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.

Table of Contents

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.

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 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]

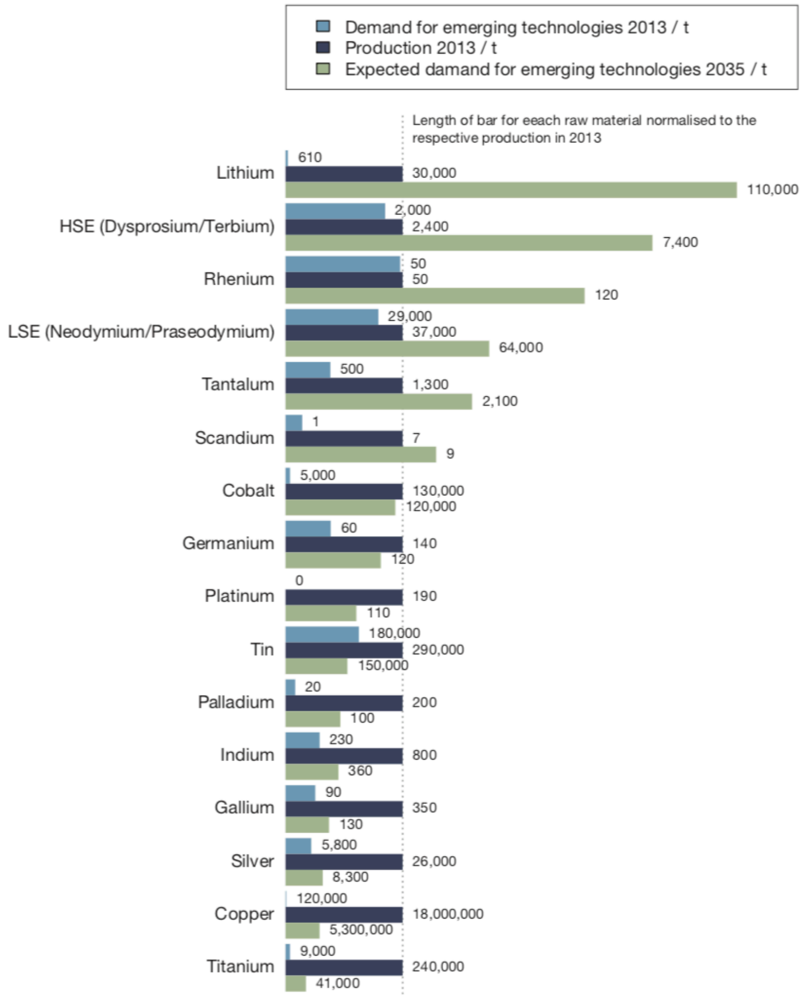


Figure 2.2 Estimated demands of the selected raw materials for emerging technologies in 2035 compared to the respective primary production level in 2013 (Marscheider-Weidemann et al, 2016)

[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%.

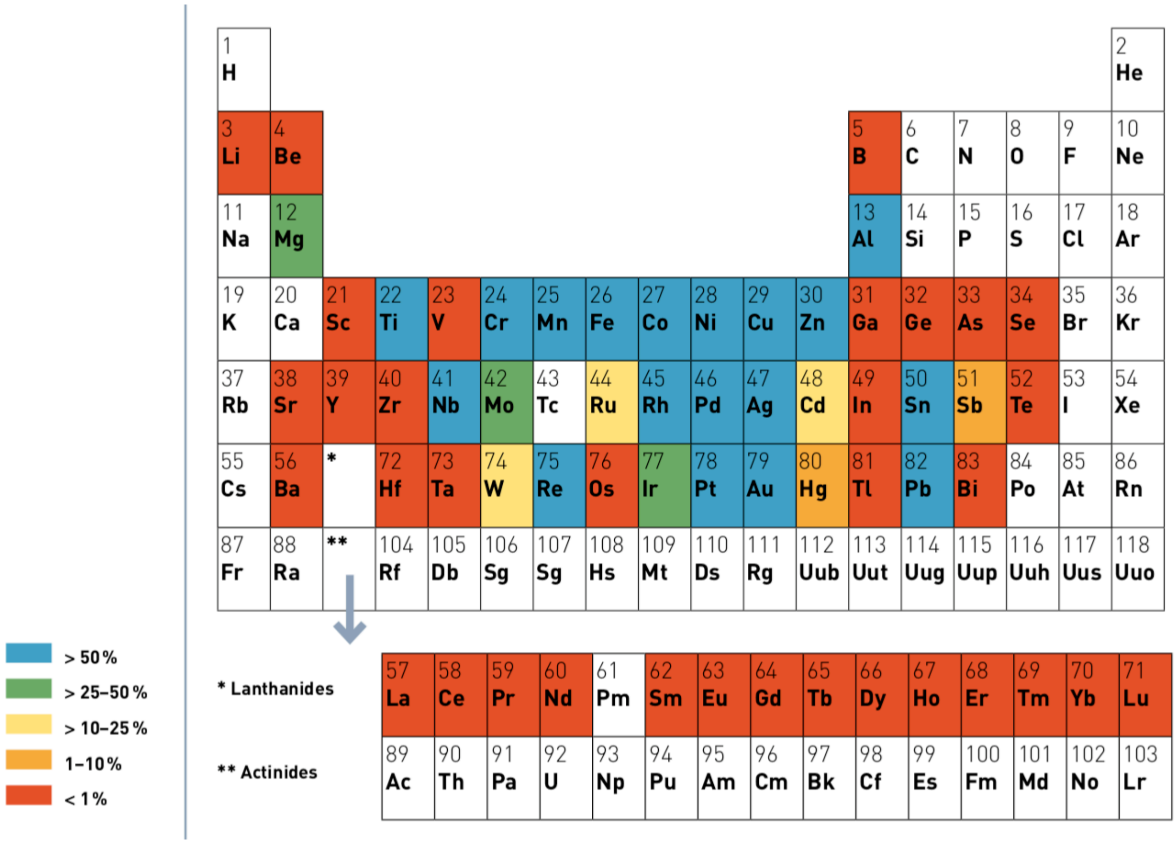


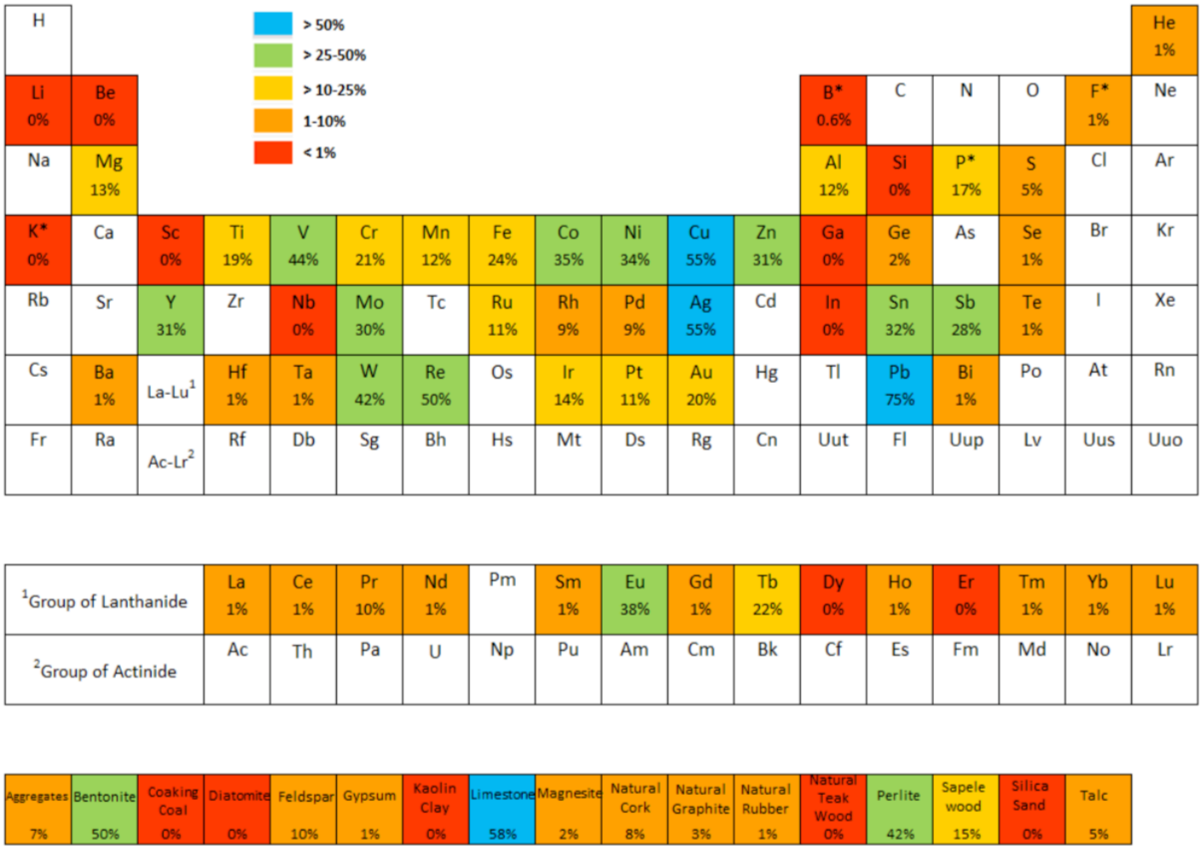
Figure 2.3 EoL recycling rate of CRM (UNEP,2011)

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.

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

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)

<u>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</u>

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

[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.

Example 1: China's policy on its rare earth elements market

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

[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]

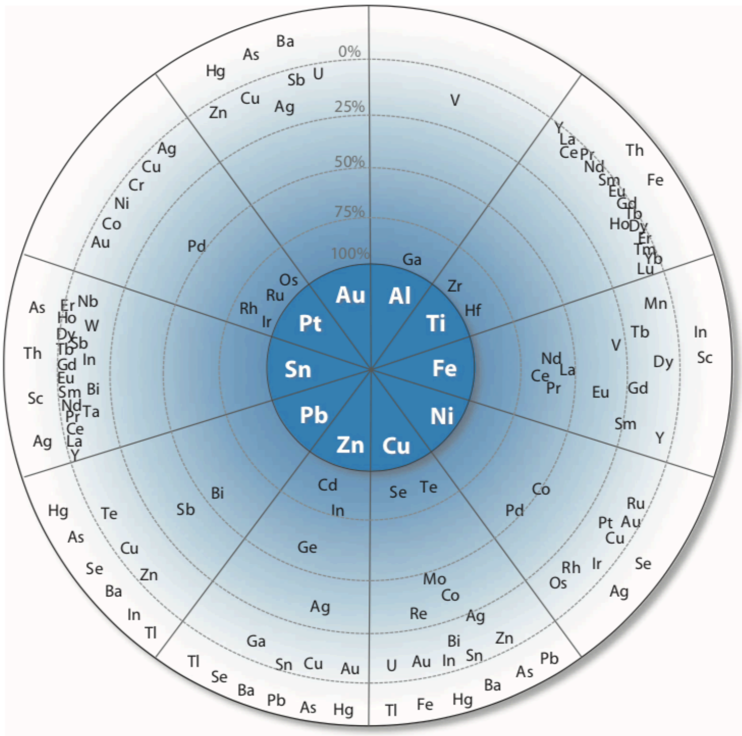


Figure 2.5 Metal wheel of companionality (Nasser el at, 2015)

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

---

[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*

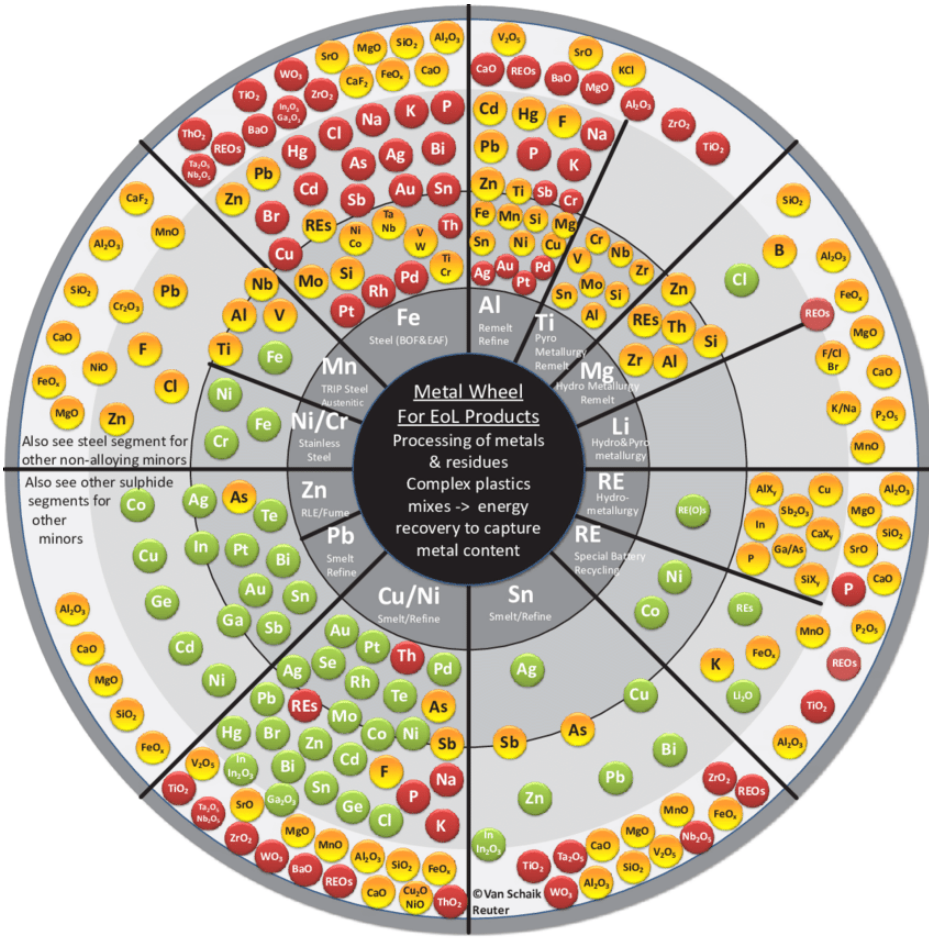
[40] ibid.

[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.



Economically viable destinations of complex EoL designed functional material combinations, scrap, residues etc. to metallurgical processing infrastructure (each segment) to produce refined metal, compounds and alloys in best available technology

Circular Economy's carrier metals processing infrastructure
Extractive Metallurgy's Backbone, the enablers of a Circular Economy (CE) as it also recovers technology elements used e.g. in renewable energy infrastructure, IoT, eMobility etc.

Dissolves mainly in carrier metal if metallic (mainly pyrometallurgy)
Valuable elements recovered from these or (dissipative) lost (metallic, speiss, compounds, alloy in EoL also determines destination as also the metallurgical conditions in flowsheet).

Compounds mainly to dust, slime, speiss (mainly hydrometallurgy)
Collector of valuable minor elements as oxides/sulphates/chlorides etc. and mainly recovered in appropriate metallurgical infrastructure if economical.

Mainly to benign lower value building material products
Relatively lower value but inevitable part of society and materials processing. A sink for metals and loss from the CE system as oxides/ compounds. Dissipative losses.

A **Mainly recovered element**
Compatible with Carrier Metal as alloying Element or can be recovered in subsequent Processing.

B **Mainly element in alloy/compound, lost if in incorrect stream/scrap/module**
With possible functionality, not detrimental to Carrier Metal or product (if refractory metals in EoL product report to slag / slag also intermediate product for cement etc.).

C **Mainly element lost, not always compatible with carrier metal or product**
Detrimental to properties and cannot be economically recovered e.g. Au dissolved in steel or aluminium will be lost.

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]

---

[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

---

[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]

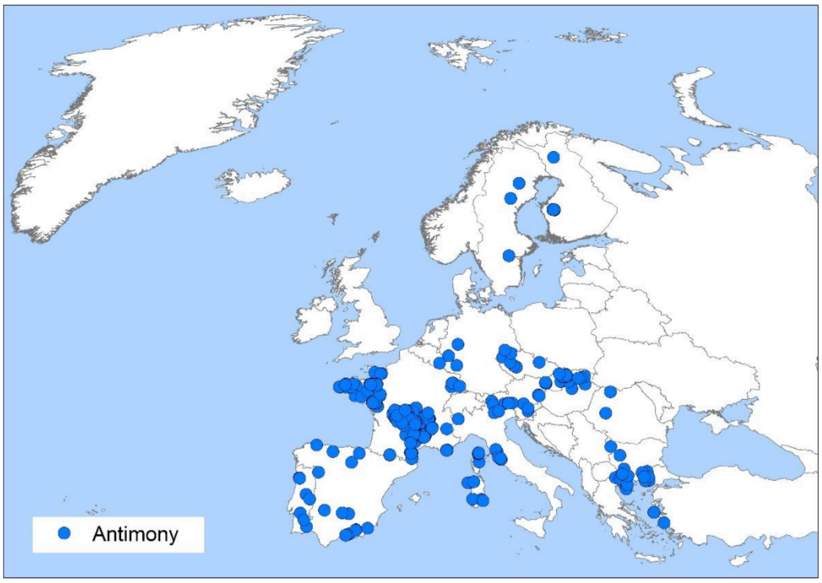


Figure 3.1 Antinomy occurrence in Europe (SCRREEN, 2018)

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

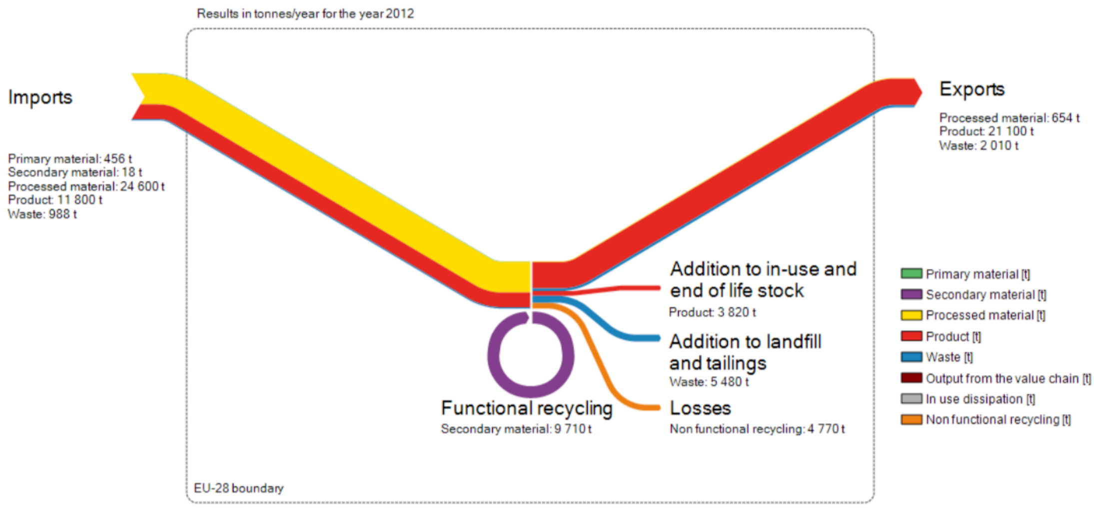


Figure 3.2 Simplified antimony material flows in Europe for 2012 (Deloitte, 2015)[152]

[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.

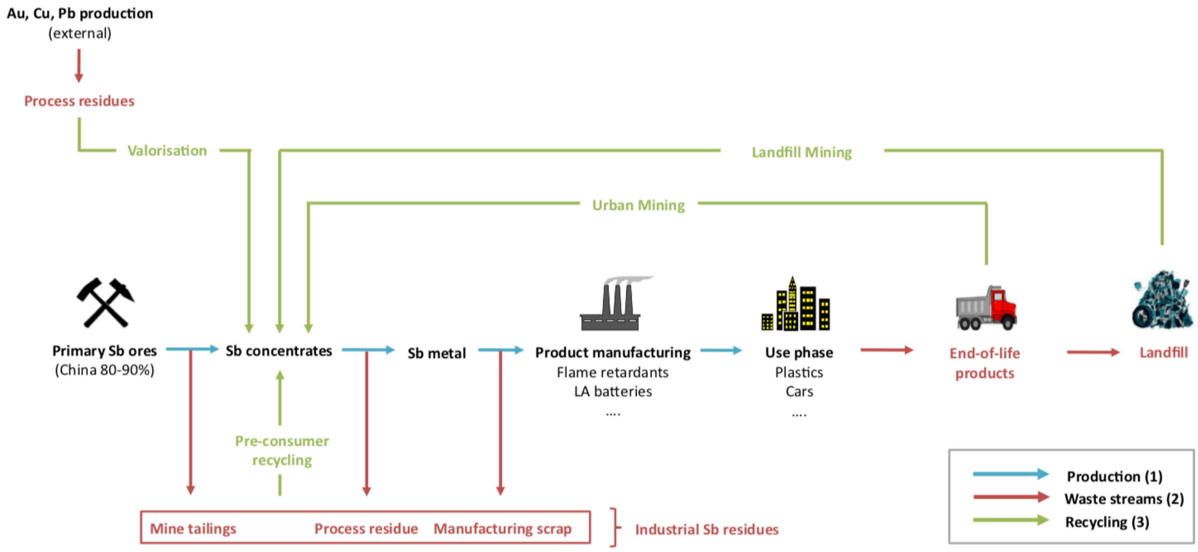


Figure 3.3 Schematic overview of the antimony lifecycle (Dupont et al, 2016)

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]

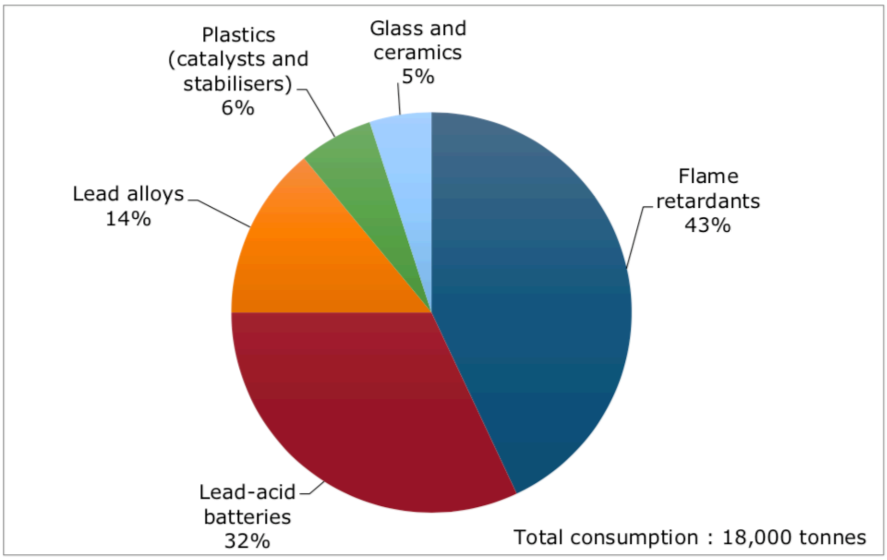


Figure 3.4 Global applications of antimony (EC, 2017a)[157]

[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.

[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]

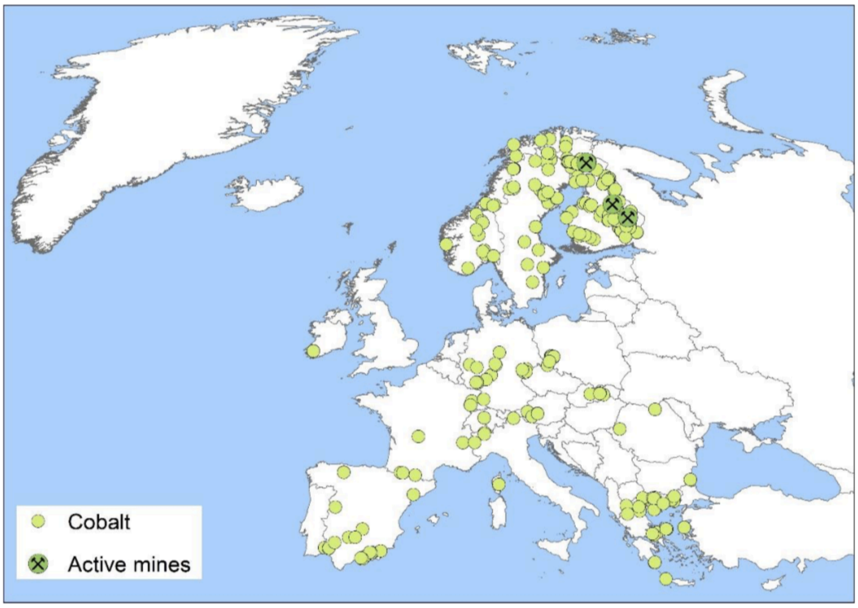


Figure 3.5 Cobalt occurrence and active mines in Europe (SCRREEN D3.1, 2018)

[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).

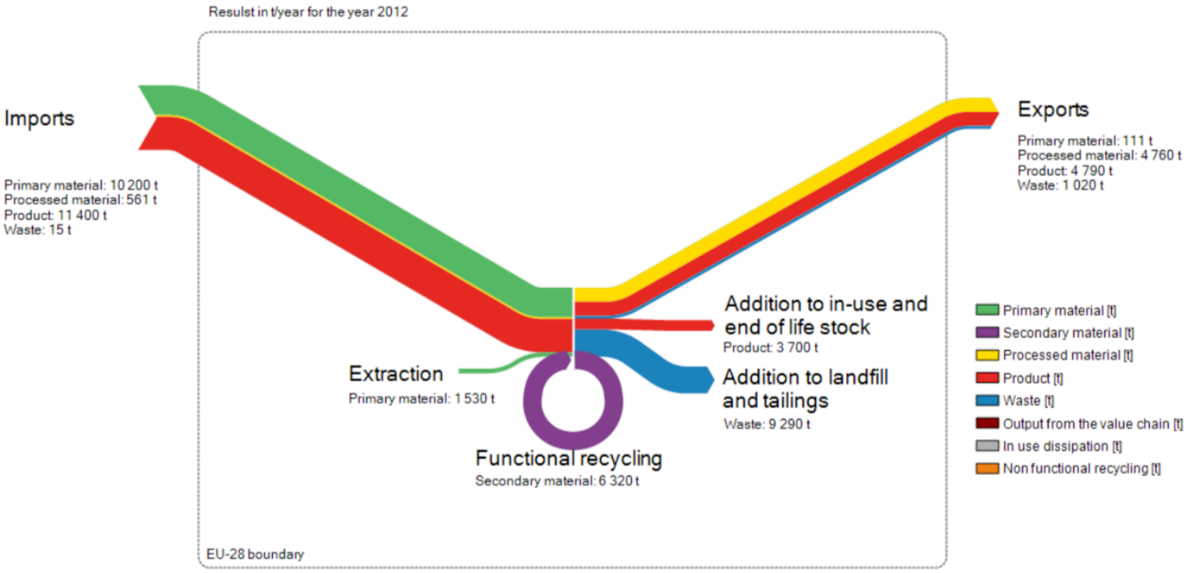


Figure 3.6 Simplified cobalt material flows in Europe for 2012 (Deloitte, 2015)

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]

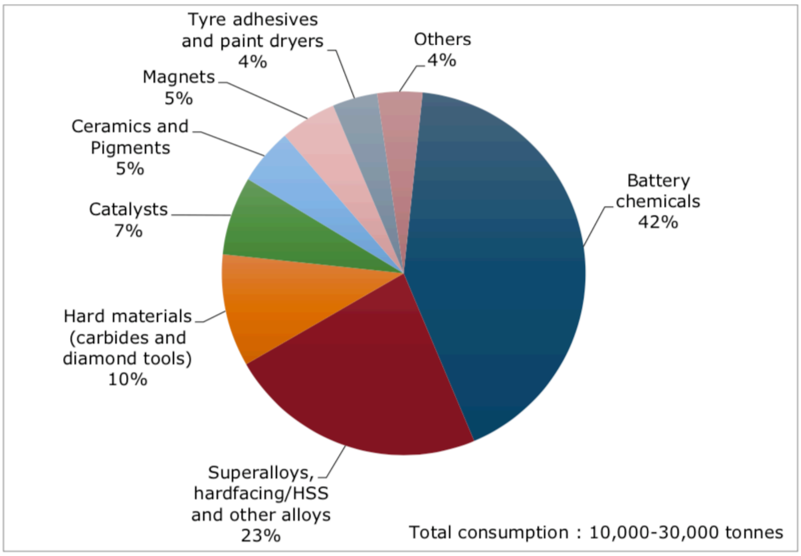


Figure 3.7 Global end use applications of cobalt in 2015 (EC, 2017a)

<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.

[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).

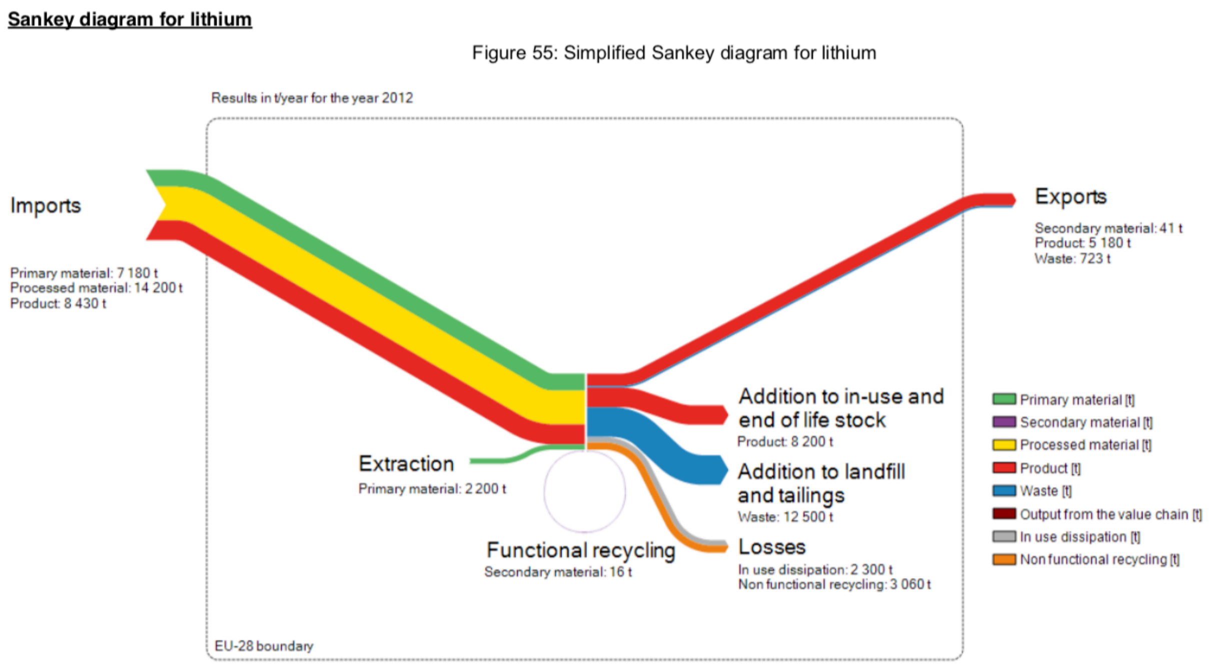


Figure 3.8 Simplified lithium material flows in LCE in Europe for 2012 (Deloitte, 2015)

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.

---

[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 (Li_2O) = 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]

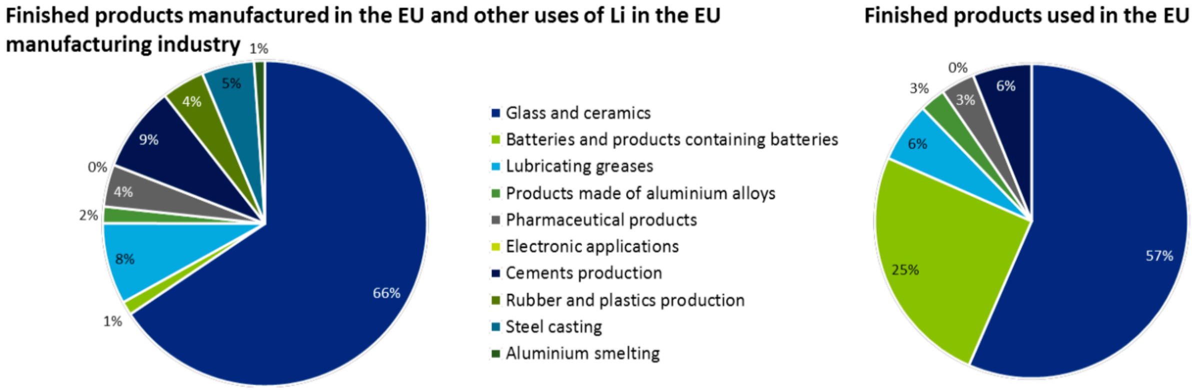


Figure 3.9 The amounts of the lithium used in different applications in the EU (in percentage) (left) and the finished products used in the EU (right) (Deloitte, 2015)

<u>EoL products</u>

- **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).

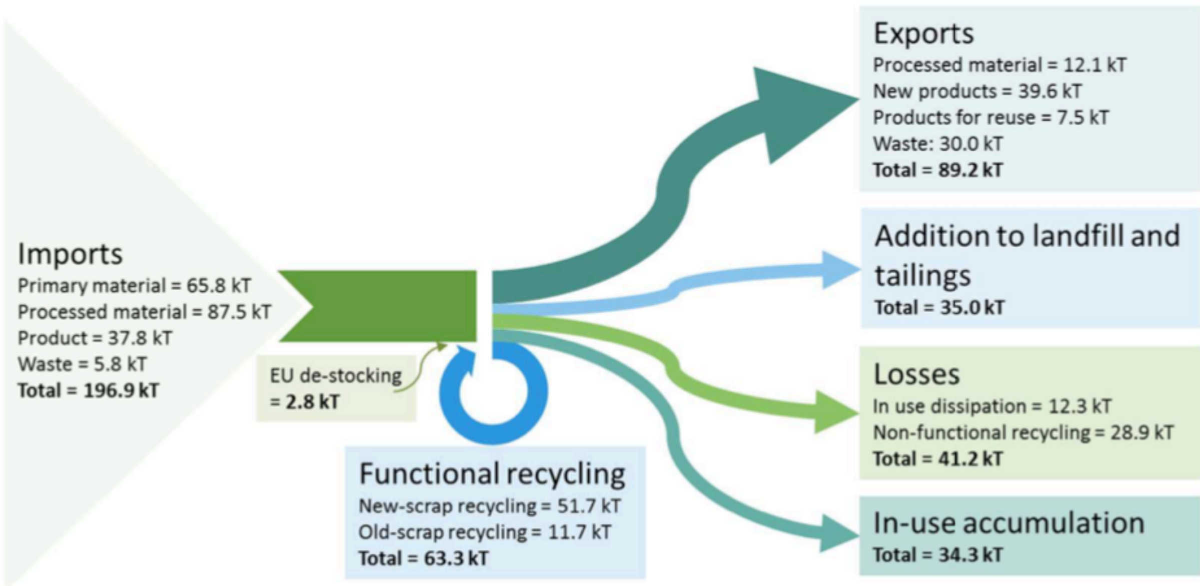


Figure 3.10 Simplified magnesium material flows in Europe for 2012 (Bell et al, 2017)[198]

[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]

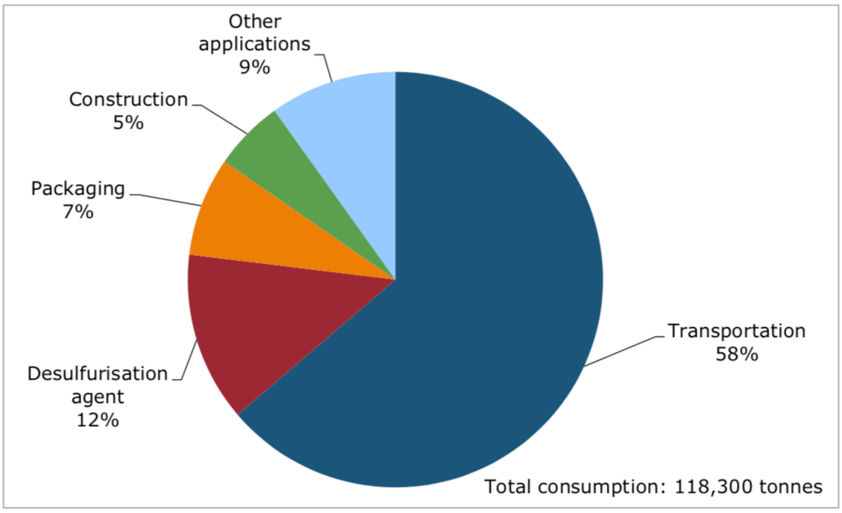


Figure 3.11 EU end use applications of magnesium, average figure for 2010-2014 (EC, 2017a)

<u>Recyclables</u>

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]

[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

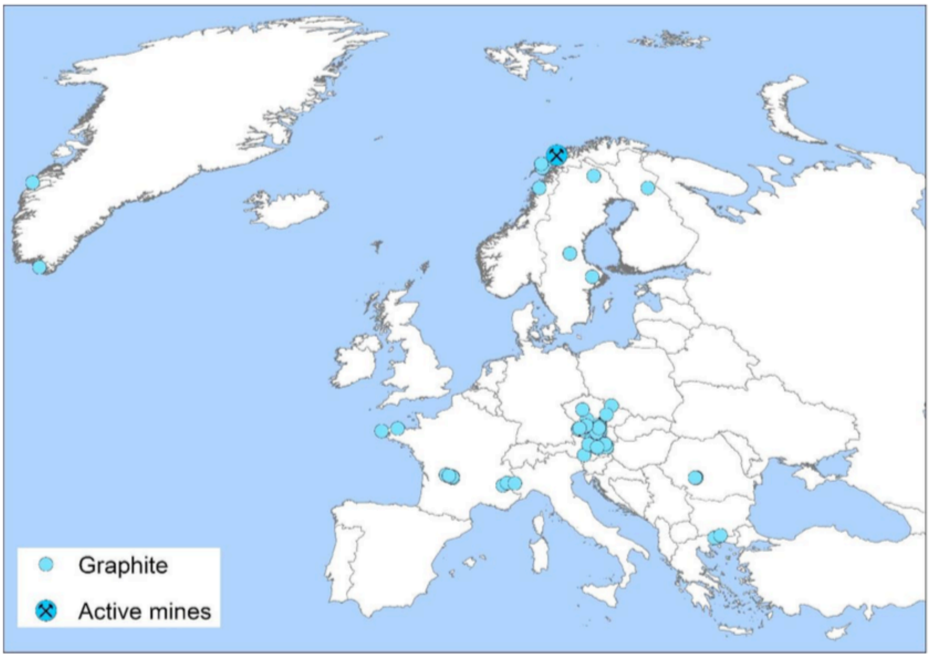


Figure 3.12 Active mine and occurrences of natural graphite in Europe (SCRREEN, 2018)

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

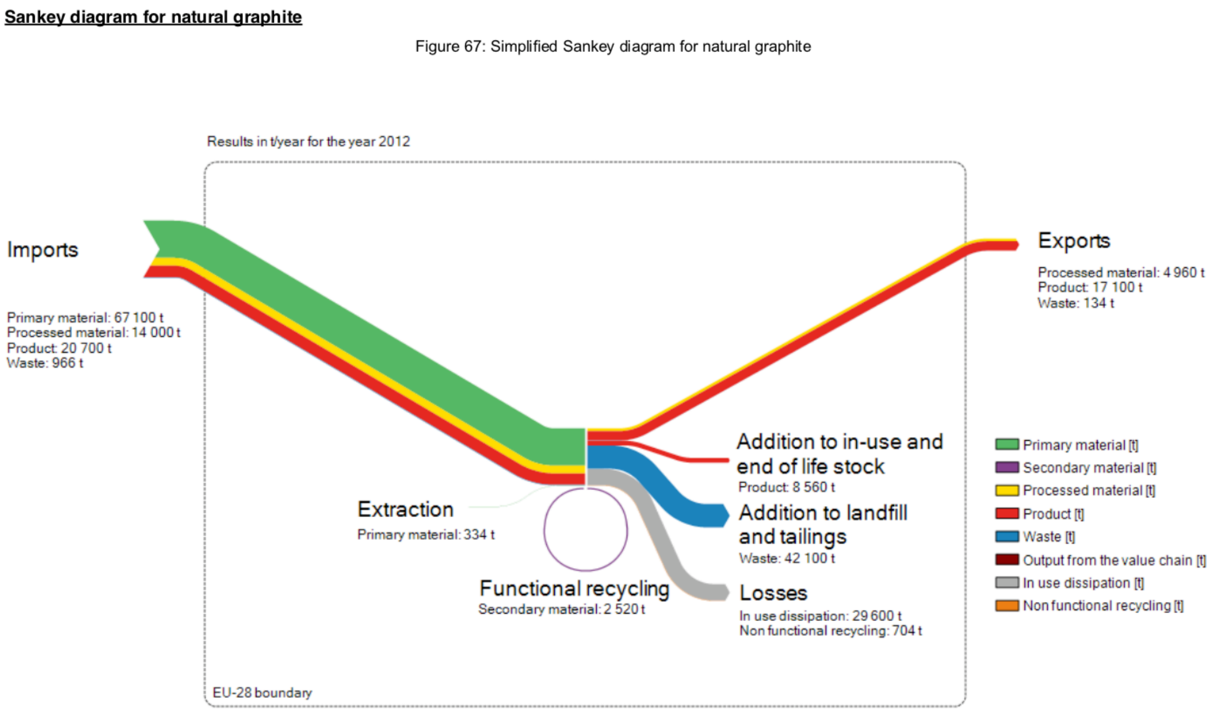


Figure 3.13 Simplified natural graphite material flows in Europe for 2012 (Deloitte, 2015)

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]

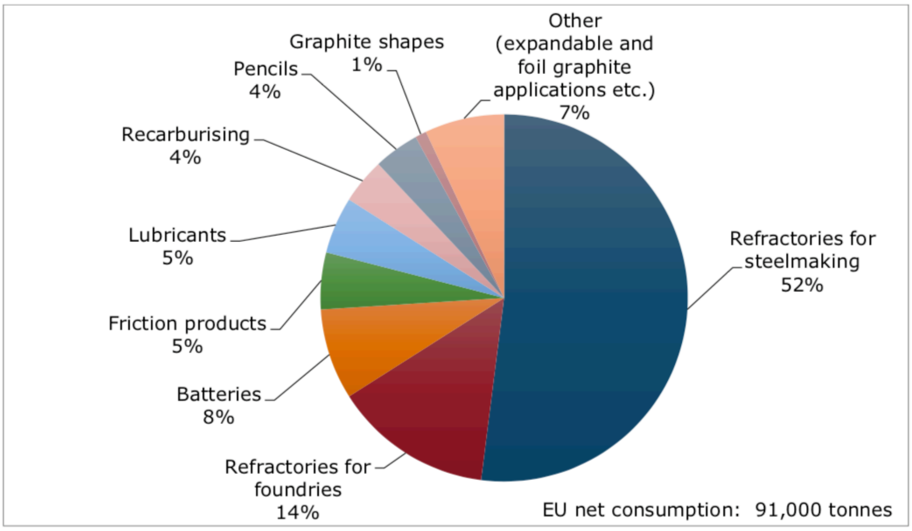


Figure 3.14 Global end use applications of natural graphite in 2014 (EC, 2017a)

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.

<u>Processing residues</u>

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

<u>EoL products</u>

- **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	

[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.

---

[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

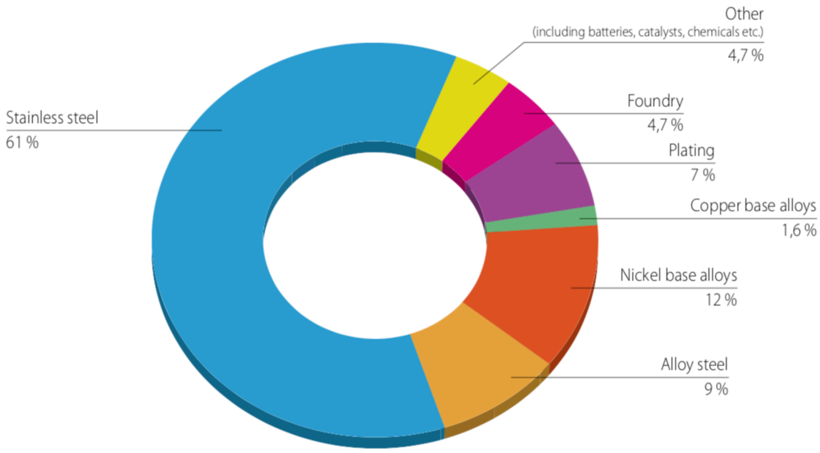


Figure 3.16 Main uses of nickel in the European Union
(Heinz H. Pariser Alloy Metals & Steel Market Research, 2011)[240]

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

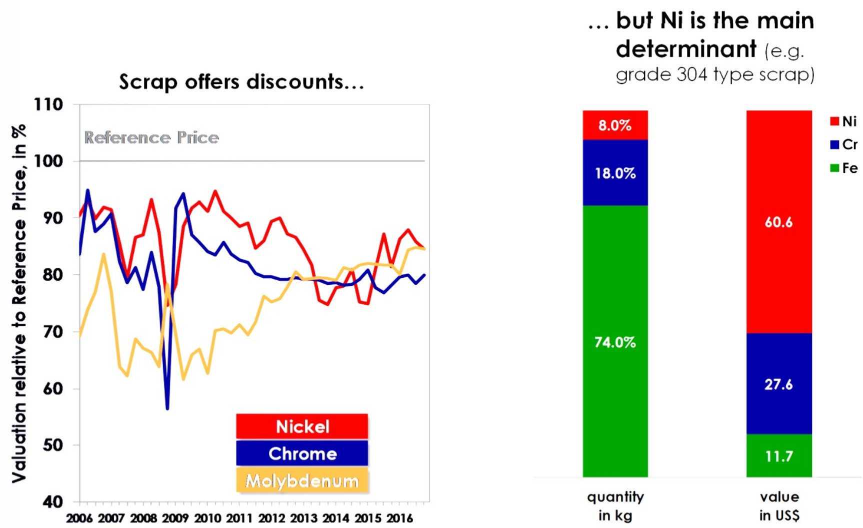


Figure 3.17 Value of scrap nickel relative to reference price under the condition of stainless steel scrap discount (left); Nickel is the key element determining the value of nickel containing stainless steel scraps (right)

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

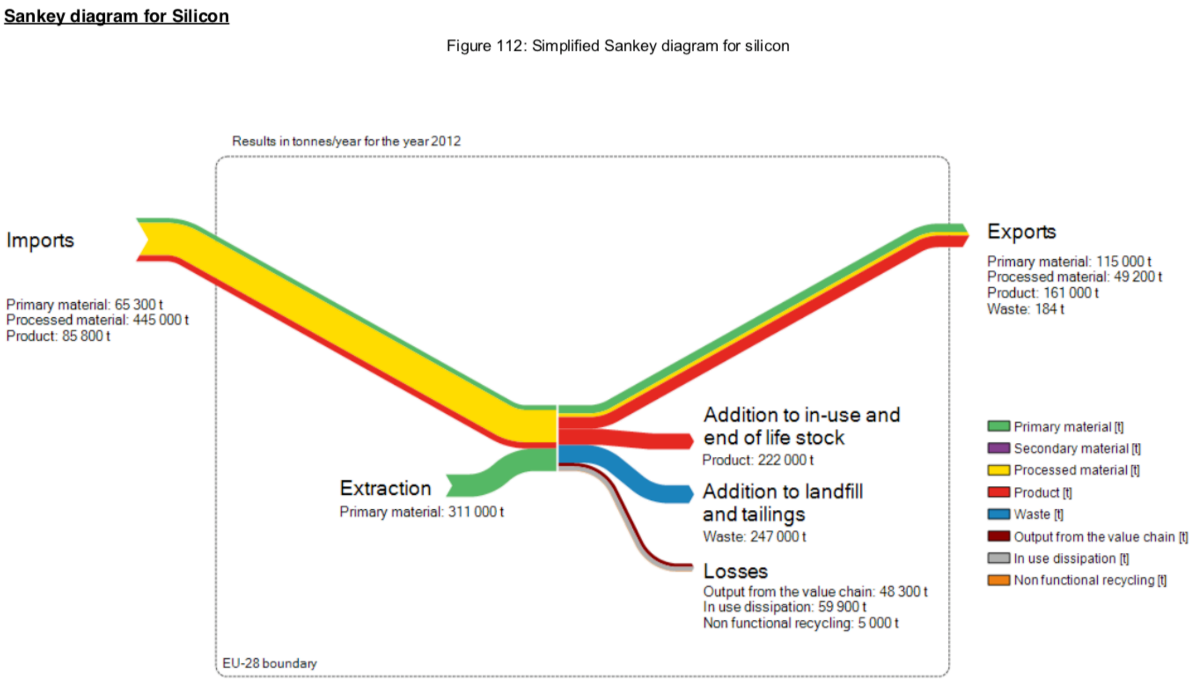


Figure 3.18 Simplified silicon material flows in Europe for 2012 (Deloitte, 2015) (excluding silica and ferrosilicon and their applications)

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.

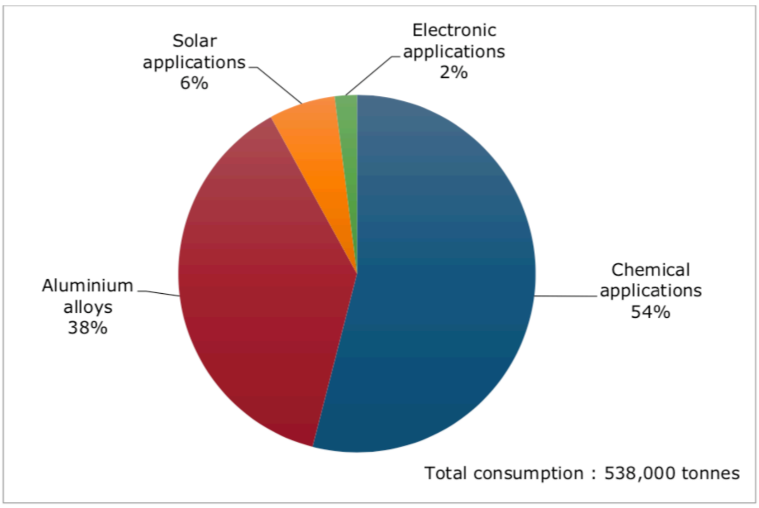


Figure 3.19 Global end use applications of silicon metal, average figure for 2010-2014 (EC, 2017a)

[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]

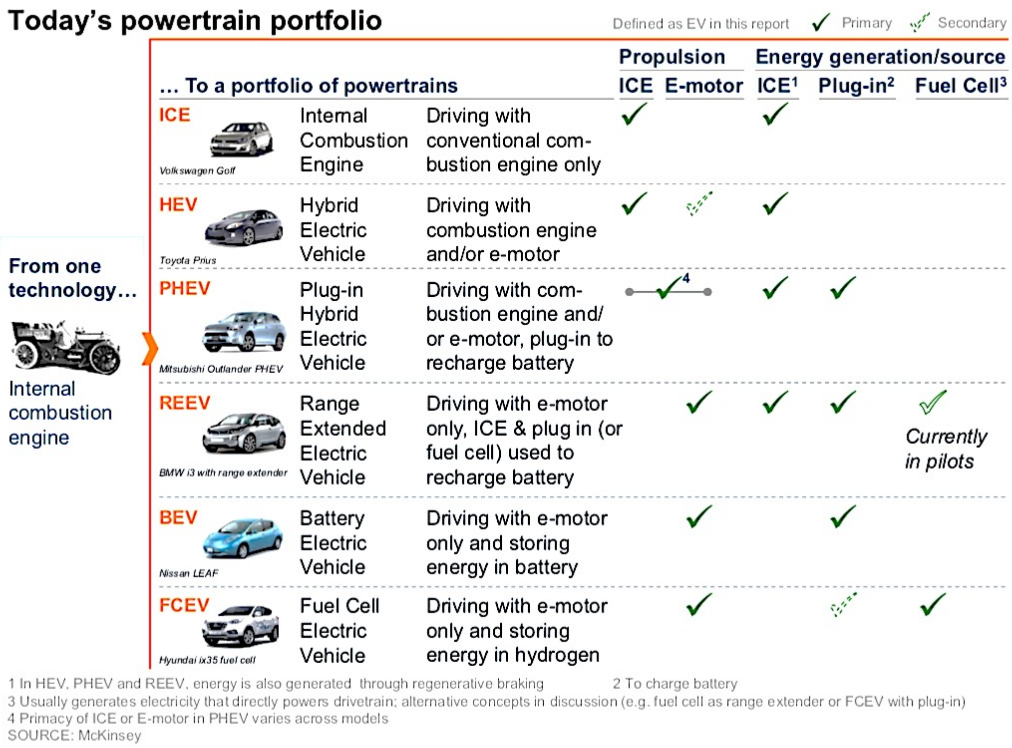


Figure 4.1 Today's powertrain portfolio (McKinsey&Company, 2014)

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]

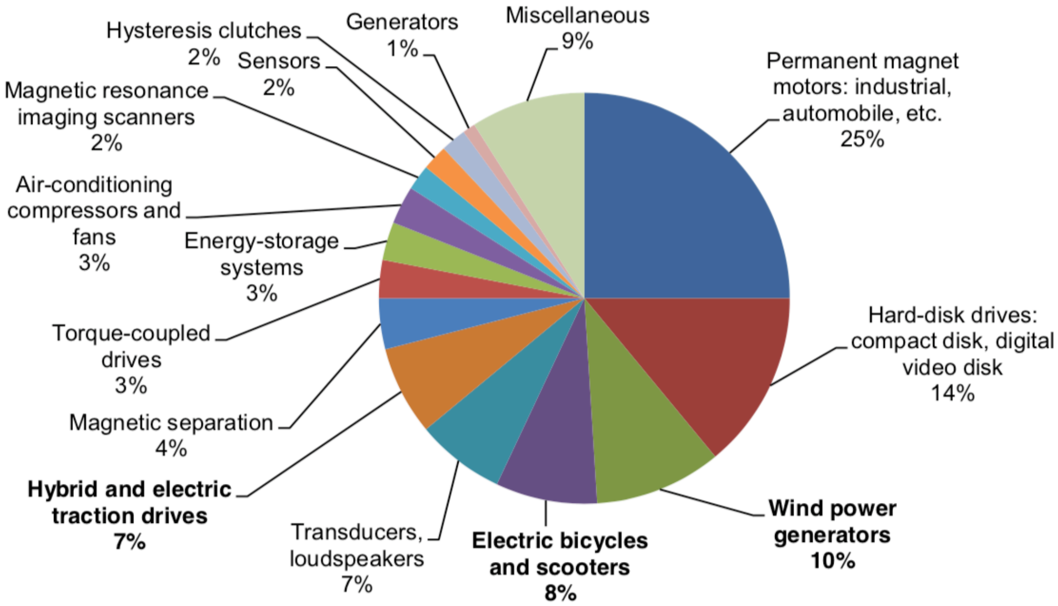


Figure 4.2 NdFeB permanent magnet used in industrial applications (Pavel et al, 2016)

[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.

[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/

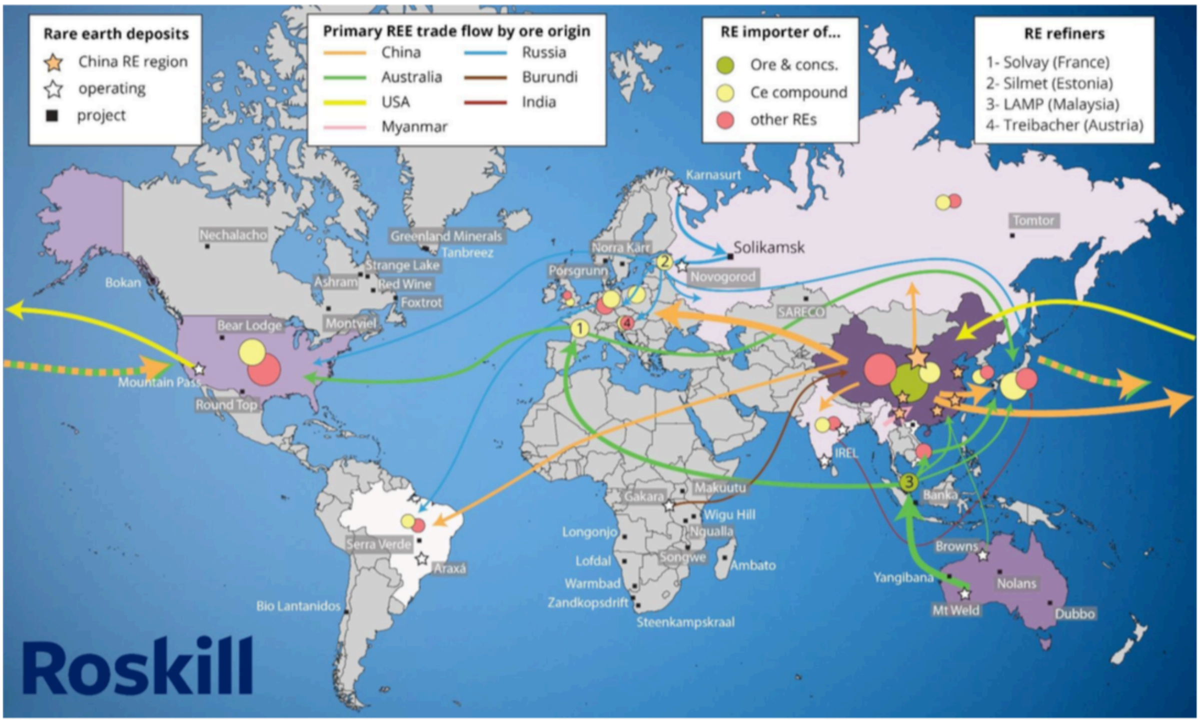


Figure 4.3 Global RE deposits, production and trade flows (Roskill, 2018)

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).

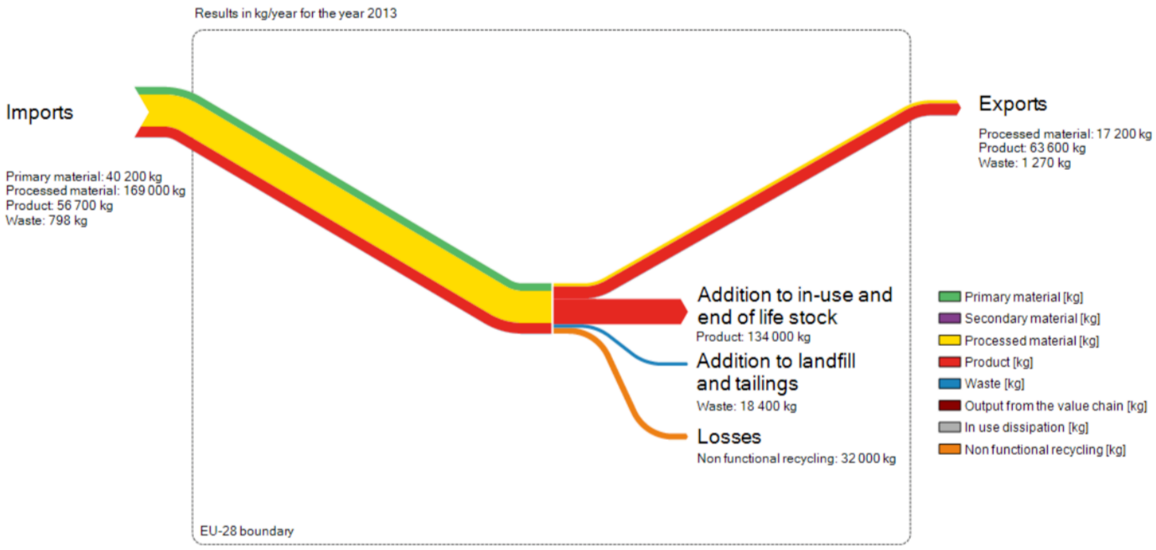


Figure 4.4 Simplified dysprosium (Dy) material flows in Europe for 2012 (Deloitte, 2015)

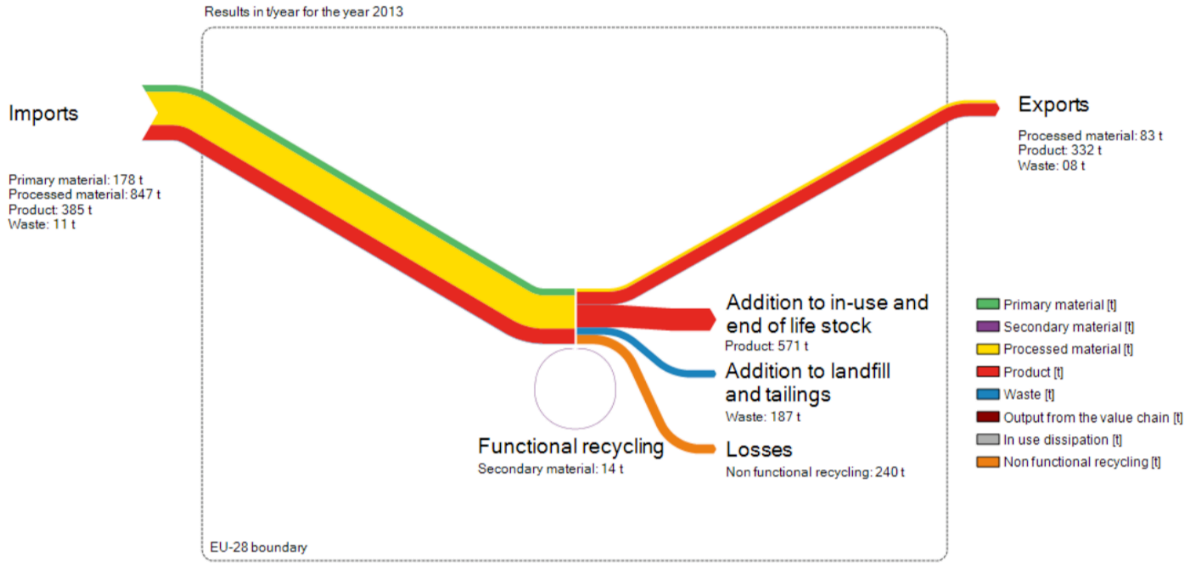


Figure 4.5 Simplified neodymium (Nd) material flows in Europe for 2012 (Deloitte, 2015)

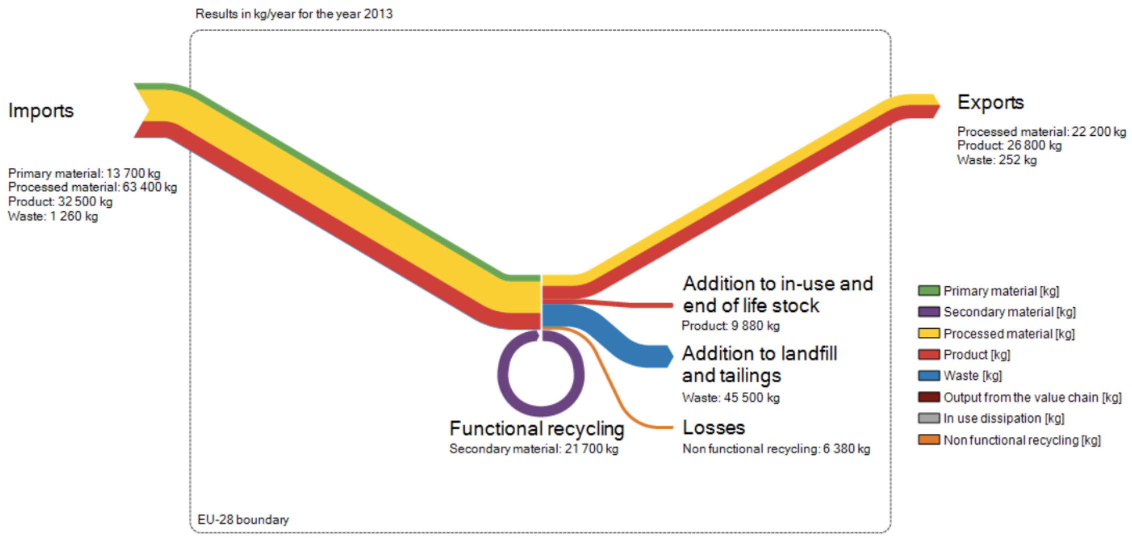


Figure 4.6 Simplified terbium (Tb) material flows in Europe for 2012 (Deloitte, 2015)

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

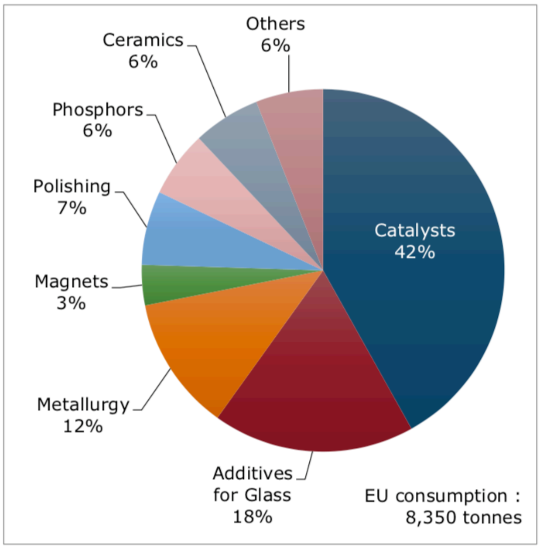


Figure 4.6 End uses of REEs in the EU (ASTER project – Guyonnet et al.)

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.

[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 .)	

[313] Wang, J., Huang, X., Wang, L., Wang, Q., Yan, Y., Zhao, N., Cui, D. & Feng, Z. (2017) Kinetics Study on the Leaching of Rare Earth and Aluminum from FCC Catalyst Waste Slag Using Hydrochloric Acid, *Hydrometallurgy* 171 (August). Elsevier: 312–19. doi:10.1016/J.HYDROMET.2017.06.007

[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

[315] Zhao, Z., Qiu, Z., Yang, J., Lu, S., Cao, L., Zhang, W. & Xu, Y. (2017) Recovery of Rare Earth Elements from Spent Fluid Catalytic Cracking Catalysts Using Leaching and Solvent Extraction Techniques, *Hydrometallurgy* 167 (January). Elsevier: 183–88. doi:10.1016/J.HYDROMET.2016.11.013

[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.