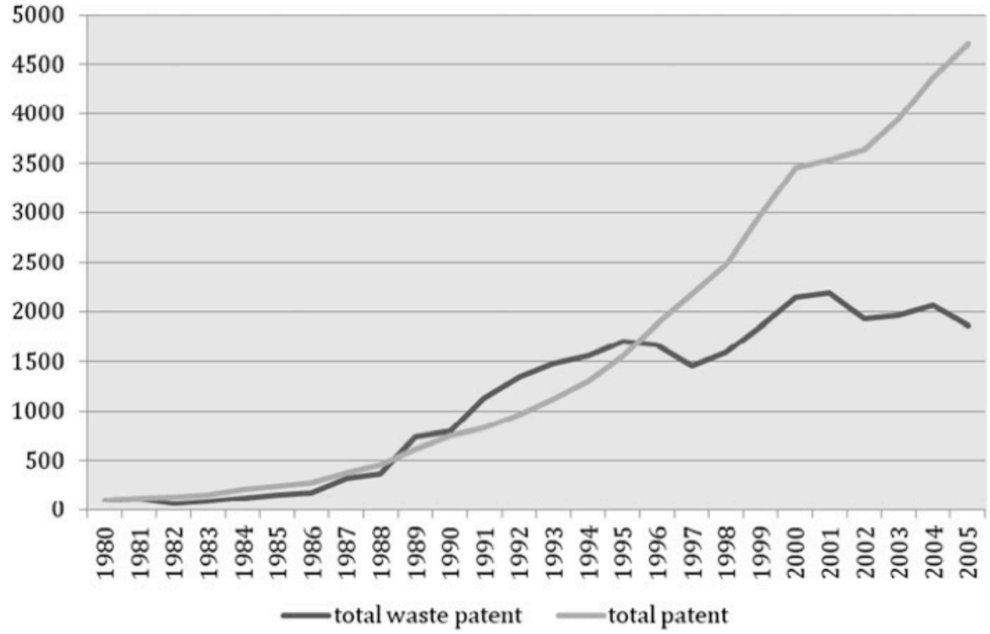

Figure 9: Number of patent applications filed under the PTC (total patent and waste patent, 3-year) (Nicolli 2013, p. 189)

Delving further into the question of why the numbers of waste patents are stagnating brings further insight. In many countries environmental problems associated with the existence and treatment of waste have been substantially reduced, and “security of disposal” has been broadly established as the objective of the waste management. Waste is in principle comprehensively collected and could be returned to the materials cycles. In fact, many actors now regard waste as a problem that has been “technically solved” (Wilts, von Gries, and Bahn- Walkowiak 2016)—although of course new challenges emerge from new products like for example wind turbines.

4.2 Sectors: Changing value chains and material flows

Circular economy eco-innovations in the European Union are clearly linked to challenges in specific sectors and value chain that are often characterised by particular resource intensity. Within its Circular Economy Action Plan the European Commission identified so-called priority waste streams as starting points for targeted measures that address the various phases of the cycle along the whole value chain. There are already viable eco-innovation activities in these different fields that highlight the innovation potential of the circular economy framework. In addition, however, the raw materials sector and especially critical raw materials also play an enormously important role in the context of new and eco-innovative technologies.

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4.2.1 *The Raw Materials Sector and its specific trends in technology and business fields*

An increasing number of raw materials can be classified as "critical" because they are both of high economic importance for the EU and vulnerable to supply disruption. The European Commission has published a list of such critical raw materials that includes, for example, rare earth elements and other precious metals, but also phosphorus.

The following sections are excerpted from a separate CICERONE paper on "The Raw Materials Sector and its specific trends in technology and business fields".[4]

Technology trends and expected raw materials demand

For high-wage industrial nations, competitive advantages on the global market are mainly from technical innovations. Taking Germany as an example, as one of the industrial countries, German industry is highly dependent on metal imports. In general, material costs account for around 40%, the largest share in the cost structure, for the German manufacturing industry (see Table 5). Hence, in order to remain its international competitiveness, securing raw materials supply is a rather important task. Since knowing the possible demand development is necessary for better estimation of long-term price and supply risks, especially when the emerging technologies are resource-intensive or -sensitive[5], DERA from Germany published a report in 2016 (revision from 2009) on emerging technologies and the forecasted raw materials demands. All information in this section was referenced from the DERA report.

Table 5: Cost structure of German's manufacturing industry in 2013 (excluding mining)

Type of cost	Share in %
Material costs	43.4
Energy costs	2.1
Personnel costs, wage labour and skilled trade services	21.9
Other costs (use of commodities, taxes, depreciation, etc.)	32.6
Gross production value without turnover tax	**100.0**

Source : Marscheider-Weidemann et al., 2016

The emerging technologies are defined as the technologies for which above-average growth in demand is expected in the future. They can be individual technology (e.g. fuel cells and RFID labels) or systematic innovations which combine existing individual technologies into new applications (e.g. automatic piloting of vehicles). They hold industrially exploitable technical capabilities triggering revolutionary innovations far beyond the boundaries of individual sectors and profoundly change economic structures, social life and the environment in the long-term.

The report identified in total 42 emerging technologies from various industrial sectors (see Figure 10) and their resource demands up to the year 2035 are estimated. The year 2035 was chosen considering mine construction could take up to ten years or more. However, it should be noted that future trends outside of these projections are plausible, for example, emerging technologies could also reduce demand for metallic raw materials.

[4] For more specific and comprehensive information and data on critical resources, please refer to CICERONE full paper «Overview of Raw Materials Sector in Circular Economy and Trends in Technology and Business Fields », by Meng Chun Lee & Wolfgang Reimer (GKZ), 2019, which is available in full length as WP5 paper. In consultation with the authors, some excerpts were used here for illustration purposes.

[5] Resource intensive: If a technology is expected to trigger an increase in demand of more than 25% of current (2016) global production of a raw material in at least one bulk metal; Resource sensitive: If a technology brings an increase in demand of more than 100% of current (2016) global production of this raw material in at least one specialty metal (i.e. resources with a worldwide production of up to thousand tons per year).

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Transport

- Tailored blanks (lightweight vehicles)
- Electrical traction motors (vehicles)
- PEM-Fuel cells (electric vehicles)
- Supercapacitors (for motor vehicles)
- Scandium alloys (aircraft)
- Autopilot (motor vehicles)
- Drones

ICT & optical technologies

- Lead-free solders
- RFID – Radio Frequency Indentification
- Flat panel displays (focus on ITO)
- Infrared detectors for night vision
- White LED
- Optical fibers
- Capacitors (microelectronics)
- Hight-performance microchips

Electrical engineering, energy

- High-efficiency industrial electric motors
- Thermoelectric generators
- Dye-sensitized solar cells
- Thin film solar cells
- Solar thermal power stations
- SOFC- Stationary fuel cells
- CCS - Carbon capture and storage
- Lithium ion batteries (for vehicles)
- Redox-flow batteries
- Vacuum isolation
- Inductive energy transmission
- Thermal storage
- Micro-energy harvesting
- Wind power plants

Medical technologies

- Orthopaedic implants
- Medical tomography

Chemical, environmental & mechanical engineering

- Synthetic fuels
- Sea water desalination
- Solid-state lasers for manufacturing
- Nano-silver

Material science & technology

- Superalloys
- High-temperature superconductors
- Hich-performance permanent magnets
- Industry 4.0
- Carbon fibers (lightweighting)
- Carbon nanotubes
- Additive manufacturing („3D printing")

Marscheider-Weidemann, Langkau, Hummen, Erdmann, Tercero Espinoza, Angerer, Marwede & Benecke (2016). *Rohstoffe für Zukunftstechnologien 2016*. DERA Rohstoffinformationen 28. Berlin

Figure 10: Identified emerging technologies sorted by industrial sectors (Marscheider-Weidemann et al., 2016)

Based on the research result of DERA, the sole demands in 2035 from the emerging technologies could equal or exceed the primary production in 2013 for five metals (i.e. germanium, cobalt, scandium, tantalum, and neodymium/praseodymium). Furthermore, the demands of three metals could be doubled comparing to the primary production 2013 (i.e. lithium, dysprosium/ terbium, and rhenium). More detailed information regarding the expected RM demand of emerging technologies is shown in Figure 11 and Table 6. The report also assessed the recycle potential of the emerging technologies, many of which are regarded as limited (i.e. economically feasible to some extent) or no (i.e. not economically feasible).

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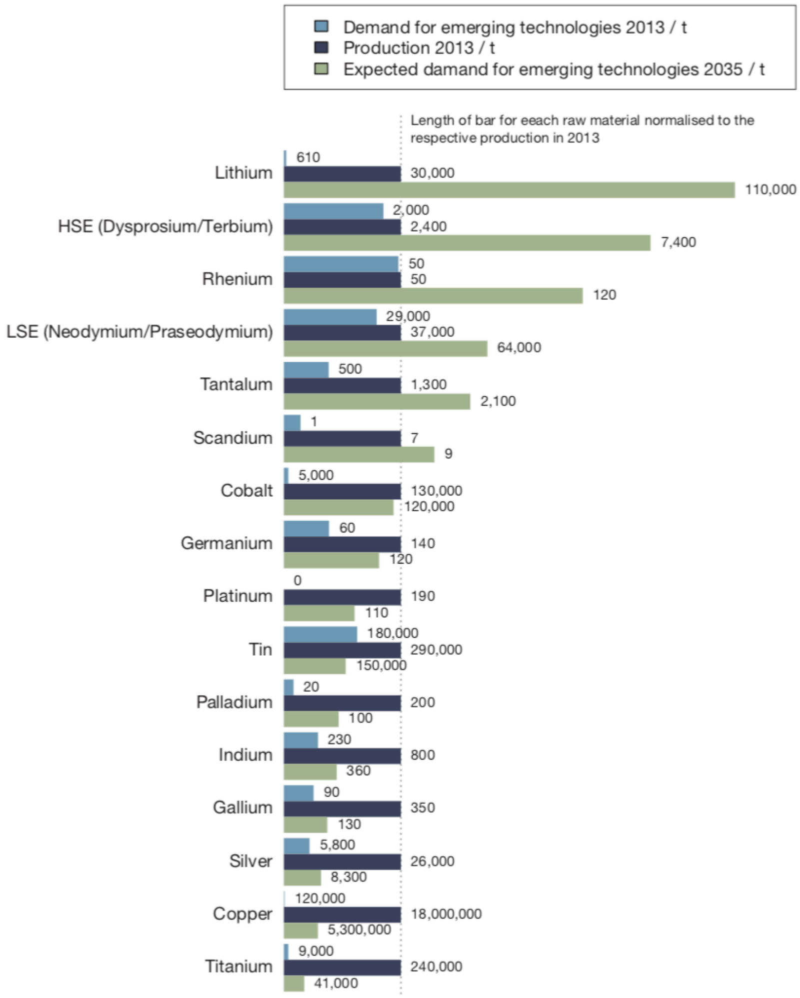

Figure 11: Estimated demands of the selected raw materials for emerging technologies in 2035 compared to the respective primary production level in 2013 (Marscheider-Weidemann et al., 2016)

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Table 6: Global demand for metals for the 42 emerging technologies in 2013 and 2035 compared to the global production volume of the respective metals in 2013*

Metal	$Demand_{20xx}/Production_{2013}$		Emerging technologies
	2013	2035	
Lithium	0.0	3.9	Lithiumion batteries, lightweight airframes
Heavy rare earths (Dy/Tb)	0.9	3.1	Magnets, e-cars, wind power
Rhenium	1.0	2.5	Super alloys
Light rare earths (Nd/Pr)	0.8	1.7	Magnets, e-cars, wind power
Tantalum	0.4	1.6	Microcapacitors, medical technology
Scandium	0.2	1.4	SOFC fuel cells
Cobalt	0.0	0.9	Lithium-ion batteries, XtL.
Germanium	0.4	0.8	Fiber optic, IR technology
Platinum	0.0	0.6	Catalysts, seawater desalination
Tin	0.6	0.5	Transparent electrodes, solders
Palladium	0.1	0.5	Catalysts, seawater desalination
Indium	0.3	0.5	Displays, thin layer photovoltaics
Gallium	0.3	0.4	Thin layer photovoltaics, IC, WLED
Silver	0.2	0.3	RFID
Copper	0.1	0.3	Electric motors, RFID
Titanium	0.0	0.2	Seawater desalination, implants

Note: the results in this table are not comparable with the previous study because they are based on a different period (22 instead of 24 years), a different reference year (2013 instead of 2006), a different technology portfolio (42 instead of 32) and more recent findings concerning innovation dynamics.

Source : Marscheider-Weidemann et al., 2016

*Note : This does not consider any raw material demand beyond these technologies.

Four emerging technologies are selected from the 42 emerging technologies and introduced in more details in the GKZ report (Figure 10) due to their substantial impacts on critical raw materials supply in terms of criticality of elements and forecasted demand in the long term. They illustrate the importance of identifying technology trends that are associated to excessive corresponding RMs demands in time and consumer as well as manufacturing markets.

Recycling rates of metals and EU CRMs

The following Figure 12 presents recent figures on the EoL recycling input rates of the EU CRMs. The EoL recycling input rate refers to how much of the total material input into the production system comes from recycling of 'old scrap' (i.e. post-consumer scrap).

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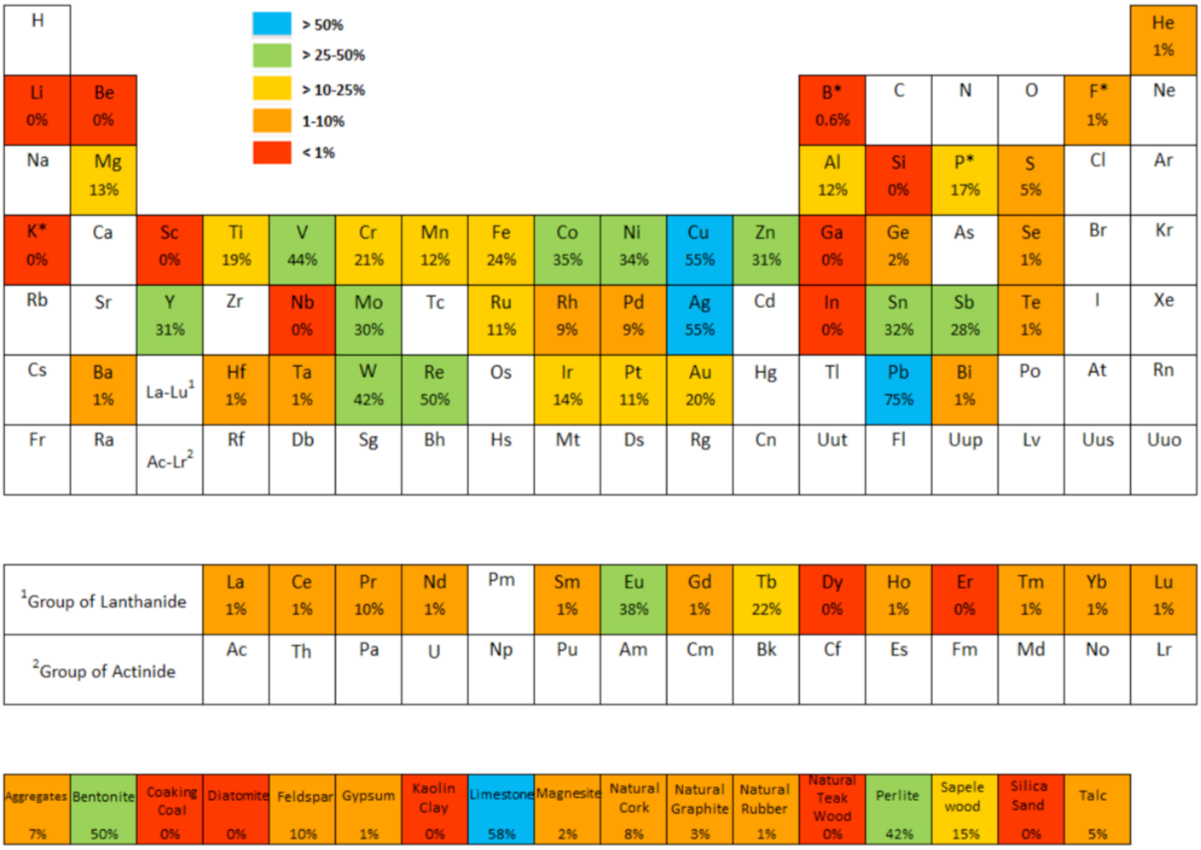

* F = Fluorspar; P = Phosphate rock; K = Potash, Si = Silicon metal, B=Borates.

Figure 12: EoL recycling input rates of the EU CRMs (JRC, 2017)

However, it should be noted that the generally low recycling input rates could be explained by several factors including the lack of economically viable sorting and recycling technologies for CRMs, the technical limitations (e.g. incapable to recover in-use dissipated materials), the long-life time of many CRMs applications, and the growing demands of many CRMs (i.e. the recycling contribution is insufficient to meet the demands, e.g. PGMs have recycling rate up to 95% for industrial catalysts and 50 to 60% of automotive catalysts but the recycling input rate is only 14%.) (Mathieux et al., 2017).

Factors affecting accessibility of critical raw materials for CE

The sections above provided an overview of the estimated future demands of raw materials due to emerging technologies and the EU CRM recycling input rates. Both imply that the further development in the secondary raw materials sector is a must and will encourage further R&D and support actions to improve the exploitation of the results. The development of the secondary raw materials sector, including R&D activities and exploitation, is nonetheless affected by many factors. In this section selected factors (i.e. identified) are introduced. The first part presents factors appearing in the raw materials market the second part showcases technical factors (i.e. metallurgy).

In the global raw materials market, four factors which can especially affect the development of secondary raw materials sector are identified:

- Accessibility to primary raw materials,

The easy access to primary raw materials limits the development of secondary raw materials markets and substitution materials markets. In contrast, limited access to primary raw materials by political

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restrictions, transport or societal resistance stimulates the development of secondary raw materials and substitution materials markets. Two examples are provided to illustrate the factor.

Example 1: Low development of secondary raw materials sector due to easy access to raw materials (international competition) – low recovery rate of lithium

Example 2: Low development of secondary raw materials sector due to easy access to raw materials (other natural forces, e.g. climate change) – newly accessible artic deposits in Greenland and Russia

- Relevant policies, regulations and political objectives

The impacts of policies and legislations on market-oriented economies are unavoidable. They may support market economies, initiating new business, or hinder market economies. The secondary raw materials sector is also affected by relevant policies, regulations and political objectives. Depending on the political decision, it could be beneficial to the R&D activities in raw materials sector but could also be detrimental. Few examples are illustrated below.

Example 1: EU policy as the driver – Electric vehicle target of the EU

Example 2: Foreign policy as the driver – China's import ban on plastic wastes

Example 3: EU policy as the barrier – Debate on the ban of lead in the EU

- Political interferences in markets

Example: China's policy on its rare earth elements market

Due to limits of the current technologies, there are raw materials that cannot be recovered from secondary sources but have visible primary raw materials supply risks. In this case, other measures (e.g. substitution) other than developing secondary sources are recommended for securing raw materials supply.

For more specific and comprehensive information and data on critical resources, please refer to CICERONE paper **Overview of Raw Materials Sector in Circular Economy and Trends in Technology and Business Fields, by Meng Chun Lee & Wolfgang Reimer (GKZ), 2019**, which is available in full length as WP5 paper. In consultation with the authors, some excerpts were used here for illustration purposes.

Recovery rates

The following Figure 13 illustrates the specific challenge of so far disappointingly low recovery rates and missed economic opportunities. The European Commission states that increasing the recovery of critical raw materials is one of the challenges that must be addressed in the move to a circular economy.

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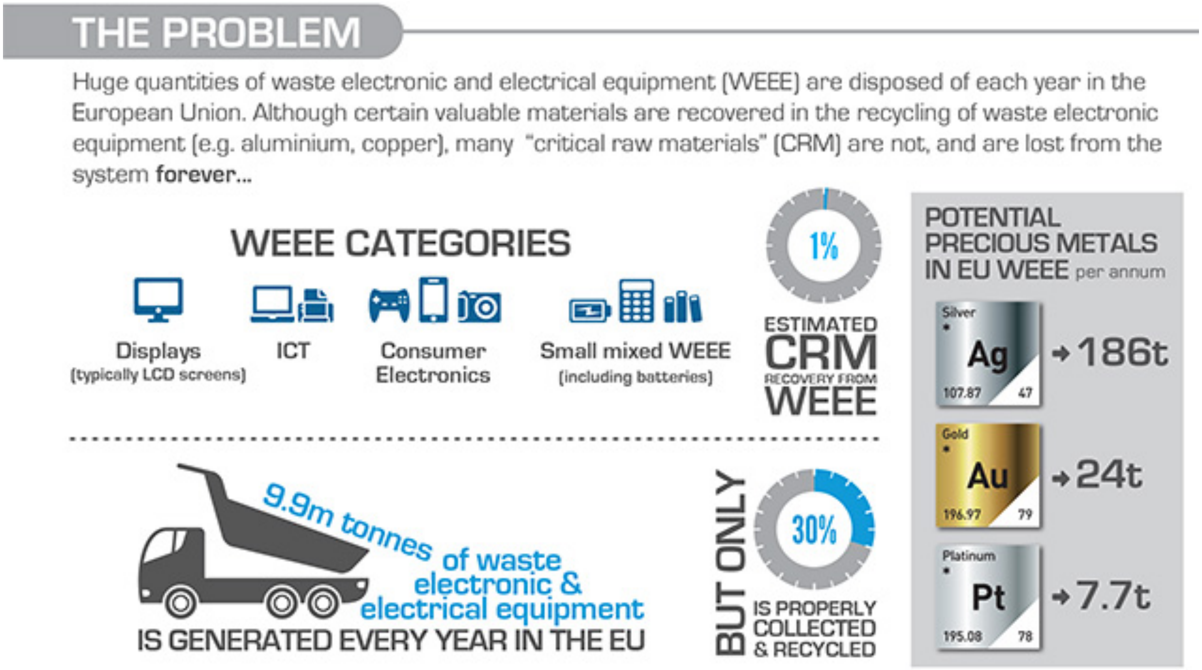

Figure 13: Recovery rates and material leakages (CRM 2014)

Key barriers include insufficient information exchange between manufacturers and recyclers of electronic products, the absence of recycling standards, and a lack of data for economic operators on the potential for recycled critical raw materials. Against this background, technical and organisational eco-innovations will have to play a crucial role in order to secure the supply of critical raw materials—that are to relevant amounts used for green technologies like fuel cells or photovoltaic panels. Projects like ReVolv aim to develop product-specific technologies that would allow in this case indium from LCD displays.

4.2.2 Plastics

The CE Action Plan has clearly stated that especially increasing plastic recycling will be essential for the transition to a circular economy. The use of plastics has grown steadily. The global production increased from 1.7 million tons in 1950 to 288 million tons in 2012 of which around 20% were produced in Europe. This has led to a generation of plastic waste of about 25 million tons; less than 25% of collected plastic waste is recycled and about 50% goes to landfill or even worse ends up in the oceans as marine litter (Plastics Europe 2013). The presence of hazardous chemical additives can pose technical difficulties and the emergence of innovative types of plastics raises new questions, e.g. as regards plastics biodegradability.

However, our current consumption patterns would not be imaginable without the use of plastics. The innovation in plastics can contribute to lowering environmental impacts and developing the circular economy by better preserving food, improving the recyclability of plastics or reducing the weight of materials used in vehicles—leading to significantly reduced fuel consumption and CO_2 emissions. On-going eco-innovations in this field also include more integrated packaging concepts that aim to minimise the use of unnecessary plastics or plastics of environmental concern and in this way support the prevention of plastics waste. Concepts like the Holis market in Austria also offer consumers the possibility to purchase only the exact amount of food that they want instead of being limited to specific packaging sizes.

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4.2.3 Bio-based products

Bio-based products made out of renewable biological resources (such as wood, crops or fibres) will have to play a crucial role in a circular economy. Bio-based materials can present advantages linked to their renewability and biodegradability; such elements of a bio-economy provide alternatives to fossil-based products and energy, e.g. in the fields of construction, furniture, paper, food, textile, chemicals as well as energy uses like biofuels (European Commission 2015). The drive to shift the material composition of consumables from technical towards biological nutrients and to have those cascade through different applications before extracting valuable feedstock and finally re-introducing their nutrients into the biosphere, rounds out the core principles of a restorative circular economy (Ellen MacArthur Foundation 2014, p. 23).

At the same time, the objective of replacing non-renewable with renewable resources may increase competition for land in a circular economy and thereby increase pressures on natural capital. Bio-based materials compete with production of both food and biomass for energy generation, as well as with land use for other purposes (including e.g. conservation of biodiversity). In general, biomass is best used in a cascade in which energy generation is the last step rather than the first. But even if biomass is primarily used for durable products, environmental impacts are not straightforward. A key example is wood as a construction material. The benefits of this renewable resource should be offset against the biodiversity impacts of increased wood harvest, with current harvesting rates in Europe already reaching 65 % of the annual increment and imports on the rise in many European countries, in particular to meet renewable energy targets. Analogous to the debate on bio-energy, the potential for uptake of bio-based materials should be critically analysed in view of overall biomass production and ecosystem resilience (EEA 2015).

Nevertheless, the European Commission has highlighted that eco-innovations in the bio-based sector have already shown their potential for innovation in new materials, chemicals and processes, which can be an integral part of the circular economy. Researchers are working to develop novel applications and processes that could potentially generate a higher added value than existing uses, such as biorefining, insect breeding, the production of C_5 and C_6 sugars, solid state fermentation, and more efficient biogas production processes (Bastein et al. 2013). The Bio Base Europe Pilot Plant is an excellent example for infrastructures to test these innovations for market readiness and to upscale their implementation and contributions to a circular economy.

4.2.4 Food waste

The European Commission has identified food waste as an increasing concern in Europe. Across the globe, nearly 30% of food is wasted throughout the agrifood supply chain. Around 100 million tons of food is wasted annually in the EU (estimate for 2012). Modelling suggests— if nothing is done—food waste could rise to over 120 million tons by 2020. The food resources being lost and wasted in Europe would be enough to feed all the hungry people in the world two times over. In September 2015, as part of the 2030 Sustainable Development Goals, the United Nations General Assembly adopted a target of halving per capita food waste at the retail and consumer level, and reducing food losses along production and supply chains. The EU and its Member States are committed to meeting this target.

Together with shifting to more sustainable diets, reducing food waste both in and out of the home is the most significant demand-side measure for reducing the carbon impact of the food system. But also supply-side eco-innovations will be able to contribute to the prevention of food becoming waste: It will require to design and develop technological innovations to improve valorisation of food

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waste, e.g. from food processing, and ICT-based platforms and tools to support new and existing solutions to reduce food waste[6]. The ResQ Club in Finland can be considered as one of the most promising eco-innovations in this specific area of a circular economy.

4.2.5 Construction and demolition

The most relevant waste stream stems from construction and demolition activities: It accounts for approximately 25% - 30% of all waste generated in the EU and consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil. Many of the materials are recyclable or can be reused, but reuse and recycling rates vary widely across the EU.

The recycling of construction and demolition waste is encouraged by a EU-wide mandatory target, but challenges on the ground still have to be addressed if waste management in this sector is to improve. For example, valuable materials are not always identified, collected separately, or adequately recovered. Given the long lifetime of buildings, it is essential to encourage design improvements that will reduce their environmental impacts and increase the durability and recyclability of their components. The GOMOS system (i.e. a modular system of reinforced concrete developed in Portugal for tiny houses) is an excellent example for necessary eco-innovations that bridge the design phase with the end-of-life phase of buildings.

4.3 The “software” perspective

Completely different kinds of eco-innovations can be found on what could be described as the software of the circular economy: Innovative forms of business models and consumption patterns that enable maintaining the value of products and raw materials as long as possible.

Not all business models in a circular economy need to be highly innovative or be completely new compared to the business models in place today, but some business models will be. Ideally they will all support the circular economy and form a part of it—either because the business model itself is completely focussed on the circular economy or because it is at least partly using the provided infrastructures, products or services enabling the circular economy.

Some businesses’ business models will focus on providing these infrastructures, products and services. Other businesses will use them either to build their business model based on this provision or they will make use of it in order to round out their business model or to fulfil legal or other requirements. As such most of the following concepts can be seen as either the core part of business models providing the infrastructure or as a part of other businesses’ business model.

The basic infrastructures to a circular economy are collection systems or platforms linking the demand and supply side in order to enable waste-as-a-resource procedures or the distribution and use of secondary raw materials. These systems will most likely benefit from a cross- border, cross-industry and cross-sector reach and from global supply chains, which will form a major part of reverse cycle networks and the distribution of (used) products, components and materials (Ellen MacArthur Foundation 2014). Businesses are needed which offer the facilities or services to treat products and materials in order to reuse, repair, remanufacture or recycle them. Many businesses will incorporate this waste-as-a-resource, either directly through using bought or self-produced waste, by-products or end-of-life products or components or indirectly through selling them.

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[6] http://eu-refresh.org/about-refresh#background

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But sometimes it might not be so easy to determine whether reusing, repairing, remanufacturing, recycling or selling would be the right treatment for a product, component or material. The businesses in a circular economy will therefore need support in this decision-making process, for example through tools that take into account various factors like for example the product's condition, the market situation, environmental effects and economic factors and so on. The provision of such tools could be another business model (Ellen MacArthur Foundation 2016). Strongly linked to the ability of making these decisions is the idea of eco-design. Already in the design stage of developing new materials, components or products, businesses in a circular economy need to think about the after-use-span and how the product can be treated and ideally enter another cascade step or life-cycle. Eco-design has to deal with the question of how the design enables easy reuse, repair, recycling etc., how disassembling (manually, technically, chemically, biologically etc.) without any losses in terms of quality or quantity can be facilitated and what materials should be used (e.g. composition, hazardous material content, pure material content). Through these considerations the durability should be enhanced, so that the materials, components or products can either enter more cascade steps or life-cycles or spend more time within one cycle. The benefits of eco- design would be energy and material savings and the chance to design out waste (EEA 2015, Ellen MacArthur Foundation 2013).

Today, most business models, regarding the provision of products, are based on selling items and generating one-time earnings. The enhanced durability of products might therefore seem contra productive—but service- and function-based business models (where product-as-a- service forms one part often referred to) will benefit from this[7]. Leasing, renting, sharing, and pooling and the so called collaborative consumption, performance contracts, predictive maintenance, and remanufacturing will form typical parts of the new service- and function- based business models (EEA 2016a, p. 15). As the earnings generated within these business models are rather performance-based and are reoccurring, instead of one-time earnings, the financial structure of such businesses will change compared to the financial structure of businesses with traditional concepts. As large scale payments at the start of the products' life- cycle are not generated, but reoccurring payments, these business models might even require new financial models (EEA 2016).

Some new business models will again deal with the provision of the necessary infrastructure like market places in order to match the offers and the demand side, some businesses will incorporate the services related to for example leasing, others will offer to provide these services for other businesses and within the organisation, and some will focus on the provision of completing services like insurances, which will be especially interesting for business models focussing on product-as-a-service options or sharing.

Generally, more connections between players of the economy will exist in a circular economy, either directly between for example businesses or indirectly through infrastructure and/or global supply chains. Another option could be through some kind of market space, which aims to match existing offers and demand in terms of products, components, materials and services in order to enable cascade usage, and longer or more cycles. And more business models than today will rely on the Internet of Things or Industry 4.0, as it will help to run business models containing for example product-as-a-service offerings, which require (real-time) information about the usage of a product or

[7] Of course, enhancing the durability of materials and leading them into cascaded usage, reusing them or recycling them is also a crucial benefit.

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component as well as its condition[8]. Feedback from products could also be used for product enhancements (Ellen MacArthur Foundation 2016).

But also eco-innovations in the field of consumption will be necessary to support the development of the circular economy, e.g. sharing products or infrastructures (collaborative economy), consuming services rather than products, or using IT or digital platforms (Fischer et al. 2015; Leismann et al. 2013). And especially such “Industry 4.0” approaches or web-based applications could become powerful enablers of a circular economy, especially in the field of collaborative consumption based on sharing, swapping, bartering, trading or leasing products and other assets such as land or time (Botsman and Rogers 2010). While such peer-to-peer interactions have long been practised on a local scale, they have developed into a different dimension through the use of online sharing marketplaces, through which the demand for certain assets, products or services is matched with their supply, usually through consumer-to- consumer (C2C) channels. A key challenge will be to set the right policy and incentives frameworks that ensures that the transition from consumers to “prosumers” actually boosts eco-innovations and does not simply lead to rebounds regarding traditional or even more resource intensive consumption patterns, e.g. spending vacation money saved by AirBnB for buying more long-distance flights.

Conclusively, Table 7 maps the application of circular economy processes in different sectors.

Table 7: Mapping of application of circular economy in different sectors

Objectives	Circular process	Examples of sectors where circular processes can be applied
Use of less primary resources	Recycling	Automobile industry, Textile industry, Building sector, Packaging sector, Critical Raw materials, Forest sector, Chemical industry
	Efficient use of resources	Building sector, Plastics industry, Mining and metals industry, Food sector
	Utilisation of renewable energy sources	Chemical industry, Food industry, Forest sector
Maintain the highest value of materials and products	Remanufacturing, refurbishment, reuse of products and components	Automobile industry, Manufacture of computer, electronic and optical products, Building sector, Furniture sector, Transport
	Product life time extension	Manufacture of computer, electronic and optical products, Automobile industry, Household appliances, Building sector, Food industry, Textile industry, Defence industry
Change utilisation patterns	Product as service	Household appliances, Transport, Building sector, Printing industry
	Sharing models	Automobile industry, Transport, Accommodation, Clothing
	Shift in consumption patterns	Food sector, Publishing sector, E-commerce sector

Source: (Rizos, Tuokko, & Behrens, 2017) p. 17

8 Example could be Philips – Lighting as a service.

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5 Conclusions

The following draws conclusions with regard to the role of innovation and R&D as well as related policies for transformations towards a circular economy.

Circular economy is increasingly represented in the strategic national policy agendas of the EU Member States

Evidence of the benefits of a transition towards a circular economy has increased over recent years. This has led to the increased embracement of the circular economy concept in society. Circular economy is currently penetrating the strategic national policy agendas of the EU Member States. A few countries address circular economy in the more generic context of their resource efficiency strategies, where it is addressed in a somewhat narrow definition based on material efficiency, recycling and waste prevention or management. However, there are examples of more ambitious and more comprehensive strategies, such as the recent circular economy strategy of Scotland that has a more systemic approach tackling the products design, durability, reuse, reparability, etc. as well as promoting new business models that can be at the core of the circular economy.

Promising eco-innovations can be found across the EU but there are gaps between good intentions and changed behaviours

Promising eco-innovations can be seen across the EU with the potential to be scaled-up. This includes in particular eco-innovations at the design phase. However, most efforts seem to be concentrated in individual markets or market niches instead of bridging the full circular model from design to disposal. Citizens seem willing to embrace environmental products through their purchasing decisions, but confusion exists as regards what is "green" and there seems to be a gap between good intentions and changed behaviours. Bottom-up approaches such as repair, reuse and sharing initiatives set powerful examples of how change may be implemented, but seem to remain in certain social niches instead of penetrating the mainstream.

Lack of knowledge and uncertainty in the transformation from waste to a circular resource management is apparent

Despite the increased presence of the circular economy in the policy discourse, the majority of activities at the Member States level is still overwhelmingly regarded as waste management measures, which indicates a lack of knowledge and general uncertainty in the transformation from waste to a circular resource management. Existing regulatory framework conditions are not favourable for engaging in circular economy activities. On the one hand, there is a need to break the "lock-in" in existing systems for waste management. On the other hand, there is a need to move towards alternative systems for consumption (e.g. sharing, reuse) and production (e.g. repair, remanufacturing). Product design is an important element in shifting to these alternative systems, therefore creating framework conditions for promoting the alternative design of products should be one of the main emphases of the circular economy policies.

Barriers to the transition towards a circular economy have to be overcome

There are also a number of barriers to the transition towards a circular economy, including the falling commodity prices since mid 2014, insufficient investment, lack of skills and know-how, limited acceptance of alternative models of consumption and business, and lack of policy coherence. In

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shifting to circular economy, there should be a systemic approach that addresses many barriers in a comprehensive way and creates favourable framework conditions (e.g. embracing regulation, institutional settings, targets, instruments, curricula, infrastructures, networks, key actors, etc.). Policies will play a key role in this.

Eco-innovation = Hardware and software solutions

Eco-innovation is an important element of all circular economy efforts. Different types of eco-innovations, i.e. product, process, organisational, marketing, social, system eco- innovation, are instrumental in transforming a linear economy into a circular economy. Building a circular economy will require boosting and creating favourable conditions for all types of eco-innovation.

The circular economy will require eco-innovations in two different fields that could be labelled as the circular economy "hardware" and "software": first being technologies and technical infrastructures and second being skills, expertise and business models that would turn this transformation into a business case.

- The patents statistics shows that whilst the growth rate of overall technological inventions is constantly growing, inventions focused on waste management and recycling has not been developing to the same extent over the last decade. This was due to limited focus on waste disposal, which has been seen as a "technically solved" problem. There is a strong need to promote R&D addressing wider concepts of circular economy, including circular design of products (e.g. durable, repairable, remanufacturable, etc.), as well as recycling, urban mining, and valorisation of waste as resources.
- The "Software" of circular economy is another highly important element that needs a strong support and framework conditions in order to develop. Business models based on the new consumption patterns and offering functionalities of products rather than the products themselves will need to gain bigger diffusion.

Creating favourable conditions for both the "hardware" and the "software" for the circular economy should become a part of a holistic policy support strategy. While supporting the "hardware" is something where policy makers can rely on the traditional innovation support instruments, development of "software" requires innovative approaches in policymaking. Much of the efforts should be focused on changing the mind-sets of consumers and creating an environment where companies can find economic prospects in business models based on sharing, remanufacturing, reuse and repair.

Stakeholders, policies and different responsibilities

For different stakeholders, circular economy will have different meanings and involve different roles and responsibilities. For each of them, framework conditions should provide direct or indirect incentives to act, plan, consume, produce or engage in business in a manner that contributes to circular economy.

To promote initiatives of circular eco-innovations the national and local governments can deploy a range of policy measures. These can be regulatory instruments, economic instruments, such as fiscal and financial incentives (taxes, fees), direct funding, demand pull instruments (e.g. procurement), R&D support measures, such as grants, infrastructure provision, supporting R&D personnel, information, education and networking support measures, and voluntary measures including performance labels and guarantees for products, voluntary agreements and commitments. Application of these measures in the context of circular economy development in Member States is

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not yet very wide. However, there is an opportunity to learn from selected policy initiatives and new practices on national and municipal levels that have been emerging.

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CICERONE T1.1

Overview of Raw Materials Sector in Circular Economy and Trends in Technology and Business Fields

AUTHORS, DATE: MENG CHUN LEE & WOLFGANG REIMER (GKZ), 2019

1. Summary

This report provides an overview of trends in technologies and business fields which may generate substantial CRM supply risks challenging a circular economy (CE) in terms of research and development (R&D) regarding recyclability and the economic viability of recycling.

The overview as given in Chapter two include future technologies and their expected RMs demands, recycling rates of critical raw materials (CRMs), as well as market and technical factors identified which can affect the development of secondary RMs market. By comparing the expected RMs demands of future technologies with todays´ recycling rates of CRMs, it can be seen that the demands of many CRM will be significantly higher than the present global primary production and rather low recycling rates. E.g. the demands of rare earth elements (REEs) and tantalum are expected to increase significantly from 2013 to 2035 but the recycling rates are currently lower than 1%. The low recycling rates can be explained by a number of factors, such as profitability, accessibility of primary RM, but also technical barriers and limits just given by the chemistry and physics of the elements considered. In order to increase CRMs (or RMs) recycling rates and develop the secondary RMs markets, many more factors should be taken into consideration, and therefore, are introduced in the same chapter, for instance, supplies and demands in the global RMs market, policies relevant to technologies and RMs, and the principles of metallurgy (i.e. metal wheels) in turn with present-days furnace technology.

One of the aims of this report is also to introduce the general CE R&D needs in metal recycling (i.e. from product designs to metallurgy processes) and specific R&D needs in metallurgy sector for recovering RMs from secondary sources. In Chapter two the specific R&D needs are summarised from the RMs used in exemplarily two application case studies comprising key technologies of some of the most pressing societal challenges (i.e. Chapter three: Domestic energy storage and Chapter four: Electric vehicles (EVs)). The CE R&D needs are identified to provide potential R&D topics with impact on securing the supply of CRM, reducing the dependency on primary sources and consequently contributing to CICERONE SRIA.

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2. Scope of the report and principle findings

This report aims to provide an overview of trends in technologies and business fields which may generate substantial CRM supply risks challenging circular economy (CE) in terms of research and development (R&D) regarding recyclability and recycling. Additionally, it highlights factors which can affect R&D in the development of the secondary RM market, (i.e. from product designs to metallurgy processes with their limitation just by the nature of the specific element. In order to highlight the importance of these relationships, two application case studies, domestic energy storage and electric vehicles (EVs) are given in later chapters as practical examples. The two applications are also selected because they are critical raw materials (CRMs) intensive applications with obvious increasing CRM demands[1] and are identified as key enablers to the development of green economy. Due to the expected increasing demands of the applications and the respective CRMs, R&D challenges in recovering relevant CRMs should be identified and corresponding R&D activities should be encouraged to secure the supply of CRM and reduce the dependency on primary sources.

It should also be noted that this report has some limitations. For instance, the selection of application case studies solely based on the high CRM intensity applications identified in SCRREEN Project Deliverable 2.2 (D2.2). Furthermore, information about further emerging technologies is limited to available information found.

2.1 Technology trends and expected RM demand

For high-wage industrial nations, competitive advantages on the global market are mainly from technical innovations. Taking Germany as an example, as one of the industrial countries, German industry is highly dependent on metal imports. In general, material costs account for around 40%, the largest share in the cost structure, for the manufacturing industry (See Table 2.1). Hence, in order to remain its international competitiveness, securing raw materials supply is a rather important task. Since knowing the possible demand development is necessary for better estimation of long-term price and supply risks, especially when the emerging technologies are resource-intensive or -sensitive[2], DERA from Germany published a report in 2016 (revision from 2009) on emerging technologies and the forecasted raw materials demands. All information in this section was referenced from the DERA report.

[1] Selection criteria: All the R2 (i.e. an expected application CRM use in 2035 relative to the current EU total CRM consumption (%)) of the application should be at least 20% higher than R1 (i.e. an application CRM use in 2015 relative to the current EU total CRM consumption (%))
Source: Monnet, A. & Ait Abderrahim, A. (2018) Report on major trends affecting future demand for critical raw materials, *H2020 SCRREEN Project* D2.2 obtained from http://scrreen.eu

[2] Resource intensive: If a technology is expected to trigger an increase in demand of more than 25% of current (2016) global production of a raw material in at least one bulk metal; Resource sensitive: If a technology brings an increase in demand of more than 100% of current (2016) global production of this raw material in at least one specialty metal (i.e. resources with a worldwide production of up to thousand tons per year).

Table 2.1 Cost structure of German's manufacturing industry in 2013 (excluding mining) (Marscheider-Weidemann et al, 2016)

Type of cost	Share in %
Material costs	43.4
Energy costs	2.1
Personnel costs, wage labour and skilled trade services	21.9
Other costs (use of commodities, taxes, depreciation etc.)	32.6
Gross production value without turnover tax	**100.0**

The emerging technologies are defined as the technologies for which above-average growth in demand is expected in the future. They can be individual technology (e.g. fuel cells and RFID labels) or systematic innovations which combine existing individual technologies into new applications (e.g. automatic piloting of vehicles). They hold industrially exploitable technical capabilities triggering revolutionary innovations far beyond the boundaries of individual sectors and profoundly change economic structures, social life and the environment in the long-term.[3]

The report identified in total 42 emerging technologies from various industrial sectors (See Figure 2.1) and their resource demands up to the year 2035 are estimated. The year 2035 was chosen considering mine construction could take up to ten years or more. However, it should be noted that future trends outside of these projections are plausible, for example, emerging technologies could also reduce demand for metallic raw materials.

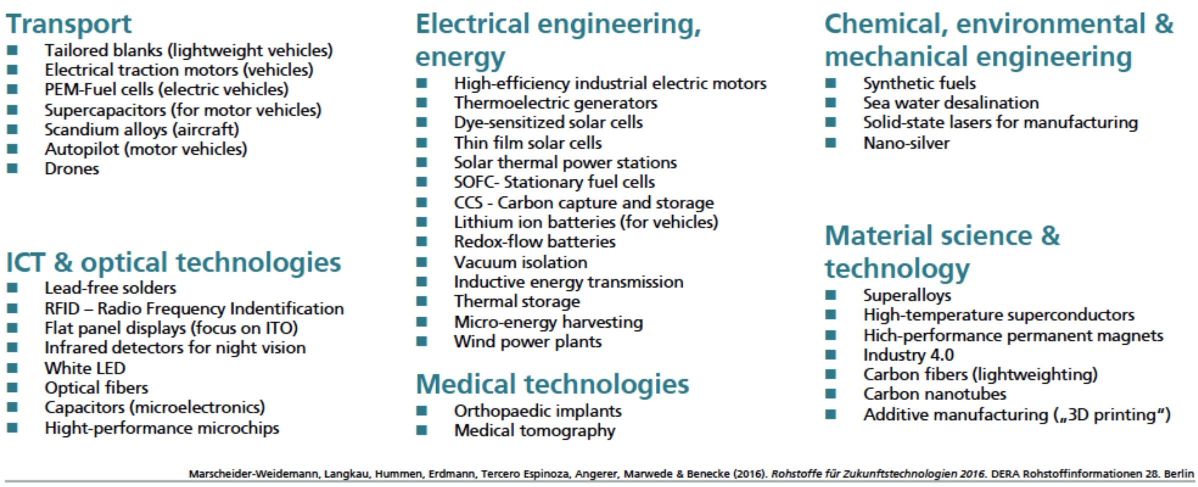


Figure 2.1 Identified emerging technologies sorted by industrial sectors (Marscheider-Weidemann et al, 2016)

Based on the research result of DERA, the sole demands in 2035 from the emerging technologies could equal or exceed the primary production in 2013 for five metals (i.e. germanium, cobalt, scandium, tantalum, and neodymium/praseodymium). Furthermore, the demands of three metals could be doubled comparing to the primary production 2013 (i.e.

[3] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L.,Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) Rohstoffe für Zukunftstechnologien 2016. DERA Rohstoffinformationen 28: 353 S., Berlin.

lithium, dysprosium/ terbium, and rhenium). More detailed information regarding the expected RM demand of emerging technologies is shown in Figure 2.2 and Table 2.2. The report also assessed the recycle potential of the emerging technologies, many of which are regarded as limited (i.e. economically feasible to some extent) or no (i.e. not economically feasible).[4]

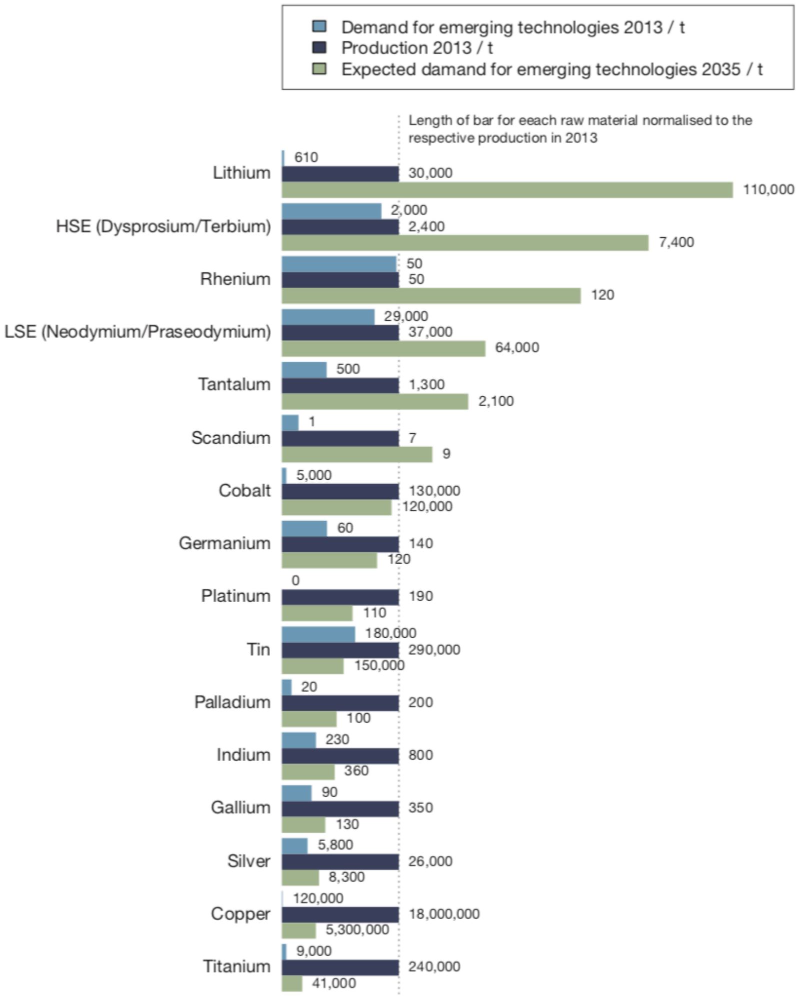


Figure 2.2 Estimated demands of the selected raw materials for emerging technologies in 2035 compared to the respective primary production level in 2013 (Marscheider-Weidemann et al, 2016)

[4] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) Summary - Raw materials for emerging technologies 2016. DERA Rohstoffinformationen 28: 13 S., Berlin.

Table 2.2 Global demand for metals for the 42 emerging technologies in 2013 and 2035 compared to the global production volume of the respective metals in 2013. (This does not consider any raw material demand beyond these technologies.)
(Marscheider-Weidemann et al, 2016)

Metal	$Demand_{20xx}/Production_{2013}$		Emerging technologies
	2013	2035	
Lithium	0.0	3.9	Lithiumion batteries, lightweight airframes
Heavy rare earths (Dy/Tb)	0.9	3.1	Magnets, e-cars, wind power
Rhenium	1.0	2.5	Super alloys
Light rare earths (Nd/Pr)	0.8	1.7	Magnets, e-cars, wind power
Tantalum	0.4	1.6	Microcapacitors, medical technology
Scandium	0.2	1.4	SOFC fuel cells
Cobalt	0.0	0.9	Lithium-ion batteries, XtL.
Germanium	0.4	0.8	Fiber optic, IR technology
Platinum	0.0	0.6	Catalysts, seawater desalination
Tin	0.6	0.5	Transparent electrodes, solders
Palladium	0.1	0.5	Catalysts, seawater desalination
Indium	0.3	0.5	Displays, thin layer photovoltaics
Gallium	0.3	0.4	Thin layer photovoltaics, IC, WLED
Silver	0.2	0.3	RFID
Copper	0.1	0.3	Electric motors, RFID
Titanium	0.0	0.2	Seawater desalination, implants

Note: the results in this table are not comparable with the previous study because they are based on a different period (22 instead of 24 years), a different reference year (2013 instead of 2006), a different technology portfolio (42 instead of 32) and more recent findings concerning innovation dynamics.

In the following those emerging technologies are selected from the 42 emerging technologies in the report (Fig. 2.1) which substantially impact critical raw materials supply in terms of criticality of elements and forecasted demand in the long term. They illustrate the importance of identifying technology trends that are associated to excessive corresponding RMs demands in time and consumer as well as manufacturing markets. The chosen examples illustrate the expected technological development in the future, the respective RM demands, recycling rates or substitutions of the RMs, and R&D needs of the technologies. On the other

1. Fuel cell for electric vehicles (EVs) – Platinum group metals (PGMs)

There are many types of fuel cells for EVs, the polymer electrolyte membrane fuel cell (PEM), named after its electrolyte, is currently the main fuel cell used for the traction motor. Although the development of fuel cell technology slowed down since 2004 because many turned to focus their research efforts on battery-powered vehicles, it has regained some importance in recent years as the batteries for EVs have not yet achieved the planned storage densities and ranges. In addition to the automotive sector, fuel cell technology also has the potential to be used for stationary domestic energy supply or the power supply for portable devices even though the installed capacity is relatively insignificant.

In general, platinum, one of the precious metals, is used as a catalyst in PEMs. Currently, it is possible to reduce the platinum contents to approximately 0.5 g per kW output in PEMs.[5] In the future, it is likely to reduce the platinum contents to 0.2 g per kW or substitute it with

[5] Mougenot, M., Caillard, A., Brault, P., Baranton, S. & Coutanceau, C. (2011) High Performance plasma sputtered PdPt fuel cell electrodes with ultra-low loading. – International Journal of Hydro- gen Energy 36(14): 8429–8434. – DOI: 10.1016/j. ijhydene.2011.04.080.

doped carbon nanotubes (CNTs)[6]. Based on the information, the expected platinum demands for fuel cell EVs in 2035 are estimated under three different scenarios (See Table 2.3). It shows that the expected platinum demands account for a significant share of the global primary production in 2013. On the positive side, recycling rate of precious metal (e.g. platinum) has been more than 97% for years in known applications.[7] The first concept and process for recycling PEM fuel cell is also available.[8,9]

Table 2.3 Global platinum primary production and demands for fuel cell EVs

RM	Primary production 2013 (t)	Demand 2013 (t)	Expected demands in 2035 (t)[10]		
			Prevalence of conventional passenger cars	Market penetration of EVs	Mobility concepts
PGMs	187	>0	>0	93	80

2. Indium tin oxide (ITO) for display technology – Indium (In)

Indium tin oxide (ITO) is a type of transparent conductive oxide (TCO) used to produce the (transparent) electrode layers of flat screens such as liquid crystal displays (LCDs), organic light-emitting diodes (OLEDs), plasma display panels (PDPs), and field emitter displays (FEDs). A large number of flat screens are adopted in different applications, for instance, television sets, computer monitors, note books, digital cameras, information displays in vehicles, and large information displays in train stations and airports.

Typically, ITO is composed of 90 % In_2O_3 and 10 % SnO_2.[11] If the atomic masses of the elements are taken into account, 74 % of ITO consists of indium. The estimated demands of indium in 2035 (See Table 2.4) are then calculated considering, for example, losted/recycled amount during manufacturing processes (i.e. sputtering), layer thickness, sizes of displays for different applications (i.e. indium content in mg/m^2), market forecasts for worldwide sales of flat-screens, and the development of the market shares of the respective display technology. The report assumed that OLEDs will replace LCD almost completely by 2035 as OLED. Although currently OLEDs have relatively small market share, compared to other display technologies, self-luminous, fast-acting OLEDs are much lighter and require less power. In addition, OLED displays have a high resolution, a large viewing angle, are very flat and flexible.[12] Therefore,

[6] Le Goff, A., Artero V., Jousselme, B., Tran, P.D., Guillet, N., Métayé, R., Fihri, A, Palacin, S. & Fon-Tecave, M. (2009) From hydrogenases to noble metal-free catalytic nanomaterials for H2 produc- tion and uptake. – Science 326: 1384–1387. – DOI: 10.1126/science.1179773

[7] Hassan, A. (2001): Rohstoffeinsparung durch Kreislaufführung von verbrauchten Katalysatoren aus der chemischen Industrie. – Reihe Texte Nr. 21/2001. –, Umweltbundesamt; Berlin

[8] Lucas, R. & Wilts, H. (2011) Weltweite Wieder- gewinnung von Platingruppenmetallen (PGM). – Meilensteinbericht des Arbeitspaketes 2.2 des Projekts „Materialeffizienz und Ressourcenschonung“ (MaRess). Wuppertal Institut, Wuppertal

[9] IUTA – Institut für Energie und Umwelttechnik e.V. (2007) Untersuchung der Recyclingfähigkeit der verschiedenen Brennstoffzellen-Typen und deren Komponenten sowie Entwicklung geeig- neter Verwertungsmethoden. Abschlussbericht AiF-Vorhaben-Nr. N 13869, Duisburg

[10] "Prevalence of conventional passenger cars" assumes low acceptance and low political support for electric cars as well as an unsolved range (BEV) and hydrogen infrastructure (FCEV) problem.

"Market penetration of e-cars", the acceptance of e-cars can be significantly increased through information campaigns, political support and technical improvements with regard to battery range and hydrogen infrastructure.

"Mobility concepts" is based on assumptions from the scenario "Market penetration of electric cars" as well as on the assumption that flexible, linked mobility concepts from public transport and sharing services will reduce the total number of cars sold by about 20 million in 2035.

[11] UMICORE (n.d.) Indium Tin Oxide (ITO) for deposition of transparent conductive oxide layers. – URL: http://www.thinfilmproducts.umicore.com/Products/TechnicalData/show_datenblatt_ito.pdf [Stand 28.11.2014]

[12] Behrendt, S., Fichter, K., Nolte, R., Kamburow, C., Antes, R. & Neuhäuser, V. (2008): Nachhaltig- keitsinnovationen in der Display-Industrie – Aktivierung von Umweltentlastungspotenzialen durch Akteurskooperationen in der Display-Branche. – Studie des IZT. Berlin

OLEDs are regarded as a promising new flat screen technology, both technologically and economically, that could displace LCD technology from the market in the future.

Table 2.4 Global indium primary production and demands for flat screen technology

RM	Primary production 2013 (t) (Refined production)	Demand 2013 (t)	Expected demand 2035 (t)
Indium	790	93 (in products)	196 (in products)
		102-130 (in production process) [13]	215-275 (in production process) [14]

The flat screen industry is aware of the risks associated with the price fluctuations and the criticality of indium. Hence, many researches are focuses on finding an alternative to ITO such as new amorphous TCOs (e.g. gallium indium zinc oxide (IGZO/IZGO), indium zinc oxides (IZO) and zinc tin oxides which have similar or even better properties than ITO, but still need at least five years to reach market maturity and some still use indium). Other transparent and conductive thin-film technologies are also being developed but they probably will not be ready for the market until 5-10 years later (e.g. ultra-thin metal foils and zinc-metal-oxide multilayer and graphene foils).

Various research projects have demonstrated the technical feasibility of recycling indium from LCDs. However, the recycling of indium from displays is not being implemented on a large-scale due to a lack of economic efficiency.[15] Since the return quantities of waste flat screens will continue to rise in the future, the recycling of indium from displays in combination with other indium-containing waste streams such as CIGS solar cells or production waste could possibly become economically viable.

3. Capacitors – Tantalum (Ta)

Capacitors are used to store electrical charges and to maintain an even current in integrated circuits (ICs). There are mainly two types of capacitors, electrolytic and ceramic-based capacitor. Tantalum electrolytic capacitor, due to its outstanding properties, were until recently a prerequisite for microelectronics (e.g. mobile phones). The current shift from tantalum electrolytic capacitor to alternative technologies resulted from the high demand of tantalum and the associated high prices. Much focus is on niobium electrolytic capacitors and multi-layer ceramic capacitors (MLCC) which have similar power range of tantalum electrolytic capacitors (i.e. low voltage with medium capacitance).

Even though the demand for tantalum is relieved by the alternative capacitors, the demand of tantalum in 2035 is still expected to be much higher than in 2013. The growth of the overall market until 2035 overcompensates for material savings and the declining market share, especially in some applications, tantalum catalyst cannot be replaced by niobium or ceramic capacitors. Relative to the global primary production of tantalum in 2013, the estimated

[13] Indium requirement for the display industry is rather underestimated in this study because other fields of application for LCDs, e.g. in other small devices such as cameras, game consoles or navigation devices, are not taken into account here. Since the consumption is rather underestimated with this forecast, the upper end of the production-specific demand is estimated here as the more realistic forecast.
[14] ibid.
[15] Chancerel, P., Deubzer, O., Nissen, N.F. & Lang, K. (2012) From CRT to flat displays - Consequences for collection and recycling. – In: Lang, K.-D., Nis-sen, N. F., Middendorf, A., Chancerel, P. (Eds.) Electronics Goes Green 2012+: Taking green to the next level: Proceedings of the Joint Interna- tional Conference and Exhibition: September 9-12, 2012, Berlin. – Fraunhofer Verlag; Stuttgart

demand in 2035 is significant (See Table 2.5). In contrast, the increasing demands of RMs such as niobium, barium, titanium, silver, palladium, nickel and tin are either manageable or neglectable comparing to the primary RM productions.

Table 2.5 Global tantalum primary production and demands for tantalum electrolytic capacitors

RM	Primary production 2013 (t)	Demand 2013 (t)	Expected demands in 2035 (t)[16]	
			Projection A	Projection B
Tantalum	1,300	128	360	1070

There is hardly any recycling of tantalum from end-use waste (<1% worldwide) and tantalum condensers are not recycled. Tantalum is recovered from end-use waste in the form of super alloys or hard metals. On the other hand, the recycling of industrial process waste, is one of the most common processes, with which about 10 to 25 % of the primary raw material can be replaced.[17]

4. Microchips – Gallium (Ga)

While most integrated circuits (ICs) are based on silicon technology, there are increasing use of gallium arsenide (GaAs) and silicon germanium (SiGe) as semiconductor materials for special performance requirements. Comparing to silicon, GaAs have some better electro properties such as higher electron velocity and mobility (i.e. transistors operating at several hundred GHz can be produced), less noise at high frequencies, and higher breakdown voltage (i.e. GaAs can operate at higher power levels). GaAs components are ten times faster than silicon components. Furthermore, they are less susceptible to interference and require less energy. Aforementioned properties make GaAs ICs particularly suitable for high frequency power applications (e.g. mobile phones, wireless local area networks (WLANs), and GPS).[18] GaAs ICs are also used in microwave electronics, cable television receivers, telecommunications equipment, military and aerospace applications. SiGe transistors are more stable at high temperatures and in the ultra-high frequency range as well. Therefore, SiGe components can also be used for such as wireless devices, WLANs, optical communication systems, hard disks, automotive chips. Since the production process of SiGe is cheaper than GaAs, SiGe is already used in certain blue tooth and WLAN applications and should be increasingly used in the future for slower high frequency chips and thus reduce the importance of GaAs.[19]

The demand for mobile phones will continue to be the driver for the GaAs industry. At the same time, WLAN will become more important as more devices start to be equipped with WLAN chips. Under the condition that demands of GaAs in 2035 doubled from 2013 and with

[16] Projection A: Growth of the total market by 4 %/a until 2035, retention of current market shares (i.e. ceramic capacitors (49 %), aluminium. (29.5%), tantalum. (16.9%) and film capacitors (4.6%))with an assumption of material efficiencies: 10 % for electrolyte condensers and 25 % for MLCCs.
Projection B: Growth of the overall market by 7 %/a, the proportion of tantalum and niobium capacitors is growing continuously to 20 % at the expense of the MLCC proportion until 2035. No material efficiency effects.

[17] Wilts, H., Lucas, R., Gries, N. von & Zirngiebl, M. (2014): Recycling in Deutschland – Status quo, Potenziale, Hemmnisse und Lösungsansätze. – URL: https://www.kfw.de/PDF/Download-Center/ Konzernthemen/Research/PDF-Dokumente-Stu- dien-und-Materialien/SuM-Recycling-in-Deutsch- land-Wuppertal-Institut-Januar-2015.pdf [Stand 13.08.2015].

[18] Hischer, R., Classen, M., Lehmann, M. & Scharn-Horst, W. (2007) Life Cycle Inventories of Electric and Electronical Equipment: Production Use and Disposal. – econinvent report Nr. 18. – ecoinvent centre, EMPA; St. Gallen/Dübendorf

[19] YOLE – YOLE DÉVELOPPEMENT (2012) GaAs Wafer Market and Applications: 2012 Edition. – Lyon

recycling rate of 90% for waste from industrial processes, the estimated demands gallium and arsenide in 2035 are shown in Table 2.6. (Demands of Si and Ge were not estimated due to the unknown total production of SiGe wafers.) However, it should be noted that development of semiconductor components is dynamic. High frequency component manufacturers are also looking for other materials that can reduce material costs.[20]

Table 2.6 Global gallium and arsenide production and demands for GaAs

RM	Production 2013 (t)	Demand 2013 (t)	Expected demands in 2035 (t)
Gallium	350 (Primary)	38	86
Arsenide	35,331 (Refinery)	47	93

While large part of the waste from industrial processes are recycled, there is currently no recycling of gallium from end of life (EoL) electronic products. Part of the reason is the greater economic incentive to recycle the precious metals contained in the products pyro-metallurgically resulting in gallium containing slag. Another part of the reason is the low concentration of gallium in the component and the wide variety of end-use products make it difficult to collect sufficient quantities for recycling.

The possibility of substituting gallium in ICs is also limited because GaAs ICs are specifically developed to cover the certain insufficiency of silicon-based semiconductors. The substitution of the components will lead to lower of functionality.[21] Even SiGe can only replace GaAs in some applications.

In the conclusion of the report, measures securing raw materials are suggested, such as, expansion and improved efficiency of ore mining or metal extraction, substitutions at the level of materials and technologies, resource efficiency in production and use, recycling, ensured by recyclable designs, and recirculation strategies and efficient recycling technologies.[22]

The purpose of introducing the report from DERA is to point out the importance of identifying technology trends and the respective potential future raw materials demands. The information is essential for formulating an effective strategy or plan in securing raw materials through different measures (e.g. secondary sources, which is introduced in more detail in the next chapter).

2.2 Recycling rates of metals and the EU CRMs

After the introduction of emerging technologies and the respective raw materials demands, the international recycling rates of metals and the EU CRMs are presented in this Section (Figure 2.3 and Figure 2.4) in order to provide an overview of metals and the EU CRMs from secondary sources.

[20] ibid.

[21] Tercero Espinoza, L., Hummen, T., Brunot, A., Hovestad, A., Pena Garray, I., Velte, D., Smuk, L., Todorovic, J., Van Der Eijk, C. & Joce, C. (2014) Critical Raw Materials Substitution Profiles obtained from http://cdn.awsripple.com/www.criticalrawmaterials.eu/uploads/Raw-materials-profiles-report.pdf - [Stand 09.12.2014].

[22] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.5

In Figure 2.3, the end of life (EoL) recycling rate is defined as dividing the recycled EoL metal (old scrap) by the EoL products (metal content) (this refers to functional recycling[23] only).[24] More recent figures relevant to the EU can be found at the Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials - Final Report by Deloitte (2015) (See Figure 2.3). In general, the recycling rate of metals can be improved as many metals have EoL recycling rates lower than 1%.

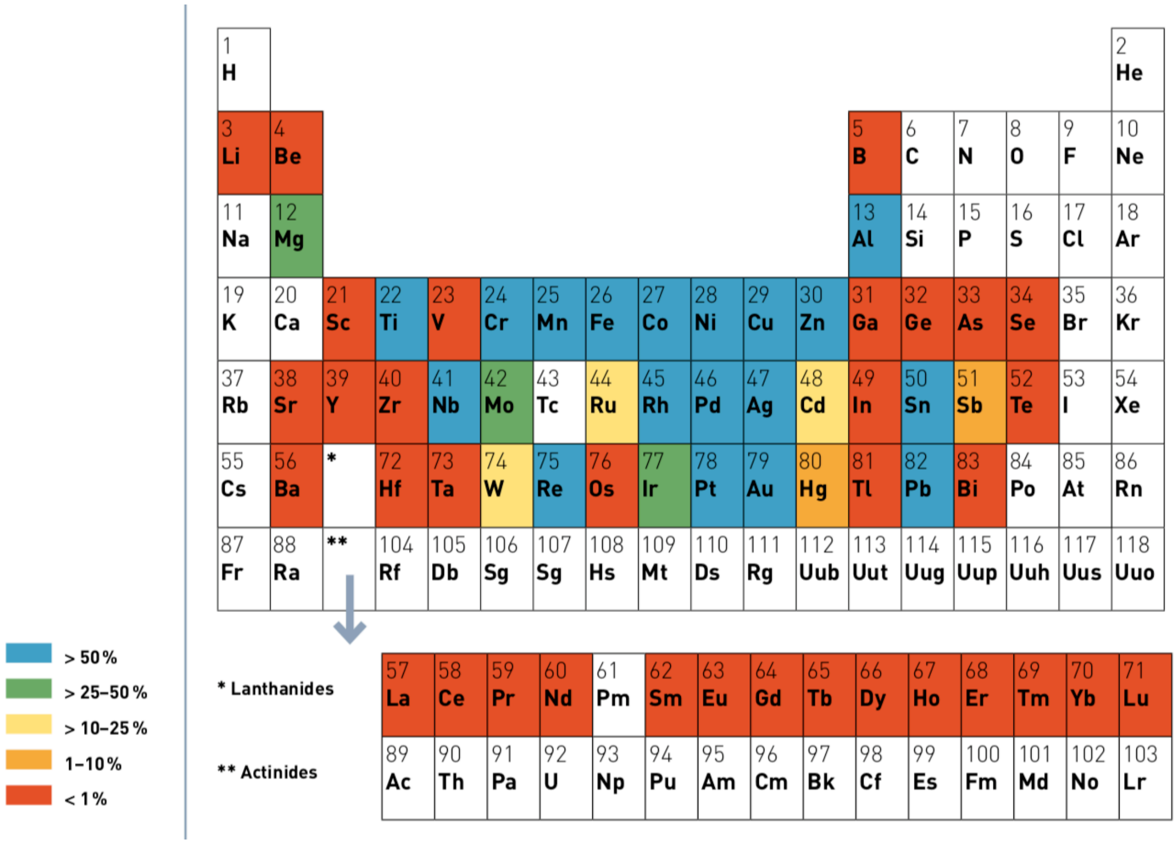


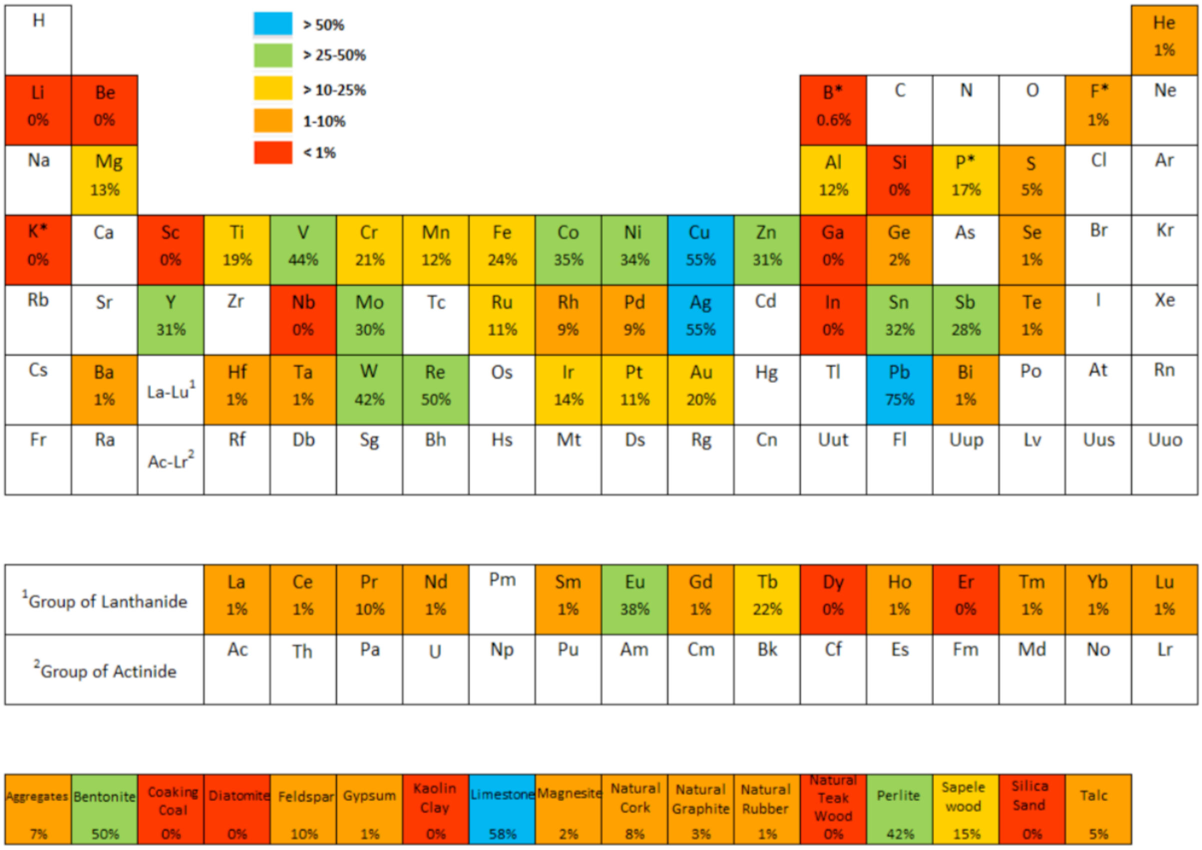
Figure 2.3 EoL recycling rate of CRM (UNEP,2011)

Figure 2.4 presents more recent figures on the EoL recycling input rates of the EU CRMs. The EoL recycling input rate refers to how much of the total material input into the production system comes from recycling of 'old scrap' (i.e. post-consumer scrap). However, it should be noted that the generally low recycling input rates could be explain by several factors including the lack of economically viable sorting and recycling technologies for CRMs, the technical limitations (e.g. incapable to recover in-use dissipated materials), the long-life time of many CRMs applications, and the growing demands of many CRMs (i.e. the recycling contribution is insufficient to meet the demands, e.g. PGMs have recycling rate up to 95% for industrial catalysts and 50 to 60% of automotive catalysts but the recycling input rate is only 14%.).[25]

[23] Functional recycling: Functional recycling is that portion of end- of-life recycling in which the metal in a discarded product is separated and sorted to obtain recyclates that are returned to raw material production processes that generate a metal or metal alloy; Non-functional recycling: Non-functional recycling is that portion of end–of-life recycling in which the metal is collected as old metal scrap and incorporated in an associated large magnitude material stream as a "tramp" or impurity elements.

[24] UNEP (2011) Recycling Rates of Metals –A Status Report, ISBN: 978-92-807-3161-3

[25] Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G. A., Dias, P. A., Blagoeva, D., Matos, C. T. de, Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. & Solar, S. (2017) JRC Science for Policy Report: Critical raw materials and the circular economy background report, *Publications Office of the European Union*, Luxembourg



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

Figure 2.4 EoL recycling input rates of the EU CRMs (JRC, 2017)

2.3 Factors affecting accessibility of CRM from CE

Section 2.1 and 2.2 provide an overview of the estimated future demands of raw materials due to emerging technologies and the international CRM recycling rates. Both imply that the further development in the secondary raw materials sector is a must and will encourage further R&D and support actions to improve the exploitation of the results. The development of the secondary raw materials sector, including R&D activities and exploitation, is nonetheless affected by many factors. In this section 2.3, selected factors (i.e. identified) are introduced. The first part presents factors appearing in the raw materials market the second part showcases technical factors (i.e. metallurgy).

2.3.1 Global raw materials (RM) market

In the global raw materials market, four factors which can especially affect the development of secondary raw materials sector are identified:

- Accessibility to primary raw materials,
- Relevant policies,
- Regulations and political objectives, and
- Political interferences in markets.

Although consumer behaviour and costs are crucial for the development, they are common factors which apply to all industries and thus excluded in this section. (All the factors identified by GKZ are available with corresponding examples in CICERONE T1.3 Memo on the adoption drivers for CE business models for SMEs.)

2.3.1.1 Accessibility to primary raw materials

The easy access to primary raw materials limits the development of secondary raw materials markets and substitution materials markets. In contrast, limited access to primary raw materials by political restrictions, transport or societal resistance stimulates the development of secondary raw materials and substitution materials markets. Two examples are provided to illustrate the factor.

Example 1: Low development of secondary raw materials sector due to easy access to raw materials (international competition) – low recovery rate of lithium

In industrial processes, lithium is used in aluminium smelting, steel casting, rubbers and plastic production and cement production. Lithium is also contained in many end-user products (i.e. finished products) for instance, batteries, glass and ceramics, and lubrication greases. According to Deloitte (2015), while the end-user products, such as batteries, glass, products made of aluminium alloys and electronic appliances, are recycled in significant proportions, there is no functional recycling of lithium since the separation of lithium from the products is either not possible or very costly.[26] In addition, DERA (2015) indicated that the large primary resources and reserves, the relatively low-cost of extraction, the dissipative distribution of lithium, and the technical demands on purity for certain applications, all have impacts on the development of the secondary sector. Currently, the greatest lithium recycling potential lies in rechargeable Li-ion batteries. However, the low amounts of lithium in Li-ion batteries, the complex compounds, high purity requirements, and the low monetary value comparing to other metals (e.g. nickel and cobalt) make recovering lithium not worthwhile during battery recycling processes. Lithium contained in Li-ion batteries is therefore bound with other residual materials in the process slag and used in the construction industry as a mineral aggregate in ready-mixed concrete. With the outlook of a growing e-mobility market, recycling quantities should increase and if the prices of raw materials rise accordingly, recovering lithium could become economically attractive.[27] (More details see Section 3.2.4)

Example 2: Low development of secondary raw materials sector due to easy access to raw materials (other natural forces, e.g. climate change) – newly accessible artic deposits in Greenland and Russia

The melting of the ice allows access to previously unexploited or undiscovered natural resources with considerable size. 13% of the world's undiscovered oil reserves and 30% of the world's natural gas reserves could be in the Arctic. The Arctic has also large mineral reserves, most of which are located in Russia, such as the Norilsk polymetallic deposit. But it also contains significant diamond reserves. The melting of the ice-shield will also provide better transport accessibility and opens shorter ship routes between the supplier and major consumer countries.[28]

[26] Deloitte (2015) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials - Final Report.

[27] DERA (2015) DERA Rohstoffinformationen Rohstoffrisikobewertung – Lithium from https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/Studie_lithium_2017.pdf?__blob=publicationFile&v=3

[28] Hodges, J., Shiryaevskaya, A. & Khrennikova, D. (2018) Bloomberg report: Melting Ice In the Arctic Is Opening a New Energy Trade Route (online article) obtained on 17.04.2019 from https://www.bloomberg.com/news/articles/2018-08-28/arctic-ice-melt-opens-lng-energy-trade-route-near-north-pole

On the other hand, global warming can also lead to more difficulties in the exploitation of Arctic resources, for example, it would lead to the multiplication of icebergs - which are a danger to installations - and a rise in sea level, flooding terrestrial production fields.

Global warming has improved the living conditions in Greenland to such an extent that not only increased exploration of the geological subsoil but also more intensive use of the mineral potential would be considered. In the event of further global warming, combined with the uncovering of additional, hitherto unknown deposits of raw materials, Greenland is likely to become a very important, potential supplier of raw materials in the long term, similar in importance to Australia. Greenland thus has a very large raw material potential - even on a global scale. The Skaergaard intrusion (Au, Pd, Pt) and the Ilímaussaq alkaline complex (U, Th, SE, Li, Nb, Be, Zr, NaF) deposits can be classified as "Giant" or even "Supergiant" metal deposits. [29]

2.3.2.2 Policies, regulations and political objectives

The impacts of policies and legislations on market-oriented economies are unavoidable. They may support market economies, initiating new business, or hinder market economies. The secondary raw materials sector is also affected by relevant policies, regulations and political objectives. Depending on the political decision, it could be beneficial to the R&D activities in raw materials sector but could also be detrimental. Few examples are illustrated below.

Example 1: EU policy as the driver – Electric vehicle target of the EU

The vote of the European Parliament for a faster shift to electric cars can be a driver for adopting CE. In 2018, MEPs voted for a stronger sales target for zero and ultra-low emission cars (e.g. electric vehicle (EV)). Zero and ultra-low emission cars should account for 20% of the total car sales by 2025, and 40% by 2030, with penalties for failing to meet these targets. This decision implies that a large number of lithium-ion batteries for EV will be needed to reach the target. However, materials used in lithium-ion batteries often have high economic importance combining with supply risk (e.g. cobalt).

A study by Drabik and Rizos (2018) identifies that increasing collection and recycling efficiency rates of EV batteries in the EU may mitigate dependence on imported materials and help to retain the value of recovered materials within the EU economy. Further benefits of increased collection and recycling efficiency rates include job creation in the recycling sector and mitigating CO_2 emissions. Hence, in order to reduce the dependency on imported materials, the EU should to continue and strengthen its support in R&I for lithium-ion battery recycling processes to improve the cost effectiveness and efficiency.[30] However, this will not cover the initial demand to feed the battery production but is rather an option in the long term when the first generation of EV is going to be recycled.

Another political instrument in stimulating CE in battery industry is the Batteries Directive (2006/66/EC). The primary objective of the Batteries Directive is to minimise the negative environmental impacts of waste batteries, contributing to the protection, preservation and

[29] DERA (2010) DERA Rohstoffinformationen: Das mineralische Rohstoffpotenzial Grönlands from https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-01.pdf?__blob=publicationFile&v=10

[30] Drabik, E. & Rizos, V. (2018) Prospects for electric vehicle batteries in a circular economy from https://circulareconomy.europa.eu/platform/sites/default/files/circular_economy_impacts_batteries_for_evs.pdf

improvement of the quality of the environment. Furthermore, it sets collection and recycling efficiency rates for certain types of batteries.

Example 2: Foreign policy as the driver – China's import ban on plastic wastes

Starting from the beginning of 2018, China's import ban on plastic wastes has impacted on global plastic waste trade. China, which has imported a cumulative 45% of plastic waste since 1992, implemented a new policy banning the importation of most plastic waste. Brooks, Wang and Jambeck (2018) estimated that 111 million metric tons of plastic waste will be displaced with the new Chinese policy by 2030. The study mentions also that 89% of the historical plastic exported to China consist of polymer groups often used in single-use plastic food packaging. As a conclusion of the study, since globally, only 9% of plastic waste produced has been recycled, the concept of CE could provide more ideas and actions for reducing quantities of non-recyclable materials, redesigning products, and funding domestic plastic waste management.[31]

In response to the China's import ban on plastic wastes, in December 2018, EU member states and the EU parliament have agreed on a plan to ban single-use plastic products such as disposable plates and straws. The final vote is on March 27, 2019. The plan involves e.g. a plastic ban on products where alternatives are readily available and affordable. In addition, member states will have to implement measures to reduce the use of plastic food containers and drink cups, and they will have to a collection rate of 90% for single use plastic drink bottles by 2025.[32]

Example 3: EU policy as the barrier – Debate on the ban of lead in the EU

On 27 June, 2018, one month after the EC launched the Strategic Action Plan on Batteries[33], the European Chemical Agency (ECHA) announced to include lead metal into the EU REACH candidate list of substances requiring authorisation (i.e. inclusion in Annex XIV to the REACH regulation). Once a substance is included Annex XIV, the substance cannot be placed on the market for use or used after a given date (i.e. sunset date). Only the companies who cannot replace the substance are granted an authorisation for the specific use(s).[34]

The inclusion of lead metal into the EU REACH candidate list is a matter of concern especially for metallurgy and battery industries[35]. As metals are eminently recyclable, the EU metals sector responding to the increasing scarcity of certain elements by recycling and refining materials. In the metallurgy industry, lead is a key enabler in the CE, because it is one of the carrier metals in the metal wheel, capable of dissolving and carrying several technology elements (e.g. Ag, Cu, Ga, Sb, Sn, Te, and Zn). Hence, limiting lead does not only have detrimental impact on metallurgy industry but also all the other industries linked to it, for instance, photovoltaics industry (CdTe solar cells), LED lighting industry (GaN) and automobile

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[31] Brooks, A.L., Wang, S. & Jambeck, J.R. (2018) The Chinese import ban and its impact on global plastic waste trade, *Science Advances*, Vol. 4, no. 6

[32] Deutsch Welle (2018): News - EU reaches agreement on single-use plastic ban, obtained on 27.03.2019 from https://www.dw.com/en/eu-reaches-agreement-on-single-use-plastic-ban/a-46797494

[33] EC (2018a) Sustainable Mobility for Europe: safe, connected and clean, COM(2018) 293 final ANNEX 2

[34] ECHA (n.d.) Understanding REACH obtained on 29.03.2019 from https://echa.europa.eu/regulations/reach/understanding-reach

[35] ILA (2018) News: EU scheme to ban use of lead risks short-circuiting Europe's battery revolution - 27/06/2018, obtained on 31.03.2019 from https://www.ila-lead.org/news/lead-in-the-news/2018-06-27/eu-scheme-to-ban-use-of-lead-risks-shortcircuiting-europes-battery-revolution

industry (lead-acid battery). The examples also illustrate the importance of keeping the lead infrastructure and know-how in the EU. While the risks of lead on human health and the environment should be carefully managed, it is unrealistic to ban lead from entering the society.[36]

2.3.2.3 Political interference in markets

In additional to being affected by policies, regulations and political objectives, the markets of CRM and general raw materials are sometimes subjected to political interferences. Therefore, the risk should be taken into consideration while assessing the necessity of developing secondary raw materials sources to ensure the raw material supply.

<u>Example 1: China's policy on its rare earth elements market</u>

China's policy on its rare earth elements (REE) market could be an obstacle for adopting CE in the EU as it is an unpredictable force outside of free economy rules. An example can be given by the supply crunch of 2010/11. The export restrictions by near-monopolist China set off a speculative rally that drove up prices by between four and nine times in less than a year.

With a market share of over 80 %, China dominates the global production of REE. In China, illegal mining has led to a further expansion of production and overcapacity in the REE market. In order to limit the massive overcapacities and environmental problems, the Chinese government pushed ahead with the consolidation of the domestic REE industry. The extensive regulatory measures by the Chinese government have initiated a structural change in the sector, with effects on international market. The China's strategy on REE focused on four areas. Firstly, the aim was to reduce the number of enterprises in the industry and to let a few big state-owned champions prevail. Secondly, the central government intended to decrease the extraction and processing of REE, in particular through a clampdown on illegal mining. Thirdly, the strategy strengthened environmental regulations and investigations on environmental protection. Lastly, the government brought down the export of REE through political export restrictions and took more rigorous actions against smuggling. A quota system was first introduced in 2006. Currently, only six REE companies are allowed to produce under these quotas.

China's changing production patterns and increasing export restrictions make the availability of REE more volatile. Volatile prices and insecure REE access threaten to undermine European innovation and competitiveness and may slow the diffusion of priority technologies, such as electric vehicles and offshore wind.[37]

2.3.2 Principles of metallurgy – Metal wheel and recycling metal wheel

In order to recover metals from potential recyclables, one should understand metal wheel and recycling metal wheel. The metal wheel (Figure 2.5) represents the companionability of metals at the primary production phase. The principle host metals, or called carrier metals, which are found in relatively high concentration and produced in relatively high volumes, form the inner circle of the wheel. The companion elements, or called minor metals, which are found in

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[36] Blanpain, B., Reuter, M. & Malfliet, A. (2019) Policy Brief: Lead Metallurgy is Fundamental to the Circular Economy, H2020 project SOCRATES, obtained on 31.03.2019 from https://kuleuven.sim2.be/wp-content/uploads/2019/02/SOCRATES-Policy-Brief-2019-Lead.pdf

[37] European Rare Earth Competency Network (ERECON) (n.d.): Strengthening the european rare earths supply-chain: Challenges and policy option, Link https://reinhardbuetikofer.eu/wp-content/uploads/2015/03/ERECON_Report_v05.pdf

relatively low concentrations and often recovered as a by-product, are placed in the outer circle at distances proportional to the percentage of their primary production that originated with the carrier metal indicated. The companion elements seldom form a viable deposit of their own but occur interstitially in the metal ores with similar physical and chemical properties.[38] In other words, each metal wheel slice shows the companion elements associated geologically and therefore thermodynamically with the carrier metals.[39]

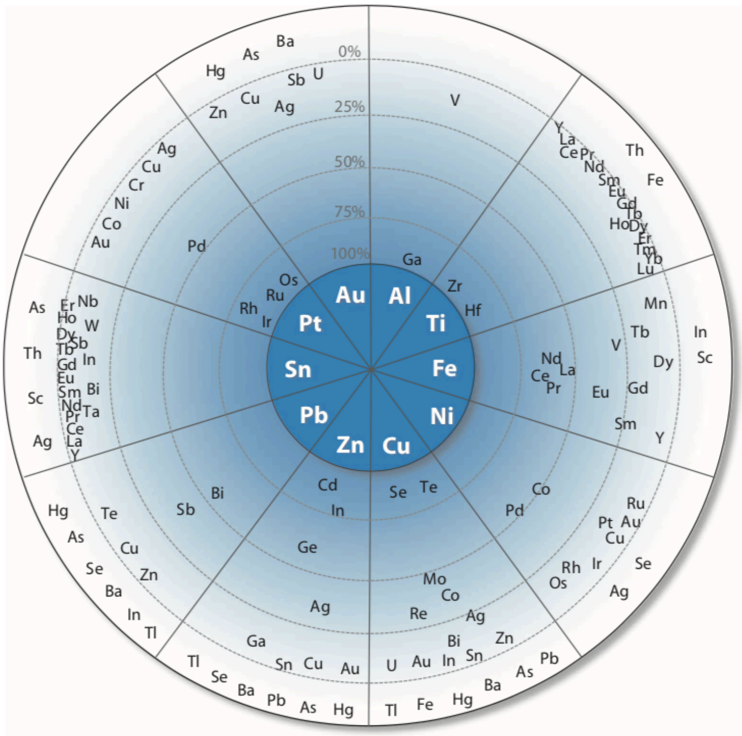

Figure 2.5 Metal wheel of companionality (Nasser el at, 2015)

The recycling metal wheel (Figure 2.6) is formed based on a same logic as the metal wheel in best available technology (BAT) for end of life (EoL) products. The inner circle are the carrier metals and the outer circle consists of the companion elements associated thermodynamically with them. As in the primary production, the recycling metal wheel shows that recovering carrier metals is implicitly linked to the recovery/recycling of minor metals due to the carrier and minor metals extractive metallurgy.[40] Special attention should be given to the green circles in the outer rings of the recycling metal wheel, the mainly recovered element. The green circles indicate the minor elements that can be recovered through their extraction from the liquid carrier-metal phase or by collecting them as compounds (oxides, chlorides, sulphides), either in a refining infrastructure or elsewhere in connected metallurgical processing.[41]

It should be noted that if a complex multi-material product has elements (and their alloys and compounds) that fall into more than one slice of the recycling metal wheel, the extractive metallurgy based on one slice of the recycling metal wheel will not be able to recover all the

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[38] Nassar, N.T., Graedel, T.E. & Harper, E.M. (2015) By-product metals are technologically essential but have problematic supply, *Sci Adv* **1** (3), e1400180

[39] Reuter, M.A. & Kojo, I.V. (2012) Challenges of metals recycling, *Outotec Oyj*

[40] ibid.

[41] Blanpain, B., Reuter, M. & Malfliet, A. (2019) Policy brief – Lead Metallurgy is Fundamental to the Circular Economy, H2020 project SOCRATES, obtained on 28.03.2019 from https://kuleuven.sim2.be/wp-content/uploads/2019/02/SOCRATES-Policy-Brief-2019-Lead.pdf

elements because the thermodynamics of the different elements and their compounds are incompatible. Since consumer products are getting more complex (e.g. WEEE has more than 50 elements at the same time), Reuter el at (2012) suggests that the metallurgy, physics and the infrastructure have to fall into more than one slice of recycling metal wheel to process these products well. At the same time, the operation should remain profitable.[42]

In addition, the metal wheel and the recycling metal wheel are also useful for developing design for recycling and design for sustainability. If product design takes thermodynamically compatibility of materials into consideration, metallurgical technologies can better process them at the end of the product life cycle. Resource efficiency can also be improved as the designers are able to make better choices from a recycling point of view whenever possible, within the limits of design and product specifications and requirements.[43]

[42] Reuter, M.A. & Kojo, I.V. (2012) op. cit., p.17
[43] ibid.

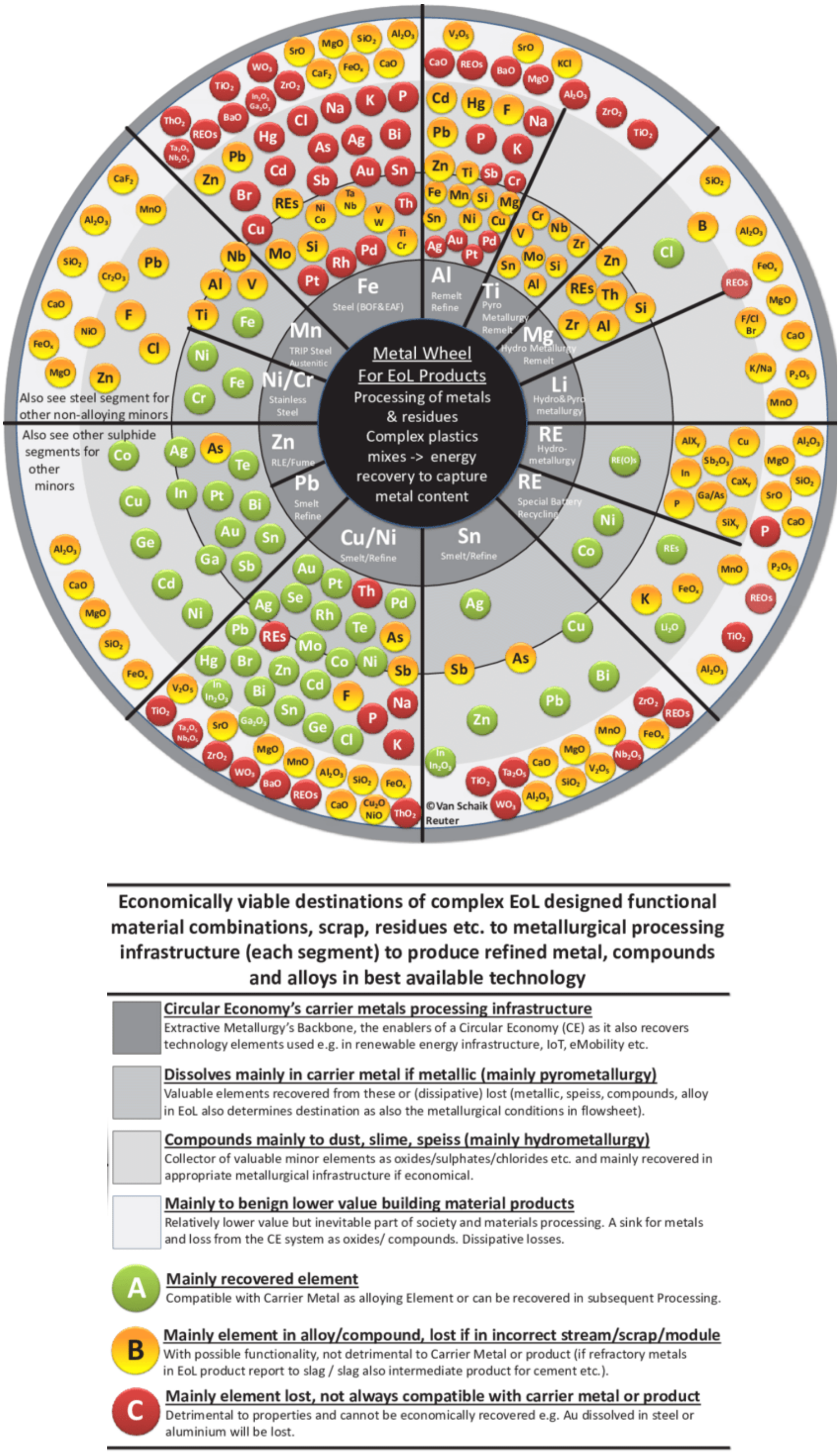

Figure 2.6 Recycling metal wheel (©Markus. A. Reuter)

2.4 Identified needs in metal recycling and R&D demands in metallurgy sector

2.4.1. Identified needs in metal recycling

The identified needs in metal recycling in this section refers to the difficulties which occur during different metal recycling stages, collection, dismantling, separation, physical processing, and smelting. Table 2.7 Indicates the identified needs at each stage except for smelting. Smelting is to be illustrated in deeper details at the R&D demands in metallurgy sector. While design is not part of the metal recycling process, it affects the efficiency of the pre-treatment and metallurgy.[44] Therefore, it is also included in the table.

Table 2.7 Identified needs of the metal recycling stages

Metal recycling stage(s)	Identified needs
(Product) Design	• Simulation of recycling processes or of product design changes[45] (e.g. predictive model[46] and Recycling index/design for recycling/recycling performance: Simulation based approach for the calculation of recycling rates (entire recycling system from dismantling to end processing)[47]) • Recycling and associated incentives should be repositioned around a product-centric approach[48,49] • Designer needs to be provided with tools/technology driven guidelines (e.g. metal wheel and predictive model): If product design brings thermodynamically compatible materials in close proximity, then metallurgical technology can deal with them well and avoid e.g. gluing or engineered a large variety of different materials into close proximity with one another for reasons of functionality which makes recycling more difficult[50,51] • Eco-design approach: New design concepts; further development of eco-design in methodology and data bases; integration into business processes and standardization.[52] • Intelligent control of system-integrated material production and resource management (e.g. simulation of the resource efficiency effects of manufacturing and recycling processes) [53] • Substitutions at the level of materials and technologies[54]

[44] EIT RM (2016) Next steps in WEEE – Closing the loop, obtained on 28.03.2019 from https://eitrawmaterials.eu/wp-content/uploads/2016/07/Success_Story_WEEE_Loop_v3.pdf
[45] BMBF (2018) Ressourceneffiziente Kreislaufwirtschaft, *BMBF*, Bonn
[46] UNEP (2011) op. cit., p.11
[47] Schaik, A.V. & Reuter, M.A. (2016) Recycling Indices Visualizing the Performance of the Circular Economy, *World of Metallurgy*, 2016(4), pp201-216
[48] UNEP (2013) Metal recycling: opportunities, limits and infrastructure, ISBN: 978-92-807-3267-2
[49] EIT RM (2016) op. cit., p.20
[50] Reuter, M.A. & Kojo, I.V.(2012) op. cit., p.17
[51] ibid.
[52] BMBF (2018) op. cit., p.20
[53] ibid.
[54] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L., Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.4

	• Resource efficiency in production and use[55]
(Tracing) Design	• IT-based tools (e.g. labelling scheme) to trace material at the end of its product life, to create transparency and to verify the use of high-quality repair and recycling processes and to prevent illegal exports[56,57]
Collection	• Lest efficient link in the recycling chain[58,59,60] • Essential metallurgical knowledge (e.g. metal wheel) should be transferred to other stakeholders within the recycling chain to take the right decisions regarding collecting and sorting procedures of increasingly complex EoL- products[61] • The open system of consumer good should be changed to a more closed system (i.e. easier to trace and ensure recovery) for more effective recycling of CRM[62] • Reverse logistics systems[63] • Intelligent networking and collection: Management and analysis of product/asset related data and intelligent control of system-integrated material production and resource management (e.g. for identification and sorting)[64]
Dismantling/Separation	• Immediate analysis (e.g. online analysis) for sensor sorting[65] • A way of separating printed circuit boards (State of art: manual dismantling)[66] • Organised and continuous exchange of information between pre-treatment and metallurgy (i.e. separated waste streams have to be assigned to corresponding recycling routes)[67] • Requiring a more detailed separation process as well as links with sophisticated metallurgy processes to recovery rarer critical metals[68] • Closed circuit for alloys and superalloys (e.g. innovative sorting and analysis techniques combined with new

[55] ibid.
[56] BMBF (2018) op. cit., p.20
[57] UNEP (2013) op. cit., p.20
[58] UNEP (2011) op. cit., p.11
[59] EASAC (2016) Priorities for critical materials for a circular Economy, obtained on 28.03.2019 from https://www.easac.eu/fileadmin/PDF_s/reports_statements/Circular_Economy/EASAC_Critical_Materials_web_corrected_Jan_2017.pdf
[60] Reuter, M.A. & Kojo, I.V.(2012) op. cit., p.17
[61] UNEP (2013) op. cit., p.20
[62] In industry, the components containing valuable metals 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. Reference: EASAC (2016) op. cit., p.21
[63] BMBF (2018) op. cit., p.20
[64] ibid.
[65] EIT RM (2016) op. cit., p.20
[66] ibid.
[67] ibid.
[68] EASAC (2016) op. cit., p.21

	approaches in metallurgy) to obtain composite metals and hybrids with defined properties[69] • Recycling 4.0: Energetically optimised material cycles of complex secondary raw materials with high added value across materials and industries.[70] *Relevant German projects: ARGOS (FONA r^4), MetalSens (FONA r^4), and SEMAREC (FONA r^4)*

2.4.2. R&D demands in metallurgy sector

In metallurgy sector (hydrometallurgy, i.e. electrolysis and pyrometallurgy, i.e. smelting stage of recycling process), there are a number of common R&D demands which do not only apply to one or two elements. The demands are summarised from Table 2.2 and listed below.

- Metallurgy, physics and the infrastructure have to fall into more than one slice of recycling metal wheel to process the complex products well[71]
- Upscaling laboratory scales to industrial scales
- Improving economic feasibility and efficiency of processes
- Economic ways to recover elements from low concentration sources (i.e. EoL products)
- Universal or flexible recycling technologies or processes for diverse applications and evolving EoL products

The identified R&D demands of selected elements are shown in Table 2.8 which are summarised from the two application case studies in Chapter three and four. Further detailed information regarding the elements are available in later chapters (see Table of Content).

[69] BMBF (2018) op. cit., p.20

[70] I.e. Companies and industries that previously had nothing to do with each other must find ways and solutions together and recognize them as a challenge for the future in order to jointly meet such complex recycling requirements with economic success.
Reference: M. Stelter (2016) Recycling 4.0 from Goslarer Tag der Metallurgie Kaiserpfalz-Preis, *World of Metallurgy*, 2016(2), pp79

[71] Reuter, M.A. & Kojo, I.V.(2012) op. cit., p.17

Table 2.8 R&D demands of specific elements

Element	Identified recyclables	R&D demands
Antimony (Sb) - CRM	Copper production	• No recycling activities at industrial scale[72]
	Municipal solid waste incineration	• Currently not economically feasible[73] • Requiring technologies can selectively remove certain elements such as antimony (MSWI residues contain various metals) in a low-cost and efficient manner[74]
	Fire retardant/ Plastics in WEEE	• Largest application but cannot be easily recycled due to the low proportions and dissipative distribution in the end products.[75, 76] • More advanced processes are required such as pyrolysis, gasification, polymerisation, or hydrogen degradation in order to convert the non-metallic fraction of WEEE to chemical feedstocks and fuels.[77] • Needs to improve the efficiency of the processes before upscaling becomes economically feasible[78]
	Lamp phosphor waste	• The valorisation of halophosphate and the recovery of antimony can be integrated in rare- earth recovery schemes and in the broader effort to recycle these lamp phosphor powders[79]
Cobalt (Co) - CRM	Spent battery chemicals	• Difficulties in sorting and identifying different battery composition as it is an evolving technology – ideally developing a universal recycling technology for mixed battery waste processing considering the differences between them[80] • Most research activities are at laboratory scale[81] • Improving the cost effectiveness and efficiency of the recycling processes[82]

[72] Dupont, D., Arnout, S., Jones, P.T. & Binnemans, K. (2016) Antimony Recovery from End-of-Life Products and Industrial Process Residues: A Critical Review, *J. Sustain. Metall*. (2016) 2:79–103

[73] EC (2017a) Study on the review of the list of critical raw materials. Critical Raw Materials Factsheets. Luxembourg: Publications Office of the European Union. https://doi.org/10.2873/398823

[74] Dupont, D., Arnout, S., Jones, P.T. & Binnemans, K. (2016) op. cit., p.23

[75] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) SCRREEN D3.2 Identification and quantification of secondary CRM resources in Europe, *H2020 SCRREEN Project* obtained from http://scrreen.eu

[76] DERA (2013) Rohstoffrisikobewertung – Antimon

[77] Guo, J. & Xu, Z. (2009) Recycling of non-metallic fractions from waste printed circuit boards: a review, J Hazard Mater, 168(2-3):567-90. doi: 10.1016/j.jhazmat.2009.02.104.

[78] Dupont, D., Arnout, S., Jones, P.T. & Binnemans, K. (2016) op. cit., p.23

[79] ibid.

[80] McKinsey&Company (2018) Lithium and cobalt – a tale of two commodities obtained on 11.03.2019 from https://www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-and-cobalt-a-tale-of-two-commodities, Expects that the industry once invests and finds an optimal recycling route when the first wave of "exhausted" EV batteries becomes available, the industry will have higher volume with a more homogeneous feed compared to what is currently available.

[81] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

[82] Lebedeva, N., Persio F.D. & Boon-Brett, L. (2016) Lithium ion battery value chain and related opportunities for Europe, *EC JRC Science for Public Report*

Lithium (Li)	Spent battery chemicals	• Need to develop techno-economically efficient processes (taken into account the environmental aspects) [83] • Efficient and feasible technologies to recover lithium in high purity from low lithium bearing sources.[84]
Magnesium (Mg) -CRM	Secondary magnesium materials	• Recycling process is currently not economical (in Germany) (e.g. Scraps not recycled by scrap processors are used directly in steel desulfurization[85] (not recycled[86])[87] • Official requirements and ideological discussions make recycling in Germany considerably more difficult (i.e. the metal-containing residual materials produced here are collected and then recycled externally. The processed raw material (granulate, ingots, semi-finished products, etc.) is then re-imported into Germany.)[88] • Developing methods to affordably reuse in-house scrap without sacrificing quality[89] • Designing alloys to improve recyclability of scrap, reduce dross, and improve dross handling[90]
	Magnesium-aluminium alloys[91]	• Developing methods to separate magnesium from aluminium for recycling (shredded material) [92] • Magnesium containing residues from aluminium refining process should be recovered (not entering cement and other similar products)[93]
Manganese (Mn)	Waste batteries	(Technologies available but no information on commercial/industrial operations)
	Mn-containing slags	• Feasibility depending on the concentration level of manganese and other valuable elements (e.g. Co and Ni) in the solution
	Mn-industrial waste solutions	• Further research on oxidative precipitation and solvent extraction are suggested

[83] Basudev, S. (2017) Review - Recovery and recycling of lithium: A review, *Separation and Purification Technology*, 172 pp.388-403
[84] ibid.
[85] Kramer, D.A. (2002)" Magnesium Recycling in the United States in 1998", USGS Circular 1196-E, obtained information from SCRREEN D4.2 (op. cit., p.25)
[86] EC (2017a) op. cit., p.23
[87] Martin Maier, Magrec Recycling GmbH (2019) DERA Industrieworkshop Magnesium (Metall) - Recycling von Magnesiumreststoffen, 23.01.2019, Berlin https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/vortrag_magnesium_maier.pdf?__blob=publicationFile&v=2
[88] ibid.
[89] Zhang, L. & Dupont, T. (2007) State of the Art in the Refining and Recycling of Magnesium, *Materials Science Forum*, Vols. 546-549 (2007) pp 25-36, *doi:10.4028*
[90] ibid.
[91] Kramer, D.A. (2002) op. cit., p.24
[92] Zhang, L. & Dupont, T. (2007) op. cit., p.24
[93] Bell, N., Waugh, R. & Parker D. (2017) Magnesium Recycling in the EU – Material flow analysis of magnesium (metal) in the EU and a derivation of the recycling rate, Oakdene Hollins Research and Consulting (The differences between this figure and the one from Deloitte (2015) are explained in the report)

Natural Graphite (C) -CRM	Spent refractories	• Normally spent refractories are used as roadbed materials or sent to landfill (not a proper use of useful components (i.e. graphite) – non-functional recycling[94]
	Spent brake lining	• Spent brake linings are normally smelted to low quality steel or disposed as hazardous waste – non-functional recycling[95]
	Spent battery chemicals	• No industrialised processes[96] • Economically justified processes needed[97] • High purity level of the recovered graphite needed (battery grade requiring 99.9%)[98] • Surface modification of graphite electrodes (min. degradation)[99]
Nickel (Ni)	EoL products	• Particular attention should be paid to EoL recovery because a significant amount of nickel is used in applications containing low concentrations of nickel (e.g. electronics and alloys) where nickel is often recovered as a minor constituent of carbon steel or copper alloy scrap but not as nickel metal or alloy. In such cases, eventual nickel recovery and reuse can become an integral part of product design.[100]
Silicon metal (Si) - CRM	Scraps from ingot crystallisation and wafer manufacturing	• Technologies recovering cut off silicon scraps due to impurities are not commercialised[101,102] • There is research on recycling of silicon wafers, however it has not yet materialised in marketable solutions[103,104]
	WEEE from capacitors and integrated circuits	• Typically not recycled[105]

[94] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) SCRREEN D4.2 Production technologies of CRM from secondary resources, *H2020 SCRREEN Project* obtained from http://scrreen.eu
[95] ibid.
[96] ibid.
[97] B. Moradi & G.G. Botte (2016) Recycling of graphite anodes for the next generation of lithium ion batteries, *J Appl Electrochem*, 46:123–148, DOI 10.1007/s10800-015-0914-0
[98] ibid.
[99] ibid.
[100] Reck, B.K., Müller, D.B., Rostkowski K. & Graedel, T. E. (2008) Anthropogenic Nickel Cycle: Insights into Use, Trade, and Recycling, *Environ. Sci. Technol.*, 2008, 42 (9), pp 3394–3400, DOI: 10.1021/es072108l
[101] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[102] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[103] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[104] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[105] Wilson, D. & Roberts, R. (2015) Components of WEEE (e-waste) – Transistors, University of Washington, Department of Electrical Engineering obtained on 26.03.2019 from https://ewaste.ee.washington.edu/students/electronic-autobiographies/

	Postconsumer waste from chemical products	• Diverse applications – some has functional industrial recycling process (e.g. silicone materials recycling) but some do not
Rare earth elements (REEs) – CRM	Processing residuals (i.e. Phosphogypsum, phosphoric acid leaching solutions, red muds, mine tailings of REEs and others (e.g. iron mines), coal ash, oil shales, and waste water (e.g. acid mine drainage from sulphide rock bearing areas))	• Limited knowledge on the mineralogy of the different REE rich phases in slags[106] • Developing processes to recover low concentration of REEs in industrial waste streams and historical wastes[107] • New methods for REEs recovery, especially from the diluted leachates and other diluted aqueous solutions [108] • Developing economic feasible processes
	REEs- containing EoL products (general)	• Developing innovative processes to recycle different REEs independently (currently, developed technologies often result in complex mixtures requiring further purification) [109] • Focusing on physical separation and concentration for economically feasible processing[110] • Knowledge of handling unusual impurities which may be presented in the recyclates[111]

[106] Binnemans, K., Jones, P.T., Blanpain, B., Gerven, T.V. & Pontikes, Y. (2015) Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review, *Journal of Cleaner Production*, V. 99, pp17-38
[107] ibid.
[108] ibid.
[109] Page, B.M. (2015) New Frontiers in Metals Recycling (online article), Chemical Engineering, obtained on 11.04.2019 from http://www.chemengonline.com/new-frontiers-metals-recycling/
[110] UNEP (2011) op. cit., p.11
[111] ibid.

Rare earth elements (REEs) – CRM	RE permanent magnets (NdFeB) (EoL product and pre-consumer scrap)	• Still at R&D stages[112] • Most commercial efforts are focusing on recovering REEs from manufacturing residuals (i.e. swarf etc.) other than EoL products[113] (Metallurgical processes at different TRLs for recovering REEs from pre-consumer NdFeB magnet scraps: hydrogen decrepitation; chemical vapour transport; liquid metal extraction; hydrometallurgical processing; pyro-metallurgical slag extraction.[114]) • EoL products: The prerequisite for future recycling is a functioning and profitable collection infrastructure. Additional conditions are dismantling procedures suitable for mass production, which should already be taken into account in the design of the application equipment (Design for Recycling). This is all the more decisive with the smaller the magnetic content per single application.[115] • Pre-consumer scrap is sent to China for recycling, as there are no such plants in Europe. [116] • Pure REs can be recovered as oxides by RM recycling using hydrometallurgical treatment. In Germany, however, the reduction of these oxides to pure metals is not technically possible at present[117]
	Phosphors (i.e. fluorescent lamps, LEDs and displays)	(Recycling of fluorescent and LED lamps is already a common practice.[118]) • Little research on recovering REEs from displays[119]
	NiMH batteries	(Existing operations in Belgium/France (Umicore and Solvay) and Japan (Honda and Japan Metals & Chemicals)

[112] Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., Buchert, M., Steenari, B.M., Gerven T.M., Jones, P.T. & Binnemans, K. (2017) REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review. *Journal of Sustainable Metallurgy*, 3 (1): 122–49. doi:10.1007/s40831-016-0090-4
[113] ibid.
[114] ibid.
[115] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L.,Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.4
[116] ibid.
[117] Bast, U., Blank, R., Buchert, M., Elwert, T., Fins- Terwalder, F., Hörnig, G., Klier, T., Langkau,S., Marscheider-Weidemann, F., Müller, J.-O., Thürigen, CH., Treffer, F. & Walter, T. (2015) Abschlussbericht zum Verbundvorhaben „Recy- cling von Komponenten und strategischen Metal- len aus elektrischen Fahrantrieben". Kennwort: MORE (Motor Recycling). – FKZ: 03X4622. Bun- desministerium für Bildung und Forschung. (Information from ibid.)
[118] Kooroshy, J., Tiess, G., Tukker, A. & Walton, A. (eds.) (2015) Strengthening the European Rare Earths Supply Chain: Challenges and Policy Options from https://reinhardbuetikofer.eu/wp-content/uploads/2015/03/ERECON_Report_v05.pdf
[119] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25

		• Battery recycling process is usually based on pyro-metallurgy even though hydrometallurgy is more beneficial for recovering REEs (after pyro-metallurgical process, REEs are to be recovered from slags)[120]
	WEEEs	(Existing operation in Japan (Kosaka Smelting and Refining))
	Sludges from glass polishing and magnet	(Existing operation in Belgium (Hydrometal SA))
Rare earth elements (REEs) – CRM	Spent catalysts (i.e. FCC and auto converters)	• FCC – No industrialised process[121] • Auto converters (Ce in the slags) – no effort has been made due to the relatively low value of Ce[122,123] • Even though catalyst accounts for around 40% of the REEs use in the EU
	Metal alloys (i.e. Tb, Pr or Gd)	• No report on production/recycling process of Tb, Pr or Gd from metal alloys
	Optical glasses (i.e. La, sometimes Gd and Y)	• No commercial process found
	Glass polishing powder	(Existing commercial process in Belgium (Hydrometal S.A .)

[120] Innocenzi, V., Ippolito N.M., Michelis, I.D., Prisciandaro, M., Medici, F. & Vegli, F. (2017) A Review of the Processes and Lab-Scale Techniques for the Treatment of Spent Rechargeable NiMH Batteries, doi:10.1016/j.jpowsour.2017.07.034.
[121] Ferella, F., Innocenzi, V. & Maggiore, F. (2016) Oil Refining Spent Catalysts: A Review of Possible Recycling Technologies, Resources, Conservation and Recycling 108 (March). Elsevier: 10–20. doi:10.1016/J.RESCONREC.2016.01.010
[122] Krishnamurthy, N. (Nagaiyar) & Gupta, C.K. (2016) Extractive Metallurgy of Rare Earths (Second edition), Taylor & Francis Group
[123] Binnemans, K., Jones, P.T., Blanpain, B., Gerven, T.V., Yang, Y., Walton, A. & Buchert, M. (2013) Recycling of Rare Earths: A Critical Review, *Journal of Cleaner Production*, v.51. Elsevier Ltd: 1–22. doi:10.1016/j.jclepro.2012.12.037.

2.5 Outline of R&D demands – Technical limitations

Due to limits of the current technologies, there are raw materials that cannot be recovered from secondary sources but have visible primary raw materials supply risks. In this case, other measures (e.g. substitution) other than developing secondary sources are recommended for securing raw materials supply. Fluorspar (commercial term for the mineral fluorite, EU CRM) is one of such raw materials and thus is given here as an example.

Fluorspar is an important mineral for manufacturing HF, which is the key intermediate for the manufacture of all speciality fluorine containing chemicals, for example, fluorocarbons (e.g. CFC).[124] While limited fluorspar is recovered from the waste streams of HF manufacture and during uranium enrichment, fluorspar is essentially consumed in use so recycling or reuse is not usually feasible.[125] Since there is only limited secondary sources, fluorspar has to be supplied by primary sources. However, the supply of fluorspar from primary sources has recognisable supply risk which can be noted from the sudden rise in price since 2018 due to supply disruption. The supply disruption resulted from sudden mine closures in China, the largest fluorspar supplier (about 50%) in the world, due to environmental inspections which coincided with a time of lower seasonal production levels due to traditional winter production cuts.[126] With the limitation in secondary sources and the volatile primary raw materials market, different measures for securing raw materials supply are recommended, for instance, substitution.

3. Application case study:

Domestic energy storage – Batteries storing electricity

In the electricity system, energy storage is defined as *the act of deferring an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier – EC (2016)*[127]. Energy can be stored in various different ways, including mechanical, thermal, chemical, electro-chemical and electrical.[128] Technology for energy storage are served at various locations, from where electricity is produced to where it is consumed and held in reserve. Furthermore, depending on the location, storage can be in different scales.[129]

This application only focuses on the electro-chemical type of energy storage technology (i.e. batteries storing electricity) in small to medium-size (kW to MW) as according to the SCRREEN D2.2, it is the most widespread technology in Europe households.[130]

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[124] BGS (2010) Mineral planning factsheet : Fluorspar, obtained on 01.04.2019 from https://www.bgs.ac.uk/mineralsUK/planning/mineralPlanningFactsheets.html

[125] EC (2018b) Report on Critical Raw Materials and the Circular Economy, *EC*, Brussels, ISBN 978-92-79-94626-4

[126] Roskill (2018) Brochure: Fluorspar Global Industry, Markets & Outlook 2018 obtained 03.04.2019 from https://roskill.com/market-report/fluorspar/

[127] EC (2016) Energy Storage – Proposed policy principles and definition https://ec.europa.eu/energy/sites/ener/files/documents/Proposed%20definition%20and%20principles%20for%20energy%20storage.pdf

[128] EC (2017b) COMMISSION STAFF WORKING DOCUMENT: Energy storage – the role of electricity https://ec.europa.eu/energy/sites/ener/files/documents/swd2017_61_document_travail_service_part1_v6.pdf

[129] DG ENER (n.d.) The future role and challenges of energy storage (DG ENER Working Paper), obtained on 28.02.2019 https://ec.europa.eu/energy/sites/ener/files/energy_storage.pdf

[130] Monnet, A. & Ait Abderrahim, A. (2018) op. cit., p.3

The common battery types include lithium-ion (Li-ion) batteries, lead-acid batteries, sodium sulphur (NaS) batteries and flow batteries.[131] Both lead-acid batteries and Li-ion batteries are suitable for application in various scales, including small to medium-size energy storage.[132] On the other hand, sodium sulphur batteries and flow batteries are applied for large-scale energy storage.[133] As this chapter focuses on small to medium-size energy storage technology, they are excluded from this report.

In Europe, lead-acid batteries have a collection and recycling rate higher than other consumer products[134] which implies that the technology is rather advance in being circular and the sourcing of the materials is not regarded as a problem. Hence, lead-acid batteries are excluded from this report. Due to aforementioned reasons, Li-ion batteries are selected as the sole main technology of this application. Li-ion batteries not only are CRM intensive (e.g. cobalt and natural graphite) but also dominant the current market (about 90% of market share) and are expected to maintain dominant until 2035.[135]

3.1. Technologies

The technologies presented in this section include Li-ion batteries, which is the leader of the current market, and the emerging battery technologies, for instance, liquid metal battery, that have potential to compete with Li-ion batteries in the coming decades.

3.1.1. Main technology

Li-ion batteries consists of a wide range of elements depending on the cells chemistries which are classified using the terminology "Generations". Currently, the core technology for energy storage (and for electrical vehicles) is represented by the optimised Li-ion battery cells of generation-1 (cathode: LFP, NCA[136]; anode: graphite) and -2a (cathode: NCM111[137]; anode: graphite). The elements of generation-1 and-2a Li-ion battery cells include lithium (Li), iron (Fe), phosphorus (P), nickel (Ni), cobalt (Co), aluminium (Al), manganese (Mn) and carbon (C).[138] In the later generations, the anode is to be made by a combination of graphite and silicon (Si). On the other hand, NCM remains as one of the main Li-ion battery cathodes in the later generations while increasing the share of nickel and reducing the amount of cobalt and manganese (i.e. NCM622, NCM811 and HE-NCM). The other coming cathode technology is the high-voltage spinel (HVS) consisting of lithium, nickel and manganese.[139,140] It is worth mentioning that there is a trend in reducing the amount of cobalt used since it is an element of main concern today due to its scarcity and its expensive price.[141,142]

[131] EC (2017b) op. cit., p.29
[132] EASE (n.d.a) Lead-acid battery obtained on 01.03.2019 http://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Electrochemical_LeadAcid.pdf and Lithium-ion battery obtained on 01.03.2019 http://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_LiIon.pdf
[133] EASE (n.d.b) Sodium sulphur (NaS) battery obtained on 01.03.2019 http://ease-storage.eu/wp-content/uploads/2018/09/2018.07_EASE_Technology-Description_NaS.pdf and Flow battery obtained on 01.03.2019 http://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_FlowBattery.pdf
[134] Monnet, A. & Ait Abderrahim, A. (2018) op. cit., p.3
[135] ibid.
[136] LFP for $LiFePO_4$; NCA for $LiNiCoAlO_2$; NCM for $LiNiCoMnO_2$ (NCM111 – $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$)
[137] Friesen, A., Schappacher, F. & Winter, M. (2017) Energy Density, Lifetime and Safety – Not Only an Issue of Lithium Ion Batteries, Helmholtz-Institut Münster (HI MS) and MEET Battery Research Center (University of Münster) http://www.fze.uni-saarland.de/AKE_Archiv/DPG2017-AKE_Muenster/Vortraege/DPG2017_AKE1.1_Winter_BatteryPerformanceSafety.pdf
[138] EC (2018c) COMMISSION STAFF WORKING DOCUMENT Report on Raw Materials for Battery Applications https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf
[139] Placke, T. (2018) Progress and Challenges: Generation 3b, MEET Battery Research Center (University of Münster)
[140] EC (2018c) op. cit., p.30
[141] ibid.
[142] McKinsey&Company (2018) op. cit., p.23

Among the elements mentioned, phosphorus (P), cobalt (Co), silicon metal (Si), natural graphite (C) are identified as CRMs by the European Commission due to their high economic importance combining high supply risk.[143]

3.1.2. Emerging technologies

In addition to the common battery types, this section introduces emerging technologies which adopt different elements for electrodes and electrolyte than the Li-ion batteries. By employing different elements, the emerging technologies reduce the risk in sourcing.

The liquid metal battery was invented by the MIT research team led by professor Donald Sadoway. While the lithium–antimony–lead[144] (Li-Sb-Pb) and lithium-bismuth[145] (Li-Bi) liquid metal batteries are for grid-scale energy storage, the magnesium-antimony (Mg-Sb) liquid metal battery[146] can be used for stationary energy storage (the scale ranges from 200kWh to hundreds of MWh[147]). Therefore, its elements Mg and Sb, are included in this report. While the chemistry of the commercialised liquid metal battery from Ambri, the spinoff of the MIT research team led by professor Donald Sadoway which published the aforementioned studies, is undisclosed, the published elements for stationary energy storage (i.e. the Mg-Sb liquid metal battery) are included in this report due to the potential demands in the future.

3.2. Primary and secondary sources of key elements for domestic energy storage

This sector reviews the primary and secondary sources of key elements for the main and emerging battery technologies. The key elements refer to antimony (Sb), cobalt (Co), (graphite (C),) lithium (Li), magnesium (Mg), manganese (Mn), nickel (Ni) and silicon metal (Si). Cobalt, (graphite,) lithium, manganese, nickel and silicon metal are the main components of the current and future Li-ion battery technology while antimony and magnesium are the elements building the electrodes of the liquid metal battery for stationary energy storage.

The elements of this sector are introduced in alphabet order.

3.2.1. Antimony (Sb) – CRM

Antimony is chalcophile, occurring with sulphur and the heavy metals, lead, copper, and silver. Nowadays, antimony metal is mostly used as a hardener in lead for storage batteries. It is also applied in solders and other alloys. The most important of the antimony compounds is antimony trioxide. It is primarily used in flame-retardant formulations for children's toys, clothing, and aircraft and automobile seat covers.[148]

3.2.1.1. Primary sources

Globally, China continues to be the largest producer in 2018 and accounts for 70% of the global mine production. Russia and Tajikistan are both the second largest mine producers and each

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[143] EC (2018b) op. cit., p.29

[144] Wang, K., Jiang, K., Chung, B., Ouchi, T., Burke, P.J., Boysen, D.A., Bradwell, D.J., Kim, H., Muecke, U. & Sadoway, D.R. (2014) Lithium–antimony–lead liquid metal battery for grid-level energy storage, *Nature* V. 514, pp 348 350 https://www.nature.com/articles/nature13700

[145] Ning, X., Phadke, S., Chung, B., Yin, H., Burke, P. & Sadoway, D.R. (2015) Self-healing Li–Bi liquid metal battery for grid-scale energy storage, *Journal of Power Sources*, V. 275, Pages 370-376 https://www.sciencedirect.com/science/article/abs/pii/S0378775314017923

[146] Bradwell, D.J., Kim, H., Sirk A.H.C. & Sadoway D.R. (2012) *J. Am. Chem. Soc.*, 2012, *134* (4), pp 1895–1897, DOI: 10.1021/ja209759s

[147] Ambri (n.d.) Ambri Brochure, obtained on 08.03.2019 from http://www.ambri.com/technology/

[148] USGS (2019a) Antimony Statistics and Information, obtained on 11.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/antimony/

produces about 10% of the global production.[149] The main antimony importers to the EU are China (90%) and Vietnam (4%) and they are also the main sources of the EU supply (average between 2010 to 2014).[150]

Figure 3.1 shows the antinomy occurrence in Europe. While some mining activities have taken place in the past, there is no active mining. However, in Bulgaria, one active exploration activity for Au-Sb deposits is recorded.[151]

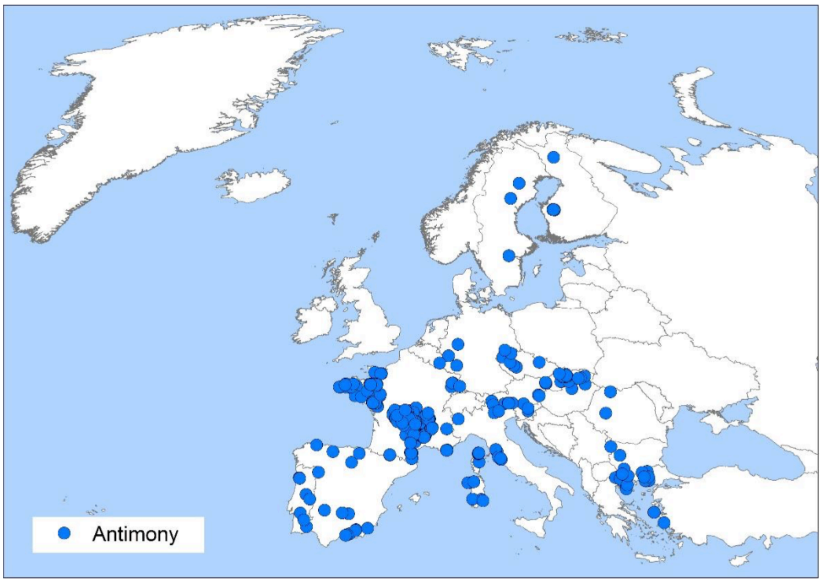

Figure 3.1 Antinomy occurrence in Europe (SCRREEN, 2018)

The simplified material flows of antimony in Europe for 2012 is provided in a Sankey diagram (Figure 3.2).

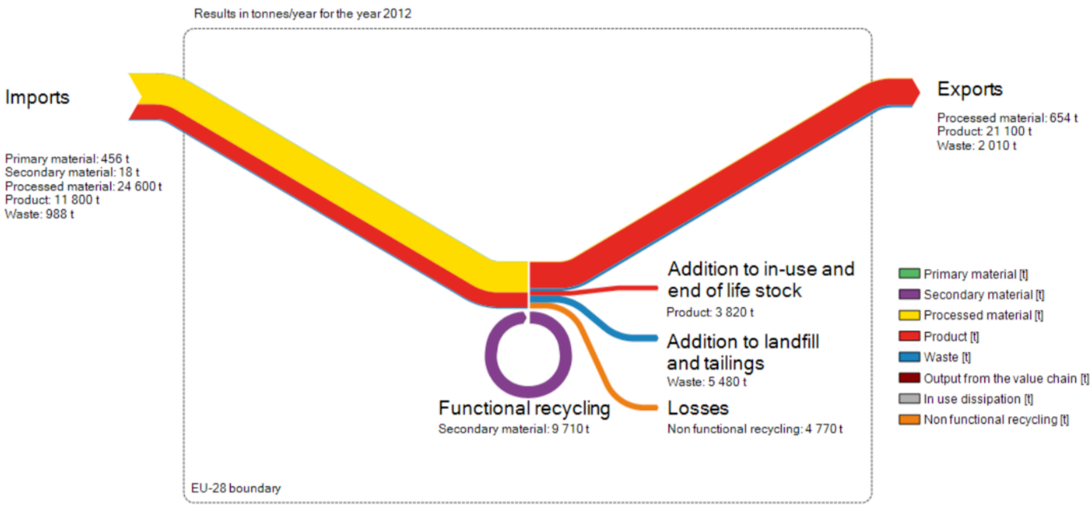

Figure 3.2 Simplified antimony material flows in Europe for 2012 (Deloitte, 2015)[152]

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[149] USGS (2019b) Antimony Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 11.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2019-antim.pdf

[150] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

[151] Lauri, L. (2018) D3.1 Identification and quantification of primary CRM resources in Europe, *H2020 SCRREEN Project* D2.2 obtained from http://scrreen.eu

[152] Deloitte (2015) op. cit., p.13

3.2.1.2. Secondary sources

In 2010, antimony secondary production accounts for 20% of the global total production of antimony.[153] Figure 3.3 presents a schematic overview of the antimony lifecycle including path of production, waste streams and recycling routes.

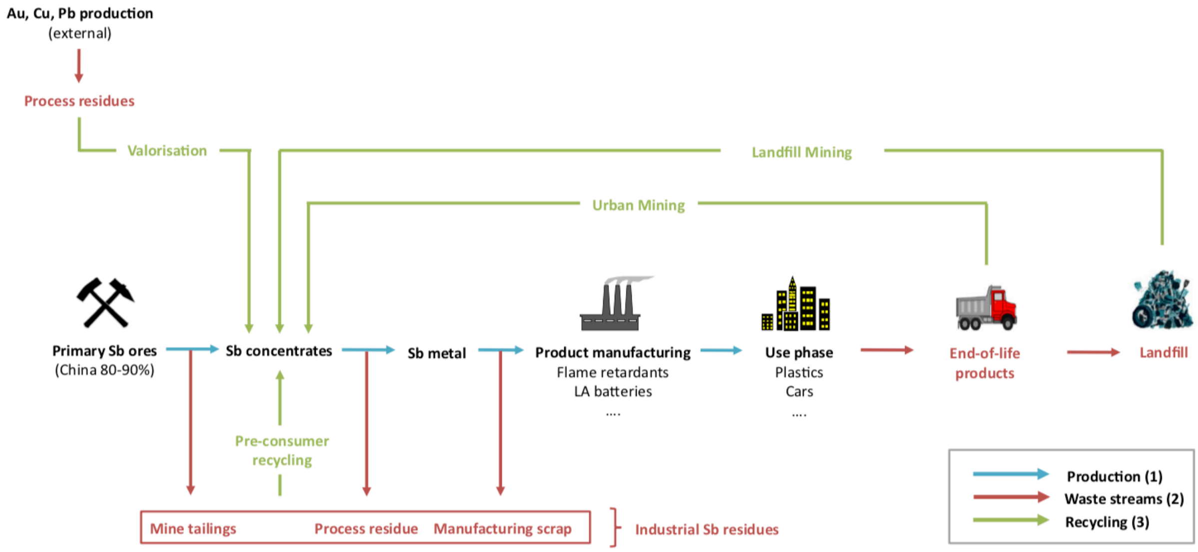

Figure 3.3 Schematic overview of the antimony lifecycle (Dupont et al, 2016)

Based on the common applications of antimony, the identified potential recyclables are listed below. In addition, Figure 3.4 shows the global applications of antimony. It should be mentioned that although the largest application is the fire retardants of plastics (e.g. for electric and electronic equipment (EEE) [154]), textiles, paints and rubbers etc., the antimony in this application cannot be easily recycled due to the low proportions and dissipative distribution in the end products.[155, 156]

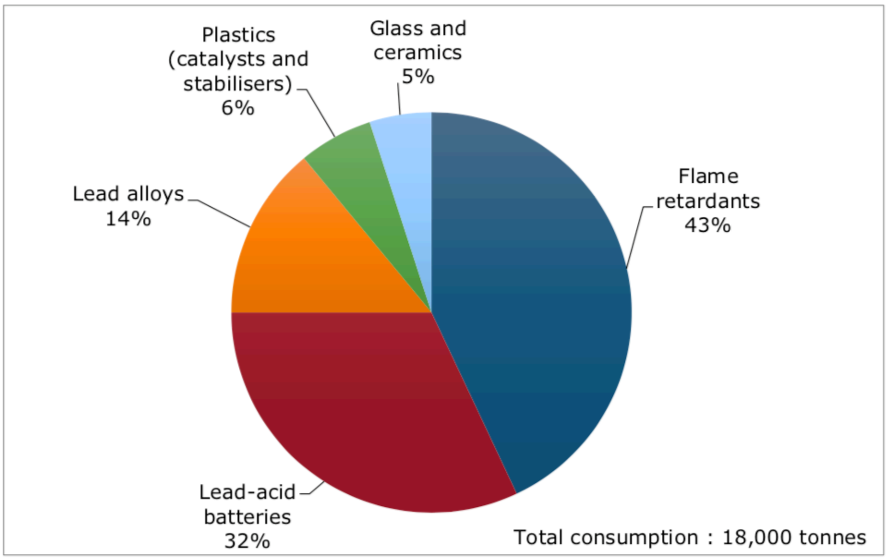

Figure 3.4 Global applications of antimony (EC, 2017a)[157]

[153] Dupont, D., Arnout, S., Jones, P.T. & Binnemans, K. (2016) op. cit., p.23
[154] ibid.
[155] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[156] DERA (2013) op. cit., p.23
[157] EC (2017a) op. cit., p.23

Processing residues

- **Processing residues** from lead, copper, gold and antimony production
- **Spent antimony catalysts**
- **Mine tailings** from lead, copper, gold and antimony[158]

EoL products

-
- **Wires and cables** from wires and cables (plastic)
- **Scraps** from lead alloys, mechanical equipment and industrial motors
- **Lead-acid batteries** from lead acid batteries
- **Wastes of EEE** (WEEE) from EEE
- **Secondary materials** from plastic (catalysts, heat stabilizers), textiles and ceramics

Antimony can be recovered in the residues of lead refining process and there are efforts put into recover antimony from secondary lead. Currently, the recycling of antimony is limited to lead-acid batteries and small quantity recycling other lead alloys, for instance, sheets, tubes and cable insulation. [159, 160] Hence, the secondary antimony is almost entirely depending on the extend of lead recycling and the market conditions of lead and lead-acid battery scrap.[26]

In addition to the existing secondary antimony production (i.g. with lead refining processes), other potential secondary sources of antimony in the future include other industrial residues (e.g. mine tailings, process residues, manufacturing scraps) from copper, gold and antimony and antimony containing EoL products (e.g. incineration ashes from concentrated fractions, for example, fire retardant plastics).[161]

3.2.1.3. R&D bottlenecks of secondary sources - Metallurgy

According to the recycling metal wheel (Section 2.3.2), antimony (Sb) is a minor element and compatible with zinc (Zn) and lead (Pb) (carrier metals). With BAT, antimony is one of the mainly recovered elements in the subsequent processing of zinc and lead.[162] Antimony is also possible to be part of copper/nickel (Cu/Ni) or tin(Sn) (carrier metals) alloys/compounds but can be lost if it falls into incorrect streams, scraps or modules or if its recovery is not economical.[163] On the other hand, antimony is lost if it falls into the iron (Fe), manganese (Mn), chromium/nickel (Cr/Ni) (i.e. steel) or aluminium (Al) refinery processing as antimony is detrimental to the product properties and cannot be recovered economically.

Plenty researches were and are conducted to recover antimony from industrial residues and EoL products. Based on the critical review done by Dupont et al. (2016), Table 3.1 indicates the researches done in recovering antimony from processing residues and the respective needs for furthering the works. Then, Table 3.2 presents the researches for recovering antimony from EoL products and the respective R&D bottlenecks.

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[158] Taken as secondary sources of antimony if considering the process as recycling industrial wastes
[159] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[160] DERA (2013) op. cit., p.23
[161] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[162] Antimony can be part of the alloys (e.g. antimonial lead) or recovered subsequently. (Dupont et al, 2016, op. cit., p.23)
[163] Antimony is treated as impurity in copper concentrate production, and thus it is removed as residues. Antimony-containing residues are an increasingly big issue in copper processing due to the deteriorating quality of primary copper ores. (Dupont et al, 2016, op. cit., p.23)

According to Dupont et al. (2016), while sufficient technologies are available to recycle antimony from residues, the main general obstacle of implementation now is the upscaling of the laboratory methods to industrial processes. Therefore, the laboratory methods should be performed at the pilot scale to assess which methods are sufficiently robust and flexible. In addition, economic feasibility studies and life cycle assessments should also be carried out to determine which methods are most promising for industrial upscaling. Another challenge for the future research is the changing composition of various residues depending on the processed products which can greatly affect the performance of the recovery process.

Table 3.1 Recovering antimony from processing residues and R&D bottlenecks (Dupont et al, 2016)[164]

Processing residues	Topics of research	R&D bottlenecks	Project examples [165]
Antimony production	**1.** Recovering Sb from flue dusts, slags and refining residues **2.** Optimising primary production process (direct reduction of wastes)		
Gold production	**1.** Recovering Sb from electronrefining slime		
Copper production	**1.** Recovering Sb from residues (e.g. slags, flue dusts, anode slime and copper electrolyte solutions)	**1.** No recycling activities at industrial scale although there is strong commitment to develop these in the future	**German projects** 1. Theisenschlamm - Recycling Theisen Sludge from the Mansfelder Smelting Process (FONA r[4], Closed in 2018)
Lead production	**1.** Recovering Sb from residues (e.g. smelting slag, Harris dross, speiss, matte, softening skim, Sb dust and slime)		

[164] Dupont et al (2016) op. cit., p.23
[165] Not part of the Dupont et al. study (op. cit., p.23) but from SCRREEN D3.2 (op. cit., p.23) and desk research

Processing residues	Topics of research	R&D bottlenecks	Project examples [166]
Spent antimony catalyst (e.g. in production of polyethylene terephthalate (PET))	**1.** Mass recycling of PET plastic could be an opportunity to recover antimony (although antimony contents are typically lower than in plastics containing antimony-based flame retardants) **2.** Recovering Sb from spent ethylene glycol residues resulting from the manufacture of PET polymers **3.** Recovering Sb from halocarbon solutions, because Sb-containing catalysts (e.g., HF/SbCl5) are used in the fluorination of chlorinated hydrocarbons **4.** Recovering Sb-containing catalyst **5.** Recovery of antimony from a spent catalyst used in the production of acrolein from propylene.		

[166] Not part of the Dupont et al. study (op. cit., p.23) but from SCRREEN D3.2 (op. cit., p.23) and desk research

Table 3.2 Recovering antimony from EoL products and R&D bottlenecks (Dupont et al, 2016)

EoL products	Topicss of research	R&D bottlenecks	Project examples
Municipal solid waste incineration (MSWI)	**1.** Recovering antimony from bottom ash, boiler ash and fly ash[167]	**1.** The technologies are all promising but the winning technology will be the one that can selectively remove certain elements such as antimony. (MSWI residues contain various metals.) **2.** Due to the mix of elements in these residues, it is crucial to develop methods which can deal with the complexity of these powders in a low-cost and efficient manner. **3.** Currently not economically feasible[168]	**German projects** 1. SESAM (FONA r[4], Closed in 2018)
Flame retardant in plastics (most effective commercial one is brominated flame retardants)	**1.** Recovering Sb from plastics where Sb is caught in the residues (bottom ashes or fly ashes, decomposition gasses)		

[167] Fly ashes are particularly interesting, due to the volatility of antimony which results in an important enrichment of antimony in the fly ashes.

[168] EC (2017a) op. cit., p.23

EoL products	Topicss of research	R&D bottlenecks	Project examples
Plastics in WEEE (a subcategory of flame retardant plastics; using mostly brominated flame retardants)	**1.** Recovering Sb from WEEE plastics	(So far, the focus is on limiting the emission of brominated compounds and producing useful fuel oil. However, valorising antimony from WEEE plastics could improve the economics of the total WEEE recycling process and offset the additional cost of de-brominating during the processing of WEEE plastics) **1.** More advanced processes are required such as pyrolysis, gasification, polymerisation, or hydrogen degradation in order to convert the non-metallic fraction of WEEE to chemical feedstocks and fuels.[169] **2.** There are technologies available to valorise the plastic components of WEEE, but that additional research needs to be done to improve the efficiency of these processes before upscaling becomes economically feasible.	**EU projects** 1. CloseWEEE (on-going) **German projects** 1. addResources (FONA r[4], Closed in 2018)
Lamp phosphor waste (Antimony is used in the halophosphate (HALO) lamp phosphors, found in fluorescent lamps)	**1.** Recovering Sb from HALO	**(**Currently, a recycling process is operated on industrial scale ([1000 t/y] by Solvay in France but the Sb-containing HALO phosphor is often still discarded as a non-valuable residue due to the absence of rare earths.) **1.** The valorisation of HALO and the recovery of antimony can be integrated in rare- earth recovery schemes and in the broader effort to recycle these lamp phosphor powders.	

[169] Guo, J. & Xu, Z. (2009) op. cit., p.23

3.2.2. Cobalt (Co) – CRM

Cobalt is a metal used in numerous diverse commercial, industrial, and military applications, many of which are strategic and critical. Globally, the leading application of cobalt is in rechargeable battery electrodes. Another major application is superalloys used to make parts for gas turbine engines.[170]

3.2.2.1. Primary sources

Congo (Kinshasa) is the global leading source, supplying more than 60% of the mined cobalt in the world. Cobalt is mostly mined as a by-product of copper or nickel except in Morocco and the artisanal mines in Congo (Kinshasa). China, on the other hand, is the global leading producer of refined cobalt. Most of the production is from importing the partially refined cobalt from Congo (Kinshasa).[171]

In Europe, cobalt is produced in Finland as a by-product in the Kylylahti Cu-Zn, Kevitsa Ni-Cu, and Talvivaara Ni-Zn mines. The current production is about 2,500 t/a. Finland is also a global significant refined cobalt producer (10% of global refined cobalt production) but most of the input materials are imported. In Greece, although its nickel ore exploited by Larco contain cobalt, the cobalt is extracted from the nickel ores and used in the ferronickel production instead of cobalt production. In Poland, cobalt occurs as a minor constituent in Kupferschiefer stratiform copper ore but it is not recovered during the processing stages.[172] Figure 3.5 shows the cobalt resources in Europe and the active mines.

Cobalt imported to Europe is mainly from Russia (91%) and Democratic Republic of Congo (7%) (average between 2010 to 2014). However, the main sources of the EU cobalt supply are from Finland (66%) and Russia (31%).[173]

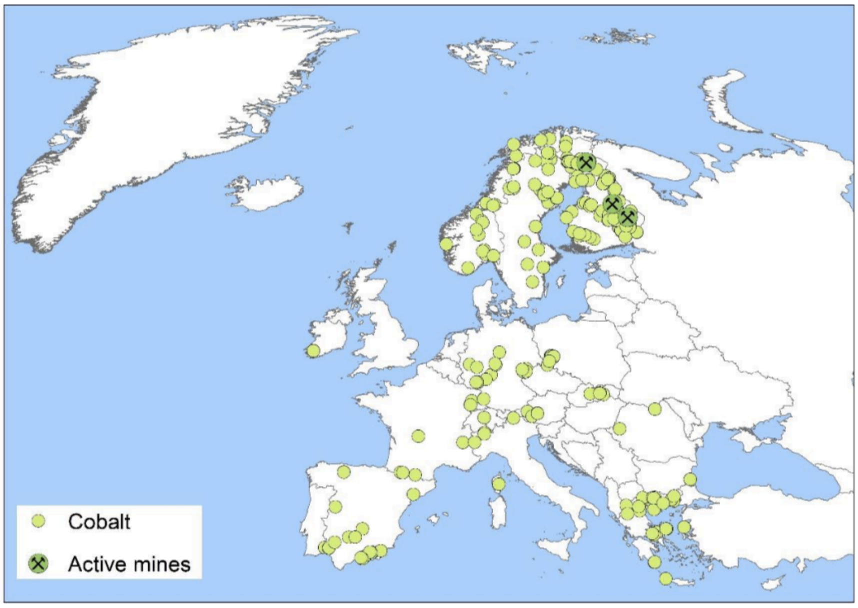

Figure 3.5 Cobalt occurrence and active mines in Europe (SCRREEN D3.1, 2018)

[170] USGS (2019c) Cobalt Statistics and Information, obtained on 15.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/

[171] USGS (2019d) Cobalt Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 18.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/cobalt/mcs-2019-cobal.pdf

[172] Lauri, L. (2018) op. cit., p.32

[173] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

The simplified material flows of cobalt in Europe for 2012 is provided in a Sankey diagram (Figure 3.6).

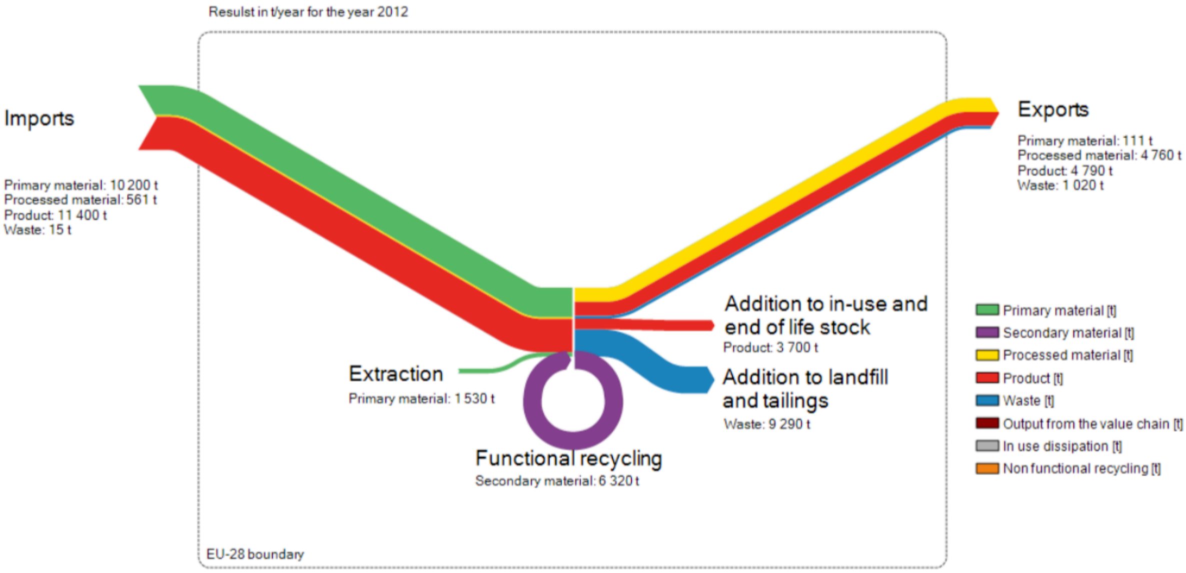

Figure 3.6 Simplified cobalt material flows in Europe for 2012 (Deloitte, 2015)

3.2.2.2. Secondary sources

Cobalt has a wide range of applications. Currently, it is increasingly used in high-tech applications, for instance, battery technology, catalyst, alloys and hard materials (Figure 3.7). A list of potential recyclables for cobalt from different applications is shown below. It should be noted that one of the applications of cobalt is pigments and it is not recyclable due to its dissipative use.[174]

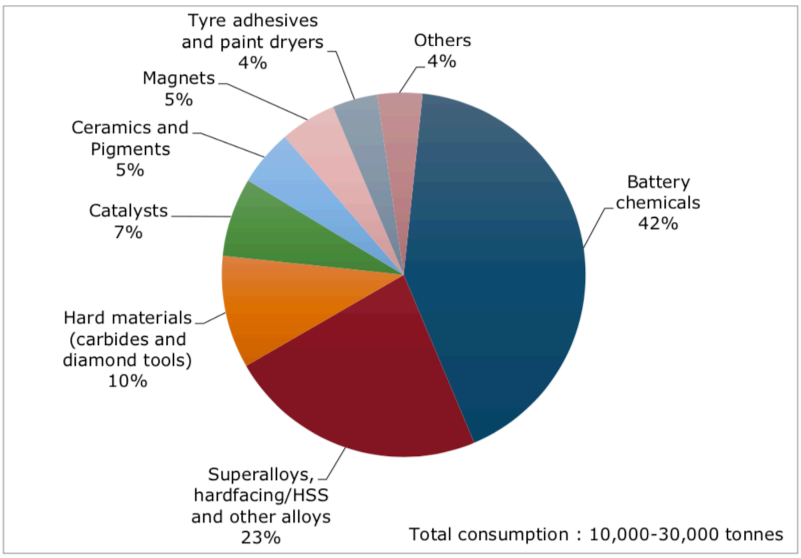

Figure 3.7 Global end use applications of cobalt in 2015 (EC, 2017a)

<u>Processing residues</u>

- **Processing residues** from smelting

[174] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

- **Flotation tailings**
- **New or processing scraps** from alloys

<u>EoL products</u>

-
- **Spent catalyst**
- **Old scraps** from e.g. turbine blades, parts of jet engines, cutting tools, and magnets
- **Spent battery chemicals** from batteries
- **Spent hard materials** (cemented carbides, diamond tools)
- **Tyre adhesive**

The recycling rate of the old scraps depends on the efficiency of the collection systems and if the recovery process is economical. Moreover, most of the cobalt containing alloys are recycled into stainless steel so the cobalt is not really recovered. [175]

3.2.2.3. R&D bottlenecks of secondary sources - Metallurgy

Cobalt is one of the minor metals in the recycling wheel (Section 2.3.2). Carrier metals that are relatively compactible are rare earth (RE) in special battery recycling process, copper/nickel (Cu/Ni) and zinc/lead (Zn/Pb) in smelting processes. Therefore, recovering cobalt depends on the aforementioned processes. Table 3.3 and Table 3.4 present the existing technologies and R&D bottlenecks in recovering cobalt from processing residues and EoL products respectively.

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[175] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

Table 3.3 Recovering cobalt from processing residues and R&D bottlenecks[176]

Processing residues	Existing technologies	R&D bottlenecks	Project examples [177]
Processing	**1.** Recovering Co from nickel refinery (hydrometallurgy) **2.** Recovering Co from waste solution of copper open pit mines (hydrometallurgy) **3.** Recovering Co from zinc smelting waste/by-product (hydrometallurgy)		**German projects** 1. REWITA (FONA r^4, Closed in 2018) – tailings at Bollrich in Goslar (Germany) 2. Theisenschlamm - Recycling Theisen Sludge from the Mansfelder Smelting Process (FONA r^4, Closed in 2018)
Flotation tailings	**1.** Recovering Co from flotation tailings of cobalt ore		

[176] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

[177] From SCRREEN D3.2 (op. cit., p.23), desk research (Innovative Technologien für Ressourceneffizienz Forschung zur Bereitstellung wirtschaftsstrategischer Rohstoffe (r4) ZWISCHENERGEBNISSE, 2018; DERA Rohstoffinformationen Rohstoffrisikobewertung – Kobalt, 2018)

Table 3.4 Recovering cobalt from EoL products and R&D bottlenecks[178]

EoL products	Existing technologies	R&D bottlenecks	Project examples [179]
Spent battery chemicals (Li-ion, NiMH and NiCd batteries)	(Usually, large Ni/Co smelters are also prepared for recovery of cobalt from spent batteries but there are plants dedicated for battery recycling.) **1.** Recovering Co from slag produced by the NiMH and Li-ion batteries smelting process (pyro-metallurgy) **2.** Recovering Co from slurry produced by the shaking tables which separate the crushed battery metals and plastic with paper (hydrometallurgy) **3.** Electrochemical processing **4.** Bio-leaching	**1.** Difficulties in sorting and identifying different battery composition as it is an evolving technology. (Potential solution could be a universal recycling technology for mixed battery waste processing considering the differences between them.)[180] **2.** Most research activities are at laboratory scale **3.** Improving the cost effectiveness of the recycling processes, development of more efficient processes[181]	**EU projects** 1. AutoBat- Rec 2020 (EIT-RM, Ongoing) **German projects** 1. NeW-Bat (FONA r[4], Ongoing) new process: electro-hydraulic comminution by means of shock waves
EoL products	**Existing technologies**	**R&D bottlenecks**	**Project examples**

[178] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[179] From SCRREEN D3.2 (op. cit., p.23), desk research (Innovative Technologien für Ressourceneffizienz Forschung zur Bereitstellung wirtschaftsstrategischer Rohstoffe (r4) ZWISCHENERGEBNISSE, 2018; DERA Rohstoffinformationen Rohstoffrisikobewertung – Kobalt, 2018)
[180] McKinsey&Company (2018) op. cit., p.23
[181] Lebedeva, N., Persio F.D. & Boon-Brett, L. (2016) op. cit., p.23

Alloys scraps	**1.** Recovering Co from slag of sulphide smelter into which the mixing alloy scraps with primary cobalt sulphide concentrates are fed (pyro-metallurgy) **2.** Recovering Co from NiCo alloys by hydrometallurgy processes **3.** Double membrane electrolytic cells (DEMC) to recover high-purity nickel and cobalt cathodes from super alloy scrap		
Spent hard materials (cemented carbide, diamond tools)	**1.** Recovering Co by melting cleaned cemented carbide with zinc metal and after zinc is distilled off, the material is crushed to screen for cobalt (pyro-metallurgy)		
Spent catalysts (oil and gas refining process, production of chemicals for plastic manufacturing, and Fisher-Tropsch fuel synthesis)	**1.** Recovering Co from leaching and roasting (electric arc furnace) spent catalyst (Co/Mo, Ni/Co/Mo/V or Ni/Mo). The process produces Ni/Co alloys (and alumina concentrate, V, Mo etc.) (hydrometallurgy and pyro-metallurgy)		
Tyre adhesive	No technology available		
Pigment	No technology available due to dilution of the metal and difficulties in collections		

Note: Major players in Europe include Freeport Cobalt (Finland) and Umicore (Belgium). Other battery recycling companies include Accurec Recycling GmbH (Germany), Glencore (formerly XStrata) (Czech Republic), Recupyl S.A. (Frence), AEA Technology (UK), SNAM (Frence), AkkuSer Oy (Finland), Batrec Industrie AG (Czech Republic), Euro Dieuze / SARP (Frence), Valdi (ERAMET) (Frence), and G&P Batteries (UK).

3.2.4. Lithium (Li)

Lithium, in elementary form, is a soft silvery white metal.[182] The global leading end-use application is batteries (56%) following by ceramics and glass (23%), lubricating greases (6%) and other uses.[183]

3.2.4.1. Primary sources

Majority of the global lithium production is from the five spodumene operations in Australia, two brine operations in Argentina, and two brine operations in Chile. The spodumene operations in Australia are the largest lithium producer in the world.[184]

In Europe, about 350 tonnes of lithium ores are extracted annually in Portugal. (Spain ceased production in 2011.) The majority of the lithium used in Europe is imported from Chile (66%), Portugal (11%) and United States (9%) (around 3,600 tonnes of lithium contained in compounds, annual average between 2010-2014).[185]

The simplified material flows of lithium carbonate equivalents (LCE)[186] in Europe for 2012 is provided in a Sankey diagram (Figure 3.8).

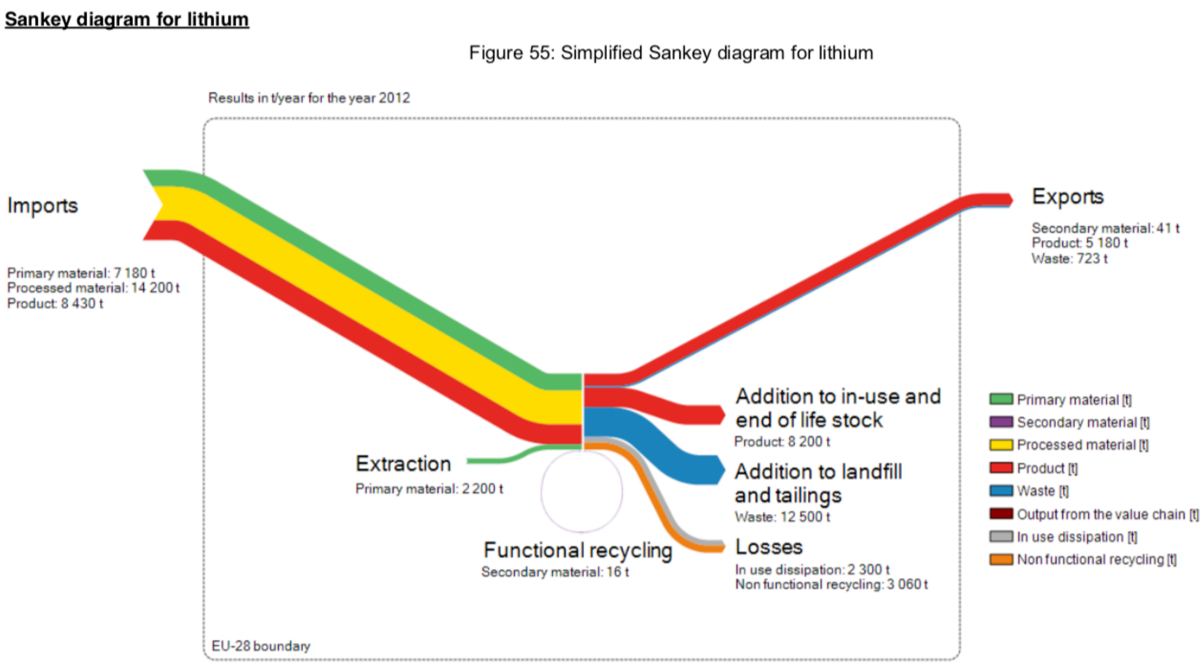

Figure 3.8 Simplified lithium material flows in LCE in Europe for 2012 (Deloitte, 2015)

3.2.4.2. Secondary sources

Lithium has various applications. In industrial processes, lithium is used in aluminium smelting, steel casting, rubbers and plastic production and cement production. Lithium is also contained in end-user products (i.e. finished products) including batteries, glass and ceramics, products made of aluminium alloys, lubrication greases, electronics, and pharmaceutical products.

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[182] DERA (2015) op. cit., p.13

[183] USGS (2019e) Lithium Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 18.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2019-lithi.pdf

[184] ibid.

[185] EC (2018c) op. cit., p.30

[186] 1 kg lithium metal equivalent (LME) = 2.153 kg lithium dioxide (Li2O) = 5.323 kg lithium carbonate equivalent (LCE)

Figure 3.9 shows the amounts of the lithium used in different applications in the EU (in percentage) and the finished products used in the EU. According to the study made by Deloitte (2015), while the end-user products, such as batteries, glass, products made of aluminium alloys and electronic appliances, are recycled in significant proportions, there is no functional recycling of lithium since the separation of lithium from the products is either not possible or very costly.[187] In addition, DERA (2015) indicated that the large primary resources and reserves, the relatively low-cost of extraction, the dissipative distribution of lithium, and the technical demands on purity for certain applications, all have impacts on the development of the secondary sector.[188]

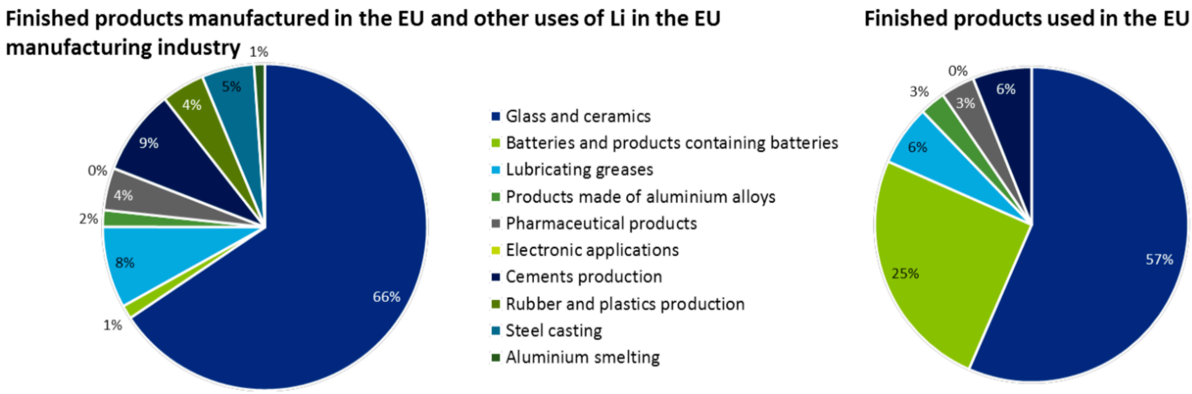

Figure 3.9 The amounts of the lithium used in different applications in the EU (in percentage) (left) and the finished products used in the EU (right) (Deloitte, 2015)

EoL products

- **Spent battery chemicals** from batteries
- **Glass/ceramics**
- **Spent additives** from lubrication greases

3.2.4.3. R&D bottlenecks of secondary sources - Metallurgy

Lithium is a carrier metal in the recycling metal wheel (Section 2.3.2) and cannot be found as a minor metal to any other carrier metals.

Currently, the greatest lithium recycling potential lies in rechargeable Li-ion batteries. However, the low amounts of lithium in Li-ion batteries, the complex compounds, high purity requirements, and the low monetary value comparing to other metals (e.g. nickel and cobalt) make recovering lithium not worthwhile during battery recycling processes. Lithium contained in Li-ion batteries is therefore bound with other residual materials in the process slag and used in the construction industry as a mineral aggregate in ready-mixed concrete. With the outlook of a growing e-mobility market, recycling quantities should increase and if the prices of raw materials rise accordingly, recovering lithium could become economically attractive.[189]

The recovery of lithium from batteries is already technically possible, for instance, in an industrial scale, lithium can be recovered by a combination of cyromilling and pyro-metallurgy processes (i.e. Toxco Inc., USA). Another example is recovering lithium by using extraction solvent for electrolyte (pyro-metallurgy processes) (i.e. SNAM, France and AEA technology

[187] Deloitte (2015) op. cit., p.13
[188] DERA (2015) op. cit., p.13
[189] ibid.

batteries, UK). Although the industrial lithium recovery from batteries is limited, several studies have reported recovery of lithium from battery recycling also by hydrometallurgy techniques, chemical extraction processes, and hybrid (hydro and pyro) metallurgy processes. The bottlenecks identified include the need to develop techno-economically efficient processes, taken into account the environmental aspects, and efficient and feasible technologies to recover lithium in high purity from low lithium bearing sources.[190]

- Project examples for recovering lithium from batteries are shown below.
    - **EU projects**
        - COLABATS (FP7, closed in 2016)
        - HYDROWEEE DEMO (FP7, closed in 2017)
        - CloseWEEE (FP7, closed in 2018)
    - **German projects**
        - LiBRi (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMU) – Erneuerbare mobil programme, closed in 2011)
        - LithoRec and LithoRec II (BMU – Erneuerbare mobil programme, closed in 2016)
        - ECOBATREC (BMU – Erneuerbare mobil programme, closed in 2016)

Regarding to lithium contained in the other EoL product, glass and ceramics, lithium is not recovered. However, broken glass can be recycled if it is of the same type. The same principle applied to the other lithium application, lubricants. Lithium is used as a chemical compound (additive) in lubricants and is not recovered. On the other hand, lubricants such as oils and greases can in principle be processed and re-used once the impurities are removed. [191]

- Project examples for recovering lithium are shown below.
    - **German projects**
        - TransTech (FONA r[4], ongoing) – Leaching technology for primary and secondary materials

3.2.6. Magnesium (Mg) – CRM

Magnesium is the eighth most abundant element in the Earth's crust and can be found in minerals and produced from seawater, lack brines and bitterns. Magnesium alloys are used as structural components of automobiles and machinery. Magnesium metal is also commonly used as an alloying addition to aluminium. The aluminium-magnesium alloys are used mainly for beverage cans. Magnesium itself can be used to remove sulfur from iron and steel. In addition, Magnesium compounds, mainly magnesium oxide, are mostly used as refractory material in furnace linings for producing iron and steel, nonferrous metals, glass, and cement.[192]

[190] Basudev, S. (2017) op. cit., p.24
[191] DERA (2015) op. cit., p.13
[192] USGS (2019f) Magnesium Statistics and Information, obtained on 21.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/magnesium/

3.2.6.1. Primary sources

China is the global leading producer of magnesite and magnesia producing about 65% of the world's production. Turkey is the second largest producer accounting for around 12% of the world's production.[193]

In Europe, there is no magnesium metal production. Instead, there is mineral magnesite production which is often used in other applications (e.g. refractory sands and metallurgical flux) than producing magnesium metal. The EU countries produce magnesite include Austria, Finland (information in 2016), Greece, Netherlands (information in 2015), Poland (information in 2016), Slovakia, and Spain. [194,195]

As there is no pure magnesium production in the EU, the supply for the manufacturing industry entirely relies on imports from China and a few other non-European countries.[196] Europe imports magnesium mainly from China (94%, average between 2010-2014) which is also the main source of the magnesium supply in Europe (94%, average between 2010-2014).[197]

The simplified material flows of magnesium in Europe for 2012 is provided in a Sankey diagram (Figure 3.10).

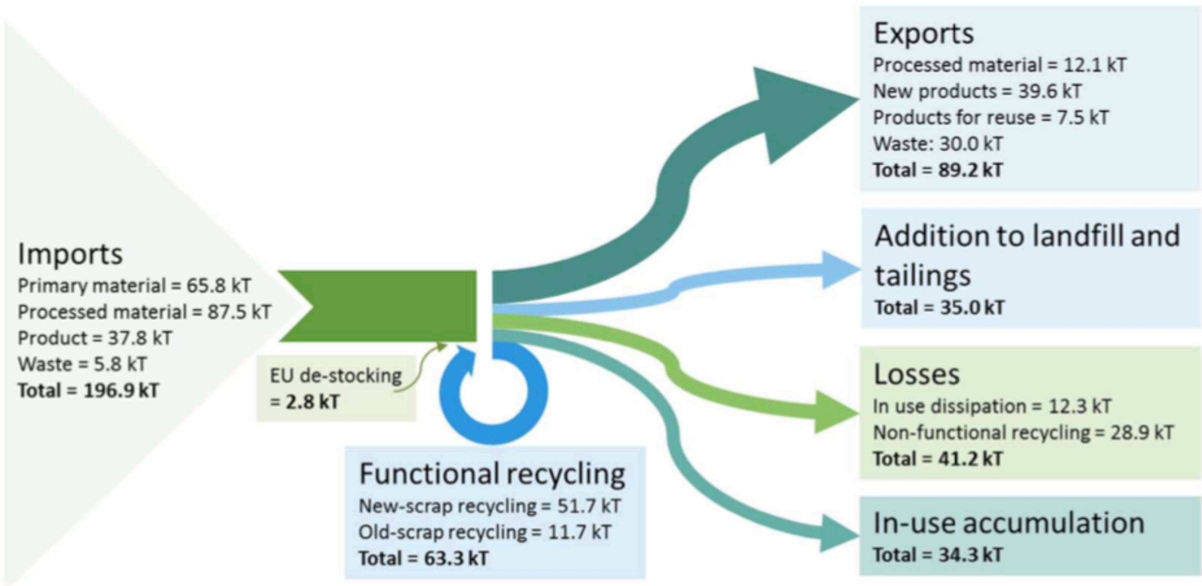

Figure 3.10 Simplified magnesium material flows in Europe for 2012 (Bell et al, 2017)[198]

[193] USGS (2019g) Magnesium Compounds Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 21.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2019-mgcom.pdf
[194] ibid.
[195] Lauri, L. (2018) op. cit., p.32
[196] EC (2017a) op. cit., p.23
[197] Lauri, L. (2018) op. cit., p.32
[198] Bell, N., Waugh, R. & Parker D. (2017) op. cit., p.24

3.2.6.2. Secondary sources

In Europe, 40% of the magnesium is used in magnesium casting. The magnesium alloys can be considered to be fully used for vehicles and other transportation applications. About an equal amount of magnesium (39%) is used in aluminium alloys (information from 2010-2014 period). The aluminium alloys are used in packaging (about 2% of magnesium), transportation (about 1% of magnesium) and construction (about 0.5% of magnesium) applications. Other applications of magnesium include pharmaceutical and agricultural chemical production. (Figure 3.11)[199]

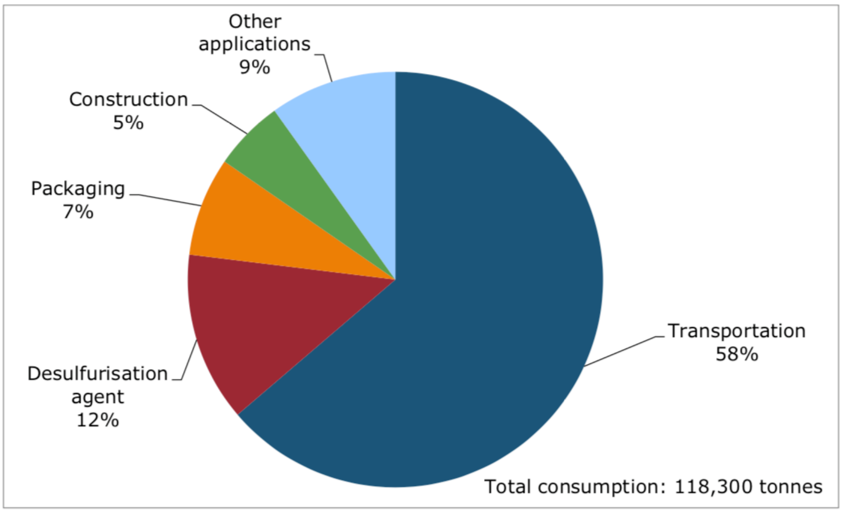

Figure 3.11 EU end use applications of magnesium, average figure for 2010-2014 (EC, 2017a)

Recyclables

Magnesium-based new scraps – Recycling or reuse of magnesium new scraps is a common practice in the magnesium industry (in-house or externally). The recycling and the reuse of the scrap reduce the demand of primary magnesium by up to 50%. Scraps with lower grades are used as reagents in steel desulphurisation and other markets, as a replacement to primary magnesium. The magnesium used in steel desulphurisation is not recycled.[200]

Magnesium-based old scraps (i.e. postconsumer scraps) – Magnesium old scraps include materials such as parts of transportation applications. They are sent to scrap processors.[201] However, the potential of recovering magnesium from the magnesium fraction in old cars is low. The use of the oily, coated magnesium scraps reduces the potential of metal-recovery, increases the melt losses, and makes the conventional recycling into high-quality die casting alloy ingots almost impossible.[202]

Magnesium-based new and old scraps together formed the secondary magnesium materials. Depending on the quality and condition of the recyclable magnesium materials, the secondary magnesium materials are sorted into eight classes (Table 3.5). According to Hanko and Ebner (2002), only class one materials can be recycled easily into high purity alloys. Based on the level of contamination, class two materials may require more complex handling. Class five and

[199] EC (2017a) op. cit., p.17
[200] ibid.
[201] Kramer, D.A. (2002) op. cit., p.24
[202] Hanko, G. & Ebner, P. (2002) Recycling of different types of magnesium scrap, Magnesium Technology 2002, TMS (The Minerals, Metals & Materials Society)

higher, on the other hand, certainly require more sophisticated recovering processes. Generally, the costs of the secondary magnesium material class two and higher determines the economical attractiveness of the recycling as the costs of this may exceed the value of magnesium recovered.[203]

Table 3.5 Eight classes of secondary magnesium materials with respective recycling methods (Hanko & Ebner, 2002)

Scrap	Characterization	Problems	Recycling Methods
Class 1A	High grade clean scrap without impurities e.g. scrap castings, biscuits etc.		Fluxfree, Recycling with flux
Class 1B	Clean scrap with a high surface in proportion to the weight		Recycling with flux
Class 2	Clean scrap with aluminum- or steel inserts. No copper- or brass-impurities	Fe-content, Si-content	Magnetic separation, if necessary ICF* and/or diluting
Class 3	Clean, dry and uncontaminated turnings and swarfs	High surface ⇒ melt losses, oxide-content	Compacting, increased flux quantity, event. cover gas
Class 4	Flux free Residues eg. dross, sludge	Oxide-content, Fe-content	Increased flux quantity, if necessary ICF* and/or diluting
Class 5	Painted or coated scrap with/without aluminum- or steel inlays. No copper- or brass-impurities	Coating/painting ⇒ melt losses, Fe-content, Si-content, Ni-content	Shot blasting, thermal decoating, if necessary ICF* and/or diluting
Class 6	Oily and/or wet turnings and swarfs	Oil and moisture ⇒ melt losses, oxide-content	Thermal treatment, chemical treatment, compacting, increased flux quantity, eventually cover gas
Class 7	Unclean and contaminated metal scrap e.g. post consumer scrap, may contain: Silicon (Al-alloys, shot blasting) Cu contaminated alloys Iron inserts Ni-coating Non-magnesium sweepings	Oil/moisture and coating/painting ⇒ melt losses, oxide-content, Fe-, Si-, Cu- and Ni-content	Magnetic separation, shot blasting, thermal treatment, chemical treatment, ICF*, diluting, distillation
Class 8	Flux containing residues from Mg-Recycling	High content on oxides, chlorides and fluorides (Mg-content < 30 %), Fe-content	Expensive hydrometallurgical processing; at time not realized

*ICF is intermetallic compound formation

Magnesium as part of aluminium value chain[204] – Around 40% of magnesium in Europe is used as an alloying element of aluminium alloys. Therefore, the magnesium in aluminium alloys is recycled as part of the aluminium value chain.[205]

3.2.6.3. R&D bottlenecks of secondary sources - Metallurgy

In the recycling metal wheel (Section 2.3.2), magnesium is a minor metal to aluminium and is used as one of the alloy elements. However, in many other slices, magnesium oxide can be easily lost in smelting or refining processes. Table 3.6 shows the existing technologies and R&D bottlenecks in recovering magnesium from recyclables.

[203] ibid.
[204] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[205] EC (2017a) op. cit., p.23

Table 3.6 Recovering magnesium from recyclables and R&D bottlenecks

Recyclables	**Existing technologies**	**R&D bottlenecks**	**Project examples** [206]
Secondary magnesium materials	(See Table 3.5)	**1.** For economic reasons (personnel costs, energy and disposal possibilities) recycling is difficult to present in Germany[207] **2.** Official requirements and ideological discussions make recycling in Germany considerably more difficult, so that the metal-containing residual materials produced here are collected and then recycled externally. The processed raw material (granulate, ingots, semi-finished products, etc.) is then re-imported into Germany. [208] **3.** Scraps not recycled by scrap processors are used directly in steel desulfurization[209] (not recycled[210]) **4.** Developing methods to affordably reuse in-house scrap without sacrificing quality[211] **5.** Designing alloys to improve recyclability of scrap, reduce dross, and improve dross handling[212]	

[206] From SCRREEN D3.2 (op. cit., p.23), desk research (Innovative Technologien für Ressourceneffizienz Forschung zur Bereitstellung wirtschaftsstrategischer Rohstoffe (r4) ZWISCHENERGEBNISSE)
[207] Martin Maier, Magrec Recycling GmbH (2019) op. cit., p.24
[208] ibid.
[209] Kramer, D.A. (2002) op. cit., p.24
[210] EC (2017a) op. cit., p.23
[211] Zhang, L. & Dupont, T. (2007) op. cit., p.24
[212] ibid.

Magnesium-aluminium alloys[213]	(Magnesium in old and new aluminium-based scraps is not separated from aluminium alloys when recycled but retained as an alloy component. (Noted there are melt losses about 8%)) **1.** Packaging: existing technologies with high recycling rates, 77% of functional recycling rate (Noted there are melt losses about one third[214])	**1.** Developing methods to separate magnesium from aluminium for recycling (shredded material) [215] **2.** Magnesium removed from aluminium during refining ends up in the salt slag that is processed to recover aluminium and salt, leaving the Mg in an oxide residue. This oxide residue can be used to produce cement, aggregates and mineral wool, all forms of non-functional recycling.[216]	

[213] Kramer, D.A. (2002) op. cit., p.24
[214] Bell, N., Waugh, R. & Parker D. (2017) op. cit., p.24
[215] Zhang, L. & Dupont, T. (2007) op. cit., p.24
[216] Bell, N., Waugh, R. & Parker D. (2017) op. cit., p.24

3.2.7. Manganese (Mn)

Manganese is the twelfth most abundant element in the earth's crust, present in rocks, soil, water and food as a trace metal commonly found in the environment. Manganese does not occur naturally in its native state as a base metal but there are plenty Mn-containing minerals.[217] Manganese is used in many industrial processes, for instance, iron and steel production, as a component in alloys, and manufacturing dry cell batteries (in oxide form).[218]

3.2.7.1. Primary sources

China accounts for more than 90% of the manganese metal output in the world and for about 76% of world's export in 2017. Netherlands is the second largest exporter whose export volumes are mostly re-exports of Chinese manganese to the EU countries. South Africa has the second largest Manganese plant outside of China and it is also the third largest export country. Germany is the fourth largest export country but similar to Netherland, the entire export volume is consisted of re-export.[219]

3.2.7.2. Secondary sources

Manganese has various industrial and metallurgical applications. The major industrial application is steelmaking. Around 30% of the manganese produced worldwide is used for its properties as a sulphide former and deoxidant. The rest of 70% of manganese is used as an alloying element. Other metallurgical uses of manganese include used as an alloying element in aluminium alloys, copper alloys, and other metal alloys.[220] The steels and alloys are then used to produce products for construction, machinery, and transportation (i.e. leading end-uses).[221]

Manganese also has non-metallurgical applications. The main non-metallurgical application is used as a depolarizer in dry-cell batteries in the form of manganese dioxide. Manganese can also be used, for instance, as agricultural fungicide, to treat waste water, and manganese ferrite (used in electronics).

The identified recyclables are waste batteries, and Mn-containing slugs and slags, industrial waste solutions (e.g. effluents from Ni-Co laterite processes, nodules processes, and waste battery). According to Zhang and Cheng (2007), manganese separation and recovery from solutions should be emphasised as this is crucial to make a process economically feasible. This technique is particularly important to separate metal values and recover manganese in the solutions from secondary manganese materials (i.e. Mn-containing steel scraps, spent electrodes, waste electrolytes, spent catalysts, and from industrial mineral processing waste effluents). Since industrial effluents contains a substantial amount of manganese, further development in this field is needed. The main challenges are the low concentration of manganese and the large amounts of impurities. Economic viability of the process is heavily affected by factors including selectivity, reagents costs, efficiency, and product quality.

[217] Milatovic, D., Gupta, R. C., Yin, Z., Zaja-Milatovic, S. & Aschner M. (2011) Reproductive and developmental toxicology, *Academic Press*, pp 439-450, ISBN 978-0-12-382032-7

[218] USGS (2019h) Manganese Statistics and Information, obtained on 03.04.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/manganese/

[219] Roskill (2018) Sample Manganese Global Industry, Markets & Outlook 2018, obtained on 03.04.2019 from https://roskill.com/market-report/manganese/

[220] International Manganese Institute (n.d.) About Mn: Applications (online article) obtained on 03.04.2019 from http://www.manganese.org/about-mn/applications/

[221] USGS (2019h) op. cit., p.54

3.2.7.3. R&D bottlenecks of secondary sources - Metallurgy

Manganese is classified as a carrier element in the recycling metal wheel but could be recovered as a minor element in aluminium processing and rare earth special battery recycling processes (Section 2.3.2). Table 3.7 shows the existing technology for recovering manganese from identified recyclables and R&D bottlenecks.

Table 3.7 Recovering manganese from identified recyclables and R&D bottlenecks[222, 223]

Identified recyclables	Existing technologies	R&D bottlenecks
Waste batteries	**1.** Batenus process for used zinc-carbon, alkaline Mn, and Ni-Cd batteries (recover manganese carbonate which could be used for the production of manganese dioxide for new batteries) **2.** Other hydrometallurgy process (leaching) for spent lithium batteries, and Mn-Zn batteries	(outlined techniques but mostly no comment on economic feasibility)
Mn-containing sludges and slags	**1.** Recovering Mn from slag leaching solutions (hydrometallurgy – leaching) **2.** Recovering Mn from electrolytic zinc anodic slime and from scrap dry cells (hydrometallurgy – leaching) **3.** Recovering Mn from water treatment plant sludge (hydrometallurgy – leaching)	**1**. (For technique 1.) Feasibility depend on the initial concentrations of Mn and other valuable metals (e.g. Co, and Ni in the solution) **2.** (For technique 2.) Evolution of Cl_2 during leaching and electrowinning might be issues and consumption of ammonia is expected to be high
Mn-industrial waste solutions (e.g. laterite effluents)	**1.** Solvent extraction – economically viable for industry **2.** Sulphide precipitation – not considered by industry, as the resulted manganese sulphide is not favourable in the market and requires further conversion (but good for optional purification of solutions) **3.** Ion exchange – resin has a limited capacity for adsorption of particular	**1.** Both oxidative precipitation and solvent extraction are recommended for future research and development for recovery of manganese from industrial waste solutions

[222] W. Zhang & C.Y. Cheng (2007a) Manganese metallurgy review. Part I: Leaching of ores/secondary materials and recovery of electrolytic/chemical manganese dioxide, *Hydrometallurgy*, v.89 (2007), pp. 137–159

[223] W. Zhang & C.Y. Cheng (2007b) Manganese metallurgy review. Part II: Manganese separation and recovery from solution, *Hydrometallurgy*, v.89 (2007), pp.160–177

	metals so is more suitable for removal of trace amounts of metal impurities for preparation of highly pure manganese solutions **4.** Hydroxide precipitation – only useful in special cases **5.** Carbonate precipitation – applicability depends on the concentration of manganese relative to that of impurities such as magnesium and calcium **6.** Oxidative precipitation – cost of the oxidants needs to be justified (i.e. too low manganese concentration is not suited)	

The recovery of manganese is also included in one of the calls for commitment from the European Innovation Partnership (EIP) on RMs. The commitment HOPE-4-0: From iron and manganese oxides wastes to valuable metal alloys using novel carbon sources materials is under the priority area: Technologies for primary and secondary raw materials production, and theme: waste management.[224,225]

3.2.3. Natural graphite (C) – CRM

Graphite is a soft, crystalline form of carbon. It exhibits the properties of a metal and non-metal. The metallic properties include thermal and electrical conductivity while the non-metallic properties include inertness, high thermal resistance, and lubricity. The major applications of graphite are high-temperature lubricants, brushes for electrical motors, friction materials, and battery and fuel cells.[226]

3.2.3.1. Primary sources

The world leading producer of graphite is China accounting for 70% of the graphite production. Brazil is the second largest producer with about 10% of the world's production. North America (Canada and Mexico together) produces around 5% of the graphite in the world and India produces about 3%.[227]

The EU mainly imports natural graphite from China (63%), Brazil (13%) and Norway (7%). They are also the main sources of the EU supply of natural graphite. Figure 3.12 shows the active mine and occurrences of natural graphite in Europe.[228]

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[224] EIP RM (2017) Annual monitoring report 2016, *EU*, Luxembourg

[225] EC (2019) From iron and manganese oxides wastes to valuable metal alloys using novel carbon sources materials (online article) obtained on 04.04.2019 from https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/iron-and-manganese-oxides-wastes-valuable-metal-alloys-using-novel-carbon-sources-materials

[226] USGS (2019i) Graphite Statistics and Information, obtained on 18.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/graphite/

[227] USGS (2019j) (Natural) Graphite Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 19.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/graphite/mcs-2019-graph.pdf

[228] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

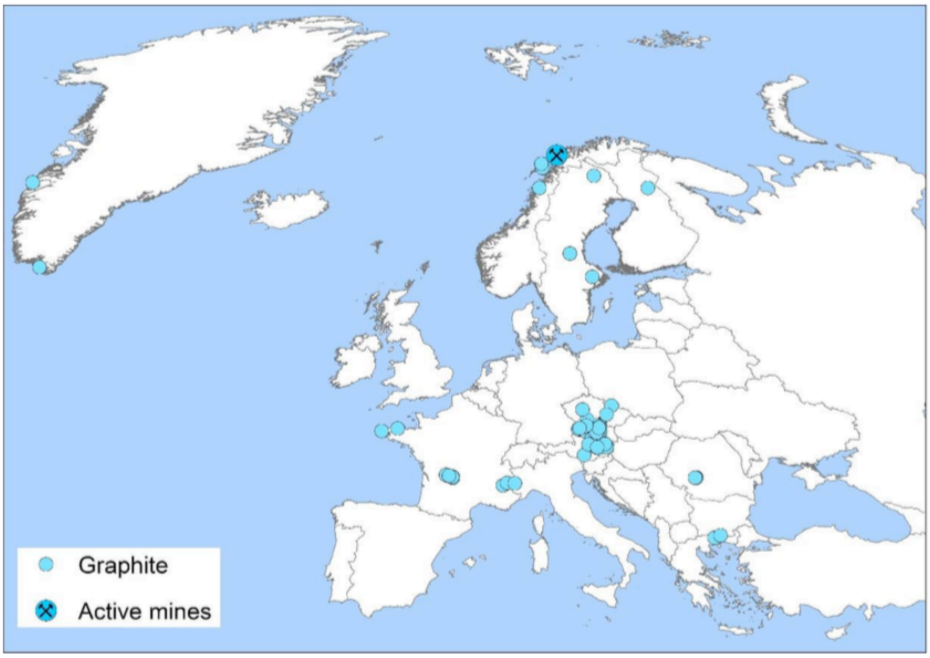

Figure 3.12 Active mine and occurrences of natural graphite in Europe (SCRREEN, 2018)

The simplified material flows of natural graphite in Europe for 2012 is provided in a Sankey diagram (Figure 3.13).

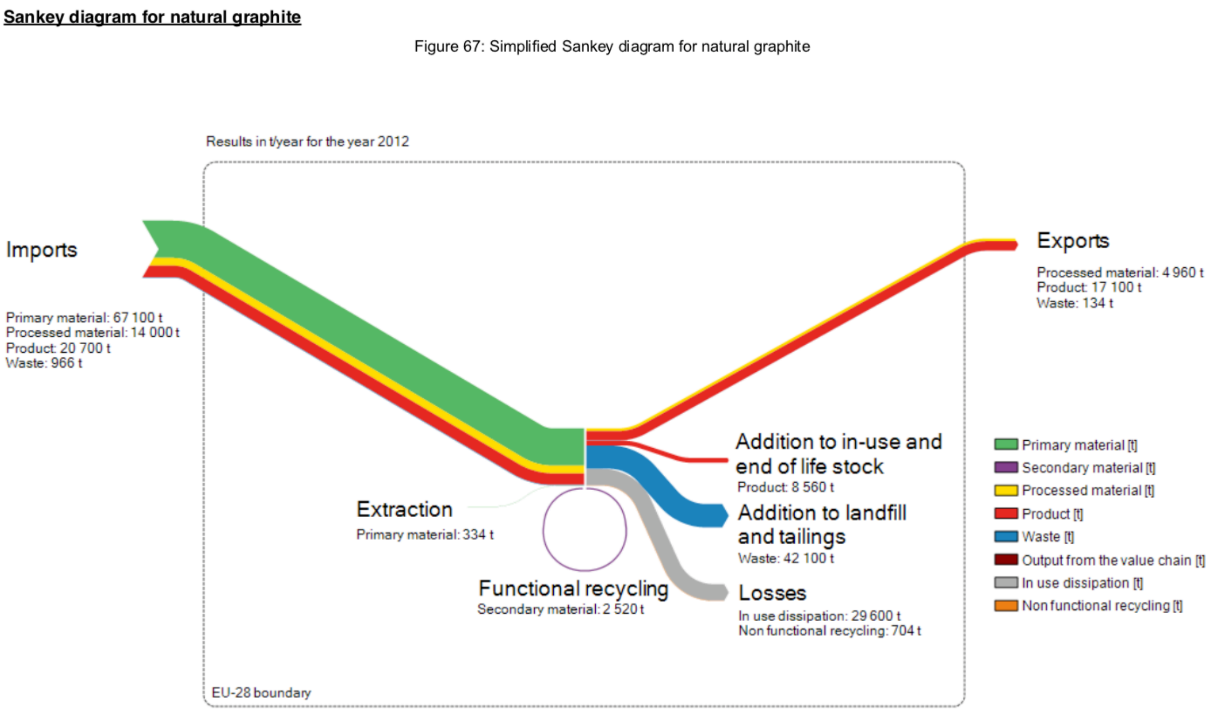

Figure 3.13 Simplified natural graphite material flows in Europe for 2012 (Deloitte, 2015)

3.2.3.2. Secondary sources

Natural graphite has many applications. The largest use of graphite is in steel making and hot metal-forming (i.e. refractories for steelmaking, refractories for foundries and re-carburising) accounting for about 70% of global consumption in 2014 (Figure 3.14). Natural graphite is also, for example, used in batteries as anode materials, added to friction products, and one of the components of lubricants.[229]

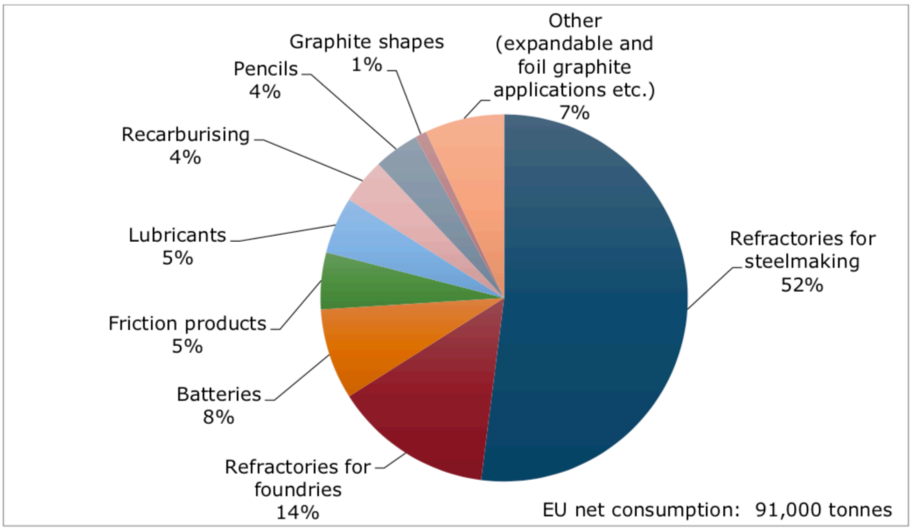

Figure 3.14 Global end use applications of natural graphite in 2014 (EC, 2017a)

Many of the natural graphite applications are dissipative in nature. Hence, a large amount of the natural graphite is lost to the environment. The identified recyclables are listed below.

Processing residues

- **Manufacturing residues**
- **Flotation middlings and tailings** from multi-stage commination-flotation process of natural graphite ore

EoL products

- **Spent refractories** from refractories
- **Spent brake linings** from brake linings
- **Spent battery chemicals** from Li-ion batteries

3.2.3.3. R&D bottlenecks of secondary sources

Natural graphite, essentially carbon, is not included in the recycling metal wheel (see Section 3.1.2.3., Figure 3). Table 3.8 and Table 3.9 present the existing technologies and R&D bottlenecks in recovering graphite from processing residues and EoL products respectively.

Table 3.8 Recovering graphite from processing residues and R&D bottlenecks[230]

Processing residues	**Existing technologies**	**R&D bottlenecks**	**Project examples**
Manufacturing residues	**1.** No information but deduced that most of the residues should be recovered in-house (collection is easy for the processor; with high concentration		

[229] EC (2017a) op. cit., p.23
[230] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25

	of graphite in residues, it is economical to recover graphite in-house)		
Flotation middlings and tailings	**1.** Recovering graphite by screening-commination-flotation process (part of these are rejected due to high impurities, mainly tailings, and are normally used as building materials.)		

Table 3.9 Recovering graphite from EoL products and R&D bottlenecks[231]

EoL products	Existing technologies	R&D bottlenecks	Project examples [232]
Spent refractories	**1.** Existing recycling refractory processes (mechanical) but not specifically for recovering graphite	**1.** Normally spent refractories are used as roadbed materials or sent to landfill (not a proper use of useful components (i.e. graphite)	
Spent brake linings	**1.** Existing recycling fraction liners processes but not specifically for recovering graphite	**1.** Spent brake linings are normally smelted to low quality steel or disposed as hazardous waste	
Spent battery chemicals	**1.** Recovering graphite by hydro-metallurgy processes (solvents) **2.** Recovering graphite by direct physical processes[233]	**1.** No industrialised processes **2.** Economically justified processes needed[234] **3.** High purity level of the recovered graphite needed (battery grade: 99.9%)[235] **4.** Surface modification of graphite electrodes (min. degradation)[236]	**EU projects** 1. CloseWEEE (ongoing)
Other: Carbon fibre-reinforced plastics			**German projects** 1.Graphit 2.0 (FONA r[4], Closed in 2018)
Carbon concrete		Separation of compounds	

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[231] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[232] From SCRREEN D3.2 (op. cit., p.23), desk research (Innovative Technologien für Ressourceneffizienz Forschung zur Bereitstellung wirtschaftsstrategischer Rohstoffe (r4) ZWISCHENERGEBNISSE, 2018)
[233] B. Moradi & G.G. Botte (2016) op. cit., p.25
[234] ibid.
[235] ibid.
[236] ibid.

3.2.8. Nickel (Ni)

Nickel is a transition element exhibiting a mixture of ferrous and nonferrous metal properties. It is both siderophile (i.e., associates with iron) and chalcophile (i.e., associates with sulfur). In Western World, around 65% of the nickel is used to make austenitic stainless steel and 12% of the nickel goes into producing superalloys or nonferrous alloys. The aforementioned alloys are widely used due to their corrosion resistance.[237]

3.2.8.1. Primary sources

Indonesia is the leading producer of nickel accounting for around 24% of the global nickel production. Philippines, as the second largest global producer, produce about 15% of the nickel in the world. Following them, the other counties with relatively larger production include New Caledonia (oversea territory of France), Russia, Australia, Canada and China.[238]

In Europe, mining activities take place in Finland, Greece, France (New Caledonia) and Spain (Sweden is at exploration stage). Figure 3.15 shows the mine sites and the other associated (presumably larger) nickel industrial activities.[239]

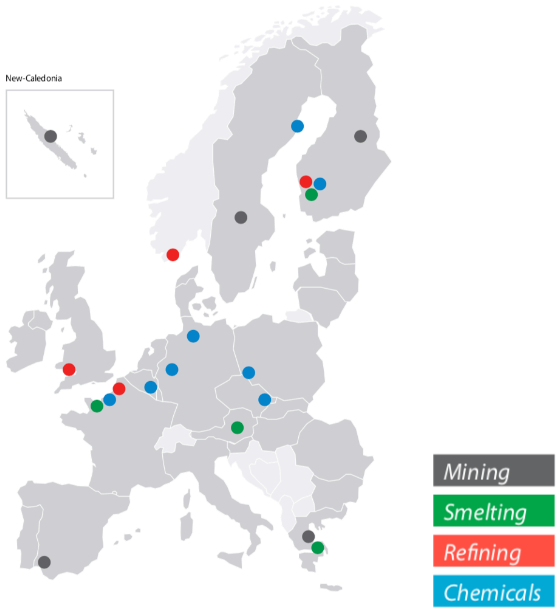

Figure 3.15 Nickel mine sites and associated (presumably larger) industrial activities (Nickel Institute, n.d.)

3.2.8.2. Secondary sources

The primary application of nickel in Europe is producing stainless steel which accounts for about 61% of the total nickel used in 2010. Nickel is also used to make nickel-based alloys, alloy steel, plating and other applications. In total, more than 85% of new nickel from primary production and most of the recycled nickel goes into alloy production. Figure 3.16 presents the main uses of nickel in the European Union in 2010.

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[237] USGS (2019k) Nickel Statistics and Information, obtained on 22.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/nickel/

[238] USGS (2019l) Nickel Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 22.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/nickel/mcs-2019-nicke.pdf

[239] Nickel Institute (n.d.) Nickel in the European Union, obtained on 22.03.2019 from https://www.oma.on.ca/en/multimedialibrary/resources/nickelintheeuropeanunionpdf.pdf

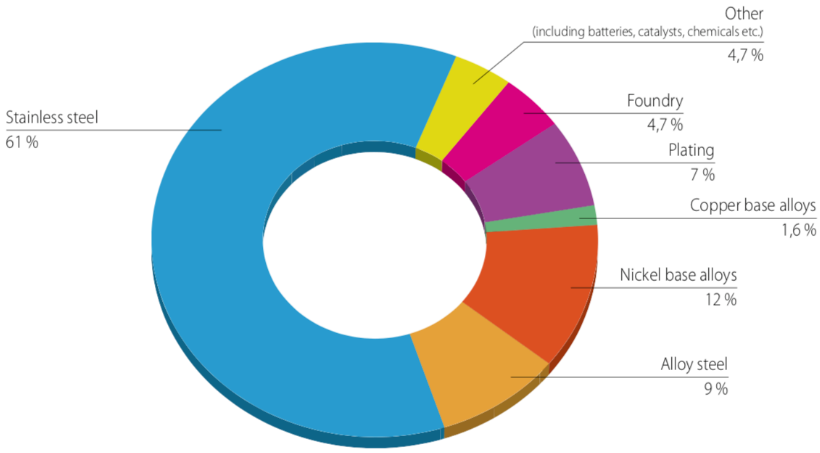

Figure 3.16 Main uses of nickel in the European Union
(Heinz H. Pariser Alloy Metals & Steel Market Research, 2011)[240]

In the EU, close to 100% of process scraps from manufacturing processes and about 80% (estimated 68% of consumer product, additional 15% entering carbon steel loop, and remaining 17% goes to landfill, mainly in metal goods and WEEE[241]) of EoL nickel-containing products are collected and recycled.[242] The fraction of secondary nickel in the total nickel input of nickel-containing product production would be higher except for the long lifetimes of nickel products. The long product life means that the nickel stocks will only be available for recycling in a few decades, limiting the chance to replace more primary nickel production by postconsumer scrap in the near future.[243]

Recycling nickel-containing scraps is a large and profitable industry in the EU. Due to the high demand for nickel, nickel-containing scraps usually are about two to three times more expensive than aluminium scraps and ten times of the price of scrap steel.[244] Figure 3.17 shows that while scrap offer discounts, the value of scrap nickel remains high (left). Nickel is the key element determines the value of nickel-containing stainless-steel scraps (right).[245]

[240] Nickel Institute (n.d.) op. cit., p.61
[241] Nickel Institute (2016) Infographic on Nickel Recycling, obtained on 25.03.2019 from https://www.nickelinstitute.org/media/2273/nickel_recycling_2709_final_nobleed.pdf
[242] Nickel Institute (n.d.) op. cit., p.61
[243] Reck, B.K., Müller, D.B., Rostkowski K. & Graedel, T. E. (2008) op. cit., p.25
[244] Nickel Institute (n.d.) op. cit., p.61
[245] Heinz H. Pariser Alloy Metals & Steel Market Research (2017) Presentation on Nickel – Mehr als nur ein Legierungsmetall! Obtained on 25.03.2019 from http://editool.vdm.berlin/archiv_akademie/1494495387_Vortrag_Heinz_Pariser-VDM_Juniorenseminar_Karlsruhe_2017.pdf

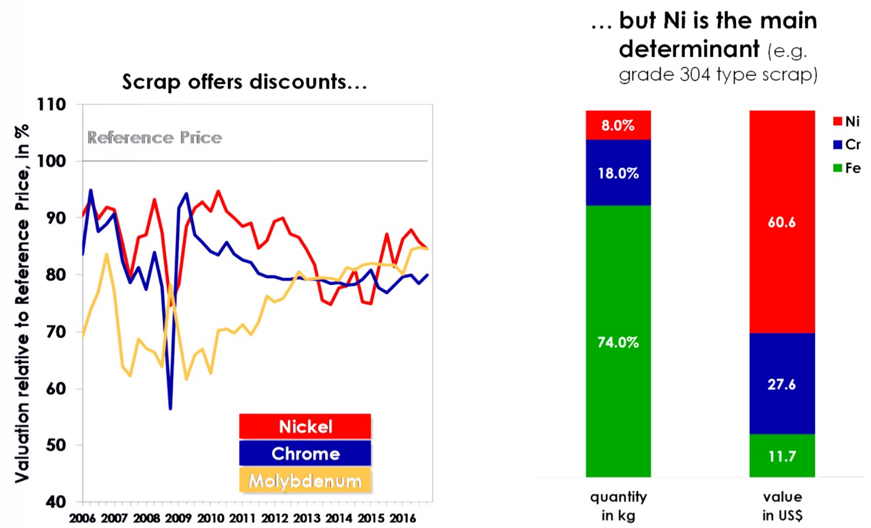

Figure 3.17 Value of scrap nickel relative to reference price under the condition of stainless steel scrap discount (left); Nickel is the key element determining the value of nickel containing stainless steel scraps (right)

3.2.8.3. R&D bottlenecks of secondary sources - Metallurgy

Nickel is a carrier element compatible with copper during the smelting and refining processes in the recycling metal wheel. In both stainless-steel processes and special battery recycling processes, nickel is one of the main recovered minor elements. Meanwhile, nickel can also be recovered with lead and zinc smelting and refining processes as a minor element. (Section 2.3.2)

According to Reck et al (2008), with growing demands of nickel, resource efficiency can be increased in primary mining and smelting stages and EoL recovery. Particular attention should be paid to EoL recovery because a significant amount of nickel is used in applications containing low concentrations of nickel (e.g. electronics and alloys) where nickel is often recovered as a minor constituent of carbon steel or copper alloy scrap but not as nickel metal or alloy. In such cases, eventual nickel recovery and reuse can become an integral part of product design.[246] Table 3.10 indicates the recycling routes and their respective recycling rates of different nickel applications except stainless steel.

Table 3.10 Recycling routes and respective recycling rates of different nickel applications except stainless steel[247]

Nickel applications (additional to stainless steel)	Recycling	Recycling rate
Nickel-based alloys	1.Alloys specific recycling route 2.Downgrade and used to mix(blend) in stainless steel scraps	High
Other nickel-containing steel alloys	1.Alloys specific recycling route	Medium

[246] Reck, B.K., Müller, D.B., Rostkowski K. & Graedel, T. E. (2008) op. cit., p.25
[247] Heinz H. Pariser Alloy Metals & Steel Market Research (2017) op. cit., p.62

	2.Downgrade and used to mix in stainless steel scraps 3. Might lost nickel in steel in processing or the other way around	
Nickel from batteries	1. As salt, Ni can be reused in battery production 2. As alloy, Ni can be reprocessed in primary nickel productions or in steel productions	NiCd batteries: High NiMH/Li-ion batteries: Low
Nickel from coating	1. Used in industrial applications: collected and used to mix(blend) in stainless steel scraps 2. Decorative coating: might lost in landfill or might lost nickel in steel in processing or the other way around	1. High 2. Minimal

3.2.9. Silicon metal (Si) – CRM

Silicon is a light chemical element. Combining with oxygen and other elements, silicon forms silicates which constitutes more than a quarter of the Earth's crust. Silica (SiO_2) as quartz or quartzite is used to produce silicon ferroalloys and silicon metal. Unlike silicon ferroalloys which demanded by the production of cast iron and steel, silicon metal is used for alloying with aluminium and for production of chemicals, especially silicones. Small quantities of high-purity silicon metal are used in the semiconductor industry.[248]

3.2.9.1. Primary sources

The global leading producer of silicon is China accounting for around 60% of the global production. However, reserves in most major producing countries are ample comparing to demand. Therefore, resources for making silicon metal and alloys are abundant and in most cases, sufficient to supply world requirements for many decades.[249]

Silicon metal of the EU is mainly imported from Norway (35%), Brazil (18%) and China (18%). Main silicon metal sources of the EU include Norway (23%), France (19%), Brazil (12%), China (12%), Spain (9%), and Germany (5%).[250]

The simplified material flows of silicon (excluding silica and ferrosilicon and their applications) in Europe for 2012 is provided in a Sankey diagram (Figure 3.18).

[248] USGS (2019m) Silicon Statistics and Information, obtained on 25.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/silicon/

[249] USGS (2019n) Silicon Statistics and Information - Annual Publications Mineral Commodity Summaries 2019, obtained on 25.03.2019 from https://minerals.usgs.gov/minerals/pubs/commodity/silicon/mcs-2019-simet.pdf

[250] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

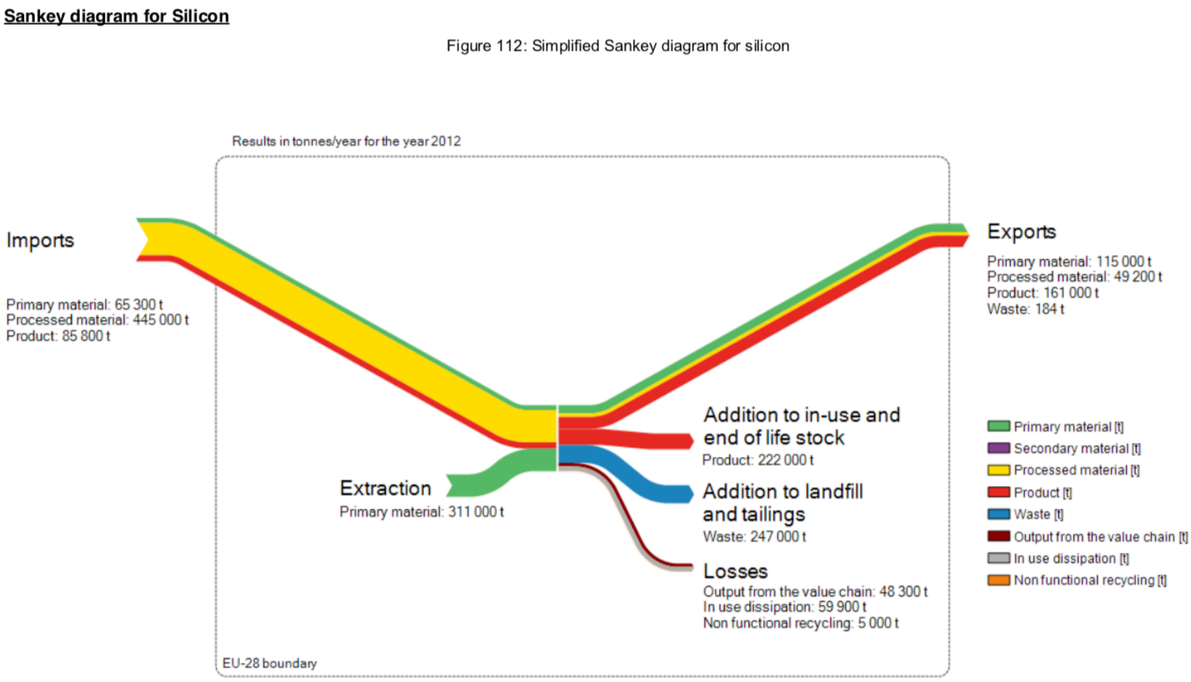

Figure 3.18 Simplified silicon material flows in Europe for 2012 (Deloitte, 2015) (excluding silica and ferrosilicon and their applications)

3.2.9.2. Secondary sources

There are two grades of silicon metal, metallurgical grade silicon (typically around 99%) and electrical grade silicon, or polysilicon (> 99.99%, with 6N to 11N purity). The metallurgical grade silicon is used in the metallurgy industry (e.g. as an alloy element of aluminium alloys) and in the chemical industry (e.g. producing silicones and silanes). The two industries represent more than 90% of the world's and the EU's silicon metal consumption. Polysilicon is used as semiconductor in photovoltaic applications or in microelectronics.[251, 252] Figure 3.19 shows the EU end uses of silicon metal.

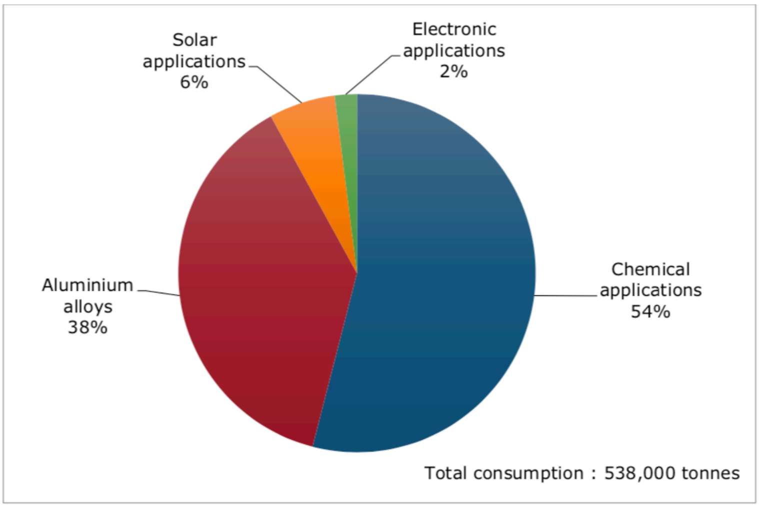

Figure 3.19 Global end use applications of silicon metal, average figure for 2010-2014 (EC, 2017a)

[251] Deloitte (2015) op. cit., p.13
[252] EC (2017a) op. cit., p.23

The identified recyclables from silicon metal applications are listed below.[253,254] Although there are plenty secondary sources of silicon, silicon metal or silicon is only recovered from a number of them. The possible reason is the low profitability of the recovery.[255] In addition, very little material is sold back into the market by metallurgical silicon users.[256]

Processing residues

- **Scraps** from silicon-containing aluminium alloys
- **Scraps** from ingot crystallisation and wafer manufacturing
- **Scraps** from solar panel production

EoL products

-
-
-
- **WEEE** from capacitors and integrated circuits
- **WEEE** from photovoltaics modules
- **Postconsumer waste** from chemical products

3.2.9.3. R&D bottlenecks of secondary sources - Metallurgy

Silicon is a minor element in the recycling metal wheel (Section 2.3.2) which could be recovered, become part of the alloy, or lost if fall into the wrong streams in the steel processes of iron, the remelt/refine processes of aluminium, and the pyro-metallurgy/remelt processes of titanium. If silicon falls into the rest of the recycling metal wheel slices, it will likely to be lost in the metallurgy processes as dissipative losses in the form of silica (SiO_2).

Table 3.11 and Table 3.12 presents the existing technologies and R&D bottlenecks in recovering graphite from processing residues and EoL products.

[253] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[254] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[255] ibid.
[256] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

Table 3.11 Recovering silicon or silicon metal from processing residues and R&D bottlenecks[257, 258]

Processing residues	Existing technologies	R&D bottlenecks	Project examples [259]
Scraps from Al-Si alloys	**1.** Recycled as Al-Si alloys[260]	**1.** There is no functional recycling of silicon metal in aluminium alloys	
Scraps from ingot crystallisation and wafer manufacturing	**1.** Cut off silicon scraps due to impurities: Impurities can be removed by refining processes (e.g. filtration), and particle sedimentation under electromagnetic fields. **2.** Cut off silicon scraps due to shaping usually directly recycled back to the ingot casting processes **3.** As silicon metal used in electronic industry is of high quality, silicon obtained from scraps can be used in the photovoltaic industry	**1.** The technologies recovering cut off silicon scraps due to impurities are not commercialised **2.** There is research on recycling of silicon wafers, however it has not yet materialised in marketable solutions	**EU projects** 1. SIKELOR (FP7, closed in 2016)
Scraps from solar panel production	**1.** Cutting and grinding silicon ingots causing around 50% of silicon lost in the sludge (purity from 50%): The silicon metal powder (purity > 99%) recovery process by ReSiTec includes chemical treatment, mechanical wet separation and mechanical drying		**EU projects** 1. RE-SI-CLE (FP5, closed in 2005)

257 Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25

258 Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23

259 From SCRREEN D3.2 (op. cit., p.23), desk research (Innovative Technologien für Ressourceneffizienz Forschung zur Bereitstellung wirtschaftsstrategischer Rohstoffe (r4) ZWISCHENERGEBNISSE, 2018)

260 Tillová, E., Chalupová, M. & Hurtalová, L. (2012) Scanning Electron Microscopy, 21 Evolution of Phases in a Recycled Al-Si Cast Alloy During Solution Treatment, *InTech*, pp411-437, ISBN 978-953-51-0092-8

Table 3.12 Recovering silicon or silicon metal from EoL products and R&D bottlenecks[263, 264]

EoL products	Existing technologies	R&D bottlenecks	Project examples [265]
WEEE from capacitors and integrated circuits		**1.** Typically not recycled[266]	
WEEE from photovoltaics modules	**1.** SolarWorld process is the known industrialised process for recovering silicon from solar panels		**EU projects** 1. CABRISS (H2020, closed in 2018)
Postconsumer waste from chemical products	**1.** Silicone materials recycling – industrialised process[267]	**1.** Diverse applications	

[263] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[264] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[265] From SCRREEN D3.2 (op. cit., p.23), desk research (Innovative Technologien für Ressourceneffizienz Forschung zur Bereitstellung wirtschaftsstrategischer Rohstoffe (r4) ZWISCHENERGEBNISSE, 2018)
[266] Wilson, D. & Roberts, R. (2015) op. cit., p.25
[267] e.g. ECO U.S.A. (company)

4. Application case study:

Electric vehicles – Rechargeable batteries and electric traction motors

Electric vehicles (EVs), or electric mobility, can be defined as vehicles for which an electric motor is the primary or secondary source of propulsion. Based on this definition, electric vehicles include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), range-extended electric vehicles (REEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). The differences between them and conventional vehicles with internal combustion engines (ICE) are shown in Figure 4.1.[268]

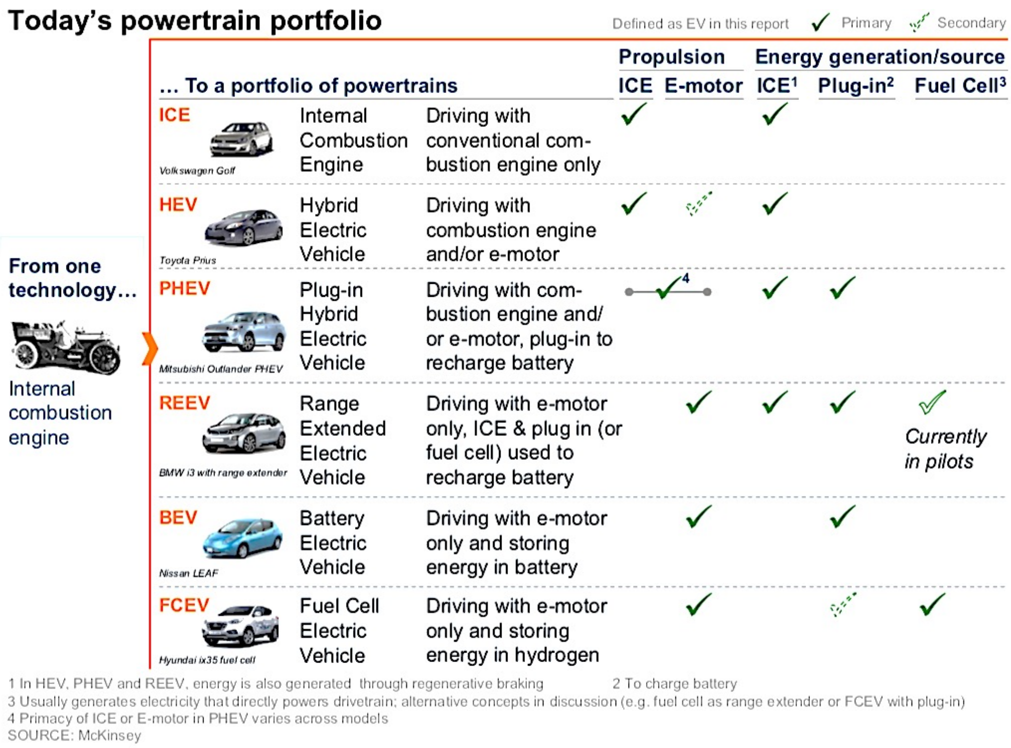

Figure 4.1 Today's powertrain portfolio (McKinsey&Company, 2014)

EVs, using electricity as an energy vector for vehicle propulsion, offer the possibility to replace oil with a wide range of primary energy sources. Because of this, EVs could ensure security of energy supply. The broad use of renewable and carbon-free energy sources in the transport sector could help the EU targets on CO_2 emissions reduction.[269]

[268] McKinsey&Company (2014) Electric vehicles in Europe: gearing up for a new phase?, *McKinsey&* Company, obtained on 04.04.2019 from https://www.mckinsey.com/~/media/McKinsey/Locations/Europe%20and%20Middle%20East/Netherlands/Our%20Insights/Electric%20vehicles%20in%20Europe%20Gearing%20up%20for%20a%20new%20phase/Electric%20vehicles%20in%20Europe%20Gearing%20up%20for%20a%20new%20phase.ashx

[269] EC (2019) Transport themes: clean transport, urban transport Electric vehicles (online article) obtained on 04.04. 2019 from https://ec.europa.eu/transport/themes/urban/vehicles/road/electric_en

4.1. Technologies

Building on the findings of the SCRREEN D2.2 Report on major trends affecting future demand for critical raw materials, this report also focuses on the identified two key components of EVs, rechargeable batteries (excluding FCEVs) and electric traction motors.

4.1.1. Main technologies

Rechargeable batteries for EVs have requirements somewhat different from the requirements for stationary electricity storage applications, consumption electronics and other niche applications. According to the assessment of requirements Fraunhofer (2012), comparing to large stationary electricity storage applications (>100kWh), rechargeable batteries for EVs emphasis more on properties such as energy density, power density[270], charging time, ambient conditions (i.e. temperature), and safety. Requirements important for both applications are life time (i.e. cycle life and calendar life) and costs (i.e. investment and operation).[271] Currently, there are several batteries types for EVs, including lead-acid batteries, nickel-metal-hydride (Ni-MH) batteries, lithium-ion (Li-ion) batteries, and sodium-metal-halide (ZEBRA) batteries.[272] A brief overview is provided in Table 4.1.

[270] Power density is very important for EVs but unclear for large stationary electricity storage

[271] Fraunhofer (2012) Product roadmap lithium-ion batteries 2030, *Fraunhofer Institute for Systems and Innovation Research ISI*, Germany

[272] Dell, R.M., Moseley, P.T. & Rand, D.A.J.(2014) Towards sustainable road transport, *Academic Press*, pp.217-259, ISBN 978-0-12-404616-0

Table 4.1 Overview of battery types for EVs (Dell et al, 2014)

Battery type	Cathode	Anode	Electrolyte	Comment
Lead-acid battery	Lead dioxide (PbO_2)	Lead (Pb)	Sulfuric acid (H_2SO_4)	1. Needing further adjustments to meet the requirements of future vehicle concepts 2. If it successes, battery costs will be significantly reduced
Ni-MH battery	Nickel Oxyhydroxide (NiOOH)	AB_2 ($ZrNi_2$) or AB_5 ($LaNi_5$) based alloys	Potassium hydroxide (KOH)	1. Ni-Cd battery is greatly restricted due to Cd's toxicity and replaced by Ni-MH 2. Compromised choice between lead–acid, with lower specific energy and cost, and Li-ion with much higher specific energy but with problems e.g. higher cost and questionable safety
Li-ion battery	See Section 3.1.1			1. Remaining question on safety 2. High cost 3. Large batteries suited to road-transport applications are commercially available
ZEBRA battery	Molten sodium chloroaluminate ($NaAlCl_4$), plus metal chloride ($NiCl_2$ or NaCl)	Na	Beta-alumina	1. This battery type must be maintained at elevated temperature so primary application is likely to be in stationary energy-storage or vehicles operated in fleets with a high degree of daily utilization and with trained drivers

Electric traction motors are the other key component of EVs as the electric propulsion system is an integral part of EVs. Among different kinds of AC (alternative current), DC (direct current) traction motors for EVs, currently, EVs mostly adopt induction motors (IM (AC), i.e. asynchronous motors whose rotor rotates more slowly than the magnetic field of the stator; in contrast, if it rotates synchronously with the magnetic field of the stator, it is a synchronous motor.[273]) and permanent magnet synchronous motors (PMSM (AC)) as their traction motors.[274,275] In general, electric motors are basically manufactured with ferrous metals such as steel and cast iron, nonferrous metals for instance, copper and aluminium, and plastic.[276] While some EVs adopts propulsion solutions without rare earth (RE) permanent magnet (e.g. Tesla Model S with copper rotor IMs and BMW Mini), many employ rare earth permanent magnet to achieve high performance (e.g. highest power density, low-maintenance and very efficient[277]).[278] Currently, NdFeB based permanent magnet is the most commercially important permanent magnet and accounts for majority of RE permanent magnet sales.[279] Figure 4.2 provides an overview of NdFeB permanent magnet used in industrial applications. It should be noted that besides being used in EV's electric traction motors, NdFeB permanent magnet is also used in permanent magnet synchronous generator (PMSG) for several wind power technologies.[280]

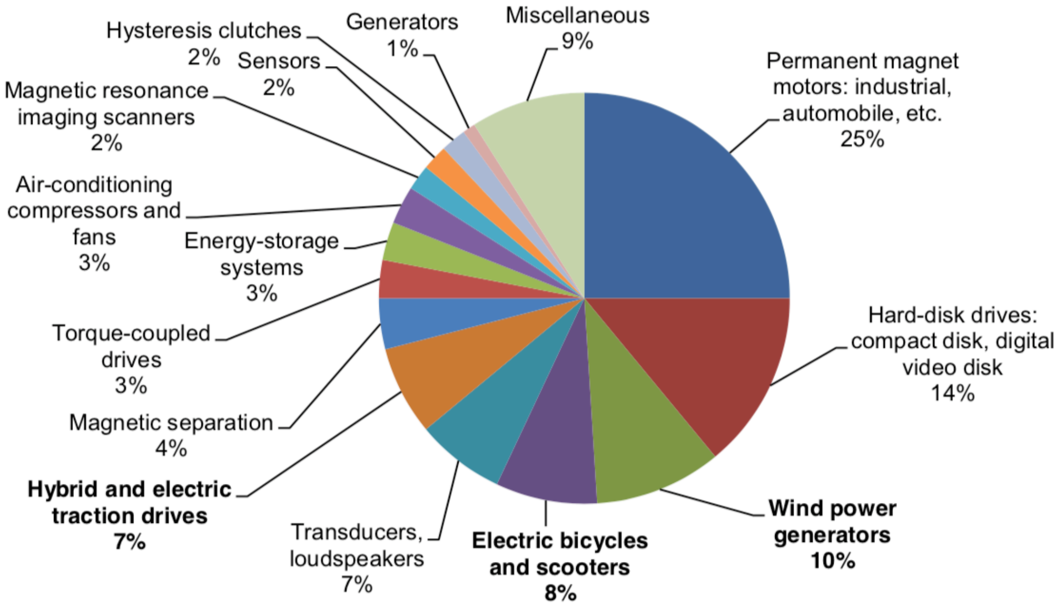

Figure 4.2 NdFeB permanent magnet used in industrial applications (Pavel et al, 2016)

[273] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L.,Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.4

[274] Rind, S.J., Ren, Y., Hu, Y., Wang, J. & Jiang, L. (2017) Configurations and Control of Traction Motors for Electric Vehicles: A Review, *Chinese Journal of Electrical Engineering*, v.3, no.3 obtained on 05.04.2019 from https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8250419

[275] Huynh, T.A. & Hsieh, M.F. (2018) Performance Analysis of Permanent Magnet Motors for Electric Vehicles (EV) Traction Considering Driving Cycles, *Energies(2018), 11, 1385; doi:10.3390/en11061385*

[276] WEG (n.d.) Motors, specification of electric motors (online article) obtained on 05.04.2019 from https://static.weg.net/medias/downloadcenter/ha0/h5f/WEG-motors-specification-of-electric-motors-50039409-brochure-english-web.pdf

[277] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L.,Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.4

[278] Huynh, T.A. & Hsieh, M.F. (2018) op. cit., p.72

[279] Pavel, C.C., Marmier, A., Dias, P.A., Blagoeva, D., Tzimas, E., Schüler, D., Schleicher, T., Jenseit, W., Degreif, S. & Buchert, M. (2016) Substitution of critical raw materials in low-carbon technologies: lighting, wind turbines and electric vehicles, *EC JRC*, ISBN 978-92-79-62960-0

[280] Pavela, C.C., Lacal-Aránteguia, R., Marmiera, A., Schülerb,E. Tzimasa, D., Buchertb, M., Jenseitb, W. & Blagoevaa, D. (2017) Substitution strategies for reducing the use of rare earths in wind turbines, *Resources Policy,* 52 (2017) pp. 349–357

The EU CRMs used in the RE permanent magnet include neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb).[281] On the other hand, it is worth mentioning that the latest R&D trend focuses on researching less expensive materials for laminations and cores to avoid using expensive RE permanent magnets in EVs.[282,283] Similar trends can be found in the development of wind power technologies. For wind power technologies, there are several approaches, such as, reducing RE amount by increasing material efficiency, directly substituting RE in the permanent magnets, substituting PMSG in wind turbines (e.g. doubly-fed induction generator (DFIG), electrically excited synchronous generator (EESG) in direct-drive turbines, and high-temperature superconductors (HTS))[284]

Substitution of critical materials represents an important approach to reducing any potential risk to their supply and possibly demand within a shorter time frame than, for instance, recovering them from end-of-life products (e.g. the operational life of a wind turbine is about 20–30 years).

Among the elements mentioned in the technologies for EVs, lanthanum (La), neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb) are listed as the EU CRM (i.e. REEs). Hence, they are selected and studied for the R&D needs in metallurgy in the sections below. The other materials such as steel, cast iron, copper and aluminium have relatively high EoL-RR (i.e. higher than 60%) and therefore are excluded from the report.[285]

4.1.2. Emerging technologies

As demands for higher energy density and power density batteries (i.e. for quick discharging and charging performance) continue to increase, conventional Li-ion batteries would soon not able to satisfy the requirements. Solid-state batteries (SSBs) with solid electrolytes rather than liquid ones, offering both high energy and power density in addition to improving safety, have attracted the public attention and are considered to be an emerging technology in the field of EV batteries.[286]

Although the materials containing in anodes and cathodes of SSBs are very similar or the same as the Li-ion batteries, the materials used in solid electrolytes are different. There are two major groups of solid electrolytes, inorganic solids (i.e. crystalline, glass, and glass-ceramic in nature) and organic solids polymers. Compositions of both solid electrolytes are still developing to overcome the identified limits.[287] Therefore, the materials are not further studied in this report. The materials for anodes and cathodes, on the other hand, can be found in Chapter 3.

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[281] Pavel, C.C., Marmier, A., Dias, P.A., Blagoeva, D., Tzimas, E., Schüler, D., Schleicher, T., Jenseit, W., Degreif, S. & Buchert, M. (2016) op. cit., p.72

[282] S.J. Rind, Y. Ren, Y. Hu, J. Wang, & L. Jiang (2017) op. cit., p.66

[283] CRM_InnoNet (2015) Roadmap for the Substitution of Critical Raw Materials in Electric Motors and Drives, *EU FP7*, obtained on 05.04.2019 from https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccv/2015/Roadmap-for-CRM-substitution_Electric_Motors_And_Drives.pdf

[284] Pavela, C.C., Lacal-Aránteguia, R., Marmiera, A., Schülerb,E. Tzimasa, D., Buchertb, M., Jenseitb, W. & Blagoevaa, D. (2017) op. cit., p.72

[285] UNEP (2011) op. cit., p.11

[286] Janek, J. and Zeier, W.G. (2016) A solid future for battery development, *Nature Energy* **volume 1**, Article number: 16141 (2016)

[287] ibid.

4.2. Primary and secondary sources of key elements for EVs' batteries and traction motors

Lanthanum (La), neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb) are identified as the materials for EVs' batteries and traction motors in the previous section. As they are part of the REEs group, they are to be introduced in the same section.

4.2.1. La, Nd, Pr, Dy, and Tb (REEs) – CRM

The REEs formed largely by the lanthanide group consists of 15 to 17 elements depending on the inclusion of yttrium (Y) and scandium (Sc) which share the chemical and physical properties with the lanthanides. The 15 elements from the lanthanide group are listed as follows: 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). While yttrium is treated with REEs because it is found in the same ore deposits and shares a large part of REEs value chain, scandium is treated separately due to its different geological and industrial properties. REEs are typically divided into two groups, the light REEs (LREEs, i.e. commonly La, Ce, Pr, Nd, and Sm) and the heavy (HREEs, i.e. commonly Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y), for physical and chemical, and commercial reasons. It should be noted that geological deposits of HREEs are scarcer than LREEs and currently operated nearly exclusively in ion-exchange clay deposits in the south of China.[288]

4.2.1.1. Primary sources

The largest global REEs producer is China accounting for 70% of the international production in 2018. The second and third largest producers are Australia (11%) and the U.S (9%). Figure 4.3 shows the global RE deposits, production and trade flows.[289] Currently, REEs are not mined in the EU even though there are recorded resources. The main countries exporting REEs to the EU are China (40%), the U.S. (34%) and Russia (25%). They are also the main REEs supply sources for the EU. The valorisation of REE occurrences in Europe is a matter of developing process technology for an economic viable production of low grade and small deposits. The valorisation of the high grade, large Greenlandic REE deposits with the carrier mineral Eudialyte has faced challenges in replacing sulfuric acid as a solvent by more environmental friendly leaching processes in order to avoid the shipping of hazardous chemicals within the ecologically sensitive environment of the Artic.

[288] EC (2017a) op. cit., p.23

[289] Roskill (2018) Rare Earths: Global Industry, Markets and Outlook to 2028, 18th edition (Sample), obtained on 08.04.2019 from https://roskill.com/market-report/rare-earths/

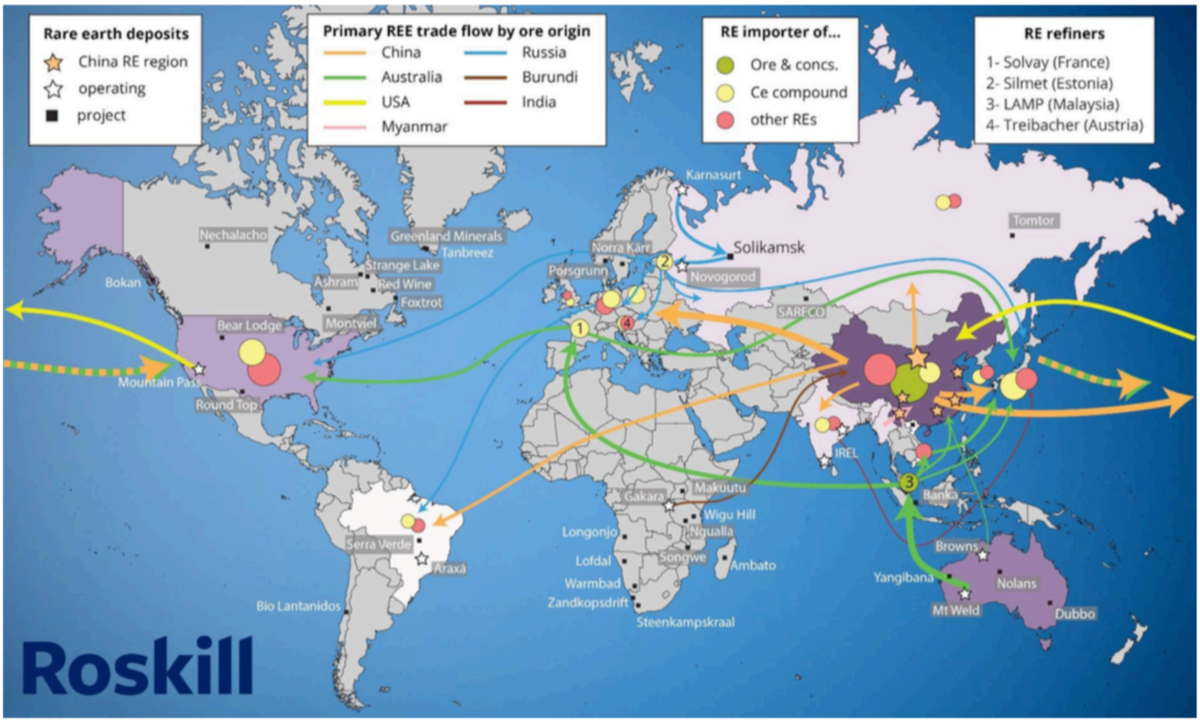

Figure 4.3 Global RE deposits, production and trade flows (Roskill, 2018)

The simplified material flows of dysprosium (Dy), neodymium (Nd), and terbium (Tb) in Europe for 2012 or 2013 are provided in Sankey diagrams (Figure 4.4, 4.5 and 4.6).

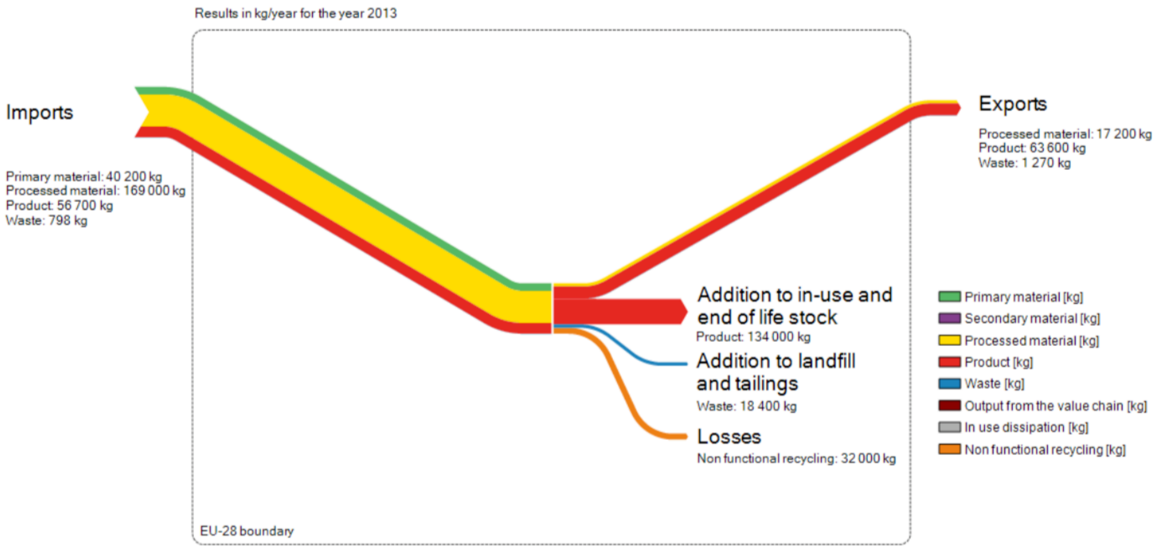

Figure 4.4 Simplified dysprosium (Dy) material flows in Europe for 2012 (Deloitte, 2015)

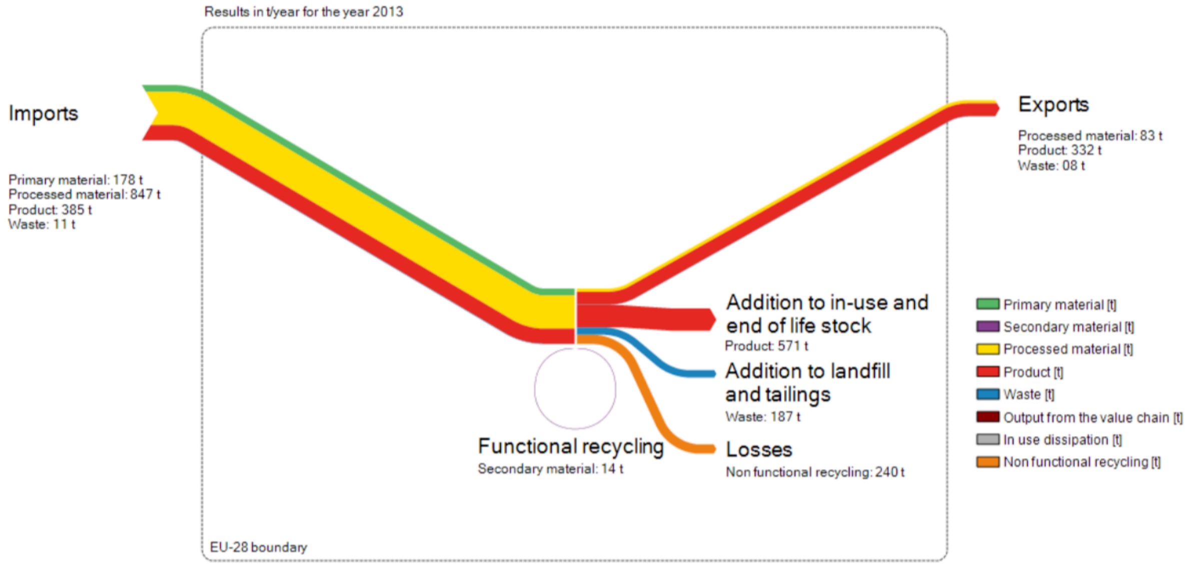

Figure 4.5 Simplified neodymium (Nd) material flows in Europe for 2012 (Deloitte, 2015)

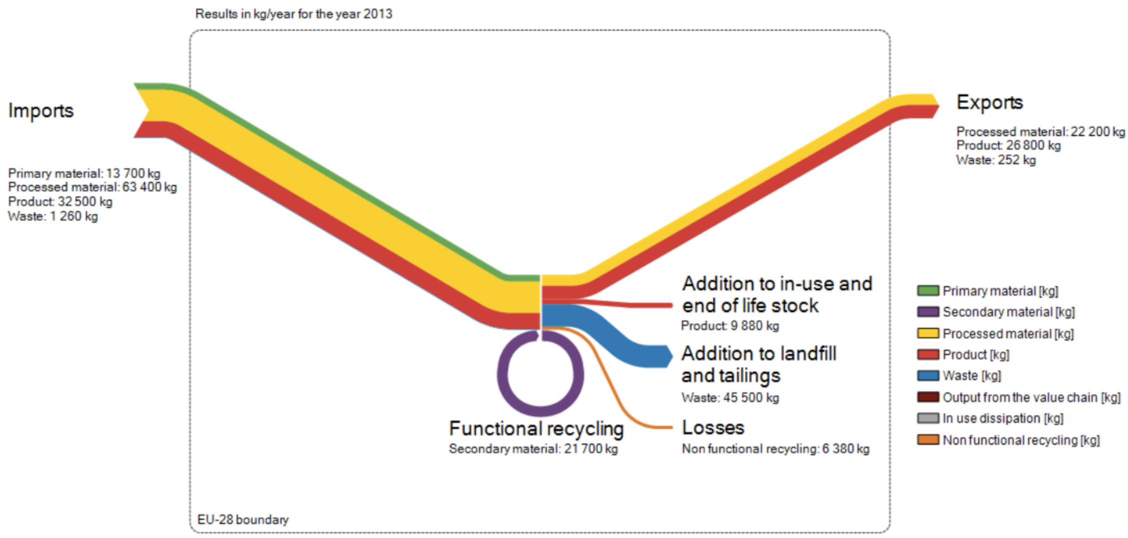

Figure 4.6 Simplified terbium (Tb) material flows in Europe for 2012 (Deloitte, 2015)

4.2.1.2. Secondary sources

REEs are used in many applications because of their magnetic, catalytic and optical properties. The main applications include in automotive, telecom, electronics, defence, renewable energies and aerospace sectors. While Figure 4.6 shows the end uses of REEs in the EU in one figure (data from ASTER project – Guyonnet et al.[290]), the major applications of individual REEs vary (see Figure 4.7). Among the selected REEs, lanthanum (La) is mostly used in fluid catalyst cracking (FCC). Neodymium (Nd) is used in diverse applications with a focus on magnets (40%). Similar to neodymium (Nd), praseodymium (Pr) is used in many different applications such as magnets, metal, batteries, and ceramics. Magnets accounts for a slightly larger share (24%) of praseodymium end uses. In contrast, dysprosium (Dy) is 100% used in magnets production. Terbium (Tb) has two main applications, phosphor (68%) and magnets (32%).[291]

[290] Guyonnet D., Planchon M., Rollat A., Escalon V., Tuduri J., Charles N., Vaxelaire S., Dubois D. & Fargier H. (2015) Material flow analysis applied to rare earth elements in Europe, Journal of Cleaner Production, Volume 107, Pages 215-228

[291] EC (2017a) op. cit., p.23

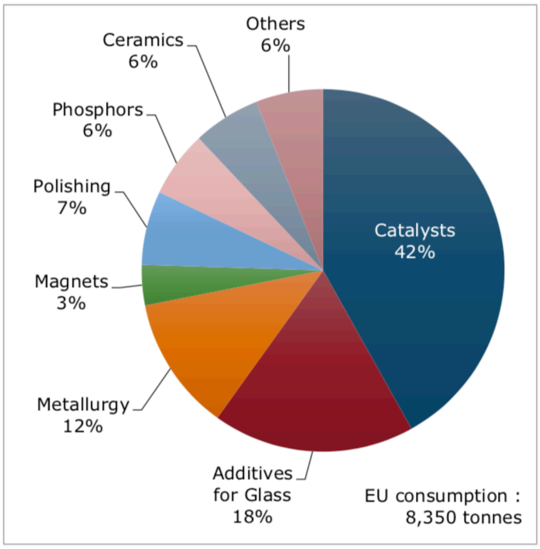

Figure 4.6 End uses of REEs in the EU (ASTER project – Guyonnet et al.)

Applications	Heavy REEs							Light REEs				
	Eu	Tb	Gd	Er	Dy	Y	Ho, Tm, Lu, Yb	Ce	Nd	La	Pr	Sm
Magnets	-	32%	**97%**	-	**100%**	-	-	-	**37%**	-	**24%**	**97%**
Metal	-	-	-	-	-	-	-	6%	12%	3%	11%	-
Batteries	-	-	-	-	-	7%	-	6%	13%	10%	12%	-
FCC	-	-	-	-	-	-	-	8%	-	**67%**	-	-
Cat Auto	-	-	-	-	-	-	-	**35%**	6%	-	10%	-
Polishing	-	-	-	-	-	-	-	11%	-	5%	10%	-
Glass	-	-	-	**74%**	-	4%	**100%**	**31%**	8%	10 %	8%	-
Phosphors	**96%**	**68%**	-	26%	-	**46 %**	-	1%	-	2%	-	-
Ceramics	-	-	-	-	-	**35%**	-	2%	11%	2%	15%	-
Others	4%	-	3%	-	-	8%	-	-	10%	-	10%	3%

Figure 4.7 Applications of individual REEs (ASTER project – Guyonnet et al.)

The priority streams for REEs recycling according to SCRREEN D3.2 and D4.2 are listed below (D3.2 information is from the final recommendation of ERECON project, 2015).

<u>Processing residues</u>

- Magnet swarf and rejected magnets – **Nd, Dy, Tb, Pr**
- Rare earth containing residues from metal production or recycling
    - Post-smelter and electric arc furnace residues (Ce, **La, critical REEs**)
    - Industrial residues such as phosphogypsum and red muds (**all REEs**)

<u>EoL products</u>

- Permanent magnets from e.g. automobiles, wind turbines, and consumer electronics – **Nd, Pr, Dy, Tb**, Sm
- Phosphors from fluorescent lamps, LEDs, LCD backlights, plasma screens, and cathode-ray tubes – Eu, **Tb**, Y, Ce, Gd, **La**
- EV Batteries from e.g. NiMH – **La**, Ce, **Nd, Pr**
- Polishing compounds – Ce
- Catalysts from e.g. FCC – **La,** Ce, **Pr, Nd**, Y
- Optical glass – **La**

Currently, among the EoL products, only the recycling fluorescent lamps and rechargeable batteries have been at industrial scale.[292] The commercial scale recycling and recovery from EoL product mostly focuses on permanent magnet scraps.[293] In addition, in 2016, Solvay, one of the REEs-based phosphor producer in the EU, stopped its recycling operations for RE containing low energy light bulbs due to the low primary raw materials prices.[294]

4.2.1.3 R&D bottlenecks of secondary sources – Metallurgy

In the recycling metal wheel (see Section 2.3.2.), REEs are carrier metals and can be processed in both hydrometallurgy processes and special battery recycling processes. REEs can also be recovered as minor metals in the other metal wheel slices, for instance, magnesium (hydrometallurgy processes), and iron (steel production).

The general challenges of recovering REEs identified by the SCRREEN D4.2 are listed below.

- **Environmental friendly recycling processes**: Developing cost efficient recycling processes that could minimize the environmental effects compared to primary production[295]
- **Knowledge gap in potential RE recyclates:** Quantity of REE materials available for recycling is unknown so there is a need to close the knowledge gap.
- **Low REs market price**: The lack of market incentives due to the low price of REs has been a significant factor to a low recycling rate as the economy of recycling processes is very reliant on the market value for the metals.
- **Inefficient REE containing EoL product collection**: An efficient collection of many REE containing end-of-life applications does not exist leading to insufficient and often non-selective collection rates. In addition, waste exports in developing countries reduce the REE potential available.
- **Low concentration of REEs in recyclates**: The current recycling systems are planned and optimized for recycling base metals significant concentrations. Therefore, they are not optimal for the recovery of REEs, which are typically present in low concentrations in complex structures.
- **Complex recycling processes due to complex product design**: The complexity of REE containing applications results in difficult disassembly and separation processes in addition to the quite high losses during collection. If common pre-treatment processes for WEEEs are used, REEs end up as fine particles and are therefore lost. The typical pyro-metallurgical processing for WEEEs is not suitable for REEs, as they tend to end up diluted in the form of their oxides in slags and are not recovered afterwards. On the other hand, implementing both physical and chemical treatments can be energy and reagent intensive.

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[292] Binnemans, K., Jones, P.T., Van Acker, K., Blanpain. B., Mishra, B. & Apelian, D. (2013) Rare earth economics: The balance problem, *Journal of Metals (JOM)*, Vol. 65, pp. 846-648
(From ERECON (2015) Strengthening the European rare earths supply chain: Challenges and policy options. Kooroshy, J., G. Tiess, A. Tukker, and A. Walton (eds.). (op. cit., p.27))
[293] EC (2014) EU Critical Raw Materials Profiles, pp. 77–85
[294] Ladenberger, A., Arvanitidis, N., Jonsson, E., Arvidsson, R., Casanovas, S. & Lauri, L. (2018) op. cit., p.23
[295] Binnemans, K. & Jones, P.T. (2013) Rare-Earth Element Recycling: Challenges and Opportunities

Table 4.1 Recovering REEs from processing residuals and R&D bottlenecks[296, 297]

Processing residuals	Existing technologies	R&D bottlenecks	General demands
Phosphogypsum	**1.** Hydrometallurgy – leaching		**1.** Limited knowledge on the mineralogy of the different REE rich phases in slags **2.** New methods for REEs recovery, especially from the diluted leachates and other diluted aqueous solutions **3.** Developing processes to recover low concentration of REEs in industrial waste streams and historical wastes
Phosphoric acid leaching solutions	**1.** Hydrometallurgy – solvent extraction and ion exchange		
Red muds (mostly for Sc)	**1.** Hydrometallurgy – leaching and bioleaching **2.** Pyro-hydrometallurgy – first recover iron from bauxite residue via pyro-metallurgy process and to subsequently concentrate the REs in an oxide slag. REs are then recovered through leaching from the slag with a diluted mineral acid.		
(Powdered) Mine tailings of REEs and others (e.g. iron mines)	**1.** Hydrometallurgy – Carbochlorination (Bayan Obo tailings), leaching		

[296] Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[297] Binnemans, K., Jones, P.T., Blanpain, B., Gerven, T.V. & Pontikes, Y. (2015) op. cit., p.26

Coal ash, oil shales and incinerator ash	**1.** Hydrometallurgy – leaching, precipitation	**1.** Coal ash – no industrial scale process was found **2.** Oil shales – challenging due to high Fe and Al contents comparing to RE concentrations **3.** Incinerator ash – low concentration of REE as widespread use of RE product in consumer good is a recent development; unlikely to be a source for secondary REEs	
Post-smelter and electric arc furnace residuals (i.e. metallurgical slags)	**1.** The slags from pyro-metallurgical process for NiMH battery by Umicore have relatively high concentration of REEs. The REEs are then recovered by Solvay through hydrometallurgical processes.	**1.** Low concentration of REEs (diluted form) in WEEE recycling slags so economic feasible processes are needed **2.** Low REEs price in the market affecting the operation (Solvay stopped the operation in point 1. In 2016)	
Waste water (e.g. acid mine drainage from sulphide rock bearing areas)	**1.** Recovering REEs possibly through iron-exchange and chelating resins	**1.** Largely unexplored	
RE magnets swarf and rejected magnets (i.e. pre-consumer NdFeB magnet scrap)	**1.** If material is not severely oxidized or corroded and contaminated, pre-consumer scraps/residues can be directly fed back to the production stream[298]	**1.** Processing waste is sent to China for recycling, as there are no such plants in Europe. [300]	

[298] Önal, M.A.R. (2017) Recycling of NdFeB Magnets for Rare Earth Elements (REE) Recovery, KU Leuven, obtained from https://lirias.kuleuven.be/handle/123456789/567531
[300] Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L.,Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.4

	2. (If point one does not apply) Metallurgical processes at different TRLs for recovering REEs: hydrogen decrepitation; chemical vapour transport; liquid metal extraction; hydrometallurgical processing; pyro-metallurgical slag extraction.[299]		

Table 4.2 Recovering REEs from EoL products and R&D bottlenecks[301]

EoL products	Existing technologies	R&D bottlenecks	General demands
Permanent RE magnets (i.e. NdFeB)	**1.** Hydrometallurgy processes **2.** Pyro-metallurgical processes **3.** Other processing for RE magnets, reprocessing of alloys to magnets after hydrogen decrepitating and gas-phase extraction[302]	(Existing/used to exist lab and commercial scale processes in France (Solvay), Japan (Hitachi, Santoku Corporation, and Shin-Etsu Chemical Co Ltd), the U.S. (REEcycle), China (Ganzhou Recycle Hi-Tech Co. Ltd), and Vietnam (Showa Donko KK); The operation in EU is in lab scale)	**1.** Developing innovative processes to recycle different REEs independently (currently, developed technologies often result in complex mixtures requiring further purification) [307]

[299] Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., Buchert, M., Steenari, B.M., Gerven T.M., Jones, P.T. & Binnemans, K. (2017) op. cit., p.27
[301] Overall information obtained from Sundqvist Oeqvist, L., Hu, X., Eriksson, J., Kotnis, J., Yang, Y., Yli-Rantala, E., Bacher, J., Punkkinen, H., Retegan, T., Moya, M.G. & Drzazga, M. (2018) op. cit., p.25
[302] Yang, Y., Walton, A., Sheridan, R., Güth, K., Gauß, R., Gutfleisch, O., Buchert, M., Steenari, B.M., Gerven T.M., Jones, P.T. & Binnemans, K. (2017) op. cit., p.27
[307] Page, B.M. (2015) op. cit., p.26

		1. Still at various research and development stages[303] **2.** Recovery of REEs are mostly focused on the major REE components Nd and Dy, (also Pr and Tb). However, the commercial efforts have focused solely on the recovery of REE from manufacturing residues (swarf etc.) not from EoL[304] **3.** The prerequisite for future recycling is a functioning and profitable collection infrastructure. Additional conditions are dismantling procedures suitable for mass production, which should already be taken into account in the design of the application equipment (Design for Recycling). This is all the more decisive with the smaller the magnetic content per single application.[305] **4.** Pure REs can be recovered as oxides by RM recycling using hydrometallurgical treatment. In Germany, however, the reduction of these oxides to pure metals is not technically possible at present[306]	**2.** Focusing on physical separation and concentration for economically feasible processing[308] **3.** Knowledge of handling unusual impurities which may be presented in the recyclates[309]

303 ibid.
304 ibid.
305 Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L.,Tercero Espinoza, L., Angerer, G., Marwede, M. & Benecke, S. (2016) op. cit., p.4
306 Bast, U., Blank, R., Buchert, M., Elwert, T., Fins- Terwalder, F., Hörnig, G., Klier, T., Langkau,S., Marscheider-Weidemann, F., Müller, J.-O., Thürigen, CH., Treffer, F. & Walter, T. (2015) op. cit., p.27
308 UNEP (2011) op. cit., p.11
309 ibid.

Phosphors (i.e. fluorescent lamps, LEDs and displays)	**1.** Various hydrometallurgy processes – leaching, solvent extraction and precipitation	(Recycling of fluorescent and LED lamps is already a common practice[310]; Existing commercial scale processes in the U.S. (Rare Earth Salts) and other R&D activities from companies in the U.S., Germany, Netherland, and Spain) **1.** Solvay (France) operating the process in commercial scale until 2016 due to the declined RE price **2.** Display – little research on the topic	
NiMH batteries	**1.** Hydrometallurgy processes **2.** Pyro-metallurgical processes [311]	(Existing operations in Belgium/France (Umicore and Solvay) and Japan (Honda and Japan Metals & Chemicals) **1.** Battery recycling process is usually based on pyro-metallurgy even though hydrometallurgy is more beneficial in recycling REEs (after pyro-metallurgical process, REEs are to be recovered from slags)[312]	
Other WEEEs	**1.** Hydrometallurgy – mainly leaching and solvent extraction	(Existing operation in Japan (Kosaka Smelting and Refining)	

[310] Kooroshy, J., Tiess, G., Tukker, A. & Walton, A. (eds.) (2015) op. cit., p.27
[311] Binnemans, K., Jones, P.T., Blanpain, B., Gerven, T.V., Yang, Y., Walton, A. & Buchert, M. (2013) op. cit., p.28
[312] Innocenzi, V., Ippolito N.M., Michelis, I.D., Prisciandaro, M., Medici, F. & Vegli, F. (2017) op. cit., p.28

Sludges from glass polishing and magnet	**1.** Hydrometallurgy – mainly leaching and solvent extraction	(Existing operation in Belgium (Hydrometal SA))	
Spent catalysts (i.e. FCC and auto converters)	**1.** FCC — Leaching with acid solutions[313,314,315]	**1.** FCC – No industrialised process[316] **2.** Auto converters (Ce in the slags) – no effort has been made due to the relatively low value of Ce[317,318]	
Metal alloys (i.e. Tb, Pr or Gd)		**1.** No report on production/recycling process of Tb, Pr or Gd from metal alloys	
Optical glasses (i.e. La, sometimes Gd and Y)		**1.** No commercial process found	
Glass polishing powder	**1.** Hydrometallurgy – leaching, precipitation and calcination[319]	(Existing commercial process in Belgium (Hydrometal S.A .)	

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314 Ye, S., Jing, Y., Wang, Y. & Fei, W. (2017) Recovery of Rare Earths from Spent FCC Catalysts by Solvent Extraction Using Saponified 2-Ethylhexyl Phosphoric Acid-2-Ethylhexyl Ester (EHEHPA), *Journal of Rare Earths*, 35 (7). Elsevier: 716–22. doi:10.1016/S1002-0721(17)60968-2

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316 Ferella, F., Innocenzi, V. & Maggiore, F. (2016) op. cit., p.28

317 Krishnamurthy, N. (Nagaiyar) & Gupta, C.K. (2016) op. cit., p.28

318 Binnemans, K., Jones, P.T., Blanpain, B., Gerven, T.V., Yang, Y., Walton, A. & Buchert, M. (2013) op. cit., p.28

319 Ferron, C.J & Henry, P. (2015) A Review of the Recycling of Rare Earth Metals, *Canadian Metallurgical*, Quarterly 54 (4): 388–94.