A circular economy for Critical Raw Materials

UNLOCKING THE CIRCULARITY POTENTIAL OF CRITICAL RAW MATERIALS

Sustainable management of Critical Raw Materials (CRMs) is key to tackling climate change and operating within the planetary boundaries. The impact of these important materials is double-sided: extraction and processing are associated with negative environmental impacts such as Greenhouse Gas (GHG) emissions and habitat loss, yet they are essential in the production of low-carbon technologies needed to power the green transition.

As introduced in "Article 1 - Understanding the CRM Act" [1] the shift to low-carbon technologies is causing the demand for CRMs to boom. Since mining remains the main source of CRMs, concerns about their future supply are growing against the backdrop of declining grades of deposits, concentration of resources to a few regions, and political instability in some major CRM-supplying countries. At the same time, demand mitigation strategies, such as increasing current mining and processing, fail to offer a sustainable long-term solution.

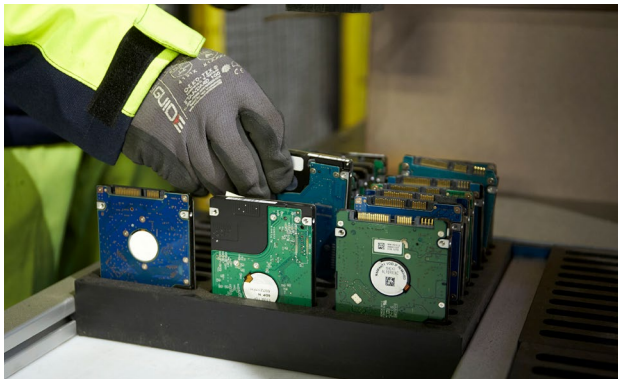
Businesses reliant on CRMs are navigating a landscape marked by potential shortages and rising costs, which could stifle innovation, especially in sectors such as high-tech and green technology. Moreover, the pressure to comply with both current and future regulations, along with growing demands from consumers and stakeholders, is compelling businesses to adopt more sustainable CRM practices.

In response, businesses are exploring strategies to optimize virgin resource extraction and enhance recycling. However, a more transformative approach lies in adopting circular economy (CE) practices to reduce the demand for virgin resources and minimize losses.

This article explores the latter. More specifically, how CE practices can shift the attention from the efficiency of resource exploitation to activities that minimise the need for such resources by keeping CRM-rich products and components in use.

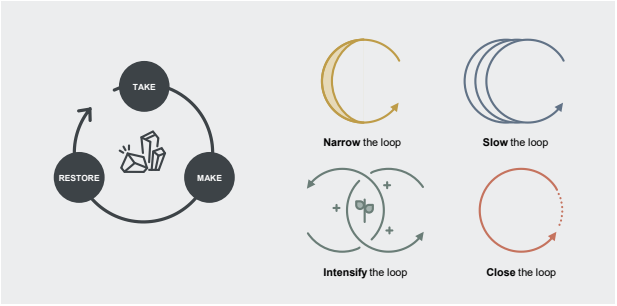
In detail, we will discuss:

1. What the CE framework is and how it helps businesses reduce their demand for CRMs
2. Why applying a CE mindset to CRMs yields strategic benefits
3. How to develop a CE strategy for CRMs following three key steps



1. WHAT THE CE FRAMEWORK IS AND HOW DOES IT HELP BUSINESSES TO REDUCE THEIR DEMAND FOR CRMS

The CE framework provides a blueprint for how to move away from the linear model to a more sustainable economic system based on three core principles: Eliminate waste and pollution, Keep products and materials in use, and Regenerate natural systems. These principles form the basis of four main strategies which businesses can use to move from a linear to a circular model for finite resources like CRMs: "narrowing", "slowing", "intensifying", and "closing" the loop [2, 3, 4, 5].



What do these CE strategies mean in practice for businesses operating with CRMs? Let us take a closer look:

- **Narrowing the loop** - refers to practices that reduce the quantity of resources embedded in or consumed by products and ultimately enhance resource efficiency. For CRMs, this may include simplifying the product design, substituting scarce materials with abundant ones and minimising manufacturing losses. For instance, Tesla is switching from nickel-cobalt-aluminum (NCA) to an alternative, older technology: the lithium-iron-phosphate (LFP) batteries thereby reducing the need for the heavily demanded cobalt [6].
- **Slowing the loop** - emphasises extending product lifespan through repair, reuse, refurbishment, and remanufacturing, thereby extending the useful life of CRMs; as well as other materials. For example, Volvo Cars collaborates with BatteryLoop to repurpose electric vehicle batteries for energy storage [7]. Caterpillar has established a process for refurbishing components to a 'like-new' condition [8], while ABB gives robots in the remanufacturing sector a second life through their global program of remanufacturing and upgrades [9].
- **Intensifying the loop** - involves boosting product utilisation efficiently, meeting the demand of a larger number of users, while reducing the needed resources. This strategy creates value by offering services rather than making new goods, or by adding services to existing products. It includes business models that allow users to share or access products, rather than owning them outright. By keeping product ownership, companies can more easily implement other CE practices such as reuse and remanufacturing. For example, Volvo Cars by offering on-demand car sharing to their customers promotes higher utilization of vehicles [10]. Another example is Epiroc's "Batteries as-a-Service" (BaaS), where customers get access to battery operation services for their electric vehicles with optimal performance and predictable costs, while Epiroc helps to keep batteries in use for longer by managing maintenance and upgrades [11]. Another player in the BaaS segment is Sandvik, which offers battery-electric mining equipment solutions for improved productivity and reduced GHG emissions to customers in the mining industry [12].
- **Closing the loop** - focuses on recycling and recovering disposed CRMs. This is achieved by designing products for recycling, implementing strategies to harvest products and parts reaching the end of their lifecycle (i.e., through take-back systems), and establishing an effective recycling system. However multiple barriers, including inadequate recycling infrastructure [13], dissipative use and low material concentration in goods, as well as a low secondary-material value, collectively hinder the economic feasibility of CRM recycling. Despite the advantages, current CRM recycling rates therefore fall short of the rising demand, with only 1% of REEs - rare earth elements - recycled globally [14], underscoring the need for alternative strategies and new technologies. Among good examples of closing the loop is "Re-Made to Matter" collaboration between Stena Recycling and Alfa Laval, focusing on recycling copper from old plate heat exchangers to produce new, more energy efficient ones, thereby contributing to overall emissions reduction [15].

Although the above examples represent standalone practices, it is essential to recognise that a synergistic approach, combining various strategies, is necessary to achieve substantial impact. For instance, estimates show how the combined effect of multiple CE practices could significantly reduce the EU lithium demand for electric vehicles, dropping it from 25% to approximately 3.5% of current global annual production. Similarly, neodymium demand for wind turbines and electric motors could decrease from 15% to 1.1% of current global annual production [16].

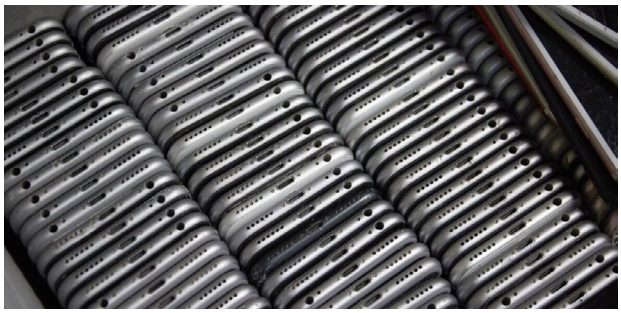
2. WHY APPLYING A CE MINDSET TO CRMS YIELDS STRATEGIC BENEFITS

CRMs are fundamental to most modern technologies. However, in a linear economy, their value is largely lost after the first use cycle of a product or a component. For businesses, adopting CE practices is an opportunity to promote the value retention of CRMs. Doing so can unlock several strategic

benefits.

2.1. Harvest more value from existing CRM investments

Many products, especially those that have a high content of CRMs, tend to hold a relatively high residual value. A case study from the Technical University of Vienna [17] revealed that 2.5-year-old mobile devices acquired at market release retain an average residual value of 46% after undergoing refurbishment to ”as-new” condition, and 17% with functional repairs alone. To illustrate, a mobile device costing 500 € can bring an additional 230 € profit after refurbishment to restore performance and finishes and 85 € after mere functional repairs for reuse (considering spares and operational costs). In contrast, the material scrap value of an average mobile device excluding the battery is worth as little as 2 € [18]. To capitalise on this opportunity, businesses need to employ CE practices that preserve product and component value from the outset, support product life extension, and provide secondary sales opportunities.



2.2. Stabilise operations by mitigating supply chain risk

Most CRMs are susceptible to supply chain vulnerability due to high geographical concentration, export restrictions, and bilateral dependencies. Over-reliance on imported virgin CRMs amplifies the risk of supply chain disruptions from international conflicts [19] or regulatory changes, posing a significant threat to stability and continuity, especially when these materials are vital for business operations. For instance, the Russian invasion of Ukraine demonstrated this dynamic, leading to pronounced market volatility in the prices of materials critical to industrial production such as aluminium and nickel [20]. Over time, we have seen first-hand how the cost and volatility of virgin CRMs fluctuate upwards. In 2020 and 2021, some REE prices tripled or quintupled after almost a decade of relative stability. In a future net-zero emissions scenario, supply shortages could lead to price increases for copper, nickel, cobalt, and lithium of several hundred per cent from 2020 levels over the next decade [21, 22]. In this context, CE practices, such as remanufacturing, can help mitigate supply chain risk by reducing dependence on virgin CRMs in favour of secondary products, components, and materials.

Sandvik exemplifies this kind of practice through their CE strategy for tungsten, a metal essential for tools, electronics, and aeronautics, with China dominating its production at over 79% in 2020 [23]. At customer sites, Sandvik transforms tungsten inserts from drill bits into new products and achieves a 64% reduction in CO_2e (metric tons of CO_2 emissions with the same global warming potential as one metric ton of equivalent GHG). Additionally, they produce Bergla®, a powder tailored for specific end-products, made from 100% recycled tungsten, which results in a 90% CO_2e reduction [24].

2.3. Reduce embodied emissions by utilising resources already in use

Businesses rely heavily on green technologies to achieve their decarbonisation targets. Despite these technologies' significant contributions to reducing operational CO_2e emissions, many of them have a substantial footprint when considering products' entire lifecycle. For instance, electric vehicles significantly reduce the emissions originating from the exhaust of internal combustion engine (ICE) cars (60-65 %). Yet, the supply chain emissions for battery electric vehicles are approximately 35% to 50% higher than those for ICE vehicles, primarily due to additional emissions related to the battery [25]. Therefore, while is crucial to minimise operational emissions, it is equally important to address the increased embodied emissions - associated with the extraction and processing - of CRMs.

Implementation of CE practices holds the potential to tackle the challenge of embodied emissions by increasing the utilisation of existing resources. The previously mentioned study from the Vienna University of Technology [17], comparing the standard disposal of a smartphone to a second-life scenario with a 2.5-year lifespan, revealed considerable reductions in global warming potential (GWP). Remanufacturing, refurbishing, and repair were found to offer GWP reductions of 25%, 55%, and 71% respectively [17]. Thus, the CE framework is an essential tool for tackling the CO_2e emissions embodied in products, which for businesses will be critical if fulfilling long-term decarbonisation targets.

3. HOW TO DEVELOP A CE STRATEGY FOR CRMS FOLLOWING THREE KEY STEPS

The CE is a cornerstone of the sustainable management of CRMs. To capture the strategic benefits of CE implementation, businesses need to adapt and re-invent their operations and business logic, from product design to organisational culture, and value proposition. Crafting a CE strategy involves not just selecting individual strategies such as narrowing the loop, but also understanding the synergies and interplay between different approaches.

To develop an effective CE strategy for their CRMs usage, businesses should: define the problem, choose the right

combination of strategies and deploy a comprehensive implementation approach.

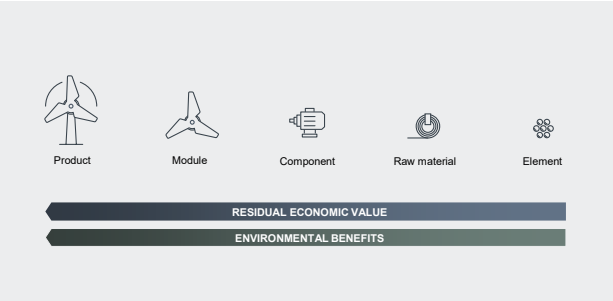
3.1. Define the problem

The initial step towards a sustainable management of CRMs is to clearly define the scope and impact of the problem. Before acting, businesses need to understand the extent of their CRM usage and the associated environmental and financial risks. This demands a careful examination of current operations and supply chains, identifying specific instances of CRM utilisation, potential waste, and management opportunities. To establish the right conditions that will facilitate upcoming changes, it is further pivotal to eliminate structural, operational, and cultural barriers within the organisation. In this crucial phase, businesses need to clearly describe the issue in a well articulated "problem statement" to guide the way forward. This will ensure that the developed CE strategy (i.e., narrowing the loop) along with actionable practices (i.e., remanufacture) are tailored to the context and the challenges faced by the business.

3.2. Choose the right combination of strategies

To effectively address the defined problem using one or multiple CE strategies, it is crucial to determine on what level to address the issue, understand the interplay between strategies, and assess their financial viability. In our view, three aspects are particularly important in this process:

First, determine the most effective strategy or combination of strategies to tackle the specific problem in your CRM management. CE strategies yield greater environmental and financial benefits when applied to the entire product (e.g., wind turbine), its modules (e.g., nacelle, rotor), or components (e.g., generator, transformer), rather than the specific CRM element (e.g., neodymium, dysprosium).



To illustrate, for products that have low concentration of CRMs per unit of mass, a recycling-centric strategy focused on closing the loop for the CRM element can be susceptible to risks of material dispersion and value dilution. In contrast, slowing the loop with traceability and product reclamation, provides access to CRMs rich components and enhances value retention through reuse, repair, or remanufacturing.

Second, be mindful of the dynamic relationship between CE strategies. Take, for example, the decision to reduce the lithium content in batteries (a strategy aimed at narrowing the loop). This might conflict with recycling efforts (closing the loop) as deploying narrowing the loop practice reduces the amount of valuable metal that can be recovered from the product in recycling at the product's EoL. Another example is extending the lifespan of products and components through reuse and repurposing (slowing the loop). In the short term, these practices have a relatively limited potential to reduce the demand for CRMs, as products' lifetimes extend over several years, yet their long-term potential is significant. Reuse also holds the benefit of avoiding material loss, when compared to recycling. On the other hand, recycling takes precedence over reuse when the material efficiency of manufacturing has improved to a level where manufacturing a new product reduces the overall material footprint [26].

Third, assess the viability of different strategies considering the revenue or savings generated by growth, reduced costs, and risk mitigation, as well as the investments and operational costs needed for strategy implementation. For the latter, this might include costs associated with hiring skilled labour, developing new infrastructure, applying for permits, and developing new sales operations. In some cases, strategy implementation results in a significant change in a business' cost structure. Implementing the reuse or remanufacturing of products can, for instance, increase operational costs due to an increase in manual labour, however, it might be balanced by lower material costs.

3.3. Deploy a comprehensive approach

Once a high-level strategy has been selected it is useful to consider the execution through four lenses of implementation: product design, business model, organisation, and system. The key lies in a comprehensive approach rather than a specific starting point, by broadening the focal view, all dimensions should be addressed.

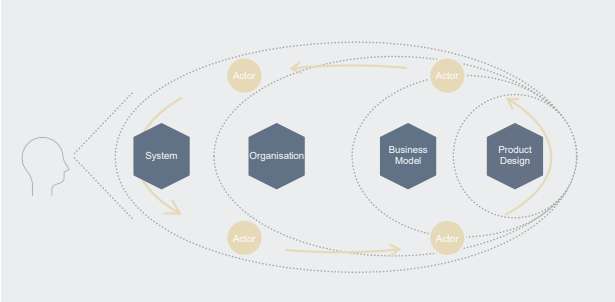
Product Design plays a crucial role by directly influencing the content of CRMs. As noted by the Ellen MacArthur Foundation, decisions made during the design phase can determine up to 80% of a product's environmental footprint [27]. Therefore, from conception, product design should be in line with the intended CE strategy to improve the efficiency, traceability, and accessibility of CRMs. In essence, products not designed for circulation cannot be effectively circulated. For instance, integrating modular product design, like smart-phones with easily replaceable components, facilitates user-friendly repairs and improves component-level stock management enabling parts harvesting for reuse and refurbishment. However, while modularity is effective for components, it neglects the elemental level

and the product as a whole. Design for disassembly and fragmentation is crucial in product development to reduce the risk of disposal and enhance material recycling. Circular design brings various benefits, including reduced need for replacements, lower energy and resource consumption, improved performance, extended product longevity, and increased EoL value.

Next is the **Business Model**. Once the product is designed, businesses must find ways to monetise or retrieve the invested value. This can be achieved by the creation of innovative pricing strategies, unique selling propositions, or even entirely new revenue streams. By keeping product ownership and offering products as a service, businesses are in a better position to ensure that products are reused, repaired, or remanufactured [28]. This approach might also lead to cost savings for their customers, as expenses are shared among multiple users.

The **Organisation** serves as the backbone for CE implementation, facilitating the interaction between the internal sphere and the external ecosystem of entities. One key to successful internal implementation lies in crafting the right combination of CE strategies and integrating them into the company's overall business and sustainability strategy. A well-structured organisation promotes innovation, fosters a culture of sustainability, and ensures that circular principles are embedded in the business. However, companies tend to underestimate the task. Integrating circularity is not a one-time action but a holistic and continuous process that should start with building readiness for change, executive support, stakeholder engagement, and clear goal setting. Then, to achieve circularity at scale organisations should establish internal alignment, disseminate learnings through relevant upskilling and leverage synergies among dedicated teams while deploying protocols to oversee raw resources usage. Along the process performance should be tracked, for instance through CRM-related key performance indicators aligned to the core business strategy.

Finally, the **System** dimension encompasses the external factors that businesses must navigate. CE implementation requires a coordinated effort from various stakeholders, with regulators and customers playing a pivotal role. Regulators hold substantial influence in shaping the CE landscape through policies such as the EU's CRM Act [29], Extended Producer Responsibility [30] schemes (e.g., textiles [31], or packaging [32]), and the ESPR proposal [33]. Customers, on the other hand, will impact the success of the chosen strategy through their behaviours, preferences, and consumption patterns. To find synergies and understand stakeholders' roles and interests, businesses can benefit from conducting a thorough stakeholder mapping process, particularly focusing on those directly involved in the CRM value chain. Collaborate closely with these stakeholders to ensure shared value creation and smooth implementation of the chosen CE strategy.



RECOMMENDATIONS FOR BUSINESSES

Businesses can use the CE as a framework to improve their management of CRMs. To get started, we recommend to:

- **Map your CRM usage across product categories**, pinpointing those with CRMs of high economic value or susceptible to supply chain risks for your initial focus.
- **Use the CE as a framework to identify solutions which help you keep CRMs in use beyond the product's first use cycle.** Explore a variety of practices to narrow, slow, intensify, and close the material loops that fit your product and business context.
- **Conduct an initial assessment of the theoretical business opportunity for each identified solution.** Consider factors such as revenue generation, cost-saving opportunities, risk minimisation, and overall costs. This assessment will help you prioritise solutions based on their financial viability.
- **Identify key stakeholders and draft points of intervention.** The process will facilitate an understanding of which actors to collaborate or build alignment with, and where interventions are necessary in the product's life cycle for successful implementation.

SHARE YOUR THOUGHTS

What do you think? How are you planning to work with CRMs and future-proof production?

It would be great to hear your thoughts and any questions you may have, email us at:

circularconsulting@stenarecycling.se

SOURCES AND LINKS

This is the second part of our three-part series on "Critical Raw Materials – Strategies for resilience". Find the series on www.stenarecycling.com. Please note that the information in this article is not exhaustive and was last edited in January 2024. For more details, see sources throughout the article.

WORKS CITED

[1] V. Neiström Ortynski and R. Paccaloni, "Understanding the CRM Act" 2023. https://www.stenarecycling.com/siteassets/what-we-offer/circular-consulting/crm_act.pdf. [Accessed 11 January 2024].

[2] N. M. Bocken, I. de Pauw, C. Bakker and B. van der Grinten, "Product design and business model strategies for a circular economy" Journal of Industrial and Production Engineering, vol. 33, no. 5, pp. 308-320, 2016.

[3] Ellen MacArthur Foundation, "Growth within: A circular economy vision for a competitive Europe" 2015. https://ellenmacarthurfoundation.org/growth-within-a-circular-economy-vision-for-a-competitive-europe. [Accessed 11 October 2023].

[4] M. Geissdoerfer, P. Savaget, N. M. Bocken and E. J. Hultink, "The Circular Economy e A new sustainability paradigm?," Journal of Cleaner Production, vol. 143, pp. 757-768, 2017.

[5] W. McDonough and M. Braungart, Cradle to Cradle: Remaking the Way We Make Things, 1st Edition ed., New York: North Point Press, 2002, p. 193.

[6] Tesla, 2021. https://digitalassets.tesla.com/tesla-contents/image/upload/IR/TSLA-Q3-2021-Quarterly-Update.

[7] BatteryLoop, "Sustainable power in real time" BatteryLoop, 2022. https://www.batteryloop.com/case-studies/sustainable-power-in-real-time/. [Accessed 24 October 2023].

[8] Caterpillar, "Caterpillar's Circular Economy" Caterpillar, 2023. https://www.caterpillar.com/en/company/sustainability/remanufacturing.html. [Accessed 15 August 2023].

[9] ABB, "Remanufacturing and Workshop Repair" ABB, 2023. https://new.abb.com/products/robotics/service/remanufacturing-and-workshop-repair. [Accessed 15 August 2023].

[10] Volvo, "On Demand" Volvo, 2023. https://www.volvocars.com/se/on-demand/app?adjust_referrer=adjust_external_click_id%3DCj0KCQjwldKmBhCCARIsAP-0rfxaWpNqvHaHmKsFvxPn7TrjE11sRkAsB2BuTe6UOUp4P7AQdRHVc0gaAg8REALw_wcB. [Accessed 15 August 2023].

[11] Epiroc WEB, "Batteries as a Service" 2023. https://www.epiroc.com/en-ke/products/parts-and-services/batteries-as-a-service. [Accessed 23 August 2023].

[12] "Sandvik," Sandvik, 25 July 2022. https://www.home.sandvik/en/news-and-media/news/2022/07/sandvik-wins-record-sek-330-million-order-for-battery-electric-mining-equipment/. [Accessed 30 10 2023].

[13] R. Koppelaar, S. Pamidi, E. Hajósi, L. Herreras, P. Leroy, H.-Y. Jung, A. Concheso, R. Daniel, F. Francisco and C. Parrado"A Digital Product Passport for Critical Raw Materials Reuse and Recycling," vol. 2, no. Criticality Versus Geological Scarcity: Different Concepts, Which May Need Tuning, 2023.

[14] Y. Geng, J. Sarkis and R. Bleischwitz, "How to build a circular economy for rare-earth elements" Nature, vol. 619, pp. 248-251, 10 July 2023.

[15] A. Laval, "Working together to solve our challenges" Alfa Laval. https://www.alfalaval.lat/industrias/energia-y-utilities/sustainablesolutions/sustainable-solutions/sustainable-partnership/re-made-to-matter-partnership/. [Accessed 19 December 2023].

[16] Metabolic; Copper8; Polaris Sustainability; Quintel; CML - Leiden University, June 2021. [Online]. Available: https://www.metabolic.nl/publications/towards-a-circular-energy-transition/.

[17] S. Glaser, R. Pamminger and W. Wolfgang, "Modelling of different circular end of use scenarios for smartphones" The International Journal of Life Cycle Assessment, vol. 26, pp. 470-482, February 2021.

[18] V. Forti, C. P. Baldé, R. Kuehr and G. Bel, The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential., Bonn/Geneva/Rotterdam: United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), 2020, p. 120.

[19] J. Torrubia, A. Valero, A. Valero and A. Lejuez, "Challenges and Opportunities for the Recovery of Critical Raw Materials from Electronic Waste: The Spanish Perspective" 2023. https://www.mdpi.com/2071-1050/15/2/1393.

[20] OECD, "The supply of critical raw materials endangered by Russia's war on Ukraine" 4 August 2022. https://www.oecd.org/ukraine-hub/policy-responses/the-supply-of-critical-raw-materials-endangered-by-russia-s-war-on-

ukraine-e01ac7be/.

[21] N. Valckx, A. Pescatori and L. Boer, "Metals may become the new oil in net-zero emissions scenario" VoxEU – CEPR's policy portal , 5 November 2021.

[22] M. Krishnan, H. Tai, D. Pacthod, S. Smit, T. Nauclér, B. Houghton, J. Noffsinger and D. Simon, "An affordable, reliable, competitive path to net zero," McKinsey, 30 November 2023. https://www.mckinsey.com/capabilities/sustainability/our-insights/an-affordable-reliable-competitive-path-to-net-zero. [Accessed 05 12 2023].

[23] SCRREEN2: Solutions for Critical Raw Materials - a European Expert Network - Factsheet: Tungsten" 2020.

[24] Sandvik, "Annual report" 2022. https://www.annualreport.sandvik/en/2022/servicepages/downloads/files/entire-en-svk-ar22.pdf. [Accessed 24 October 2023].

[25] A. Form, A. Hultberg and C. Berry, "Polestar and Rivian pathway report" 07 February 2023. https://www.kearney.com/industry/automotive/article/-/insights/polestar-and-rivian-pathway-report-. [Accessed 24 October 2023].

[26] A. Månberger, "Critical raw material supply matters and the potential of the circular economy to contribute to security" Intereconomics, vol. 58, no. 2, pp. 74-48, 2023.

[27] Ellen MacArthur Foundation, "An introduction to circular design" 7 June 2022. https://ellenmacarthurfoundation.org/news/an-introduction-to-circular-design. [Accessed 10 August 2023].

[28] Stena Circular Consulting, "As-a-Service – Unlocking business value". https://www.stenarecycling.com/what-we-offer/stena-circular-consulting/success-stories-tools/reports-toolkit/product-as-a-service/. [Accessed 24 October 2023].

[29] European Commision, "Critical Raw Materials Act" https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en. [Accessed 11 January 2024].

[30] Naturvårdsverket, "Extended Producer Responsibility (EPR)" https://www.naturvardsverket.se/en/guidance/extended-producer-responsibility-epr/. [Accessed 11 January 2024].

[31] European Commission, "Circular economy for textiles: taking responsibility to reduce, reuse and recycle textile waste and boosting markets for used textiles", 05 July 2023. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_3635. [Accessed 11 January 2024].

[32] Naturvårdsverket, "Extended producer responsibility for packaging". https://www.naturvardsverket.se/en/guidance/extended-producer-responsibility-epr/producer-responsibility-for-packaging/. [Accessed 11 January 2024].

[33] European Commision, "Ecodesign for Sustainable Products Regulation". https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en. [Accessed 11 January 2024].