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Green technologies and critical raw materials

Strategies for a circular economy

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This policy paper has been commissioned by Henrike Hahn, Member of the European Parliament from the Greens / EFA to support her legislative activities on the European strategy for critical raw materials.

It aims at answering key questions regarding critical raw material demand for green technologies in comparison to other applications and potentials for substitution, recycling, and material efficiency from a scientific perspective.

In this paper, the authors explore how greening technologies can be defined and the extent to which they or other applications and industries contribute to increasing the demand for raw materials. Furthermore, potentials for substitution, material efficiency and innovation will be examined based on examples. The role of recycling will be investigated showing the supply potential for key examples and estimations of economic effects. In the end, policy options to foster a more circular economy will be outlined.

The paper is intended to provide a quick overview of the most important topics and does not claim to be exhaustive regarding this very comprehensive topic.

1 Green technologies and critical raw materials

What are other factors besides green technologies that contribute to the EC's projected rise of critical raw material demand in the future? Are all – or only some – of critical raw materials on the Commission's list relevant and applicable to the key green sectors such as the renewables and non-fossil fuel transports?

Projections of material demand until 2030 and 2050 describe a rapid increase for critical raw materials required for greening the economy e.g. such as lithium, cobalt or graphite needed for batteries or rare earth elements for permanent magnets in wind turbines [JRC 2020a, Buchert et al. 2017]. The increase is often many times higher than current demand. For instance, the JRC calculates that lithium demand for batteries in electric vehicles could face a 45-fold increase until 2050 in a high demand scenario, in the case of cobalt it could increase 15-fold or for nickel to almost four times the current demand [JRC 2020a]. There are three things to consider when interpreting the numbers.

Firstly, the scenarios themselves work with assumptions that are often uncertain. E.g. future batteries might be bigger or smaller than assumed, less vehicles might be sold due to changes in behaviour, vehicle use-phases might be longer or shorter. Therefore, usually different scenarios need to be calculated to cover different development paths. When looking at medium or low demand scenarios the increase in demand for lithium is not as drastic. In the medium demand scenario, a more than 20-fold increase and in the low demand scenario a less than 10-fold increase are projected. Moreover, the horizon up to 2050 is very long, accordingly the certainty is weak – technological advancement and market changes in these timeframes are not predictable [JRC 2020a].

Secondly, the numbers in the JRC study refer to an increase in relation to current EU consumption, which in this case refers to the five-year global average 2012 – 2016 and the EU's economic share (22%) amounting to 6 000 tons of lithium [JRC 2020a]. The value is rather small, comparing it to future demand therefore leads to high factors, like the mentioned 45-fold increase.

Thirdly, the framing of the increase might be somewhat misleading as it implies massive increases. In relative terms this is often true since a 45-fold increase is a lot. But in absolute terms the increase does not look that drastic anymore. Looking at a global scale the lithium production in 2019 which amounted to 86 000 tons and considering a 45-fold increase would translate to a total of 3.8 Mt. Comparing this to iron ore production in 2019, which amounted to ca. 2 454 Mt, a different perspective is given [USGS 2021]: 646-fold – iron ore vs. lithium. Of course, iron ore production is largest among all metals, nonetheless it helps to realise the proportions of future extraction that are debated. The 45-fold increased demand in 2050 of lithium corresponds to ca. 0.0016% of current iron ore production.

1.1 Defining green technologies

To answer the question what other factors there are besides greening of the economy contributing to the projected increase of critical raw materials demand in the future, one must first define what green technologies include. In many cases there is an overlap between e.g. digitalisation and green technology. For instance, the use of robotics, 3D printing or digital technologies could be also interpreted as measures aiming at greening the economy although they also clearly fall in the category of digitisation. The UN defines environmentally sound technologies as '*techniques and technologies capable of reducing environmental damage through processes and materials that generate fewer potentially damaging substances, recover such substances from emissions prior to discharge, or utilize and recycle production residues […]*' [UN-STATS 2016]. In their paper on green technologies Pan et al. [2019] define them as *'any process, product or service that reduces negative environmental impacts while protecting human health and ecosystem quality'.*

Both presented definitions are very broad and include a wide variety of applications. To be more precise, in this paper, green technologies include those that replace more traditional technologies without introducing completely new functions. Accordingly, alternative powertrains such as battery electric vehicles replacing internal combustion engines or photovoltaics and wind turbines that replace e.g. coal-fired power plants are defined as green technologies in this context, but robotics, e.g. are excluded.

1.2 What are Critical Raw Materials?

The term critical raw material is often associated with scarcity, but sometimes goes beyond that and is connoted with negative environmental impacts. But on EU level there is a clear definition. To understand the context of the critical raw material (CRM) debate, the methodology to determine which materials are critical will be outlined. The European Commission first published a list of CRMs in 2011, which has been updated every three years. In 2020, the fourth list has been published with a selection of 30 identified CRM based on an updated methodology from 2017 [EC 2017]. In the Critical Raw Materials report the EC states that *'critical raw materials are considered to be those that have high economic importance for the EU and a high supply risk' [EC 2020a].* Accordingly, economic parameters are at the core of the assessment. Basically, two assessments are performed:

Firstly, the economic importance is evaluated based on the importance of the material for the EU economy regarding end-use applications and value added of corresponding EU manufacturing. Secondly, the assessment is complemented by evaluating substitution options for the materials in different applications.

This methodology is very suitable to describe the current supply situation, but it does not look into the future. For instance, lithium only became critical when the EU adopted the strategy to invest in a domestic cell manufacturing. Therefore, the assessment of increased raw material demand when projecting future needs based on currently critical materials does not reflect risks for materials that might become critical. Perhaps the most interesting example is copper. Due to a diversified supply situation and some domestic production the status quo is uncritical. But the demand for copper will increase dramatically due to its use in almost any electric appliance.

Furthermore, the environmental and social challenges related to a raw material is not considered at all for the list of critical raw materials.

1.3 Critical raw materials needed for green technologies

Currently the list of critical raw materials consists of 30 materials, which were determined using the methodology described above. But how many of the raw materials are needed for green technologies and to what extent are green technologies decisive when it comes to an increased demand? Table 1 shows the most recent list of critical raw materials with selected applications and sectors where they play a role and a colour-coded assessment of the raw material's importance for greening the economy. Moreover, the importance of demand from other sectors is displayed by an arrow. Accordingly, looking at borate the demand is estimated to be medium (🟡). It is crucial in the manufacturing of permanent magnets ($Nd_2Fe_{14}B$) for wind turbines or electric engines. However other applications are responsible for most of the demand and it will remain so in the future. The use in glass applications alone accounts for almost half of the demand [EC 2020c].

The overview below tries to provide an estimation whether green technologies are the key driver for the demand of each raw material and to which extent other sectors are relevant.

Table 1 List of CRM with applications and important sectors [based on EC 2020b and own assumptions]

Importance of green technologies for current and future demand		Relevance of demand from other sectors for current and future demand	
		Very high	↑
High	🔴	High	↗
Medium	🟡	Medium	→
Low	🟢	Low	↘
		Very low	↓

CRM	Selected applications	Importance for green tech	Relevance of demand from other sectors
Cobalt	Batteries, super alloys, catalysts, magnets	🔴	→
Lithium	Batteries, glass and ceramics, steel, and aluminium metallurgy	🔴	↘
Niobium	High-strength steel and super alloys for transportation and infrastructure, high-tech applications (capacitors, superconducting magnets, etc.)	🔴	↗
Tantalum	Capacitors for electronic devices, super alloys	🔴	↗
Heavy rare earth elements	Permanent magnets for electric motors and electricity generators, lighting phosphors, catalysts, batteries, glass, and ceramics	🔴	→
Light rare earth elements		🔴	→
Borate	High performance glass, fertilisers, permanent magnets	🟡	↑
Phosphorous	See phosphate rock	🟡	↑
Silicon metal	Semiconductors, photovoltaics, electronic components, silicones	🟡	↘
Gallium	Semiconductors, photovoltaic cells	🟡	→
Germanium	Optical fibres and infrared optics, satellite solar cells, polymerisation catalysts	🟡	↗
Indium	Flat panel displays, photovoltaic cells and photonics, solders	🟡	↗
Natural graphite	Batteries, refractories for steelmaking	🟡	↗

Scandium	Solid oxide fuel cells, lightweight alloys, 3D printing	🟡	↗
Platin group metals	Chemical and automotive catalysts, fuel cells, electronic applications	🟡	↗
Bauxite	Aluminium production	🟢	↑
Fluorspar	Steel and iron making, refrigeration and air-conditioning, aluminium making and other metallurgy	🟢	↑
Antimony	Flame retardants, defence applications, lead-acid batteries	🟢	↑
Baryte	Medical applications, radiation protection, chemical applications	🟢	↑
Beryllium	Electronic and communications equipment, automotive, aero-space and defence components	🟢	↑
Bismuth	Pharmaceutical and animal feed industries, medical applications, low-melting point alloys	🟢	↑
Coking coal	Coke for steel, carbon fibres, battery electrode	🟢	↑
Hafnium	Super alloys, nuclear control rods, refractory ceramics	🟢	↑
Magnesium	Lightweight alloys for automotive, electronics, packaging or construction, desulphurisation agent in steelmaking	🟢	↑
Natural rubber	Tires, rubber components for machinery and household goods	🟢	↑
Phosphate rock	Mineral fertilizer, phosphorous compounds	🟢	↑
Strontium	Ceramic magnets, aluminium alloys, medical applications, pyrotechnics	🟢	↑
Titanium	Lightweight high-strength alloys for e.g. aeronautics, space and defence, medical applications	🟢	↑
Tungsten	Alloys e.g. for aeronautics, space, defence, electrical technology, mill cutting and mining tools	🟢	↑
Vanadium	High-strength-low-alloys for e.g. aeronautics, space, nuclear reactors, chemical catalysts	🟢	↑

1.3.1 Selected CRMs needed for greening the economy

Lithium

Lithium is a soft and silvery-white metal. It can be obtained from ores through classic mining processes or from brines through evaporation and processing of the gained salts. In some cases, the greening of the economy is the main driver of future demand. Lithium required for traction batteries is one example. In the past lithium has been mainly used in ceramics and for greases. But the demand in those sectors will not change decisively as the markets are mature. Lithium-ion batteries (LIBs) started to play an increasing role with the uptake of more and more cordless devices such as laptops, power tools or smartphones. But with the market uptake of electric vehicles a completely different level of material supply is necessary. Figure 1 depicts how the share of lithium demand in different applications changed in the last 10 years. While in 2011 only ca. 23% of the material was used in batteries, today more than 70% are needed to produce LIBs. Accordingly, the growth of lithium demand is clearly connected to green technologies. The trend is likely to continue in the future with batteries becoming even more important.

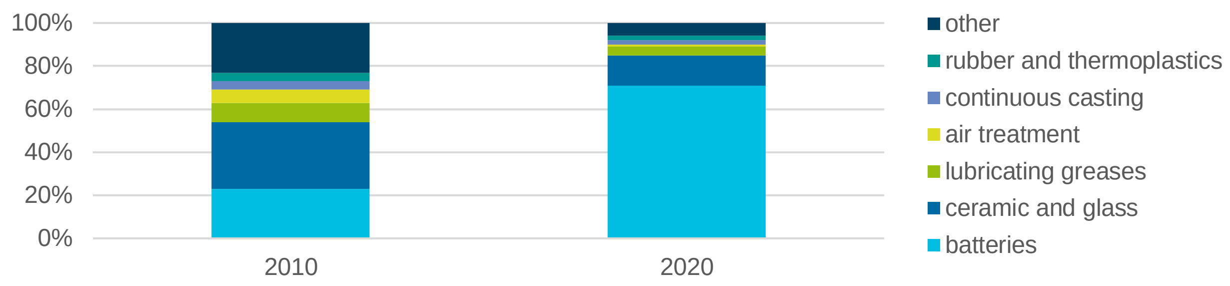

Figure 1 **10-year development of lithium applications [USGS 2012, USGS 2021]**

Due to the growing demand for batteries, mine production for lithium has increased from 28 100 tons to 82 000 tons[1] per year from 2010 to 2020 [USGS 2012, 2021]. In the case of lithium, the importance for green technologies is high ● and the demand for other applications is comparatively low ➘; especially considering the future increase in lithium demand for batteries.

Rare Earths Elements

A total of 17 different metals are grouped under the term rare earth elements (REEs). They are mostly obtained through mining and leaching and complex chemical separation. Global mine production of rare earth elements was around 240 000 tons in 2020 [USGS 2021]. For environmental technologies, the rare earth elements used for neodymium-iron-boron permanent magnets are primarily important. The four most important REEs are the light rare earth elements neodymium and praseodymium and the heavy rare earth elements dysprosium and terbium, all of which are very relevant for neodymium-iron-boron permanent magnets. Their use in green technologies such as wind power generators and electric motors for electric vehicles are the main driver for demand. In addition to green technologies, rare earth elements are also used in many other applications such as industrial catalysts or glass and ceramic applications [USGS 2021]. Therefore, the classification is high ● for green technologies and medium ➔ for other applications.

Cobalt

Cobalt is a hard, lustrous, and silver-grey metal. It can be obtained from cobalt containing ores but is mostly produced as by-product of nickel and copper production. Global mine production of cobalt in 2020 was around 140 000 tons, 95 000 tons of which came from the Democratic Republic of Congo [USGS 2021]. The use of cobalt has been widely discussed in the media due to a substantial share of the metal being mined in the artisanal and small-scale mining sector. The sector is often connected to low health and safety standards as well as child labour. Regarding future demand the situation compared to lithium is not as clear but still distinct that batteries are the key driver of demand. For instance, the established superalloy segment is expected to grow but to a much smaller extent compared to batteries [CRUX Investor 2021]. This means a high ● rating for green technologies and a medium ➔ rating for other applications.

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[1] Data in metric tons of lithium content

1.3.2 Selected CRMs partly needed for greening the economy

Platinum

Platinum is a precious, dense, ductile, and silverish-white metal. It is usually obtained as by-product from nickel and copper production, like other noble metals. For other raw materials the situation isn't as clear. The material demand for platinum in road transport is very dependent on the adaptation of fuel cell electric vehicles (FCEV). Should a large-scale deployment take place, demand might increase, but the estimations of future FCEV material requirement per car are comparable to catalytic converters used in diesel vehicles [JRC 2020a]. Therefore, an increase might not even be necessary as a shift from one application to another can take place.

Furthermore PEM (polymer electrolyte membrane) electrolysers are important facilities to produce hydrogen. Relevant quantities of platinum are needed for one of the two electrodes in PEM electrolysers.

However, besides applications for environmental technologies, significant amounts of platinum demand are used for the jewellery and investment sectors, as well as for applications such as industrial catalysts. Therefore, the importance of platinum for environmental technologies is rated as medium ●, while the importance for other applications is rated as high ↗.

Indium

Indium is a silvery white and soft metal. In comparison to metals like tin or nickel is not produced directly from a specific ore but is obtained as a by-product during the processing of ores of other metals, commonly zinc. Indium is rare and its production volume is very low (968 t in 2019) compared to many other metals [USGS 2021]. With around 65% the main use in 2000 was to produce indium tin oxide (ITO). From this amount about 76% were used to produce flat panel displays in 2015 [RMR 2021], so only a minor share of the total indium use remains for green tech like solar panels, which are part of the remaining 24% of ITO. The remaining 35% of indium is used in a broad variety of applications like plating, control rods in nuclear power plants and various chemical compounds. This means for indium a medium ● rating for green technologies and a high ↗ rating for other applications.

1.3.3 Selected CRMs not needed for greening the economy

Magnesium

Magnesium is a light and silvery grey metal. It can be obtained through the Pidgeon process (burned dolomite together with baryte and ferrosilicon is heated to 1 000°C, so that gaseous magnesium is obtained, which is condensed outside of the oven) or through molten salt electrolysis of magnesium chloride. IMA [2017] shows, that its main use (44%) is in the automotive sector where it is usually used as alloy. Other uses are as packaging material in an aluminium-magnesium alloy (19%), as construction parts (also aluminium-magnesium alloy) (12%) or it is used for the desulphurisation of iron (11%). The remaining 14% come from casting parts outside of the automotive sector and other uses of alloys plus some minor applications. Besides the use for lightweight construction in the automotive sector, which is done for electric vehicles as well as for classic vehicles with internal combustion engines alike, there are no relevant use cases for magnesium in greening the economy. Therefore, magnesium for environmental technologies is rated low ●, while for other applications it is rated very high ↑.

Beryllium

Beryllium is a lightweight, brittle, and steel-grey metal. It is a special case regarding global supply. There is basically only one large scale mining site in the USA resulting in an extremely limited supply structure [Dehoust et al. 2020]. Beryllium is mainly used in different variants of electronic applications and the defence sector. In the EU ca. 80% of beryllium are used in copper-beryllium alloys for high performance electrically conductive terminals and mechanical components. The rest is used in beryllium metal matrix composites (>50% Be) and beryllium-oxide ceramics for electrical insulation components with high thermal conductivity [EC 2020c].

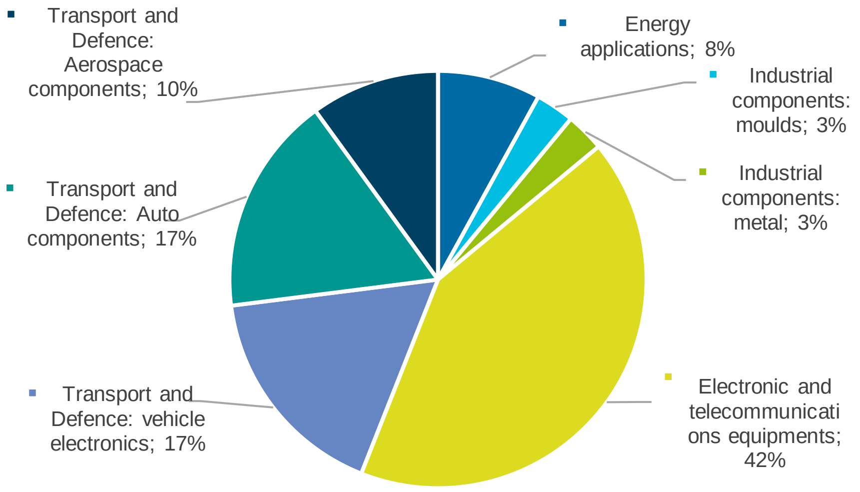

Figure 2 Uses and end-uses of beryllium in the EU 2012-2016 [EC 2020c]

It is projected that in the next 5 to 10 years there will be an increase in demand. The growth is not coming from green technologies when considering the applications above [EC 2020c]. Beryllium for environmental technologies is rated low ●, while for other applications it is rated very high ↑.

Vanadium

Metals that are mainly used to produce high-quality steel alloys, such as tungsten and vanadium are a good example that shows that demand is mainly driven by ‘conservative’ sectors. Vanadium is a hard and silvery-grey metal. It is obtained through classic mining and processing with several steps like roasting and extraction. In the EU it is almost entirely used in different products of the steel industry [EC 2020c].

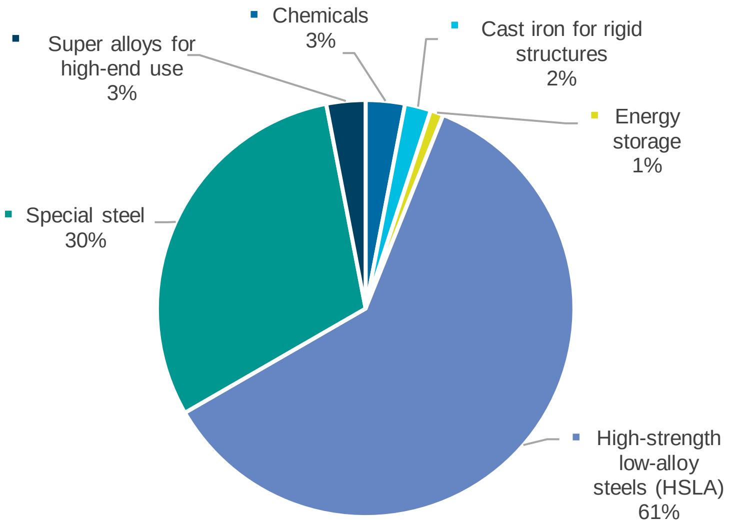

Figure 3 **Uses and end-uses of vanadium in the EU 2012-2016 [EC 2020c]**

The demand for vanadium in the EU is projected to increase in all applications (steel, titanium, chemicals, and energy storage). The growth is driven by increases in steel production and an increasing unit consumption of vanadium per ton of steel [EC 2020c].

The use of vanadium in redox-flow batteries could increase in the future which would correspond to driving demand from the green technology category. Nonetheless projections indicate that steel will still dominate vanadium demand [Roskill 2021]. Therefore, vanadium is rated low 🟢 for green technologies, while for other applications it is rated very high ↑.

1.4 Defence and aerospace sectors

Beside other sectors and applications the defence and aerospace sectors play a crucial role in demand of CRMs. Due to the highly specialized applications alloys of specific characteristics containing critical raw materials are often required.

The JRC identified 39 materials required for the manufacturing of such specialized and high-performance applications in the defence sector. For around a half of those materials the EU is completely import-dependant [Pavel & Tzimas 2016].

For instance, rare earth elements are crucial for remotely controlled aircrafts, targeting lasers or satellite communications. Niobium, vanadium, or molybdenum are needed for the manufacturing of combat aircraft fuselages or beryllium is needed for lightweight alloys used in jets [JRC 2020a]. Moreover the following materials play an important role in the defence sector: beryllium, boron, dysprosium, germanium, gold, indium, magnesium, molybdenum, neodymium, niobium, praseodymium and other REEs, samarium, tantalum, thorium, titanium, vanadium, zirconium and yttrium [Pavel & Tzimas 2016].

Since the defence and aerospace sectors are also at the forefront of technological development many green technologies are also used there. For example, lithium-ion batteries are needed in many defence applications, nonetheless the civil sector is the main driver of future demand [JRC 2020a].

Overall, it is very hard to estimate future demand in the defence sector. Since it is of strategic-political relevance, figures and specific data are not available.

2 Strategies for flattening the CRM demand

What policy tools could flatten the future demand for CRM? What are the possibilities to substitute some of critical raw materials with green alternatives, natural or synthetic, that would reduce the pressure to expand mining activities? What is the potential for such green alternatives in Europe?

This document focuses on the technical options to curb demand for critical raw materials. One relevant aspect beyond this scope would be a change in behaviour (the idea of sufficiency with e.g. less individual transport with own car and more public transport or car sharing instead). However, only technical solutions like substitution possibilities, material efficiency and technical innovations will be discussed in the following paragraphs.

2.1 Substitution

Substitution of critical raw materials can be achieved by a 1-to-1 substitution of one raw material by another raw material. For example, natural graphite can be replaced by synthetic graphite in a lithium-ion battery (LIB). Furthermore, components in a product can be substituted without changing the function. For instance, a permanent magnet in an electric motor with rare earths can be substituted by an electric motor without critical metals such as the asynchronous motor.

The following three selected substitution options will be further explained a) synthetic graphite substitutes natural graphite in an LIB b) LFP cell chemistry (no cobalt included) replaces NMC (including cobalt) in an LIB c) asynchronous motor substitutes e-motor with permanent magnet including rare earth elements in an electric vehicle.

2.1.1 Example I: Synthetic graphite substitutes natural graphite

Most natural graphite is mined in China (about 64% of world production in 2019) [USGS 2021], with all production of battery-grade spherical graphite from natural graphite flakes taking place on Chinese soil [Shaw 2020]. Lithium-ion batteries most commonly employ graphitised carbon as anode material, taking advantage of the exceptional electrochemical properties in such materials [Dolega et al. 2020]. However, there are two types of graphite – natural and synthetic graphite (also called artificial graphite). While natural graphite is mined and then purified, synthetic graphite is synthetically produced by heating a carbon-based precursor. Producing natural graphite for use in batteries requires extraction, separation, and processing to generate the necessary structure for graphitic anode materials – and with these activities come certain environmental and waste-related issues (e.g. groundwater pollution, waste production, excessive energy demand). Synthetic graphite production on the other hand requires high amounts of energy and involves a long processing time. Several weeks are needed for the calcination, graphitisation, and cooling processes, during which the materials must be heated to ≥2500°C before cooling [Gomez-Martin et al. 2018]. The energy sources for heating pose the largest environmental concern for synthetic graphite, and the carbon sources, waste products from coal and oil industry, are not renewable. Although both, natural and synthetic graphite, have similar chemical structures, their electrochemical behaviours and prices differ. Synthetic graphite can be produced in a constant high quality with certain specifications and is more versatile in its use, but it is also more expensive [Dolega et al. 2020]. Therefore, their usage profile slightly differs. Natural graphite is commonly used for all applications where its quality is sufficient due to the lower prices. Substituting natural graphite with synthetic graphite for further applications is thus comparably easy but at a higher price.

2.1.2 Example II: LFP cell chemistry substitutes NMC cell chemistry

Staying on the topic of lithium-ion batteries (LIBs), it is possible to substitute the positive cathode material of NMC (lithium nickel cobalt manganese oxide, $LiNi_xMn_yCo_zO_2$), containing the CRM cobalt [EC 2020a], by other cobalt-free cathodes like, e.g. LFP (lithium iron phosphate, $LiFePO_4$). Most of the cobalt is produced in the Democratic Republic of the Congo (DRC), amounting to nearly 70% of global supply [USGS 2021]. NMC is mostly used for traction batteries for electric vehicles, as it has several advantages like, e.g. a high energy density and sufficient lifetime and safety. LFP on the other hand is the standard material for LIBs applied in stationary energy storages and traction batteries for electric vehicles with more space like buses, as it is cheaper at the moment and can lead to an even longer lifetime of a battery [Hesse et al. 2017]. However, it has a lower energy density leading not only to a higher weight and volume of the battery, but also to more other (inactive) materials needed per unit of storable energy. This disadvantage can be partly overcome by using an innovative cell design (see Example II: Thinner electrode foils). On the other hand, replacing NMC by LFP has also disadvantages in terms of recyclability, as no sufficiently valuable materials can be recovered to pay for the recycling effort [Betz et al. 2021]. When considering the sustainability and cost of a product, the end of life, especially the recyclability, must be considered as well.

2.1.3 Example III: Asynchronous motor substitutes permanent magnet synchronous motors

Apart from the lithium-ion battery (LIB), the electric motor is a central component of electric vehicles. Car manufacturers use different electric motors in their various models. In the resource debate, electric motors are primarily addressed in reference to permanent magnet synchronous motors (PSM) since these electric motors are equipped with permanent magnets based on neodymium iron boron (NdFeB) magnets. NdFeB magnets contain around 30% by weight of rare earth elements: the light rare earth elements neodymium and praseodymium and the heavy rare earth elements dysprosium and terbium. Dysprosium and terbium are relevant for stabilising the magnetic function of the PSM even at higher temperatures, an important role for use in electric vehicles [Schueler et al. 2016]. About 60% of rare earths are produced in China in 2019 [USGS 2021] and listed as CRMs [EC 2020a].

Apart from PSM, there are also other types of electric motors, which operate without permanent magnets: electrically excited synchronous motors (EESM) and asynchronous motors. These electric motors, which do not require rare earth elements, in turn require significantly more copper than the PSM and are also not as energy efficient [Buchert et al. 2011, Bast et al. 2014]. Hybrid and plug-in hybrid electric vehicles (HEVs and PHEVs, respectively) generally use PSMs that contain NdFeB magnets with rare earth elements. The lighter and smaller PSMs are necessary here because the additional combustion drive in HEVs and PHEVs requires additional installation space. In electric vehicles without additional combustion drive, on the other hand, there are different types of electric motors, depending on the manufacturer and model. Thus, there is the chance of substituting one with the other, depending on the focus.

2.2 Material efficiency

Material efficiency addresses the decrease of material use compared to the current situation. Usually this is implemented during the development of products and processes, as saving materials directly relates to economic savings. The latter means, that there is a strong driver to implement material efficiency. Thus, low hanging fruits are already harvested in most cases when technologies are in a mature state. When they are still in development there is still potential that can make the difference for the breakthrough of a technology in the market.

2.2.1 Example I: Fuel cells

In case of the fuel cells one factor to achieve this breakthrough is the reduction of use of platinum. Platinum is very expensive, and its reduction can decrease the costs of fuel cells. Another influence factor is the scaling of the production which would have a bigger impact, but the demand for platinum needs to be decreased before a high number can be produced.

2.2.2 Example II: Thinner electrode foils

Another good example again relates to lithium-ion batteries (LIBs). The electrodes of the LIB consist of a double-sided coating of a current collector, which is usually aluminium for the cathode and copper for the anode. These aluminium and copper foils have been made thinner over the years without major negative impacts on the battery cell performance. This not only saves material, but also increases the energy content per weight and volume, as less additional material is used in a cell with the same capacity.

2.2.3 Challenge: Recycling

Material efficiency is important for the cost and material savings described, but it also has an impact on recycling. When the content of recyclable materials is lower, recycling is less interesting from an economic point of view. It also has a direct impact on material efficiency when materials are lost because their content in a product is so low that recycling is uninteresting from an economic perspective or there is no longer a technical solution to recover the material. In the first case, recycling must be mandatory and priced into the selling price of the product, with specific and realistic targets for the material in question. In the second case, there are only two solutions, developing better recycling techniques or designing the product for recycling to enable or facilitate extraction.

2.3 Innovation

Another technical way to reduce CRMs or create new or more efficient ways for their production is innovation. However, there is always a risk that a new technology with higher performance and thus a potential for reduced CRM consumption is simply used in the same or even increased quantity, as the demand also increases with it. For instance, increases in the energy density of batteries in power tools did not lead to smaller batteries but to their adaption in more demanding applications. While in the past, cordless power tools were restricted to e.g. drills, today chainsaws and rotary hammers can be purchased with lithium-ion batteries (LIBs). Another example is that the user gets a product with better performance like an electric vehicle with a higher driving range instead of smaller batteries being installed and thus saving material. Leaving the rebound effects like this one aside, there are several examples of innovation leading to reduced CRM consumption for the same benefit, which are described in the following section: Solid-state batteries and jellyroll-to-module improving battery technology, larger wind turbines leading to higher efficiencies and innovation in primary mining making it possible to extract raw materials out of former waste products.

2.3.1 Example I: Battery technology innovation

Lithium-ion batteries (LIBs) are in constant development, especially in terms of energy content per material used. Every improvement in energy content also leads to a reduction in the amount of material used per stored energy. However, there are physical limits on how much energy a LIB can store on a material level. Furthermore, as explained before, NMC cells, the standard for the automotive industry with one of the highest energy contents, also contain cobalt, a CRM. To avoid using this and instead make use of cobalt-free LFP as cathode material and get a similar energy content, there are two innovations, which are already applied on the market. The first one is a technology called jellyroll-to-module. The core of the innovation is the omission of part of the cell housing and the direct use of the battery stack, consisting of anode, cathode, separator, and electrolyte, in a larger housing that usually contains several individual cells. This technology is so far only possible with LFP, mainly due to safety issues, but leads to similar energy contents as commercial NMC cells. The second innovation concerning batteries is the solid-state battery, which enables the use of lithium metal as anode material instead of the standard anode material graphite. This strongly increases the energy density and either can lead to less material used per stored energy or make it viable to use LFP instead of NMC. Solid-state cells with LFP, lithium metal and a polymer electrolyte are already on the market for certain applications, however with the disadvantage of higher operating temperatures leading to increased energy consumption [Dühnen et al. 2020].

2.3.2 Example III: Larger wind turbines

There are four different types of wind turbines, but all four contain rare earth elements (REE) in NdFeB magnets in varying quantities [JRC 2020b]. What they all have in common is that they depend on the occurrence of wind and its speed. As a rule of thumb, the wind is stronger at higher altitudes [Wallasch et al. 2017]. To save CRMs, it is therefore advisable to increase the height of the concrete base of the wind turbine to increase the height of the hub and use the magnets employed more often and with greater efficiency. This requires durable materials and an internal control system that monitors weather conditions to prevent damage to the wind turbine from too strong winds, but also saves raw materials.

2.3.3 Example IV: Recovering material from old tailings

Opening new mines and constructing the corresponding infrastructure often leads to significant changes in landscapes and negative environmental impacts. In many old mine-sites waste rock and tailings still contain significant amounts of material that were not recovered due to technical restraints in the past. Many examples show that reprocessing of old tailings can lead to a high yield of recovered raw materials. In many cases this is even beneficial from an environmental standpoint since the waste rock can then be stored more appropriate after treatment. While not necessarily a huge issue in Europe, in other places old mining residues are in direct vicinity to housing of local population

Ongoing research in Europe shows that valorisation routes for sulphidic tailings from copper-zinc, zinc-lead, and mixed ores can be reprocessed potentially retrieving CRMs such as indium, germanium, or gallium [SULTAN 2020].

3 The role of recycling

What is the overall potential and the business potential for recycling critical raw materials to mitigate the need for additional amounts of these materials? How large are potentials for job creation in the recycling sector and in the mining sector?

Recycling is the most crucial element for a circular economy. The EC has clearly stated through the Circular Economy Action Plan and the Green Deal that it is of the highest strategic importance for a sustainable raw material supply. But what role does recycling currently play in green technologies and what are future potentials for recycling?

3.1 Outlook recycling of EVs

Recycling of end-of-life products is essential to reduce the dependency from primary resources. In addition, in the case of lithium-ion batteries (LIBs), a proper recycling of spent LIBs is absolutely necessary due to the risk of fire. As a lot of green technologies are currently in the ramp-up phase, secondary material, however, can only cover a minor share of the needed raw materials for producing green technologies in the short term. A larger amount of recycled material is conceivable in mid-term future. A good example for a technology on the rise is the case of traction batteries for the electric vehicle market. In the following figure a scenario from 2020 to 2035 of the lithium-ion traction batteries for electric vehicles put on the market (POM; dark blue bars) and the potential collected end-of-life batteries (EoL; light blue bars) is shown. From this development the raw material demand for produced LIBs and secondary raw material potential from EoL batteries can be estimated. The figure illustrates that in the short-term only a small part of the raw materials demand can be covered by secondary materials. In this ramp-up phase of a (new) green technology it is important to develop a proper recycling infrastructure including collection, transport, storage, and recycling of EoL batteries.

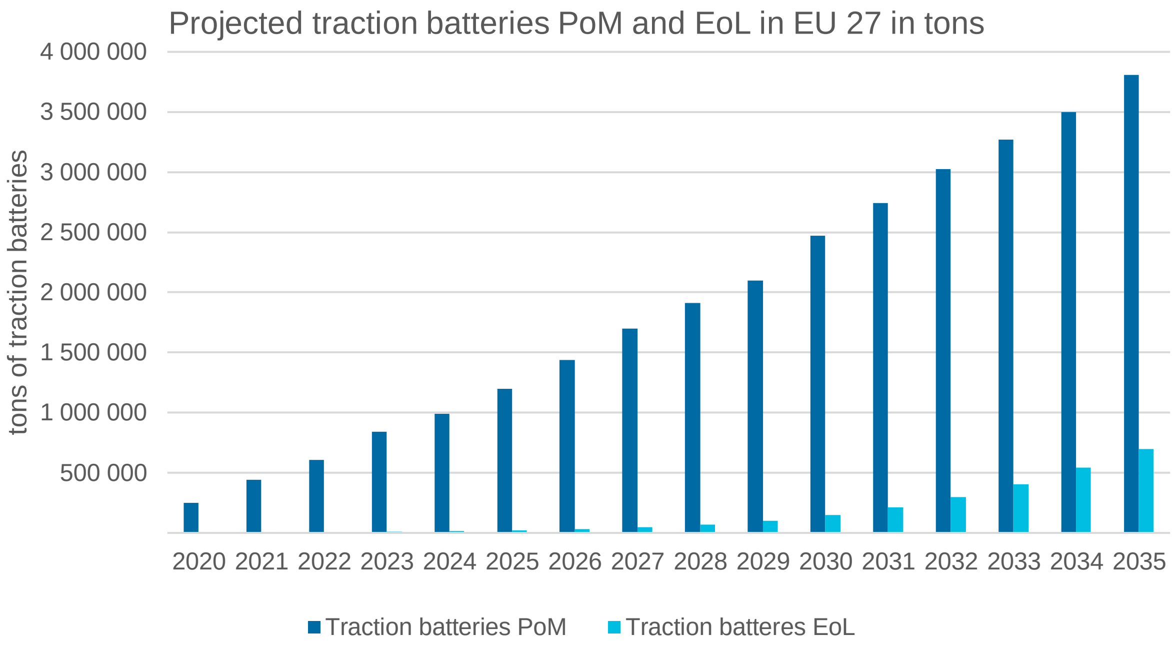

Figure 4 **Projected traction batteries PoM and EoL in EU 27 in tons [based on Stahl et al. 2021]**

Although in short term secondary materials won't be available in large amounts, there are developments that underline the importance of recycling. Cobalt rich cathode chemistries have been used in the first EVs, accordingly they will reach the end of their use phases first and will need to be recycled. Due to the ongoing trend to decrease cobalt contents in the cathode of newer generations of LIB, recycling of cobalt from e.g. one old battery can potentially be used to build two new ones.

Recycling in mature markets have a large potential for high recycling input rates. For example, recycling of lead-acid batteries is widely established and their production relies on secondary raw materials.

3.2 Job opportunities in recycling and mining

In this section a short overview of jobs created by mining and recycling will be given. When comparing them, it should be noted that they do not necessarily compete. It is not a question of either mining or recycling. When it comes to the question of raw material supply, both play a crucial role. Depending on the sector or market the importance of the two will vary. Generally, in mature markets recycling becomes increasingly important. Emerging markets on the other hand need primary raw materials as there is no stock yet. Sometimes an emerging market can benefit from the raw materials of a declining market, as it might be the case with platinum in automotive catalysts that could be used for fuel cells.

3.2.1 Jobs in mining

Currently, Europe is highly dependent on the import of raw materials. Only limited mining activities are taking place in Europe with a strong focus on the Scandinavian countries. Accordingly, discussions are growing louder around mining in the EU, both to become more independent and to ensure sustainable mining practices. Regardless of advantages and disadvantages of increased mining activities in the EU, the following section will investigate one aspect specifically, namely job creation in the mining sector.

Job creation through mining is often a topic discussed in connection to resource-rich developing countries. The effects of mining on job creation are very difficult to assess. Direct employment only covers one aspect and evaluating indirect effects on other sectors is challenging. For example, total mining production in Sweden peaked in the early 1970s, directly employing about 12 000 people. After a decline until the mid-1980s, production in 2008 is almost at the same level as in the peak phase, but only about 5 000 people are still needed for production [Moritz et al. 2017].

Regarding direct employment it must be underlined that productivity gains over the last decades resulted in significant reduction of manual labour required. Moritz et al. [2017] state that mining '*is an industry that requires large capital investments and the number of direct jobs is relatively low'*. Productivity increases are likely to continue hand in hand with technological process digitisation and automation [Moritz et al. 2017].

Indirect employment is much harder to grasp as it is connected to uncertainties and assumptions. Nonetheless, mining has linkages to the rest of the economy. A more direct link is the use of raw materials in downstream activities such as refining. Also, backward linkages to the production of machinery are possible. Directly employed households might have increased incomes to be spent in the local community. Moreover, fiscal effects are possible, when increased tax revenues are invested in the community. In the case of Sweden, a job multiplier a little below 1 has been determined, meaning that for each directly employed person in mining almost one more job in another sector is created [Moritz et al. 2017]. This is of course only a rough value that will differ depending on the individual raw material mined and the region where it is located.

3.2.2 Jobs in recycling

Recycling describes a very broad range of different processes and activities that differ very much depending on the product that is being recycled. Recycling of plastic bottles is completely different to recycling of end-of-life vehicles or lead acid batteries. Therefore, in the following the example of lithium-ion battery (LIB) recycling will be used to estimate the level of potential job generation.

Like the case of mining, jobs in recycling are both direct and indirect. However, the number of different occupations directly connected to recycling that take place at geographically separated locations are more diverse when compared to mining. The recycling process itself is not the most labour-intensive part of the process. The collection and transport logistics as well as the disassembly of batteries to modules and cells are currently done manual. A prediction whether some sort of automation can take place is hard to predict. Currently, every OEM uses different battery designs and architectures resulting in a variety of problems with disassembly. Just to name one example, the use of glue, screws or both leads to difficulties in terms of adapting the disassembly process. Currently there is no standardization regarding the design of the battery which might be helpful in having a more automated process.

Jobs can be created to varying degrees at each step of the recycling process, from collection, transport, disassembly, processing to recycling. There are no reliable statistical data on job creation thus far. Nonetheless, there are some indications to estimate the numbers. Drabik & Rizos [2018] interviewed recyclers and collected information to determine employment effects. They concluded that per 1 000 tons of end-of-life LIBs ca. 15 jobs were created. Only 20% of the jobs are connected to recycling itself, while 80% cover collection, logistics and disassembly. It should be noted that technical development is not taken to account and the numbers therefore reflect status quo. The authors point out that the numbers do not include effects on other sectors e.g. the construction of recycling facilities [Drabik & Rizos 2018].

Calculating with volumes presented shown in Figure 4 a total of about 2 250 jobs could be created in 2030 and already about 10 500 jobs in 2035 in the traction battery recycling sector alone in the EU. And these figures should only be understood as the beginning of what will then be a significantly larger increase in employment by 2050.

Other important future fields for additional job creation in the EU recycling sector can be identified:

- Improved ELV recycling,
- Improved WEEE recycling,
- Improved packaging waste recycling,
- Recycling of solar modules,
- Recycling of wind turbines (onshore and offshore),
- Recycling of fuel cells and electrolysers,
- Recycling of selected components from decommissioned nuclear power plants and fossil fuel power plants.

The OECD emphasises the opportunities for resource-importing countries to use reprocessing as a source of growth and employment [OECD 2018]. An EEA publication highlighted that employment in the EU in recycled materials increased from 229 286 to 512 337 between 2000 and 2008. This represented an annual growth rate of 10.57% [EEA 2011].

3.3 Economic effects of recycling in the battery industry

A brief overview of employment effects has been presented in the section above. However, other economic effects of recycling need to be underlined. It helps to reduce the import dependency of the EU regarding raw materials. Drabik & Rizos [2018] estimated that in 2030 materials with a value between 408 and 555 million EUR could be recovered. In 2035 the value adds up to between 909 and 1 200 million EUR [Drabik & Rizos 2018].

The value of recovered materials is largely dependent on raw material prices, which are extremely hard to predict. For instance, the price of cobalt is rather volatile. In the beginning of 2018, prices went above 80 000 USD per tonne, in mid-2019 they were only slightly above 25 000 USD per tonne. Prices in 2021 until May alone ranged between 30 000 and 50 000 USD per tonne [LME 2021].

Moreover, the battery compositions also play a vital role in recycling and economic effect. The first traction batteries put on the market had high cobalt contents in comparison to today's trends. The high cobalt content makes those batteries more attractive for recycling. Current and future batteries have a reduced cobalt and higher nickel content. Moreover, other cell chemistries such as LFP (lithium-iron-phosphate) are currently discussed for use in smaller electric vehicles in the EU. The material composition is less attractive for recycling since the amount of valuable materials is considerably lower than in other variants of the LIB.

4 Policy options

What policy measures could support businesses to adapt to the increased recycling needs / circular economy in CRM?

There is a variety of measures that can help to stimulate the recycling sector and foster a circular economy. In the following some general strategies such as recycled content quotas or increased collection rates will be presented and point to potentials for optimisation in current legislation.

4.1 Recycled content

A crucial point to promote recycling is a healthy market that is not distorted by extremely low primary raw material prices. One approach is to impose mandatory quotas of recycled content.

The prices of recycled materials compete with the prices of primary raw materials. Sometimes, mined raw materials are cheaper, making recycling economically unattractive. The introduction of a mandatory recycling quota can stimulate the recycling industry by artificially creating a scarce commodity with high demand and low supply.

In a growing market like Li-ion batteries, relatively small quantities of end-of-life products are available for recycling. As a result, the cost of recycling batteries is high because there are no economies of scale. In a normal market situation, this leads to high prices for secondary raw materials and low demand compared to primary raw materials. In the worst case, there is no recycling at all, or materials are downgraded because high quality recycling is not economically viable.

The introduction of mandatory recycled content in new products could change this situation. Companies producing goods would then be forced to source secondary raw materials. Since there would only be a limited amount of recycled material available, but demand would be high, prices would rise. Recyclers would then be compensated for their efforts and would not be in direct competition with cheaper primary materials. In a more mature market, secondary materials could become more competitive with primary materials, even without quotas on recycled content.

In the new battery regulation proposal, the European Commission (EC) is already proposing recycled content for new batteries for Ni, Li and Co. In 2027, companies will only have to declare the recycled content of these materials, but in 2030 there will be specific minimum recycled content values (12% cobalt, 4% lithium and 4% nickel). In 2035, these values will be further increased (20% cobalt, 10% lithium and 12% nickel) [European Commission 2020].

4.2 Material specific recycling rates

A synergetic measure on the other side of the value chain, which can help to increase the recovery of CRM from products although it is not commercially feasible, are material specific recycling rates. An example, where these are planned, is the new Proposal for a Battery Regulation from the EC. For LIBs, according to the new proposal, certain general recycling efficiencies must be met (65% by 2025 and 70% by 2030 for the whole battery). However, also certain specific materials must be recovered. While copper, cobalt, and nickel must be recovered at 90% in 2026 and 95% in 2030, the CRM lithium, where no recycling is taking place at all today in the EU, 35% have to be recovered in 2026 and 70% in 2030.

Accordingly, material specific recycling rates make sure that critical raw materials do not get lost but remain in use.

4.3 Regulation on EU level

Many waste streams are addressed on an EU regulatory level. In many cases there are possibilities to improve the legislation to make sure that a circular economy is fostered:

4.3.1 WEEE Directive

The WEEE Directive does not specifically address certain critical raw materials such as silicon, indium or others which are of relevance for photovoltaics.

For the handling of photovoltaic panels, the WEEE Directive stipulates that "*Member States shall adopt appropriate measures to minimise the disposal of WEEE in the form of unsorted municipal waste, to ensure the correct treatment of all collected WEEE and to achieve a high level of separate collection of WEEE, notably, and as a matter of priority, for […] photovoltaic panels […].*" Article 5 (1)

PVs fall into equipment category 3 according to Annex III of the WEEE Directive. The minimum recycling targets according to Annex V Part 3 a) for this category are:

- 85% shall be recovered, and
- 80% shall be prepared for re-use and recycled.

In addition, equipment category 5 also includes small equipment with integrated photovoltaic panels. For this category, according to Annex V Part 3 c) minimum recycling targets are:

- 75% shall be recovered, and
- 55% shall be prepared for re-use and recycled.

Although at first 85% recovery seem like a lot, the threshold leaves a lot of room for optimisation. Often critical metals such as indium are not used in large volumes in a specific application. E.g. copper-indium-gallium-diselenide (CIGS) PV panels only contain ca. 27 kg of indium per MW, in comparison there are ca. 60 tons of steel needed per MW [JRC 2020b]. In summary there is the possibility to circumvent recycling specific materials since other materials that are easy to recycle are present in large enough volumes.

4.3.2 ELV Directive

The ELV Directive does not specifically mention critical raw materials. The points of the ELV Directive listed below could also be understood in the context of improved recycling of parts with CRM:

- Article 4 paragraph 1 (b) and (c):

In order to promote the prevention of waste Member States shall encourage, in particular:

> (b) the design and production of new vehicles which take into full account and facilitate the dismantling, reuse and recovery, in particular the recycling, of end-of life vehicles, their components and materials
>
> (c) vehicle manufacturers, in liaison with material and equipment manufacturers, to integrate an increasing quantity of recycled material in vehicles and other products, in order to develop the markets for recycled materials

- Article 6 paragraph 3 (c):

> Member States shall take the necessary measures to ensure that any establishment or undertaking carrying out treatment operations fulfils at least the following obligations in accordance with Annex I […] stripping operations and storage shall be carried out in such a way as to ensure the suitability of vehicle components for reuse and recovery, and in particular for recycling.

Point 4 in Annex 1 specifies this information:

4. Treatment operations in order to promote recycling:

- removal of catalysts,
- removal of metal components containing copper, aluminium and magnesium if these metals are not segregated in the shredding process,
- removal of tyres and large plastic components (bumpers, dashboard, fluid containers, etc), if these materials are not segregated in the shredding process in such a way that they can be effectively recycled as materials,
- removal of glass.

Only the catalysts are a specific part containing CRM, that is addressed here. The Directive could be extended to include parts in which CRMs are (could be) installed.

In Article 7 paragraph 2 (b) it is set that “Member States shall take the necessary measures to ensure that the following targets are attained by economic operators: […] no later than 1 January 2015, for all end-of life vehicles, the reuse and recovery shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the re-use and recycling shall be increased to a minimum of 85 % by an average weight per vehicle and year.” This means that 10% of the 95% goal can be fulfilled by energetic valorisation.

Like the WEEE Directive the ELV directive has high targets but looking at the composition of an ELV [Monier et al. 2017] 70% of the total weight are ferrous metals, which are easily recycled. Tyres, glass, catalytic converter, lead-acid battery and bumpers make up for another 10%. This means from all the remaining materials only 5% needs to be recycled and another 10% needs to be put into an energetic valorisation. Looking at 4% non-ferrous metals, which include the CRM, a big part of those are not recycled for economic reasons, e.g. the permanent magnet in all the small motors, like for the adjustment of the outer mirrors, will be destroyed through the shredding and will not be recovered. Like mentioned above there is the possibility to circumvent recycling specific materials since other materials that are easy to recycle are present in large enough volumes.

4.4 Design for recycling

Guidelines specifically for applications where CRMs are or can be used do currently not exist (e.g. for electronic and electrical equipment). The following are principles from the design-for-recycling guidelines described in [Öko-Institut 2021] for plastics applications that can also be adapted to applications where CRMs are used. Compared to plastics, the electronic and electrical equipment may consist of several components with different recycling needs. An important principle of Design for Recycling (D4R) is the dismantlability and separability of components, e.g. metal parts from plastics such as housings or cable insulation, which are highly likely to contain flame retardants that can be problematic from a recycling point of view.

Even before a product is produced, the designer should consider in which waste stream the product will eventually end up and whether it can be collected, sorted, and recycled under the currently prevailing conditions. D4R guidelines should be material and product specific. For D4R to be implemented successfully, knowledge of how the product and material will behave at end-of-life under the given waste management practices in the countries is crucial. D4R criteria cannot be adopted one-to-one across all countries.

D4R should consider the following points:

- The material must be identified in the commonly used sorting schemes and correspond to one of the output fractions.
- It must be possible to recycle the material on an industrial scale, not laboratory-scale processes promised for the future.
- The material itself should have a high recyclable content.
- The material should be easy to recycle, i.e. there should be no recycling system incompatibilities such as inseparable bonding.

When drafting a D4R policy, the following points should be considered:

- Existing knowledge gaps in the transparency of recycling processes could be addressed by starting from guidelines that are effective for certain products and then adapting them to address whole product families. Different guidelines for the same product should be avoided.
- Ensure regular updating by integrating developments on product design, disruptive recycling technology and trends in consumption.

- It was indicated that increased recyclability may lead to a decreased functionality. Guidelines will only be accepted by the market if a level playing field is created by involving all stakeholders and formulating precise standards. The coherence with other initiatives and regulatory requirements (e.g. Ecodesign Regulation) is also important.

- Testing processes to assess recyclability and to demonstrate compliance with the guidelines through protocols are needed for all sectors and products, while introducing measures to reduce the financial burden imposed by the costs of lab testing and auditing at the same time.

- Promoting the guidelines along the value chain is important, e.g. through awareness raising campaigns, involvement of the industrial stakeholders within the development of the guidelines and creation of a label.

Finally, any trade-offs should always be considered when determining D4R criteria.

4.5 Collection rate

In order to be able to recycle as many raw materials as possible the products containing them must first be collected. One crucial element of this endeavour is the statistical collection of data in that regard and meaningful targets that need to be achieved and that are increasing over time. A great example is the collection rate of batteries. Starting from 2012, 25% of batteries need to be collected and 45% from 2016 onwards. Since the establishment of the targets collection rates in most Member States significantly increased. Although the data quality between the Member States might differ, the relative improvement of each country is real (compare Figure 5).

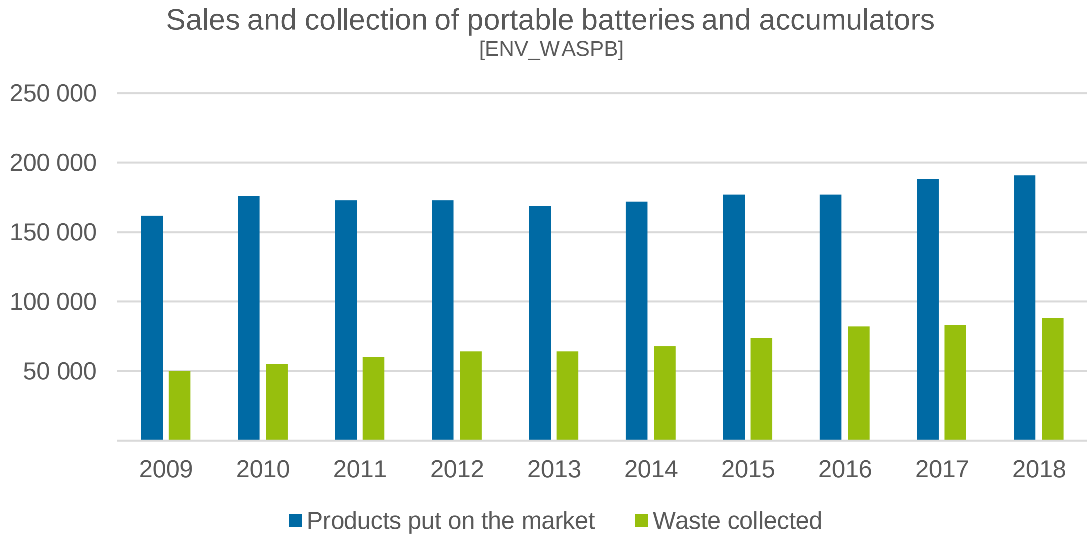

Figure 5 **Development of sales and collection of portable batteries and accumulators [Eurostat 2021]**

Another option to increase collection rates of any product are deposit systems. E.g. collection & recycling rates of PET plastic bottles in Germany lead to significantly increased recycling and collection rates. The same is true for aluminium cans. Hoarding effects could be reduced when a deposit needs to be paid.

Also, alternative business models, where products are not owned by the end-user but are only leased can lead to an easier collection.

4.6 Systemic shifts

Finally, systemic shifts can reduce demand pressure for critical raw materials. A good example of this is the transport sector. Increased expansion of public transport, combined with modern drive technologies, will mean a strong increase in electric buses. The production of these electric buses also requires critical raw materials for lithium-ion batteries and electric motors. However, by switching from private motorized transport to public transport - in this case electric buses - larger net amounts of critical raw materials are saved. This can be explained by the fact that the specific material input for lithium-ion batteries, electric motors, etc. for the same service (passenger kilometres) is considerably lower in the case of electric buses compared to electric cars. Many other relevant areas can be identified for potential savings through systemic shifts: Freight transport, urban and regional planning, infrastructure planning, electric appliance rental centres, etc.

5 Conclusions

The paper clearly showed that the increasing demand for CRM is only partly triggered by greening the economy. Other sectors such as digitisation, defence and aerospace or the steel industry are large purchasers of CRMs. Green technologies that are emerging have very high growth rates resulting in very large factors when comparing future demand to current demand. Accordingly, the framing often exaggerates the required volumes. Comparing projected demand in tonnages to current production of other materials provides a different perspective. Future demand for battery materials only amounts to a fraction of current iron ore production.

From a scientific standpoint the potential to flatten the demand for CRMs in the short-term through recycling, substitution and other measures is limited. In the mid- to long term, recycling must play a key role. Therefore, policy needs to be set today to establish a functioning recycling market when large volumes of EoL vehicles, wind turbines, electric engines etc. are reaching the end of their use phase. Moreover, technological innovation and material efficiency can contribute to lowering demands. Instruments needed to foster such a development include:

- The EU must make sure that a market for secondary raw materials is established, that is not competing against primary raw materials.
- The EU must make sure that funding for technological development of recycling processes is ensured.
- The EU must undertake actions to improve the Design for Recyclability in all products containing CRMs.
- The EU should support material specific recycling rates instead of recycling quotas based on the total weight of an application.
- EU can set standards through regulation and therefore has a lot of leverage to trigger change towards a more circular economy. The proposal for a Battery Regulation and the upcoming impact assessment of the ELV directive are just two examples.
- EU policy must promote systemic shifts, such as in passenger and freight transport, to promote resource efficiency and thus also save critical raw materials.

What should be kept in mind is that often the increased input of critical raw materials in green technologies can lead to net beneficial effects for the environment. By using lithium and cobalt in batteries to build electric vehicles CRM are used. But simultaneously huge volumes of fossil fuels needed to fuel internal combustion engine vehicles are saved.

The paper clearly shows that recycling will not be providing sufficient material in the short to midterm to supply emerging applications that are needed for greening the economy. In particular, the growing lithium-ion battery demand for electric vehicles will only allow larger shares of recycled content in the mid-term future [Buchert et al. 2017, Buchert et al. 2019]. The supply of primary materials will remain crucial. Therefore, sustainable mining needs to be promoted. Regardless whether mining takes place within the EU or in other countries it must be ensured that sustainable (from an environmental AND social perspective) practices are applied.

In the long term a circular economy must be the target for all policies on the EU level regarding raw materials. Current changes in regulation need to set the basis for closed cycles in the future. By designing forward looking policies with ambitious and realistic targets that evolve over time, all stakeholders involved can adapt to the requirements. Moreover, there is a clear investment security for recyclers, reducing financial risks and ensuring sufficient recycling capacities in the future.

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