Heraeus
Precious Metals

Myth vs. Facts:
What is Really Needed for Platinum Group Metals Recycling in the Hydrogen Economy

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Abstract / Introduction

The green hydrogen industry needs reliable policies to increase manufacturing capacities for key components and to guarantee resilient supply chains for critical raw materials. For the green hydrogen industry, the most important critical raw materials are the Platinum Group Metals (PGM) platinum, palladium, ruthenium and iridium. They cannot be substituted and are used across the whole value chain: production, processing, and end-use of green hydrogen **(figure 1)**.

Consequently, the critical raw material strategies of most countries consider Platinum Group Metals and want to ensure resilient supply chains. As industrial players and policy makers start to explore measures (including raw material mining, recycling, or programs for strategic reserves) policy makers should be careful not to follow an "one size-fits-all" approach. In our opinion, the important differences in the supply chains and application of different raw materials need to be considered.

This is especially true for the recycling of Platinum Group Metals, where common misconceptions dominate the political discussion. In this whitepaper, we address some of the biggest misconceptions. We aim to enrich the public discussion by presenting facts and clarify the myths about Platinum Group Metals recycling:

Myth 1 The recycling of Platinum Group Metals is a new challenge that the hydrogen industry is facing.

Fortunately, Platinum Group Metal recycling is anything but new and also not a technological challenge. It is well established and constitutes an essential part in many industries relying on the use of Platinum Group Metals.

Myth 2 The recycling of Platinum Group Metals suffers from low capacities and low technological readiness similar to the challenges seen in the recycling of battery materials.

There is sufficient capacity for Platinum Group Metal recycling. Recycling is handled routinely on industrial scale employing specialized highly evolved technologies that guarantee the highest recovery rates. The existing industry can easily absorb additional waste streams from the growing hydrogen economy.

Myth 3 Recycling rates of Platinum Group Metals are low and below the targets defined in the EUs Critical Raw Material Act.

In the contrary, the recycling rate for each of the Platinum Group Metals are actually among the highest for all critical raw materials. The rates only seem to be low, as publicly available data is misunderstood.

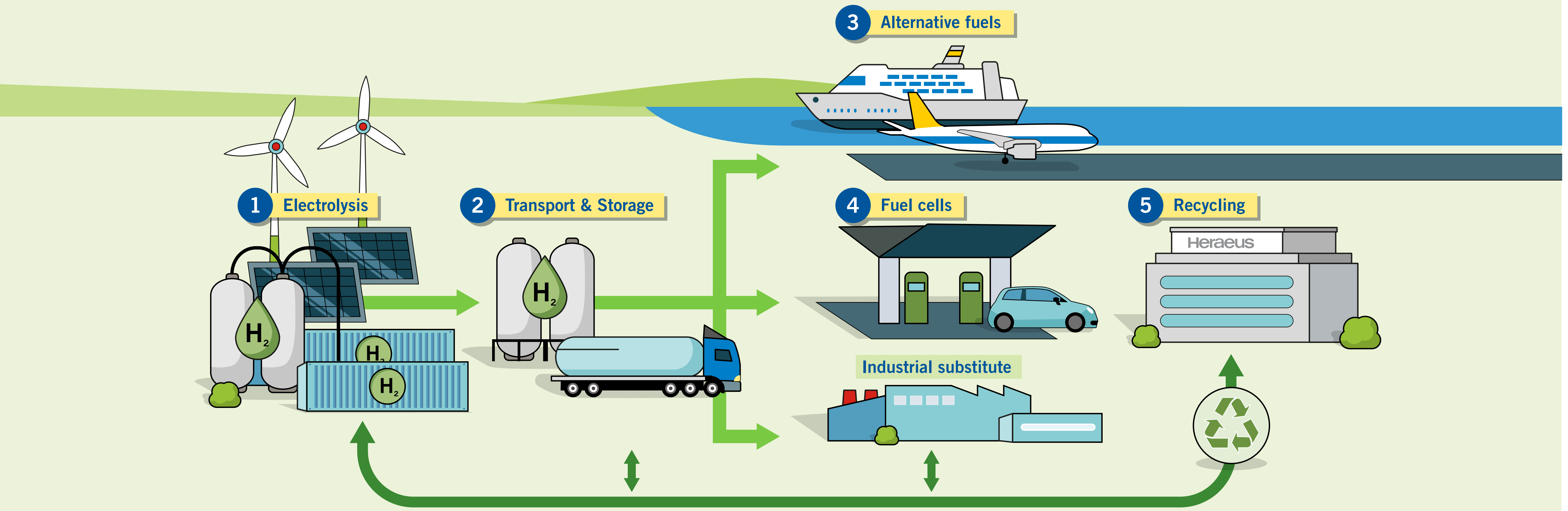

Figure 1. Use of PGMs in various technologies along the chain of hydrogen production, transport, and use.

The Role of Recycling in the Supply of Precious Metals

Chapter 1

Precious metal used in industries can have two origins: Platinum Group Metal mines, and recycling.

In open loop recycling, the recycled Platinum Group Metals are sold back to the market.

In closed loop recycling, the recycled Platinum Group Metals are not returned to the market, but stay in the same product cycle and are directly remanufactured into new products.

For Platinum Group Metals, the closed loop recycling volumes are typically large, but invisible to the market.

Apparent recycling rates calculated from open loop recycling volumes only, are significantly smaller than total recycling rates.

The requirement for a sustainable supply of Platinum Group Metals is neither new nor unique to the hydrogen industry. A stable supply with Platinum Group Metals is at the core of the technical and economic viability of many mature industries. Those industries are relying on fully integrated precious metals houses which offer the three pillars to ensure a sustainable Platinum Group Metal supply chain:

1) Platinum Group Metal trading to secure the necessary amounts,
2) product and technology development, and
3) recycling as part of the mature circular economy in the Platinum Group Metal sector.

The origin of primary material

Primary supply of Platinum Group Metals is largely concentrated at mining operations in South Africa, and Zimbabwe **(see figure 2)**. Mined ores thereby contain all PGMs at different ratios determined by geology. After base metal extraction, fine metals and Platinum Group Metals are extracted and refined, either directly at the mining companies or at precious metal refiners.

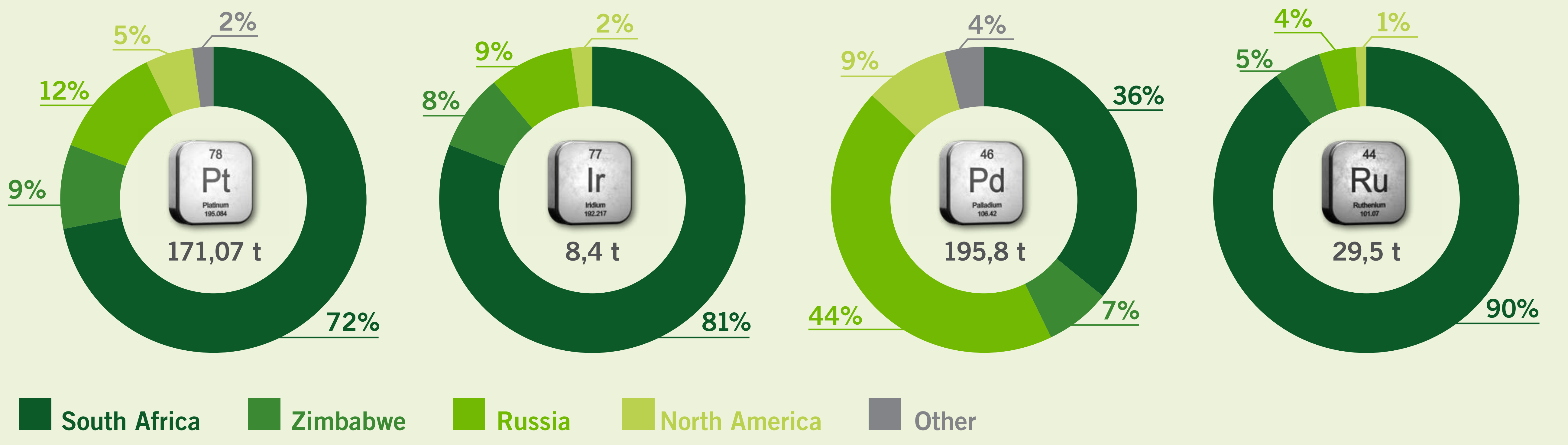

Figure 2. Primary Supply for platinum (Pt), iridium (Ir), ruthenium (Ru), and palladium (Pd) in koz for the year 2024. South Africa is by far the leading supplier for all PGMs other than palladium, which is also a by-product of nickel mining.[1]

1 Data provided by SFA Oxford Ltd.

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Gross demand, net demand and the role of recycling for Platinum Group Metals

The annual industrial demand for platinum group metals ("gross demand") is only partially met by primary supply, i.e., through mining. In fact, a significant amount of total annual demand is secured by recycled metal across all Platinum Group Metals thanks to mature and well-established Platinum Group Metal recycling **(figure 3)**.

In closed loop recycling, the metal ownership remains with the industrial user of the metal, and recycling is provided as a service for the spent, or end-of-life, product containing Platinum Group Metals. The metal is recovered from the spent product and can be re-used within the same application. These closed loop recycling volumes are not sold on the market and therefore not publicly visible. In fact, mature industries meet a large share of their annual gross demand through closed loop recycling. Only the remaining net metal demand is sourced from the market.

Open loop recycling contributes to the traded Platinum Group Metal volumes and is defined as secondary supply. Platinum Group Metals are recycled and subsequently sold back to the market and therefore publicly visible. A common example for open loop recycling are scrap collectors who receive and, if necessary, dismantle end-of-life products to extract recyclable materials. The PGM-containing parts are shipped to specialized precious metals companies, which recover, refine, and buy the Platinum Group Metals from the scrap collector.

The total Platinum Group Metal recycling rates therefore need to consider the sum of open and closed loop recycling volumes in relation to the gross demand. While both the open loop and closed loop volumes are ultimately based on long-term market observation, open loop data are easier to obtain and more often published in market reports. Closed loop recycling volumes, on the other hand, are not part of most market reports and releiable estimates require a more in-depth observation of precious metal processing over all industries. With only the volumes of the net market demand, i.e. open loop recycling volumes and primary supply, conveniently available, the public discussion on Platinum Group Metal recycling rates is typically erroneously referencing open loop recycling rates alone.

Consequently, Platinum Group Metal recycling rates that enter the public and political discussion severely underestimate the actual recycling rates.

Figure 3. Gross demand of Platinum Group Metals, i.e., the annual metal requirement in a respective industry, and how it is sourced. In mature industries a significant share is sourced through closed loop recycling, which is, recycled material that does not change ownership during the recycling and remanufacturing process. The material that cannot be sourced through closed loop recycling, hence, is not already owened by the user, is the net demand which has to be met from the market. Traded PGM amounts come from primary supply from the mines and open loop recycling, i.e., recycled material that is not used by its original owner but sold to the market.

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Figure 4. Gross demand[2] for iridium, ruthenium, platinum, and palladium in the year 2024 and its contributions. Gross demand is met by closed loop recycling volumes and net demand covered from the market. Net demand largely reflects primary supply from mined metals (adjusted for aboveground stocks) and secondary supply through open loop recycling. The actual total recycling rates are based on gross demand and the total recycling volume, i.e., the sum of open loop and closed loop recycling, and are much larger than suggested by the volume of recycled material on the market alone.

In this whitepaper we show actual recycling rates based on open loop and closed loop recycling amounts. **Figure 4** shows the estimated gross demand for iridium, ruthenium, platinum and palladium for the year 2024 and the contributions from recycling volumes and primary supply. Contributions from open loop recycling is estimated to be relatively low at only 3% for iridium and 1% for ruthenium, 11% for platinum and a considerably higher 21% for palladium. In contrast, the estimated total recycling rates calculated as the share of the recycling volumes from open and closed loop recycling at the estimated gross demand are significantly higher: 55% for iridium, 50% for ruthenium, 51% for platinum, and 46% for palladium. **It is worthwhile to point out that for all Platinum Group Metals the actual recycling rates are already far above the 25% target aimed in the EU critical raw materials act.**[3]

2 Own calculations, Data provided by SFA Oxford Ltd.

3 European Critical Raw Material Act Article 5 §1; Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020, Official Journal of the European Union 2024. http://data.europa.eu/eli/reg/2024/1252/oj

Recycling of Platinum Group Metals

Chapter 2

Large recycling capacities for Platinum Group Metals are already available world-wide

Platinum Group Metals from hydrometallurgical recycling have up to 99% lower CO_2 footprint in comparison to primary metals.

Collection infrastructure and regulatory requirements are the biggest challenge for Platinum Group Metal recycling in the hydrogen sector.

Three general steps:
Collection, pretreatment, refining
Recycling of materials always starts with the collection of the materials, which often is the biggest challenge, followed by pretreatment and disassembly of equipment and the eventual chemical refining process **(see figure 5)**. Low recycling rates in a particular industry are typically the consequence of difficult to collect end-of-life and waste streams and/or costly disassembling of devices with low individual PGM content, rendering recycling uneconomic (consumer electronics, spark plugs, etc.). Once the PGM-containing waste stream has been collected and sufficently pretreated, all Platinum Group Metals in such waste are chemically recycled. There are sufficient capacities to treat all available materials today, as well as to absorb additional waste streams, e.g., from the growing hydrogen economy.

Business models in the recycling industry include companies that only focus on either one of the steps shown in **figure 5**, or a combination of two or more. Especially for open loop recycling, service providers for pretreatment and concentration maintain the contact with smaller customers and provide the logistics for the waste collection, while the refining process itself is handled by the integrated precious metal companies.

Collection

Consumer goods
- Automotive
- Electronics
- Medical equipment

Industrial waste
- Heterogeneous process catalysts
- Homogeneous process catalysts
- Crucibles

Production scrap
- Pastes, powders
- Surplus materials and cutoff
- Cleaning tools and tissues

Pretreatment

Disassembly of components
- Removal of non-PGM containing parts

Concentration
- PGM-rich ashes
- Precipitates
- Secondary mixed metallic concentrates
- Bio-metallurgical slurries

Refining

Pyro-metallurgical refining
- PGM bullions,
- PGM sponge

Hydro-metallurgical refining
- PGM sponge
- PGM salts
- PGM solutions

Figure 5. The recycling value chain of collection, pretreatment and refining with various necessary steps and resulting intermediary products along this chain.

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The recycling process in a nutshell

Precious metals service providers help to navigate the often complex waste logistics and processing steps of recycling at the highest efficiency and best return rates. For the customer the process starts with a comprehensive questionnaire about the amount and traits of the material. Based on this information it determined what legal and regulatory settings apply and how and where the material can be treated. Then, the materials are shipped to the recyclers facilities and a representative sample is drawn either from the waste directly or from a concentrated ash. This sample is analyzed both by the recycler and the customer, and the Platinum Group Metal content will be agreed between both parties.

Based on the overall amount and composition of the waste and the determined Platinum Group Metal contents a return rate and timeframe for the material recovery will be contractually agreed.

Localisation and logistics for waste streams

Through the international networks of the globally active precious metal houses, yields can be maximized through accumulation of similar waste streams at highly specialised sites. Such companies either can provide the necessary know-how for the shipment of Platinum Group Metal containing wastes as regulated internationally through the Basel Convention and associated local legislation. Or they can help to leverage the advantage of full or partial localization where necessary. Localisation of refining activities is market driven, i.e., becomes prudent if sufficient demand arises in an area, but is also influenced by tariffs, regulations and limitations on shipping raw materials between markets from which a net loss in efficiency and higher costs can result.

Recycling methods:
Pyro-metallurgical and hydro-metallurgical

To regain high yields of Platinum Group Metals a sophisticated chain of processing is necessary. The first step is usually the concentration of the PGM content (e.g., by incineration). The second step is the sepration and purification of each single metal. The method for this metal refining step depends on the content of the waste stream. In pyro-metallurgical refining, the metals are refined in a smelter, which can handle a large variety of materials. It is suited for large-scale, mixed material recycling and, for example, employed for automotive exhaust catalysts with ceramic matrices. In hydro-metallurgical refining, the metal is refined through a wet-chemical treatment. This method is fast, energy efficient, more selective, also suited for lower metal volumes, and hence offers a more efficient treatment for iridium and ruthenium refining.

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More than just a financial benefit: The carbon footprint

The business model for recycling is simple: The value of the regained material outweighs the service fee for recycling. However, the benefit of recycling is not only financial. Recycled Platinum Group Metals exhibit a significant reduction in the carbon footprint compared to primary sourced Platinum Group Metals from the mines. The International Platinum Group Metals Association (IPA) conducts regular life cycle assessment (LCA) studies across the industry according to the ecobilancing norms ISO 14040 and 14044 **(see figure 6)**. These studies suggest that recycled Platinum Group Metals exhibit a reduction in the implied CO_2-equivalent per gram of more than 98% compared to primary material.[5]

Carbon footprint of Precious Metals (LCA Study)

Primary vs. recycled precious metals in kg CO_2-eq per gram

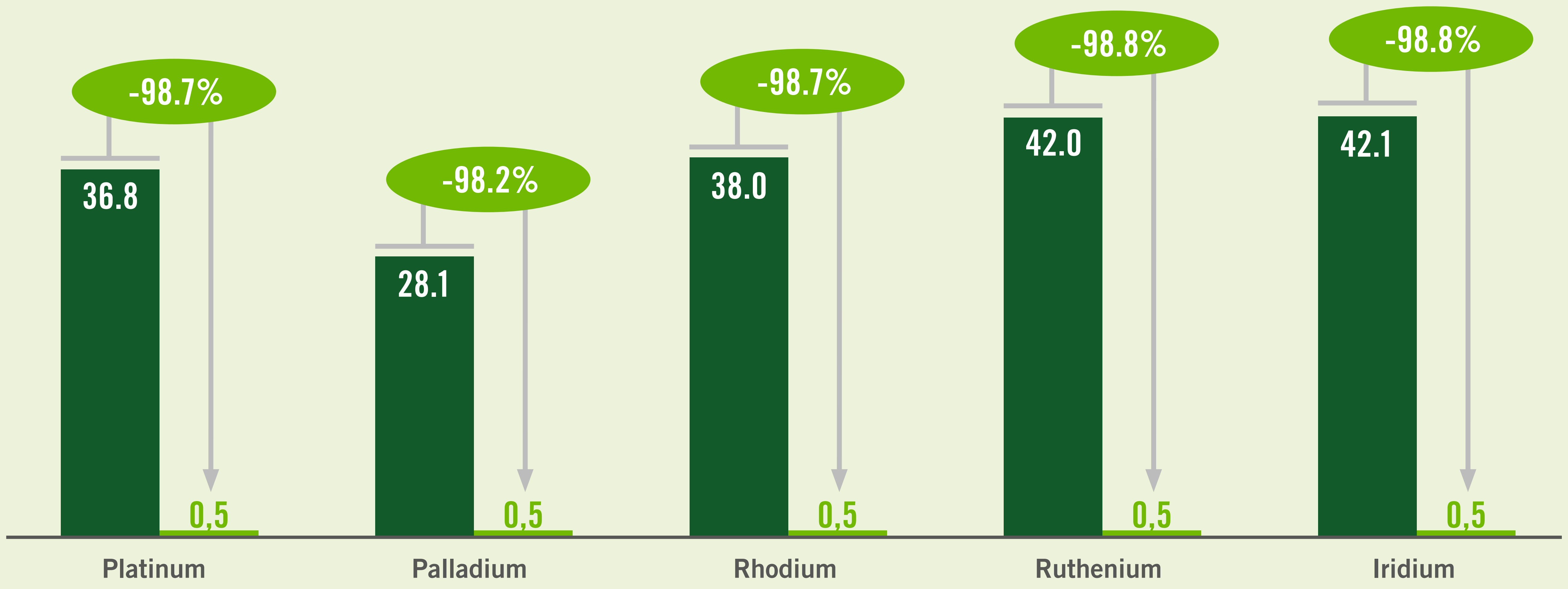

Figure 6. Comparison of CO_2 footprints for primary and recycled PGMs according to the life cycle assessment conducted by IPA and Sphera in 2025 for the precious metals industry for the reference year 2022.[4]

4 IPA and Sphera (2025) The Life Cycle Assessment of Platinum Group Metals Reference year 2022 [White paper]; https://ipa-news.com/assets/contentimg/sustainability/ipa-lca-3-fact-sheet-final-april-2025.pdf

Chapter 3

Platinum Group Metal recycling technologies are ready and at sufficient capacities to support green hydrogen technologies.

The hydrogen industry can profit from a mature network of refineries and established precious metal handling services.

Collection systems for recycling in the hydrogen industry lack far behind that of legacy industries.

The logistics and regulatory environment of material collection in open loop recycling needs to improve.

Closed loop recycling outside of production scraps is not widely adapted.

End-of-life considerations are not yet sufficiently part of the business cases along the value chain for electrolyzers.

In the previous chapter the process steps for Platinum Group Metal recycling were summarized from a general perspective. In the following we want to point out industry observations on the status of recycling in the hydrogen economy. We point out how the growing hydrogen economy can profit from the existing recycling networks and capacities that have been build over decades in other industries. The chances to increase supply chain stability and to mitigate stress on the primary supply through recycling are especially high for iridium used in PEMWE.

Current public discussion and policy proposal
Policy makers have recognized the potential of recycling for resilient raw material supply chains and strive to apply learnings from other technologies in the green electricity sector to the hydrogen sector. However, often these solutions do not match, as the role models show very different challenges: Recycling of battery materials, recycling of solar cells, or the recycling of rare earth materials all suffer from bottlenecks in either availability or capacity of the actual chemical refining processes. For the PGMs used in the green hydrogen sector those processes are already available at capacity, widely used and routinely applied for production scraps and end-of-life materials at high recovery rates. The misconception of the actual recycling volumes, is however an inherent feature of a mature recycling industry in which closed loop material in a true recycling sense is returned directly to the same user and does therefore not appear in market statistics. (ref Chapter 2)

Closed loop or open loop recycling for the hydrogen industry?
Production scrap recycling in the hydrogen industry has actually already reached high maturity. Closed loop recycling of production scraps is an essential part of the cost calculations for producers of catalyst coated membranes, the precious metal containing core component of both PEM electrolyzers and fuel cells.

For end-of-life recycling, the situation is less advanced. The production facilities for hydrogen that employ electrolysers and hydrogen purification catalysts would present an excellent field for closed loop recycling. Closed loop recycling can improve supply chain stability for next generation facilities and the resale value of the used raw material should be part of Levelised Cost of Hydrogen (LCOH) calculations.

Recycling of fuel cells in mobility and transport applications is also less advanced. This is despite the conceptual similarity to the recycling of end-of-life exhaust catalyst from internal combustion engine vehicles and the high value of the precious metal in fuel cells.

Collection and dissassembly for industrial applications
Awareness for the positive economy of Platinum Group Metal recycling is unfortunately still lacking in the industrial use of electrolyzers. The cost constribution of raw materials to total electrolyzer costs is getting smaller and with this the awareness for raw material recycling. Maintanenance contracts and end-of-life take back options to aggregate the scrap material, can solve this problem, but are not fully established in practice. Hydrogen production is thus lacking behind comparable sectors, like the electrolytic production of HCl and NaOH through the Chlor-Alkali process where such methods are widely applied.

Invest in disassembly lines by specialised collectors needs the certainty that end-of-life equipment can be reclaimed from the end users or alternatively the OEMs. For industrial applications, for electrolyzers end-of-life regulations or business-to-business contracts that clarify the end of life ownership of raw materials would be an advantage.

Platinum Group Metal Recycling for the Hydrogen Economy

Value Composition for PEMFC Stack Recycling

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The costs for an automotive fuel cell stack are still dominated by the high development and qualification costs for specialized parts at relatively small production volumes. The low volumes and low utilization rate of production equipment also mean that manufacturing costs of engineered parts make up a large share of the stack production costs.

A purely raw-material focused recycling is driven by the value of PGMs in the fuel cell stack. **Figure 7** shows the cost of a fuel cell stack based on the model system and analysis by

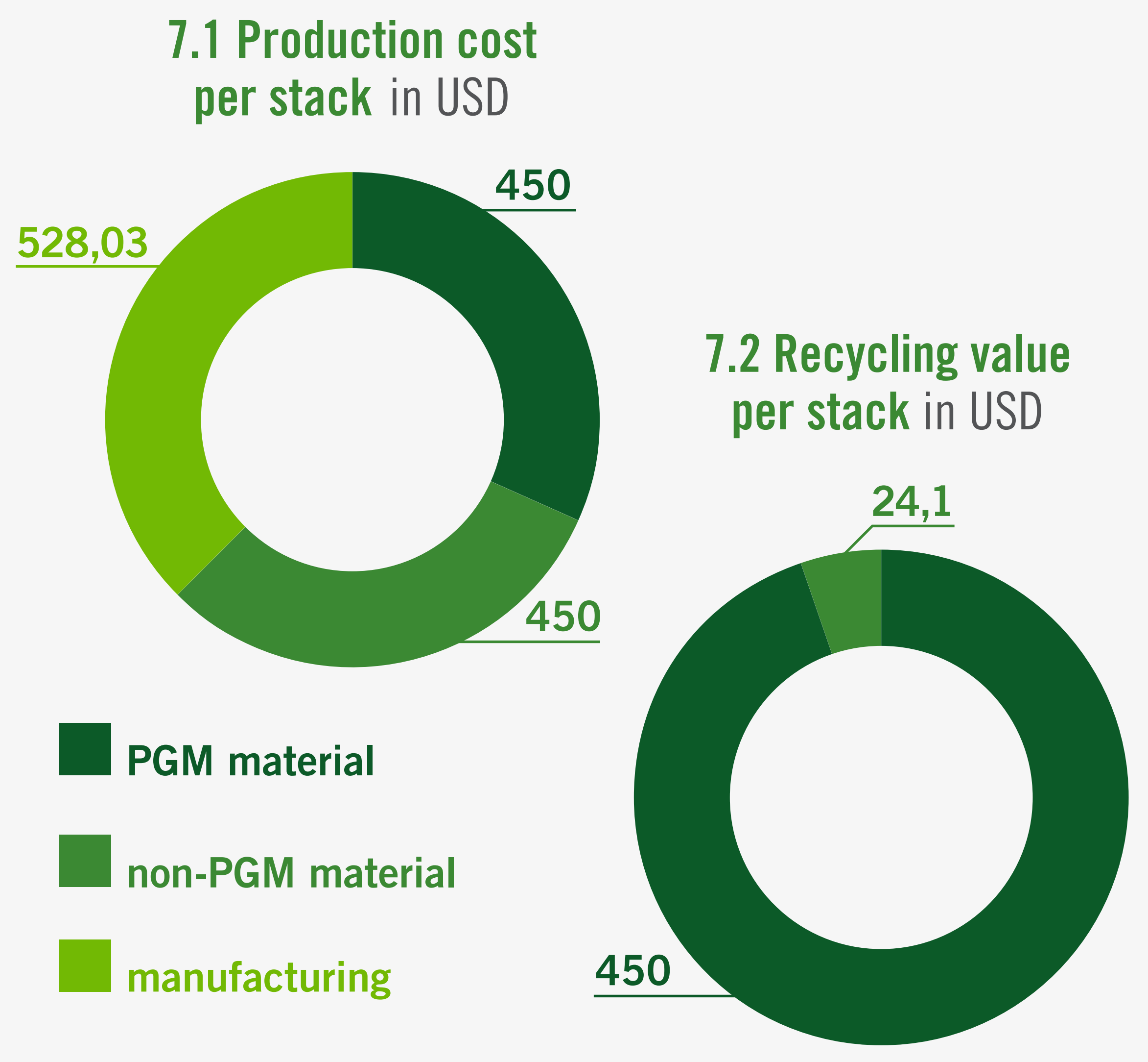

Figure 7. 1. Cost of stack manufacturing (100.000 stacks/a) and raw materials in USD according to Strategic Analysis 2021[5] **2.** The estimated recycled raw material values for the same stack.

Strategic Analysis conducted for the US Department of Energy between 2017 and 2021. The material and manufacturing cost for the different parts are shown in **figure 7.1** and the remaining recycling value of materials are shown in **figure 7.2.** Currently the recycling value is dominated by the value of the Platinum Group Metal that can be almost fully recovered. Platinum Group Metals in a fuel cell stack are located within the so-called catalyst coated membrane (CCM), a lamination of a proton conducting membrane made of specialty polymers and the two PGM containing catalyst layers, at the center of each of the up to 400 individual cells **(see figure 8)**. Each cell sandwiches the CCM within a succession of graphitic or metallic components that electrically connect the CCM and enable the transport of gas, water and heat to and from the cell.

To recover the Platinum Group Metals in the best-case scenario the stack needs to be disassembled and stripped down to the catalyst coated membrane. The catalyst coated membranes are then treated through existing processes by a precious metal refiner and the precious metal price is reimbursed. Stack recycling is thus economical if collection and disassembly can be conducted at lower costs than the Platinum Group Metal resale price recovers. This business case is easier to achieve if more additional value can be generated from the stack (e.g., from other components and further material) or costs for disassembly can be reduced. To realize easier and cost-efficient dismantling processes, the stack design is pivotal. Design-to-recycle techniques can drastically improve the cost structure and scalability of end-of-life processing.

To generate additional value, second life options and criteria for non-PGM parts and materials need to be developed through collaboration along the supply chain. Other than for the Platinum Group Metals, these markets are non-existent today and need to be built from the bottom up. Retaining direct functional value will be difficult, as functional parts like bipolar plates are highly specific in design for a particular OEM and would require 100% inspection for degradation. Membranes can in principle be remanufactured from the dissolved or dispersed specialty polymers they consist of. The material has alternative applications, which makes downcycling an option. In any case, the original manufactures of the polymers will need to define quality categories, and the materials will need to be characterized for degradation effects and sorted for reuse cases at significant costs. For now, that hinges the economic case for recycling solely on the value of the Platinum Group Metals.

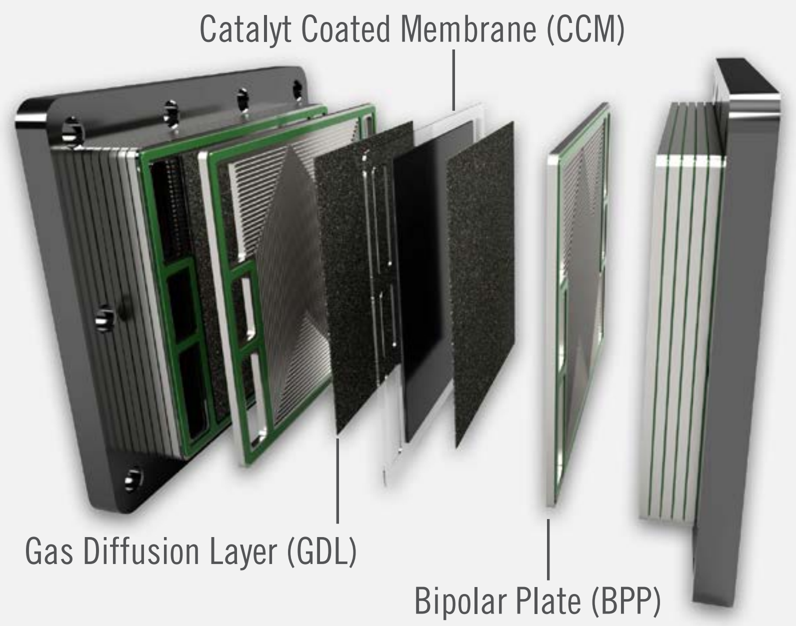

Figure 8. Example for a PEM single cell, showing the Catalyst Coated Layer connected parts, the Gas Diffusion Layer (GDL) and Bipolar Plate (BPP).

5 B. James, J.M. Huya-Kouadio, C. Houchins, M. Gomez (2021) Final Report: Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications (2017 - 2021) (Report Number Final-Report-DOE-SA—7600). Strategic Analysis https://doi.org/10.2172/2309724

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Collection and dissasembly for end-user applications
For transport and mobility applications of hydrogen fuel cells, the existing collection infrastructures of the automotive industry for catalytic converters can serve as a model. The recycling value of PGM-containing catalytic converters is widely appreciated and devices are recovered at scrap yards. Treatment and recycling of catalytic converters is often regulated, e.g., through the EU directive on End-of-Life Vehicles (ELV Directive) in the European Union, or state laws in the USA. The value of the raw materials actually helps to offset the majority of the treatment costs. Logistic providers collect the catalytic converters as part of an open loop recycling, and specialised companies disassemble the parts and often concentrate the Platinum Group Metal before contacting the final refiner.

Due to the much lower number of fuel cell vehicles, this infrastructure is however currently not applied to fuel cells. Specialised know-how, training and equipment at all parts of the collection chain would be necessary which is not yet economically viable for individual scrap yards. At the current number of end-of-life vehicles, even the higher Platinum Group Metal contents of fuel cells in comparison to catalytic converters, cannot fully offset the treatment costs of stacks.

On the technological side, more effiencent ways of disassembly are being developed by larger players in the market and calls to improve design for end-of-life processing are getting louder. On the regulatory side certainty and clarity for the recycling sector is needed to support investment in the circular economy. Unclear or non-existing waste codes for end-of-life fuel cell stacks and the various stages of disassembly of stack components causes uncertainty along the recycling infrastructure how to receive and send on the various stages of disassembly which increases the finanical risk.

Fuel Cell Electric Vehicles and its various recyclable parts are still omitted from the EU directive on End-of-Life Vehicles (ELV directive). The International Platinum Group Metals Association (IPA) for the precious metals industry called for their inclusion in the ELV direction in a recent position paper. Important arguments are long-term material security and resilience, certainty and job protection for a highly developed recycling infrastructure in Europe, and technolgical leadership.

Refining and value added to Platinum Group Metal recycling
The refining processes for Platinum Group Metals from the hydrogen industry are fundamentally the same which are already employed for many different industries, or in fact related to processes employed in the initial refining of mined materials. Therefore, calls to develop the chemical processes or to build up recycling capacities are misdirected, because the technical know-how is well established and exisiting recycling capacities can easily absorb the additional material expected from the hydrogen industry. Raw material values of Platinum Group Metals are high and transparent to all partners along the value chain as materials are either listed on the commodity exchange or monitored by the London Bullion Market Association (LBMA). Customers of recyled materials additionally benefit from reduced carbon footprints in their supply chain, as life cycle assessment are already common pratice in the Platinum Group Metal industry.

The same levels of transparency for non-PGM components could provide additional incentives for the existing disassembly value chains to commit to the hydrogen sector with more investment. As of now, a lack of a clearly communicated functional value, material value or reuse cases of non-PGM components, (see info box on page 10 for details) or a clear commitment to find such reuse cases by the OEMs impedes an expansion of the circular economy to materials other than Platinum Group Metals.

Conclusion

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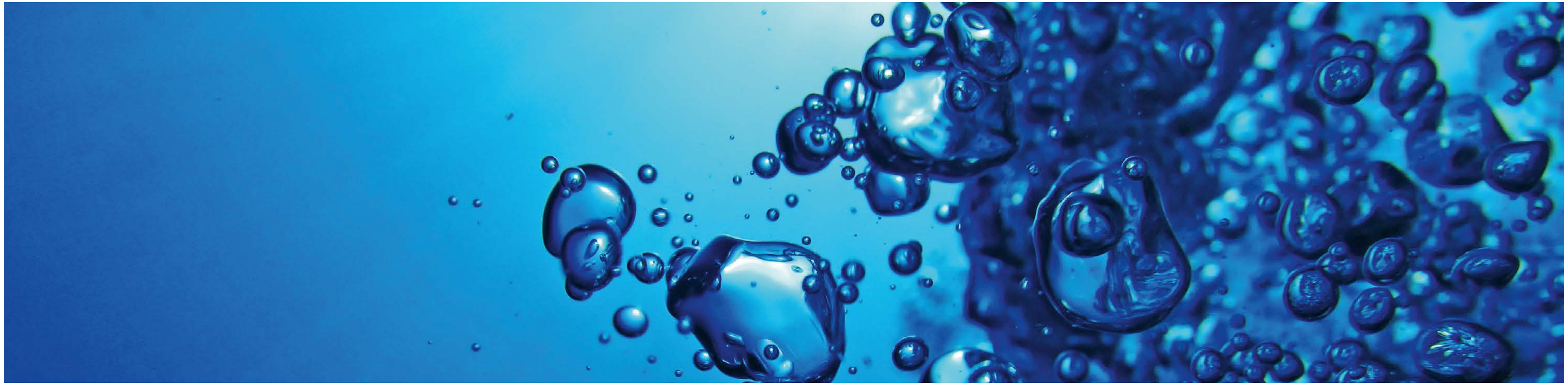
The Platinum Group Metal industry and its facilities are ready to support the recycling for all parts of the hydrogen economy. Platinum Group Metal recycling and management is an established and competitive industry that supports the chemical and electronic industries since many years. Technologies for chemical recycling and refining exist and are established at large capacities that can already absorb additional waste streams from the growing hydrogen economy. The real recycling rates for Platinum Group Metals already exceed the quota set by for example the EU Critical Raw Materials Act. That means at the current stage neither the lack of developed recycling technologies nor their capacities are the limiting factor to increase recycling rates in the hydrogen economy.

What's truly needed to support recycling in the hydrogen sector is:

- **Regulatory certainty** to simplify the logistics surrounding the recycling process to enable predictable recycling business cases along the value chain.
- **Ownership of raw material** at the end of equipment life needs to be clarified for industrial applications like electrolyzers, etc. PGM-containing fuel cells need to be part of the EUs End-of-Life Vehicle regulation.
- **Waste codes** need to be set up to generate certainity for the transport of wastes from the hydrogen industry to the recycling sites.
- **Design for disassembly** can reduce the cost of logistics and open up more material for recycling by enabling a selfsuficient economy for the disassembly lines.



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Heraeus is a globally active, family-owned technology group. Based in Hanau, Germany, the company comprises 15 operating companies whose products and services span the Business Areas of Metals & Recycling, Healthcare, Semiconductor & Electronics, and Industrials. In fiscal year 2024, Heraeus generated revenues of €29.4 billion and employed roughly 15,200 people across 40 countries. This makes Heraeus one of the top ten largest family-owned enterprises in Germany.

With deep expertise in advanced materials, Heraeus is a leader across key global industries. The group ranks among the foremost providers of precious metals, supplies quartz glass for the semiconductor and telecommunications sectors, and manufactures sensors for the steel industry. In addition, its materials and technologies for medical technology help improve the quality of life for millions of people worldwide.

Innovation is the central driver of Heraeus's success. Each year, six percent of revenues (based on revenues excluding precious metals) are reinvested into research and development. Beyond that, the company partners with leading research and educational institutions around the world.

About Heraeus Precious Metals

Heraeus Precious Metals is globally leading in the precious metals industry. The company is part of the Heraeus Group and covers the value chain from trading to precious metals products to refining and recycling. It has extensive expertise in all platinum group metals as well as gold and silver.

With more than 3,000 employees at 16 sites worldwide, Heraeus Precious Metals offers a broad portfolio of products that are essential for many industries such as the automotive, chemicals, semiconductor, pharmaceutical, hydrogen and jewelry industry.

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