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Working paper of CRMs and CE (interconnection of critical raw materials and circular economy)?

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Summary

Critical raw materials and strategic raw materials play a key role in renewable energy technologies, e-mobility, defence and space. However, how much circular economy is in focus in solutions, infrastructure and assets containing critical raw materials? And does greater circularity lead to lower criticality? Criticality of raw materials and circular economy may not be typically mentioned in the same sentence, but they should. Circular economy presents a concept to keep materials in use whenever possible, recycle the materials and use recycled materials and residues to prevent waste generation and losing the valuable elements. This working paper of critical raw materials (CRMs) and circular economy (CE) summarizes the current understanding about interconnections of CRMs and CE. Currently, demand for using recycled materials is increasing, and demand to extend the lifecycle of the materials based on durability and repairability will play role in CE transition. Demand for recycling critical raw materials and strategic raw materials is probably forced in the future. Traceability would support circularity of critical raw materials, and it is closely linked with digital applications such as material and product passports. This working paper is targeted at a broad audience and decision makers to increase the knowledge about critical raw materials and strategic raw materials in circular economy.

Approval

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INTERCONNECTION OF CRITICAL RAW MATERIALS AND CIRCULAR ECONOMY

- MYTHS OR REALITY -

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Critical and strategic raw materials play a key role in renewable energy technologies, e-mobility, defence, and space. However, how much focus is there on the circular economy in these solutions, infrastructure and assets containing critical raw materials? And does greater circularity lead to lower criticality? The criticality of raw materials and circular economy may not typically be mentioned in the same sentence, but they should. Circular economy presents a concept to keep materials in use whenever possible, recycle the materials, use recycled materials and residues to prevent waste generation and the loss of valuable elements.

This working paper of critical raw materials (CRMs) and circular economy (CE) summarizes the current understanding about the interconnections of CRMs and CE. Currently, demand for using recycled materials is increasing, and the demand to extend the lifecycle of the materials based on durability and repairability will play a role in the CE transition. Use for recycled critical and strategic raw materials will likely be forced in the future. Also, traceability would support circularity of critical raw materials, and it is closely linked to digital applications such as material and product passports. This working paper aims to increase knowledge about critical and strategic raw materials in the circular economy.

INTERCONNECTION OF CRITICAL RAW MATERIALS AND CIRCULAR ECONOMY

Key concepts and state of art

The EU's Critical Raw Materials Initiative and Circular Economy Action Plan interlink in certain areas. The circular use of critical raw materials in the EU is analysed in extractive waste, landfills, and in sectors such as electric and electronic equipment, batteries, automotive, renewable energy, defence and chemicals and fertilisers (Mathieux *et al.*, 2017).

Critical Raw materials and Strategic Raw Materials (Grohol and Veeh, 2023) focuses on materials that are assessed critical or strategic. Moreover, CRMs can be distributed in low quantities across large variety of products that can challenge the management of CRMs.

CE Action Plan (CEAP) (European Commission, 2020a) prioritizes certain product groups such as electronics, ICT and textiles as well as steel, cement and chemicals that use critical raw materials.

Critical raw materials

Ensuring a sufficient raw material supply to meet demand is seen as economically important and directly supporting economic and social sustainability. EU level critical and strategic raw materials listing arises from the growing concern of securing raw materials for the EU economy. The Commission launched the European Raw Materials Initiative already in 2008 (COM(2008)699), and one of its priority actions was to establish a list of critical raw materials (CRMs) at the EU level that is frequently updated. (European Commission, 2018). The fifth list (2023) contains 34 CRMs that are particularly important for high technology products and emerging innovations and therefore of high economic concern.

Critical and strategic raw materials

Critical and strategic raw materials in the EU's 2023 assessment (Grohol and Veeh, 2023) include (strategic raw materials bolded, copper and nickel with italics as they are considered strategic but not critical):

- Aluminium/Bauxite
- Antimony
- Arsenic
- Baryte
- Beryllium
- **Bismuth**
- **Boron/borate**
- **Cobalt**
- Coking coal
- Feldspar
- Fluorspar
- **Gallium**
- **Germanium**
- Hafnium
- **Heavy rare earth element (HREE)**
- Helium
- Light rare earth elements (LREE)
- **Lithium**
- **Magnesium**
- **Manganese**
- **Natural graphite**
- Niobium
- **Platinum group metals (PGM)**
- Phosphate rock
- Phosphorus
- Scandium
- **Silicon metal**
- Strontium
- Tantalum
- **Titanium metal**
- **Tungsten**
- Vanadium
- ***Copper***
- ***Nickel***

Circular economy

Circular economy is an economic system in which life cycle thinking, sustainability, and systems thinking are at the core. Circular economy targets to maintain the value of materials i.e., keep materials in use whenever possible, recycle and use secondary raw materials to prevent waste generation and loss of the valuable elements, like critical raw materials. EU actions towards circular economy are listed in CE Action Plan (CEAP) (European Commission, 2020a) taking the product life-cycle into consideration from production to consumption, repair and remanufacturing, waste management, and secondary raw materials.

Beyond the current state of art circular economy strategies are often referred to as R-strategies, which offer a framework to support and design circularity through lifetime extension strategies (R3-R7) and recycling and recovery strategies (R8-R9) (see Figure 1). On the other hand, (R0-R2) strategies can radically change the game and reduce, for example, the need for raw materials using alternative materials and CRMs substitution.

CE and criticality concepts share common ground regarding recycling (R8). However, CRMs tend to be used in smaller volumes in products compared to base materials (cement, paper, plastics, iron, and copper) and they may not receive high-profile attention solely from CE perspective. On the other hand, the shorter loops of the CE models (R3-R7) overlook criticality and CRMs in many discussions. (Tercero Espinoza, Schrijvers, *et al.*, 2020)

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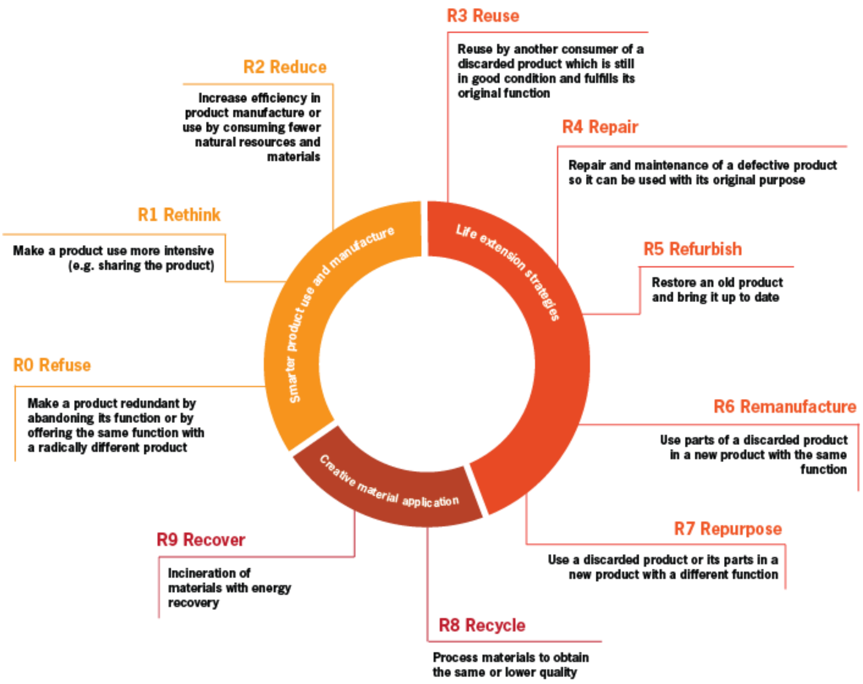


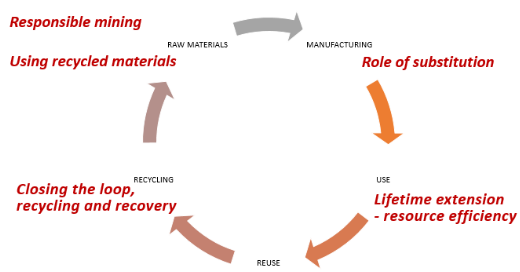
Figure 1. Circular R-strategies (R0-R9) after (Potting *et al.*, 2017)**.**

Concerning critical raw materials, the concept of circularity often seems to be limited to actions related to recycling (R8) and increase of secondary raw materials supply (R2). Still, this report discusses the current state of art and defines circularity and circular use beyond recycling. It includes attempts to prolong the lifespan of products using critical raw materials and enhance the use, functionality and performance of the recycled raw materials and residues (R0-R9). Also, to enable materials traceability, digital material passports and product passports serve as enabling technologies to support digital raw material circularity.

Wind and photovoltaics rely on CRMs

Wind and photovoltaic energy technologies rely on variety of materials such as neodymium (Nd), praseodymium (Pr), dysprosium (Dy), indium (In), gallium (Ga), and silicon metal (Si). The long-lifetime assets, such as wind turbines, will enter the recycling state, for example after 30 years. Therefore, raising circularity strategies (R3-R7) such as reuse and repurpose are relevant options to secure the availability of resources in the energy transition. (Mathieux *et al.*, 2017)

CRMs through the lifecycle



Responsible mining

Due to the expectations for the increased use of renewable energy and e-mobility, and therefore the growing need for critical and strategic raw materials, there is a common understanding that mining is essential for ensuring the raw materials supply. The way forward is responsible mining, which includes implementing circular economy strategies in primary raw materials production and the treatment of mine tailings. (Kinnunen *et al.*, 2022)

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Case cobalt
Improvements in the battery technology and recycling alone will not save the electric mobility transition from the future cobalt (Co) shortages in the short- to medium-term. However, in the longer term, cobalt-free batteries (substitution strategies) and progress in recycling can help mitigate the severity of cobalt shortages. (Zeng *et al.*, 2022)

Using recycled raw materials

End-of-life materials, industrial side-streams, residues and even waste materials are potential sources of raw materials. Some of these potential secondary raw material streams may be hidden and undervalued due to the lack of secondary raw material markets, and technological knowledge regarding their utilization as a raw material. Besides end-of-life materials, the production and manufacturing themselves generate side streams and residues, potentially including valuable CRMs. Increasing pressure to use recycled materials and design out waste are key strategies in circular economy. However, there are ongoing arguments about the quality and available quantity of recycled materials. The success of recycling and valorization strategies depends on factors such as the technical performance of recycled materials, their environmental acceptability, the presence of hazardous elements, and legislation. Furthermore, the emerging concept of direct recycling (material reuse) can significantly reduce environmental impacts of recycling.

Coming legislation in EU
The Commission proposed a new proposal for a Batteries Regulation (European Commission, 2020b) on 10 December 2020. Article 8 focuses on the minimum share of recycled content.

Role of substitution

Substitution is considered one strategy that can reduce the reliance of the economy on imported critical and strategic raw materials. Substitution of CRMs encompasses four sub-strategies: substance for substance, service for product, process for produce and new technology for substance (Tercero Espinoza and et al., 2015).

In criticality discussion, substitution is recognized as a means to reduce use of CRMs. Substitution can also help decrease the risk of scarcity and lower costs associated with raw materials, serving as economic drivers. Safe and sustainable by design principles include the substitution of toxic substances, and in the context of CE discussion, substitution of primary raw materials or fossil fuels with renewables is recognized. Circular strategies (R0-R2) can radically change the game and reduce the demand for raw materials through the use of alternative materials and the substitution of CRMs. (Tercero Espinoza *et al.*, 2015)

Substitution is not a standalone strategy; it can have implications for recycling. Developed recycling technologies may not be needed for substituted materials, or recycling may become economically challenging when valuable elements are replaced with abundantly available ones. Generally, substance for substance or material substitution, particularly, requires material design driven by economically viable technical performance, and aims to enhance specific functionalities such as mechanical durability, thermal or electrical properties or chemical stability. In the contexts of CRMs, the term "substitution" is more commonly used than "sustainable design" or "circular design". However, these terms overlap, as substitution can increase circularity, and CE discussion emphasizes sustainability to achieve circular business opportunities.

Substitution
Examples of the active substitution research and development include low-cobalt or cobalt-free cathodes for batteries, cobalt-free batteries (Castelvecchi, 2021), REE-free magnets and cobalt-free hard metals.

Lifetime extension - booster for resource efficiency

Circular economy and criticality share common ground when it comes to recycling, and discussions align on this aspect. However, lifetime extension (R3-R7) is another story. Design for durability and repairability are one of the key strategies for material lifetime extension, which in turn keeps CRMs in circulation for a longer period.

Durability targets for optimum mechanical, chemical and thermal properties of materials, and plays a crucial role in lifetime extension, especially in consumer products such as electronics. Concerning physical durability, product performance is improved with durable materials, for example, against aging and fatigue.

Repairability is a central strategy for lifetime extension. It can involve material repairability, as well as tasks such as cleaning, component replacement or software updates. To

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increase repairability, there needs to be information sharing about materials, components, and products, facilitated through digital material and product passports. Still, higher focus on repairability would need the information sharing about materials, components, and products, as in a form of digital material and product passports.

R strategies have significant impact on CRMs demand
Repair strategies can have a significant effect on CRMs demand in the energy transition. Studies have examined the potential impact of combining circular strategies on the annual metal demand for ten metals, including iridium, lithium, neodymium, dysprosium, cobalt, praseodymium, platinum, nickel, silver and silicon. Among the four strategies studied, the Reuse strategy (repair, refurbish and repurpose) had the greatest effect on reducing the total demand for the metals. (Metabolic et al., 2021)

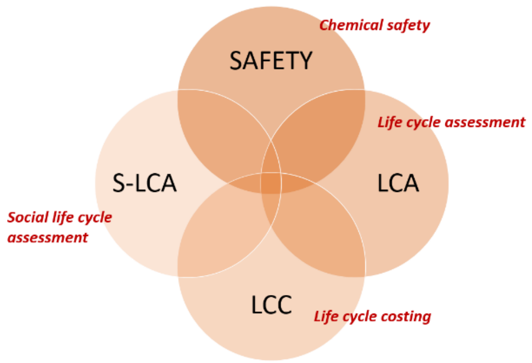
Closing the loops, recycling and recovery

The concept of urban mining is an important part of the circular economy and provides a degree of independence from natural resources, increasing supply security. Urban mining focuses on the management and utilization of secondary raw materials. Therefore, relying solely on the "recycling rate" is not sufficient to fully recognize and assess its information content. Several important framework conditions contribute to the success of urban mining. These include the presence of collection and recycling infrastructures, incentives for recycling, mandated recycling rates, penalties for landfilling; availability and costs of labor and recycling technologies, regulations for environmental protection, public and worker's health and safety, and regulations governing scrap trade. (Tercero Espinoza, Rostek, *et al.*, 2020)

Closing the loops concepts also encompass industrial symbiosis and closed loop recycling in industrial processes, and their valuable CRMs recovery. Utilizing process residues and side streams, which may contain CRMs used in industrial processes, not only complements zero waste strategies but also offers potential materials for substituting more scarce ones.

CRMs Recycling rates
The recycling input rate, which measures the proportion of secondary sources in the raw material supply, is generally low for CRMs. Only vanadium, tungsten, cobalt, and antimony have a higher recycling input rates ranging from 28% to 44 %. However, for many other CRMs (Be, Borate, Ga, In, Nb, P, Sc, Si-metal, Baryte, Bi, Fluorspar, Hf, He, Natural rubber, Ta) the End-Of-Life recycling Input Rate (EOL-RIR) remains at levels between zero and 1 %. (European Comission, 2018).

Sustainable design and assessment



The development of new sustainable low carbon technologies has three consequences: an increasing need for materials (volumes), an increasing number of elements and the need for new materials.

Green transition requires CRMs
New green energy technologies, electrification, and increasing digitalization require new raw materials that were previously needed rarely or for other applications. For example, lithium, which is currently crucial for electric vehicle batteries, a single car lithium-ion battery pack (such as NMC532) could contain around 8 kg of lithium, 35 kg of nickel, 20 kg of manganese, and 14 kg of cobalt. Forecasts suggest that the demand for Lithium is expected to grow by about seven times between 2020 and 2030 (Castelvecchi, 2021).

Design for Sustainability and Circularity

The Commission initiative for Safe and Sustainable by Design (SSbD) establishes a framework for design and assessing the safety and sustainability of chemicals and materials. The SSbD framework encourages innovation to replace hazardous substances in products and processes. It aims to develop new chemicals and materials, optimise or redesign production processes and the use of substances currently on the market to improve their safety and sustainability. (European Commission, 2022b, 2022a). SSbD guidelines and framework documents

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have been published by JRC (JRC, 2022), European Environmental Agency (EEA, 2021) and CEFIC (Cefic, 2021), covering both the design phase and assessment as the next step.

The implementation of the life cycle design concept for the development of innovative products and applications is supported by regulations. The Extended Producer Responsibility approach in regulations for different sectors, such as the electronics, will increase efforts to design products with high performance, longer lifespans and optimized recycling processes. Initiatives like the Sustainable Products Initiative (European Commission, 2022b) and other regulations in this direction can serve as the driving force for manufacturers to become more responsible for how their products are treated at the end of their life cycles, as they will bear part of the costs traditionally covered by the Public Administration.

Furthermore, this approach can lead to increased investments in finding substitutes for CRMs to minimize costs during the use and end-of-life phases, thus influencing global demand. In fact, this approach would consider the real costs associated with placing a product or service in the market.

Assessment and indicators

To determine whether the substitution or recyclability of CRM can lead to a more sustainable CE system, the sustainability assessment should be performed. This can be achieved through the Life Cycle Sustainability Assessment methodology combining the **Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment** to identify the environmental, economic and social impacts. The Environmental Footprint, already adopted by the EU as a suitable tool for evaluating the sustainability of products and services, can provide an estimation of the reduction of environmental and social impacts by substituting a CRM in a product, as well as confirm the economic viability of such a scenario. The identification of the environmental, economic and social hotspots along the lifecycle of a product and the correct traceability of the CRMs it contains can facilitate eco-design practices as well as substitution strategies.

Case permanent magnets
A comparison of carbon dioxide equivalents between different recycling routes and the reuse strategy on NdFeB magnets reveals that only direct recycling technologies and the reuse strategy decreased environmental impacts (carbon footprint) compared to virgin NdFeB magnet production. (Bailey, 2019)

Currently, **recycling indicators** are an important part of criticality assessments and circularity reporting in the EU.

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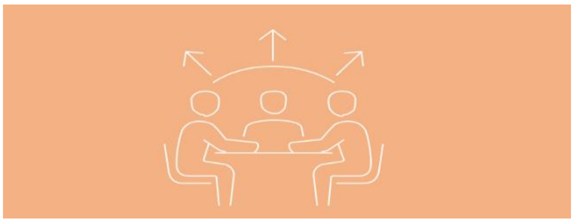
Figure 2. Heatmap created based end of life recycling input rate (EOL-RIR) data (Directorate-General for Internal Market *et al.*, 2020).

European reporting on the transition towards a more circular economy (CE) as well as the process of determining critical raw materials (CRM) both rely on the end-of-life recycling input rate (EOL-RIR) for individual raw materials (see Figure 2). However, it could be beneficial to include complementary indicators that address the recycling rates of CRMs. (Tercero Espinoza, 2021)

Circularity can be assessed through a set of indicators at various levels (materials, product, company, industry, national, global). These indicators can provide information on the content of recycled/secondary raw materials, the use phase and lifetime, and end-of-life recycling. However, currently it is unclear how to select and evaluate suitability of various indicators for a specific case and value chain. The new standard ISO/DIS 59020 Circular economy, measuring and assessing circularity is also under development, and may give guidance in the future for assessing circularity.

Circular economy business models

Service economy



Service economy, or servitization, is an economic model, where value is created by providing services instead of manufacturing goods or adding services to products (Baines *et al.*, 2009). Manifestations of service economy include sharing economy and product-as-a-service type models.

Sharing economy connects owners of goods with individuals or companies that would like to use them. It is facilitated by the development of sharing platforms that aim to boost the productivity of produced goods. This would decrease the need for manufacturing new goods, thereby reducing the consumption of CRMs.

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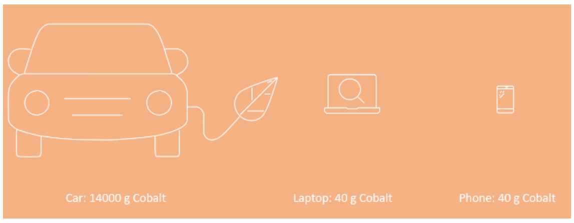
In **product-as-a-service** models, the manufacturer retains ownership of an asset and offers it to customers as a service. In this model, the company offering the product has an incentive to optimize the use and life cycle of the goods and utilize different circular strategies (R0-R9). This can lead to increased resource efficiency, extended product life cycles and reduced waste, ultimately resulting in reduced consumption of CRMs.

Service economy and CRMs
Service economy holds significant potential for reducing the critical raw material consumption across various economic sectors. Smartphones, tablets and laptops is one of the key application areas for service economy. A product-as-a-service company for smartphones, tablets and laptops refurbishes the returned devices and returns up to 98% of them back to use, with the remaining portion being recycled (Sitra, 2021). Extending the lifetime of these devices is crucial because they contain many critical and strategic raw materials such as lithium in batteries, silicon and gallium in semiconductors, PGM in integrated circuits and displays, rare earths in various components, copper in circuits and wiring, and indium in screens (Carrara *et al.*, 2023).

Recycling as a business model



CRMs and CE share common ground only in recycling of all circular strategies (R0-R9). The CRMs and CE business models are dependent on their economic viability. However, there are some **challenges related to recycling**. As an example, for electric Li-ion batteries, it is currently cheaper to mine lithium than to recycle it (Castelvecchi, 2021).

It could be argued: 'We can recycle almost everything – if someone pays for it!' Although several CRMs have a reasonable concentration and content in some products or parts thereof (see CEWASTE-Project, www.cewaste.eu) the current contribution of recycling to the total material input into the production system is considered low by the Joint Research Centre (JRC) despite government encouragement to transition towards a circular economy (Mathieux *et al.*, 2017).So, are CRMs with a high recycling potential not recycled in the end? Some of them are, like for example palladium, a highly valuable precious metal. Palladium recycling from electrical and electronic equipment (EEE), catalytic converters in cars, etc. is economically feasible under the current economic framework conditions. But is the high recycling potential determined by economic feasibility?

High recycling potential

High recycling potential physically implies that a material to be recycled has a sufficiently high concentration and accessible content in a device or a component therein to enable its recycling with a reasonable balance of effort and benefit (Deubzer *et al.*, 2019). Efforts physically are understood as investments in recycling infrastructure and technologies, expended energy and materials in (preparation for) recycling processes, space, and labor. The benefit would be the amounts and quality of recycled materials as a result of these expenses. Organizational and technological progress influences the balance of efforts and benefits and can thus increase the recycling potential. A better organization may, e.g., reduce the cost of collection. Better treatment technologies can result in higher energy and material efficiency of recycling processes, and thus improve the expense-benefit ratio and the economic feasibility by reducing the related cost. Organizational and technological progress are thus an important leverage to improve the recycling of materials.

Economic feasibility

What is the role of economic feasibility in conjunction with the recycling potential and actual recycling of – especially critical –materials? Is it that it just requires a smart business idea and an innovative business model to make recycling happen where it has not happened before?

Economic feasibility can be considered to have a hard and a soft core. The hard core of economic feasibility is that all efforts required for recycling must yield an economic profit for involved private operators, or at least must not cause costs that are not covered in cases of public operators such as, e.g., municipal waste management entities. Otherwise, recycling cannot happen since operators would have to stop their activities soon because of accumulating financial deficits. Organizational and technological progress as well as innovative business models can facilitate recycling of critical and other materials by reducing costs or increasing

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economic benefits. The soft core of economic feasibility is that it is not a fixed and rigid status. Economic feasibility of recycling is the result of economic framework conditions which are only partially based on natural laws that are inalterable. Economic framework conditions therefore can be adapted to enable recycling.

WEEE recycling
The sound treatment and disposal of waste EEE (WEEE) in many cases was economically not feasible and was considered an increasing problem since the late eighties of the 20th century with ever increasing volumes of WEEE. Consequently, the EU WEEE Directive was enacted with its Extended Producer Responsibility (EPR) that obliges producers of EEE to cover the cost of sound treatment and disposal of WEEE. This adapted the economic framework conditions and enabled business models of economic operators and sound treatment of WEEE, recycling of materials and management of hazardous substances because these related efforts were financed by the producers.

The sobering insight from the above: If we want more and/or better recycling of (critical and strategic) materials, the investments and development inputs are needed, especially until the technologies reach economic viability. Once a long-term stable financing mechanism and clear rules are established that provides economic operators with a business perspective, private investments can be unlocked and integrate CRM recycling into the competitive market economy driving effective and efficient solutions. In the end, if the EU societies want (more) recycling of CRMs, it requires, besides research in technologies and business models, the readiness to finance these activities.

Specific cases – How CE strategies can increase supply security

Call for circular strategies come through circular and more sustainable economy. Demand to extend the lifecycle of the materials, beside the activities such as business models, also physical material durability and repairability will play a role in this transition. New performance expectations, e.g., increased durability, may lead to increased need for critical materials, and more complex alloy compositions to obtain higher requirements in performance. Also, demand for recycling of critical raw materials is increasing and probably forced by future legislations (recycling targets e.g., in proposed battery directive), in order to secure the supply of recycled materials. Reduction potential of circular strategies have been investigated, for example, in Metabolic project (https://www.metabolic.nl/) for various metals, including Li, Co, Nd, Ni, Cu.

Combining circular strategies is effective
When circular strategies are combined, the reduction potential is huge:
-the demand for lithium for electric vehicle batteries and battery storage drops from 25 % to about 3.5 % of current global annual production
-neodymium demand drops from 15 % to 1.1 % of current global annual production, for use in permanent magnets in wind turbines and automotive electric motors. (Metabolic *et al.*, 2021)

eMobility circular strategies

The demand for recycled or secondary materials content is on the rise, including critical raw materials. This is exemplified by initiatives such as the proposed battery directive in the EU. This increasing demand can be met through various approaches, such as recycling, direct recycling, material reuse, and closed-loop recycling within technological solutions, as well as the substitution of specific materials. Substitution also plays a significant role in shaping the value chains of batteries. For instance, cobalt-free lithium iron phosphate batteries are gaining popularity, contributing to the reduction of cobalt dependency.

In addition to batteries, there is, currently, research and development related to permanent magnets due to the Rare Earth Elements (REEs). Circular economy strategies, such as the reuse of magnets, hold the potential to decrease the environmental impact associated with permanent magnets. Furthermore, direct recycling or material reuse offers opportunities to reduce both environmental impacts and recycling costs. Electric motor eco-design plays a key role in selecting the appropriate permanent magnet types and optimizing their performance. For example, substituting NdFeB magnets with other chemistries that do not contain REEs can be explored as a means to address CRM challenges.

Decarbonization strategies include mobility electrification, including example Li-ion batteries on central position. Battery value chains are developing, and battery life cycle environmental, economic, and social impacts are of concern. Characteristics for electric battery value chain is expectations of exponential growth in metals extraction,

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the uncertainties of reuse and end-of-use safety and recyclability.

The developing electric battery value chain will be supported by EU Battery Regulation, proposed 10 December 2020 targeting batteries that are more sustainable through their life cycle and contribute the zero pollution ambition (European Commission, 2020b). The proposal strongly addresses the principles of circular and climate neutral economy, including social, economic and environmental issues. The legislation is changing for more open information sharing about materials and lifecycle aspects, e.g., remaining useful life. This is expected currently on battery value chain that concern CRMs such as cobalt, natural graphite and lithium.

Battery regulation

The proposed battery regulation contain requirements through battery lifecycle e.g. minimum requirements for recycled material in new EV Batteries, Battery Passports, producers to provide information on performance and durability over expected lifecycle, extended producer responsibility, track battery data throughout use and end of life, recycling efficiencies and material recovery rates etc. (Melin *et al.*, 2021)

Status of CRM recycling in waste management

The components listed in Figure 3 contained in (WEEE) and end-of-life vehicles (ELVs) were identified to bear sufficiently high concentrations and contents of certain CRMs.

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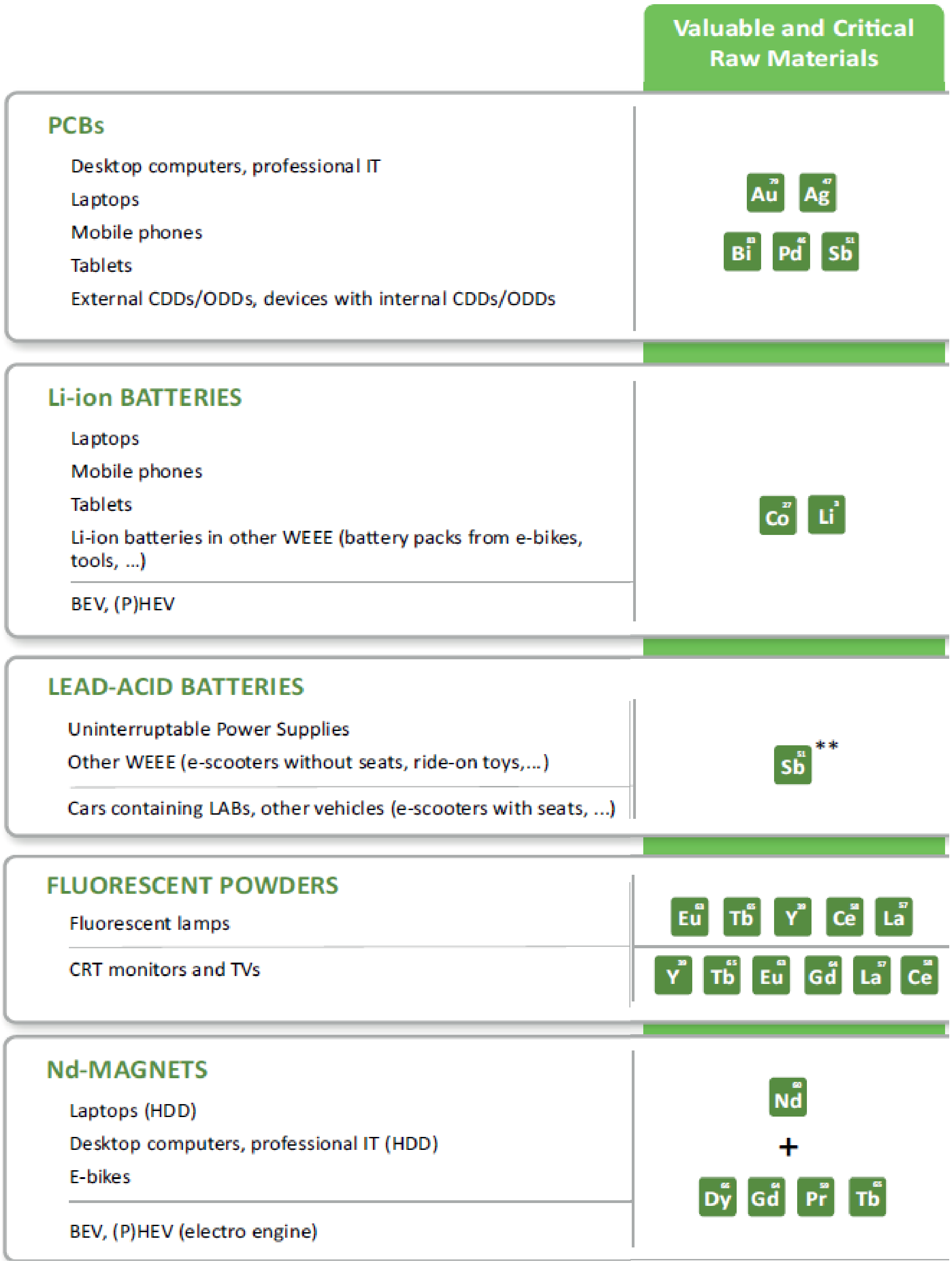

BEV: Battery electric vehicle
(P)HEV: (Plug-in) hybrid electric vehicle
Source: CEWASTE project.

Figure 3. Components of WEEE and ELVs with concentrations of CRM relevant for recycling, after CEWASTE-Project (CEWASTE, 2021)

Palladium, along with antimony and bismuth to a certain extent, are already commercially recycled from printed circuit boards (PCBs). Cobalt is also recycled from certain Li-ion batteries, and antimony from lead-acid batteries.

The REEs in the phosphors of fluorescent lamps – and in principle from phosphors in/for LEDs as well - were recycled from 2012 on after the steadily increasing prices for primary REEs until around 2011 (Recycling International, 2011; Deubzer, 2013; Molycorp, 2015).

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Following the price slump thereafter, the operations had to be stopped few years later due to lacking profitability. Lacking profitability also prevents recycling of other CRMs from components in Figure 3. However, the development of new and improved recycling technologies remains at technological readiness levels below successful industrialization, primarily due to the absence of long-term stable financing mechanisms that would enable attractive business models, and clear conditions and requirements for the collection and treatment of respective WEEE/ELV components.

Conclusions and topics for further discussion

Critical raw materials (CRMs) and circular economy (CE), myths or reality? Insights into the current state of the art are summarized in this working paper.

CRMs and CE are interconnected, but they also focus on different aspects such as elements, materials, and value chains. However, circularity strategies can be utilized to support the reduction of raw materials' criticality.

It is crucial to be aware of CRMs and their potential for circularity, especially as the design of new low carbon, climate-friendly, and sustainable technologies often lead to an increased use of CRMs in various elements, value chains, and volumes. Emphasizing recycling and use of recycled materials are essential to leverage the concept of the life cycle and circularity, also enabling the full potential of other circular economy strategies and the substitution of CRMs, including the substitution of critical raw materials with abundantly available elements.

Circular product design, materials development, role of substitution to support circularity is important. There is growing interest in exploring other circularity strategies (R0-R9) alongside recycling. From a circular economy perspective, it is evident that recycling and recovery alone are not sufficient. It is necessary to explore additional circularity strategies (R0-R7) that follow the waste hierarchy, such as refusing, rethinking, reducing, reusing, repairing, refurbishing, remanufacturing, and repurposing, in order to preserve the value of materials. Furthermore, circular economy business models, such as as-a-service models, play a significant role in promoting circularity.

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References

Bailey, G. (2019) Life cycle assessment of new recycling and reuse routes for Rare Earth Element machines in hybrid/electric vehicles. doctoral thesis. KU Leuven.

Baines, T.S. et al. (2009) 'The servitization of manufacturing: A review of literature and reflection on future challenges', Journal of Manufacturing Technology Management. Edited by R. Roy, 20(5), pp. 547–567. Available at: https://doi.org/10.1108/17410380910960984.

Carrara, S. et al. (2023) 'Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study', Publications Office of the European Union [Preprint]. Available at: https://single-market-economy.ec.europa.eu/system/files/2023-03/Raw%20Materials%20Foresight%20Study%202023.pdf .

Castelvecchi, D. (2021) 'Electric cars and batteries: how will the world produce enough?', Nature, 596(7872), pp. 336–339. Available at: https://doi.org/10.1038/d41586-021-02222-1.

Cefic (2021) SAFE AND SUSTAINABLEBY-DESIGN: BOOSTING INNOVATION AND GROWTH WITHIN THE EUROPEAN CHEMICAL INDUSTRY.

European Commission (2018) European Commission, Report on Critical Raw Materials and the Circular Economy, 2018. Available at: https://doi.org/10.2873/331561.

Deubzer, O. (2013) 'Project Cycling Resources Embedded in Systems Containing Light Emitting Diodes (cycLED)'. Available at: https://www.izm.fraunhofer.de/en/abteilungen/environmental_reliabilityengineering/projekte/cycled.html (Accessed: 14 April 2023).

Deubzer, O. et al. (2019) BASELINE AND GAP/OBSTACLE ANALYSIS OF STANDARDS AND REGULATIONS. CEWASTE Deliverable 1.1.

Directorate-General for Internal Market, I. et al. (2020) Study on the EU's list of critical raw materials (2020): final report. LU: Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2873/11619 (Accessed: 9 June 2023).

EEA (2021) Designing safe and sustainable products requires a new approach for chemicals. Available at: https://www.eea.europa.eu/publications/designing-safe-and-sustainable-products-1 (Accessed: 13 April 2023).

European Commission (2020a) 'Circular economy action plan', European Commission, (March), p. 28. Available at: https://doi.org/10.2775/855540.

European Commission (2020b) 'Green Deal: Sustainable batteries for a circular and climate neutral economy'. Available at: https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_20_2312/IP_20_2312_EN.pdf (Accessed: 14 April 2023).

European Commission (2020c) Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL concerning batteries and waste batteries. COM(2020) 798 final.

European Commission (2022a) ANNEX to the COMMISSION RECOMMENDATION establishing a European assessment framework for 'safe and sustainable by design' chemicals and materials. C(2022) 8854 final.

European Commission (2022b) COMMISSION RECOMMENDATION of establishing a European assessment framework for 'safe and sustainable by design' chemicals and materials. C(2022) 8854 final.

Grohol, M. and Veeh, C. (2023) Study on the Critical Raw Materials for the EU. Available at: https://single-market-economy.ec.europa.eu/system/files/2023-03/Study%202023%20CRM%20Assessment.pdf.

JRC (2022) Safe and sustainable by design chemicals and materials. Available at: https://data.europa.eu/doi/10.2760/879069 (Accessed: 13 April 2023).

Kinnunen, P. et al. (2022) 'A review of circular economy strategies for mine tailings', Cleaner Engineering and Technology, 8, p. 100499. Available at: https://doi.org/10.1016/j.clet.2022.100499.

Mathieux, F. et al. (2017) Critical Raw Materials and the Circular Economy. Background report, Report EUR 28832 EN. Available at: https://doi.org/10.2760/378123.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730227

Melin, H.E. et al. (2021) 'Global implications of the EU battery regulation', Science, 373(6553), pp. 384–387. Available at: https://doi.org/10.1126/science.abh1416.

Metabolic et al. (2021) Towards a circular energy transition.

Molycorp (2015) 'Rare Earth pricing much less volatile'. Available at: https://i.insider.com/5418482469bedd2b4285259f?width=1200 (Accessed: 14 April 2023).

Potting, J. et al. (2017) Circular Economy: measuring innovation in the product chain. PBL2544. The Hague: PBL Netherlands Environmental Assesment Agency.

Recycling International (2011) 'Rhodia expands rare earth recycling reach'. Available at: https://recyclinginternational.com/e-scrap/rhodia-expands-rare-earth-recycling-reach/8929/ (Accessed: 14 April 2023).

Sitra (2021) 'The most interesting companies in the circular economy in Finland 2.1.' Available at: https://www.sitra.fi/en/cases/3stepit-offers-more-than-just-the-leasing-of-laptops-up-to-98-per-cent-of-devices-re-enter-circulation/ (Accessed: 12 April 2023).

Tercero Espinoza, L., Schrijvers, D., et al. (2020) 'Greater circularity leads to lower criticality, and other links between criticality and the circular economy', Resources, Conservation and Recycling, 159(January), p. 104718. Available at: https://doi.org/10.1016/j.resconrec.2020.104718.

Tercero Espinoza, L., Rostek, L., et al. (2020) The promise and limits of Urban Mining.

Tercero Espinoza, L. and et al. (2015) Critical Raw Materials Substitution Profiles. CRM Innonet.

Tercero Espinoza, L.A. (2021) 'Critical appraisal of recycling indicators used in European criticality exercises and circularity monitoring', Resources Policy, 73(July), p. 102208. Available at: https://doi.org/10.1016/j.resourpol.2021.102208.

Zeng, A. et al. (2022) 'Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages', Nature Communications, 13(1), p. 1341. Available at: https://doi.org/10.1038/s41467-022-29022-z.

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