**How companies improve critical raw material circularity: 5 use cases: findings from the International Round Table on Materials Criticality**

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BRIEF REPORT

# How companies improve critical raw material circularity: 5 use cases

## Findings from the International Round Table on Materials Criticality

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### Abstract

This report showcases five examples of industries applying circular strategies for CRMs: (1) recycling of tungsten carbide scrap by H.C. Starck Tungsten, (2) recycling of battery cathode materials by SungEel Hitech, (3) recovery of rare earth elements from hard disk drives by Hitachi Group, (4) closed rhenium loops by Rolls-Royce, and (5) recovery of platinum group metals by Umicore. The adaptation of business models appears to be one of the biggest enablers of raw material circularity. Ideally, all involved stakeholders (including the manufacturers, the users, and the recyclers) have a common interest in, and are incentivized by retaining the material's value, which stimulates transparent material flows and close cooperation. This is enabled by retained ownership and with long-term, well-defined relationships between the value chain actors. Such relationships can be enhanced by vertical integration, or by long-term contractual agreements. The benefits of implementing circularity provide a mandate for governmental intervention in stimulating circularity strategies, for example via regulations and subsidies, to overcome initial investment thresholds.

**Keywords** Critical raw material · Companies · Recycling · Circular business models

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## Introduction

The project 'International Round Table on Materials Criticality' (IRTC) is connecting researchers and industry representatives working on criticality on an international level. During the European Commission's Raw Materials Week 2021, IRTC organised a workshop on company strategies for managing a more circular use of critical raw materials (CRMs). After IRTC had investigated the potential of circular strategies to mitigate criticality of critical raw materials in earlier events, discussions and publications (Cimprich et al., 2022; Tercero Espinoza et al., 2020), the workshop aimed at understanding how circular strategies are actually implemented in business practice. The full workshop report is published by van Nielen et al. (2022). Five examples from the industry presentations are summarised and analysed here: (1) recycling of tungsten carbide scrap by H.C. Starck Tungsten, (2) recycling of battery cathode materials by SungEel Hitech, (3) recovering of rare earth elements from hard disk drives by Hitachi Group, (4) closing rhenium loops by Rolls-Royce, and (5) recovering platinum group metals by Umicore. Each case is depicted by a figure showing the steps of the implemented circular strategy. An overview of the strategies, the motivation(s) for their adoption, success factors, and the overall benefits is provided in Table 1. These aspects form the basis of the final conclusions drawn in this report.

## Case 1: H.C. Starck Tungsten: recycling tungsten from various applications

### Company and market

H.C. Starck Tungsten (HCST) recycles all types of tungsten scrap via chemical recycling processes. With its headquarters in Goslar, Germany, HCST as leading global supplier produces tungsten chemicals, powders, and carbides. Other production sites are in Sarnia, Canada, and Ganzhou, China. HCST is part of Masan High-Tech Materials (MHT), which owns the largest tungsten mine outside China, in Vietnam.

Twenty-five to 30% of the total global tungsten (W) demand is supplied by recycling. For hard metal tools and heavy metal parts, the recycling rates are 50–75%. Recycling rates can still be increased in energy, lighting, and chemical applications.

Analysis of the 100-kt global W demand reveals that 60% is used in hard metals, and from this, 25% is used in the automotive industry and 23% in mining and construction. The tool industry is very active in these two application sectors, and high recycling rates can be demonstrated.

### Business model

HCST has a strong global Technology & Innovation division with a highly experienced R&D team and is holder of many patents, allowing to develop and subsequently commercialise innovative recycling technologies. In Goslar, the main product is tungsten carbide (WC) which is generated via carburization of tungsten metal powder (W) with carbon black under hydrogen atmosphere. Processing of tungsten units is quite demanding since W has the highest melting point (3422 °C) of all metals of the periodic table. WC powder itself melts at 2785 °C. To increase its toughness, customers add about 5–20% metallic binder, usually cobalt, to generate a so-called hard metal. The properties of this material are determined by the particle size of WC grains, ranging from nano-grains <0.2 µm over fine and medium grades up to extra coarse 10-µm particles.

Two types of tungsten carbide scrap are mainly recycled by HCST. Hard scraps arise mainly from return of used tools out of milling, drilling, cutting, and shaping industries as well as out of mining and road construction business and heavy metals. Soft scraps, like grinding sludges, often contain additionally organic oily components. For recycling of hard scraps, two approaches are available: In direct physical recycling ('Zinc reclaim'), the hard metal is decomposed into a Co and WC phase, which can then be reused. This approach has in fact low processing costs, but the big disadvantage is that it needs clean sorted scrap because eventually all impurities in the waste stay in the recycled material. The second approach, applied in Goslar, is holistic chemical recycling. The hard metal (often also named cemented carbide) is decomposed into single elements, and all types of scrap can be processed. The scraps usually contain 60–90% W, along with other valuable metals like Co, Ni, Cu, Ta, V, and Cr. Also so-called heavy metal hard scraps (e.g. W-Fe/Ni, W-CuAg alloys) or pure tungsten hard scrap units can be fed without any problems into the standard hard metal recycling line. For soft scraps, the recycling process starts with roasting. Both hard scraps and roasted soft scraps then go to an alkaline smelt to oxidise WC to sodium tungstate. The melting cake is then crushed, ground, and dissolved in water. A series of hydrometallurgical processes remove impurities out of the crude sodium tungstate solutions, to yield finally clean, white ammonium paratungstate (APT). APT is the tungsten product used to set the base pricing for the global tungsten market and all kinds of tungsten units. APT can be converted to chemicals like ammonium metatungstate (AMT) and tungstic acid (TA), but also to WC through sophisticated calcination, reduction, and carburization steps. The physical characteristics of WC are mainly controlled by the chemical and physical fingerprint of the used respective APT precursor and the applied furnace technologies and parameters over the downstream chain till WC. Tailor-made post-processing comminution and classification techniques finally customise the WC powder properties.

HCST pursues a secure and stable material supply. With 90 years of experience in W recycling, a broad range of wastes can be recycled at Goslar.

HCST combines their growing recycling activities with certified procurement to ensure a safe, sustainable, and competitive raw material supply. With Masan High-Tech Materials as the new owner, new horizons for recycling beyond tungsten open up. New technologies are being developed, e.g. to recycle Co-Ta-W sludges and black masses from lithium batteries. A single plant setup would provide economies of scale and would benefit both HCST and the environment. Such an arrangement can reduce economic barriers to implementation by sharing one infrastructure to improve circularity, rather than building an entirely new second separate process.

The tooling industry is a well-established industry, but it is also well understood that lowering carbon dioxide emissions is one of the current worldwide challenges, especially for Europe as a centre of high-tech industrial countries. Machining will continue to be essential; however, applications might change, such as the shift from internal combustion engines to electric vehicle traction motors with battery management systems, as well as conventional powder metallurgical-based tool

**Table 1** Analysis of context and benefits of circularity strategies in 5 case studies

| Case study | Circularity approach | Motivation to adopt the circular strategy | Success factors | Overall benefits of the circular approach |
|---|---|---|---|---|
| H.C. Starck Tungsten: recycling tungsten from various applications | • Develops innovative and competitive technological processes to recycle different types of tungsten scrap<br>• Foreseen: holistic recycling also of other types of elements found in tungsten scraps | • Economic viability<br>• Further strengthen tooling business/customer retention<br>• Increase circular volumes by closing recycling gaps in chemical applications | • Worldwide broad secondary sourcing with an efficient mixture of spot business, long-term contracts and tolling<br>• Long-time experience and know-how in recycling of refractory metals and their markets<br>• Modern and innovative technology platform in pyro- and hydrometallurgy as well as in demanding crucial high-temperature techniques<br>• Strong globally acting T&I division with dedicated R&D specialists to foster new technological approaches also in direction of sustainability | • Provision of a sustainable and reliable, stable supply of tungsten<br>• Recycling of multiple types of elements in a single plant setup allows for economies of scale and increased competitiveness<br>• Environmental benefits due to decreased need of mining |
| SungEel Hitech: recycling battery materials | • Hydrometallurgical recycling of Lithium-ion batteries | • Economic viability | • Growing market, allowing for economies of scale | • Contributing to meeting an increased demand for the recycled materials<br>• Environmental benefits due to decreased need of mining |
| Hitachi Group: recovering rare earths from magnetic hard disk drives | • Reuse and recycling of electronics parts and materials from devices manufactured by the same company | • Governmental incentives<br>• Alignment with the company's environmental vision | • Setting up collection infrastructure<br>• Vertical integration of manufacturing, collection, disassembly, and EoL recycling<br>• National standardization and certification of recycling procedures<br>• Governmental support to invest in recycling equipment | • Secure supply of raw materials<br>• Economic viability<br>• Environmental benefits due to decreased need of mining |
| Rolls-Royce: closing rhenium loops in jet engine turbine blades | • Closed-loop recycling of manufacturing waste and end-of-life products<br>• Lifetime extension of turbines via repairs and replacements of parts<br>• Innovative repair practices, avoiding the need to dismantle the turbines | • Strong price fluctuations and unstable supply of critical raw materials with high importance in the company's products | • Tight relationships with suppliers of alloys<br>• High-quality and well-defined scrap properties<br>• Providing turbines as 'products as a service', allowing for maintenance throughout the lifetime<br>• B2B relationship between product suppliers and product users | • Economic benefits for Rolls-Royce, for their suppliers, and for their customers<br>• Decreased disruptions during engine maintenance<br>• Environmental benefits due to decreased need of mining |

**Table 1** (continued)

| Case study | Circularity approach | Motivation to adopt the circular strategy | Success factors | Overall benefits of the circular approach |
|---|---|---|---|---|
| Unicore: recovering platinum group Metals from chemical processing catalysts | • Lifetime extension via regeneration of used catalysts<br>• Product-service systems<br>• Recycling of PGMs as key value carriers | • High costs of CRMs<br>• High price volatility of CRMs<br>• Improved supply security for PGMs | • B2B relationship between product suppliers and product users<br>• User maintains ownership of the product throughout regeneration and recycling processes of the catalysts<br>• No dispersion of products during the use phase<br>• Limited number of actors and long-term contracts, enhancing transparency | • Economic benefits for the user of the catalyst<br>• Decreased dependence on primary PGM suppliers (increased diversity of supply)<br>• Environmental benefits due to decreased need of mining |

manufacturing technologies to new competitive technologies in additive manufacturing. HCST is currently participating in a newly commenced project in which the energy efficiency along the whole tungsten value chain, from the raw material (ores/scraps) to the finished tool, is being investigated to highlight the areas with the highest potential to further decrease the carbon dioxide footprint. This project is subsidised by the Federal Ministry of Economics, Germany, being a part of the programme ‘Application-oriented non-nuclear research & development within the 7th energy research program of the federal government of Germany’, with 6 consortium partners from the hard metal/tool industry and 2 research institutes.

For the time being, recycling requests for tungsten-containing chemicals are still quite low. Hence, to further increase and to stabilise recycling rates and to lower supply risks, circularity with regard to chemical applications of tungsten containing compounds (e.g. catalysts in the oil and gas industry) should be strengthened. Processes and logistics are to be improved, and downcycling has to be avoided. Furthermore, holistic highly flexible metal recycling should be targeted, not only focusing on tungsten, but also beyond on other valuable elements such as Ta, Co, Ni, or Li (Figure 1).

## Case 2: SungEel Hitech: recycling battery materials

### Company and market

SungEel Hitech is specialised in the hydrometallurgical recycling of the full range of cathode materials. The company, founded in 2000, is located in Gunsan, South Korea, and expects a revenue for the year of 2021 of €100 million. Lithium-ion battery (LIB) recycling started in 2008, with the construction of the first pre-treatment plant. In 2011, a hydrometallurgical plant was opened, which could recover an increasing number of metals. Along with the increasing demand for battery electric vehicles, closing the loop of LIBs is becoming a hot topic. The recycling market is projected to grow to $18 billion in 2030. Many new companies are emerging in the field, and OEMs like Tesla and Volkswagen are also starting their own recycling activities. Recycling can reduce $CO_2$ emissions by 70% compared to mining. South Korea is at the forefront of LIB recycling, which is facilitated by the large amount of domestic manufacturing of LIBs and a subsequently quickly growing market.

### Business model

The battery cathode contains cobalt, nickel, lithium, manganese, and aluminium. These elements are mainly

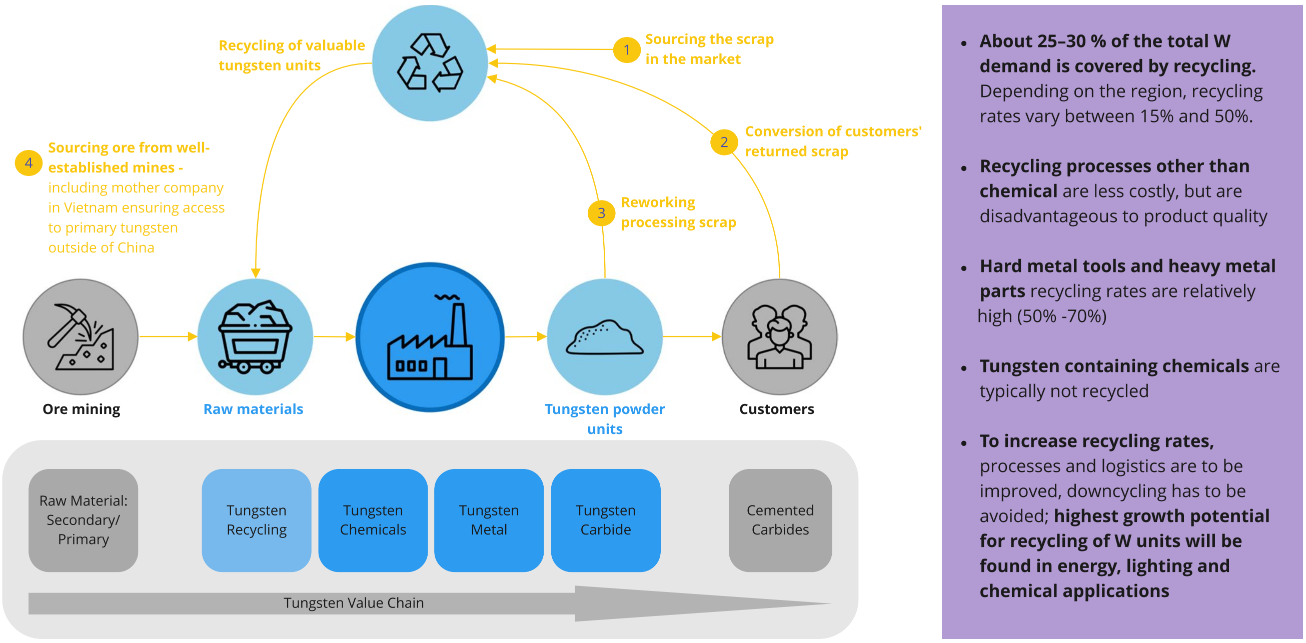


**Fig. 1** Circular tungsten industry by H.C. Starck Tungsten

recovered because of their high price. The recycling of anode materials is still under investigation. Recycling processes can be categorised as pyrometallurgical, hydrometallurgical, or as direct recycling. Each approach starts with the disassembly of end-of-life (EoL) batteries. The battery pack needs to be discharged first. Then, the case can be opened, and the cells are taken out. Currently, some steps are manual, but robots can take out the modules. The cells can have a cylindrical, prismatic, or pouch shape. The reasons for using manual labour are the limited quantity of EoL batteries and the multitude of different battery pack designs.

The subsequent processes are different for differing treatment routes. In the pyrometallurgical route, the disassembled cells are directly put into in a smelting furnace. This yields Ni, Co, and Cu alloys, while Li and Mn exit as slag from where they can be recovered in subsequent processes. The operational expenditure (OpEx) is low but the capital expenditure (CapEx) is high, requiring large production scales. The hydrometallurgical route, in contrast, needs further pre-treatment to make battery powders: discharging, mechanical shredding, crushing, and sieving. The powders are dissolved in sulphuric acid; then the metals (Co, Ni, Li, Mn) are separated in several stages of solvent extraction. The CapEx and energy consumption are low, but wastewater treatment is needed. Direct recycling aims to reuse the cathode materials by activating the lithium. The process is cheap and consumes even less energy. However, it has many limitations, such as requiring a single cathode type, and thus puts hurdles on commercial implementation.

SungEel Hitech has been one of the first companies to commercially implement the hydrometallurgical route. SungEel's process can recover six major elements, mainly as sulphates: Co, Cu, Ni, Mn, Li, and Al. These are supplied to cathode material manufacturers. Currently, SungEel operates 6 pre-treatment plants and 2 hydrometallurgy centres. By 2025, this will be expanded to 12 and 3 plants, respectively. As a result, 18 kt metal will be produced annually. The vision is to grow further towards \$1 billion sales by 2030 (Fig. 2).

## Case 3: Hitachi Group: recovering rare earths from magnetic hard disk drives

### Company and market

Hitachi Group is a manufacturer of NdFeB magnets, among other activities, with main operations in Japan. Hitachi is providing not only products but also services by product health monitoring and product life extension. For example, Hitachi monitors the products in operation, foresees the time of their failure, and proactively replaces components that may develop problems. Five years ago, Hitachi Group formulated its Environmental Vision. This vision defines the goals in environmental business practice as well as long-term ambitions for environmental innovation. The vision aims for three goals: a resource efficient society, a low-carbon society, and a society harmonised with nature.

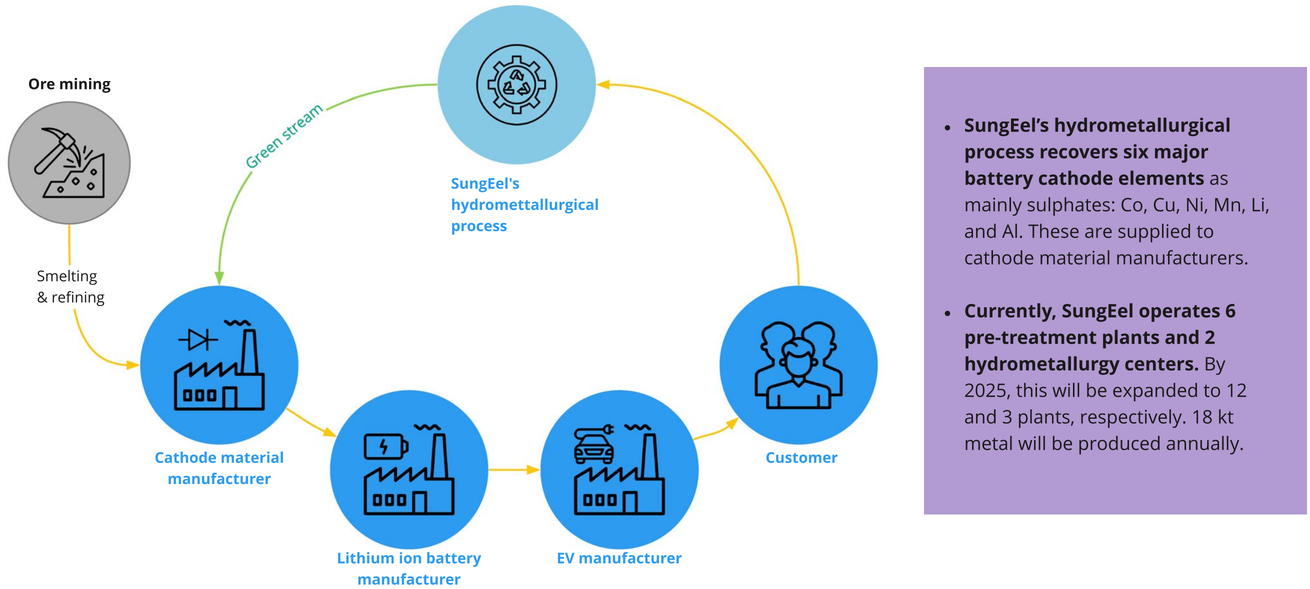


**Fig. 2** Closed-loop lithium-ion batteries by SungEel Hitech

One motivation for recycling is resource scarcity. For the majority of resources, the reserves have declined in the past 10 years. Hitachi, like other manufacturers in Japan, is impacted by stagnated imports of raw materials. Also, governmental incentives, via regulation and subsidies, stimulated the more circular use of raw materials (see also Cimprich et al., 2022).

## Business model

To achieve a circular use of resources, Hitachi established the 'Product Recycling Service Center'. After use, products are collected in recycling centres certified by the Ministry of Environment of Japan under the National Permit System for industrial waste. They go then back to intermediate processors, and finally recyclable materials go back to metal smelters. Hitachi's Product Recycling Service Center is a collaboration between Hitachi's business and services division and 16 affiliates, which are together recycling 100 different products. This system is applied throughout Japan and includes regulations to standardise security management and recycling procedures.

Used products such as servers, PCs, and hard disk drives (HDDs) are disassembled into parts, in many cases by hand. The constituting materials are separated. This process has handled in total about 500 t of products in 5 years. HDDs account for 10 t (20,000 drives). Besides HDDs, automated teller machines (ATMs) form a significant contribution to the recycled product flows. The number of ATMs collected by Hitachi is varying, with recent years showing a growing trend. Since ATMs are IT electronics that demand high security, trusted information sharing between the manufacturer (Hitachi Channel Solutions, Corp.) and the disassembler (Hitachi Industrial Equipment Nakajo Engineering, Nakajo EG) is of high importance.[1] About 2000 ATMs per year are being delivered to Nakajo EG, collected both via Hitachi's National Permit System channels as well as independently by Hitachi Channel Solutions. During disassembly, the ATM is broken down to single-material components as much as possible. There are about 20 part types and until now, 7000 parts have been reused in maintenance. ATMs are made of mainly metal, but also circuit boards, cables, batteries, HDDs, plastics, and glass. 99.6% by weight can be recovered.

A HDD is composed of several components and materials. Hitachi is sending back the collected used resources to Hitachi Metals, Ltd. Then, rare earth elements are extracted from the voice coil motors by the technology of Hitachi Metals, to be reused for magnets. Manual disassembly can only process 10–12 HDDs per hour. Therefore, Hitachi developed an automatic HDD disassembler between 2009 and 2011 with support of a government grant. The machine can process 140 HDDs per hour. In 6 years, it has extracted 26 t magnets, fulfilling 10% of Hitachi's need for magnets. Moreover, significant $CO_2$ emissions are avoided.

Switching to a circular flow reduces the quantity of disposed materials and opens new ways for adding value, such as magnet reuse and material recycling. This contributes to a better coexistence of humans and nature. Hitachi

[1] In former times, Hitachi manufactured ATMs and similar equipment in Tainai City, Niigata. Nakajo EG is the local successor of this legacy and still retains engineers with in-depth structural knowledge of ATMs.

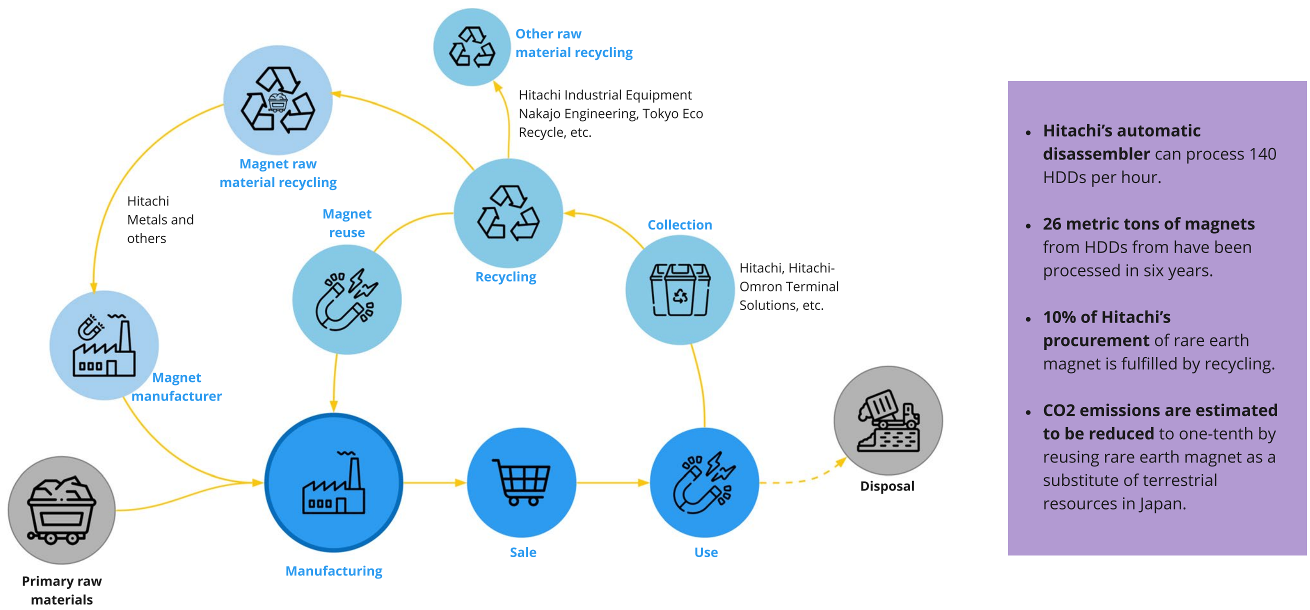


**Fig. 3** Circular HDD magnet management by Hitachi

commenced the scheme purely as a way to reduce environmental impacts, incentivised by the passage of Japanese laws such as the *Act on Recycling of Specified Kinds of Home Appliances* and the *Basic Act on Establishing a Sound Material-Cycle Society*, but can now produce recycled materials at a lower cost due to automation. The initial investment spurred by regulatory action was an important motivator for realizing this process. As early generation processes were automated, the economics improved to the point where the recycling is now economically viable and can be continued in the future (Fig. 3).

## Case 4: Rolls-Royce: closing rhenium loops in jet engine turbine blades

### Company and market

As a manufacturer of power systems in the sectors of airspace, defence, and energy, Rolls-Royce's manufactured products have to meet very high requirements for safety and performance. Often, the products have very particular material requirements, which are illustrated here at the example of jet engine turbine alloys. Turbines experience very high temperatures and forces, which they can withstand better with alloying additions. Various alloying elements have been used in nickel superalloys, including rhenium. This started with the first generation of single-crystal alloy designs. Although the rhenium content of these alloys is only a few percent, its high raw material price influences alloy costs significantly. Rhenium is furthermore mostly supplied as a by-product, leading in addition to strong price fluctuations in the market (see also Cimprich et al., 2022).

### Business model

Given the high-performance requirements, substitution of CRMs in turbine alloys is very challenging. The only example of successful substitution is the replacement of ruthenium, which took about 10 years. Instead, Rolls-Royce aims to manage supply risk through increased efficiency and material stewardship — such as retaining the materials in closed-loop supply chains using a variety of options for material flow management, chiefly the Revert programme. In this programme, wastes are returned to the alloy supplier for reprocessing in aerospace-grade material. In return, Rolls-Royce receives clean alloys at a discounted rate. The discount is greater than the scrap value of the waste on the open market. This is economically beneficial for both parties.

The recycling covers two waste flows: manufacturing waste and end-of-life (EoL) products. Manufacturing waste includes turnings or chips from machining, and runners from investment casting of turbine blades. All of these wastes are collected as a single alloy flow. Rolls-Royce also applies more complex processes to recover rhenium-bearing alloys from grinding sludge and blast media. These significant reclamation efforts are driven by both the market value and the strategic value.

For EoL recycling, Rolls-Royce has a circular business model with service contracts for civil aerospace, referred to

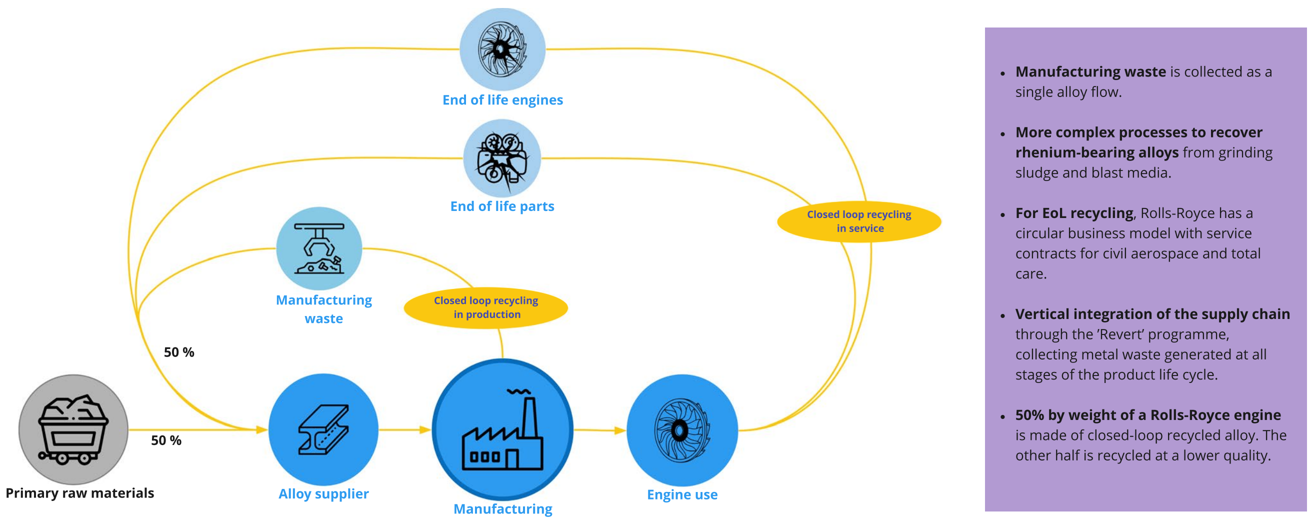


**Fig. 4** Closed loops of turbine blades and their materials at Rolls-Royce

as 'TotalCare': assets are offered with a contract fixing the fee per flying hour to cover maintenance. This forces Rolls-Royce to think about life cycle costs and life cycle extension, while also giving access to replaced parts. These parts can be reused, repaired, or reprocessed.

The net result is that 50% by weight of a Rolls-Royce engine is made of closed-loop recycled alloy. The other half is recycled at a lower quality. For example, titanium can be contaminated and has a lower margin for purification. This demonstrates how Rolls-Royce manages materials in a more circular way.

Rolls-Royce's 'TotalCare' business model prioritises repair over replace. The cost benefits of repair are passed on to the customer, which creates a win-win situation. On top of the more complex repair such as shop visits and engine overhaul, Rolls-Royce has also developed innovative 'on wing' repairs using boroscopes and even lasers, to re-finish blade damage without needing to dismantle the engine. This model maximises engine availability and minimises disruption, since both Rolls-Royce and the customer have an incentive to have the engine running as much as possible.

The revert programme decreases Rolls-Royce's material costs. The saving is greater than the value of the material on the scrap market. This is made possible by the high quality of the material we return to the supplier — it is not contaminated, and it is certified as being a specific alloy type.

In manufacturing, Rolls-Royce typically captures and recycles 95–100% of chip and swarf for Ti and Ni alloys. EoL parts can have higher losses due to the extra processing that is needed to extract the alloy. Some components (such as disks and other critical rotating parts) often have limits on their recycled content. This is driven by safety. Other, less sensitive parts can accordingly use more recycled content (Fig. 4).

## Case 5: Umicore: recovering platinum group metals from chemical processing catalysts

### Company and market

Umicore is a global materials technology and recycling group. The company recycles over 20 metals including CRMs, among them platinum group metals (PGMs). Various combinations of PGMs are used in process catalysts, both in oil refining and in catalytic chemical syntheses. The annual consumption of PGMs in a specific application can range from tens to hundreds of kilogrammes. PGMs are not only essential in process catalysts, but also in automotive catalysts, H2-electrolysis, electronics, fuel cells, and other applications. Since PGMs have high market prices and their content in catalysts is relatively high, they have significant influence on the catalyst costs. Combined with the high PGM price volatility, this urges industrial users to minimise the PGM life cycle losses. Hence, already for decades, PGM catalysts are integrated in circular strategies.

### Business model

In this circular strategy, a distinction is made between suppliers (catalyst manufacturers) and users (operating a process which uses catalysts). If the industrial user is the focal actor in the life cycle (see also Cimprich et al. (2020)), usually all other processes are contracted as a service by this actor. Consequently, this B2B business model focuses on product performance and services. In the first use, the user pays a split price for the catalyst manufacturing process and the PGMs contained in the catalyst itself. From the moment of shipping the catalyst

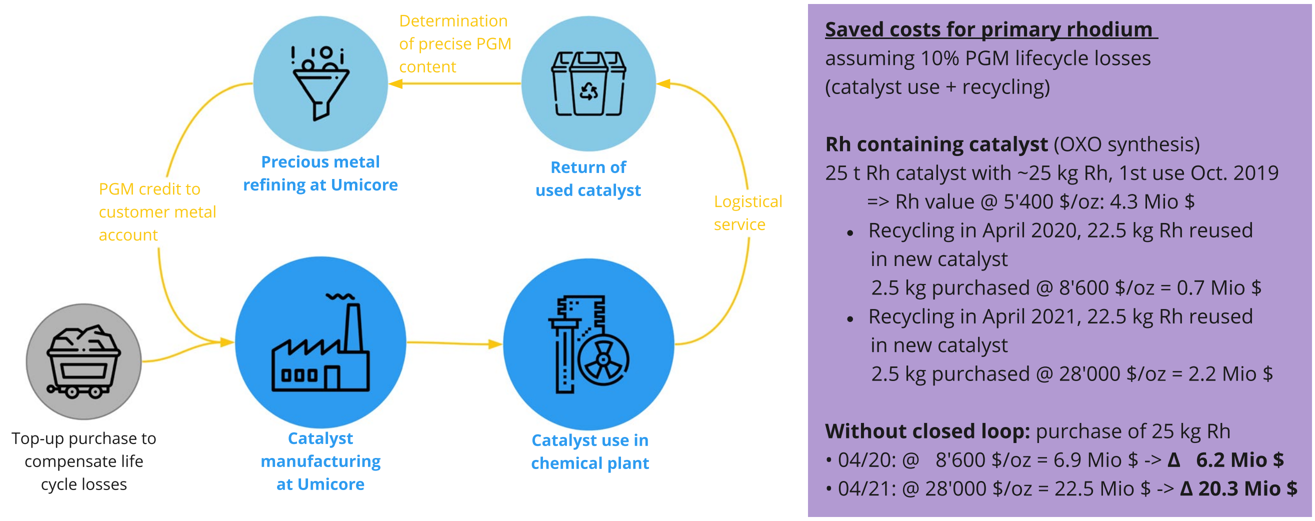


**Fig. 5** Circular Rh-Oxo catalyst management by Umicore

onwards, the user owns the PGMs. The user maintains contracts with service providers for regeneration to extend the lifetime and for recycling of spent catalysts to reclaim the PGMs. At the EoL, PGMs are recovered and treated under a 'toll refining' service based on sampling and the analytically measured PGM content. In most cases, the catalyst manufacturer is also operating the recycling service. The recovered PGMs are used to produce a new catalyst, and hence not subject to market price volatility. Only small losses need to be compensated with virgin PGMs. Full transparency is achieved because a limited number of professional actors are involved and the catalyst remains at a fixed location during the use phase.

In the example of a Rh-Oxo catalyst, Umicore supplies the catalyst (containing, e.g. 25 kg of rhodium) to a chemical plant. After around 6 months, it is exchanged and returned to Umicore, where the exact Rh content of the spent catalyst is determined. The recycling is done against a service fee, and the recovered rhodium is credited to the customer's account. Umicore uses these PGMs to produce and supply a new catalyst. Assuming a total life cycle loss of 10% rhodium, the user saves \$6–20 million each year, depending on the market price. Therefore, the user benefits from better economics and lower price risks, reduced dependence on primary PGM suppliers, and significant $CO_2$ footprint reduction.

PGM process catalysts are a potential role model for circular metal businesses. The drivers are high product values, vulnerability to price fluctuations, and PGM supply risks. The success is based on a B2B business model which inherently rewards high performance products and services along the lifecycle. The professional and long-term interaction between industrial actors secures full transparency (Fig. 5).

## Discussion

This report provides an overview of typical circularity strategies for critical raw materials, companies' motivation to implement them, potential success factors, and overall benefits that the circularity strategies provide, which were discussed during the European Commission's Raw Materials Week 2021.

Companies' dependencies on primary critical raw materials can be decreased by increasing material efficiency via product lifetime extension, as well as by recycling the materials at the product's end of life. Increased recycling requires innovative recycling technologies, enabled by companies with strong R&D capacity that can respond to changing application types and complex material compositions, but also by markets with growing demand and predictable raw material prices. Recyclability is furthermore enhanced by design for recycling, especially for materials that are dispersed in products and that are difficult to take out, which is the case for many critical raw materials (Tercero Espinoza et al., 2020).

However, design for recycling alone is not sufficient. In the case of electronic devices, relevant relationships between producers and users are often business-to-consumer (B2C) models: after having sold the electronic device to a customer, there is no link anymore between the manufacturer and the customer (especially after warranty period has ended). Subsequently, at the end of life, there exists no link between the recycler and the original manufacturer. The stakeholders do not collaborate along the lifecycle, and there is little interest in transparent material flows and design for recycling. Even if a manufacturer would produce an electronic device which is well recyclable, the manufacturer would not benefit from this, as in the common B2C situation the products are not returned to the manufacturer. At the EoL, many types of the devices are mixed and are — if at all — collected at municipal level.

A common theme across the five examples of raw material circularity presented at the workshop was the ability to add the circular strategies to existing operations. HCST, Hitachi, Rolls-Royce and Umicore all have existing processes for recovery and recycling of high value materials as part of their base operations. Incorporating an additional stream of material into these processes is more economical than creating an entirely new circularity process from scratch. Similarly, SungEel was able to develop a pre-treatment facility to improve the economics of known hydrometallurgical processes.

One of the biggest enablers of raw material circularity is the adaptation of business models. Ideally, all involved stakeholders have a common interest in retaining the material's value, which incentivises making material flows transparent and cooperating closely. This is enabled by retained ownership, either by manufacturers via product-service-systems, as implemented by Rolls-Royce, or by users, as demonstrated in the Umicore case. This goes hand-in-hand with long-term, transparent relationships between the value-chain actors. Such relationships are enhanced by vertical integration, as observed in the case of Hitachi Group, or by long-term contractual agreements. B2C relationships could mimic such B2B relationship via leasing contracts, in which the product is leased until its end of life. This could result in a new interpretation of extended producer responsibility, where comprehensive collection at EoL is followed by a guaranteed, high-quality, recycling. This would create an inherent incentive for longevity, improved repairability, and 'design for recycling'.

Another important enabler is the use of regulatory requirements and subsidies to create sustainable processes. This can be seen most clearly in the Hitachi case. The initial capital and process development effort was invested in response to a new law, and supported by subsidies. However, process improvement over time (through automation in the presented example) made the process economically sustainable. This provides inspiration for future efforts to implement circularity in cases where the economic case is limited by initial capital investment barriers. Targeted regulations and subsidies could help 'start-up' circularity processes that could then become economically viable without subsidies over time.

The benefits of implementing circularity strategies are manyfold, not only for business practices but also for more sustainable societies in which economic activities are maintained while environmental impacts are decreased. This provides a mandate for governmental intervention in stimulating circularity strategies, for example via regulations (e.g. comprehensive take-back obligations, mandatory use of certified, high-quality recycling processes, minimum recycled contents, or requirements regarding the labelling of materials present in products) and subsidies to overcome initial investment thresholds, as observed in the Hitachi case. Currently, regulations are often focused on the linear use of products. New business models that favour circularity might require amendments of existing regulations, which are, ideally, streamlined across Europe and beyond to facilitate the transport of end-of-life products.

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## Declarations

**Conflict of interest** The authors declare no competing interests.



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