Heraeus

Precious Metals

Platinum crucibles for use in laboratory applications

The Platinum Standard 2023

Setting the PGM agenda for the years ahead

Produced in collaboration with SFA Oxford

THE PLATINUM STANDARD

May 2023

Issue 19
© Published in May 2023 by SFA (Oxford) Ltd.

Designed and typeset by Daniel Croft.

CONTENTS

TPS COLLECTION: AGENDA-SETTING COMMENTARY

The Platinum Standard was first launched in May 2014

One-half review, one-half preview, The Platinum Standard *comprises analytical commentary on those issues we believe will set the PGM agenda for the year ahead*

If you are interested in reading the collection, you can now download past editions via the SFA (Oxford) website

FOREWORD — HIGH TIME FOR HYDROGEN: OPPORTUNITIES FOR PGMS

Foreword — High time for hydrogen: Opportunities for PGMs

The SFA (Oxford) team is delighted to be hosting the Oxford Platinum Lectures 2023 and presenting this year's edition of *The Platinum Standard*. At this year's event, we are looking at the ever-closer interplay between platinum-group metals (PGMs) and various hydrogen technologies, as the world seeks to transform its energy systems to reduce the risks of global warming, while maintaining (and, indeed, enhancing) our familiar comfortable and healthy lifestyles. We are fortunate to have articles from two companies that are developing and driving disruptive technologies, based on PGM properties, which will be needed to complete the sustainable hydrogen value chain.

The PGMs have a long history of alleviating some of the problems of humankind's making and of substantially improving our quality of life. Transport in the form of the internal combustion engine (ICE) over the past century or so has allowed many people to travel and have experiences that were unimaginable in the days when the horse and cart was the usual means of transport.

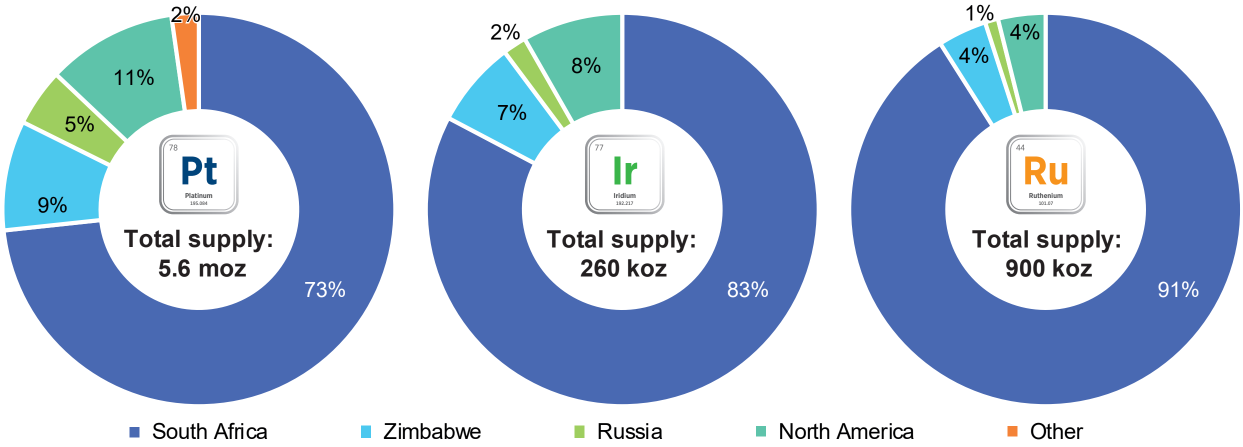
Unfortunately, that democratisation of the ICE car is leading towards an uncertain future. In 1923, there were 383,525 cars on the roads of Great Britain. A century later, there are over 35 million cars on the roads, a number which leads to unsustainable negative consequences, replicated at scale all around the world.

Burning carbon-based fuel in these cars comes at a huge cost to the health of both our planet and its inhabitants. Fortunately, platinum, palladium and rhodium, in ever more effective autocatalysts, have helped to remove the main harmful products of combustion. Abating almost all emissions of oxides of nitrogen, carbon monoxide, unburnt hydrocarbons and particulate matter has allowed us to continue to drive our growing fleet of gasoline and diesel cars, with poor air quality affecting primarily the most densely driven roads.

Burning fossil fuels in air also releases carbon dioxide, and its accumulation in the Earth's atmosphere contributes to global warming, causing irrevocable harm to many vital global ecosystems and communities. Fortunately, the PGMs – this time mainly platinum, iridium and ruthenium – are ready to aid humankind once again by enabling the pivot to a hydrogen-based economy from a carbon-based economy. The production of green hydrogen from renewables promises to help decarbonise not just transport but also many key heavy industrial processes, enables us to continue to travel and to enjoy higher standards of living and wellbeing without jeopardising the planet's future.

Mined supply of platinum, iridium and ruthenium is heavily skewed towards South Africa. The Merensky and UG2 orebodies are the highest-grade resources of these key catalyst metals and are forecast to produce 73%, 83% and 91% respectively of global primary supply in 2023. As the hydrogen economy flourishes, security of long-term primary supply has come to the forefront. South Africa's power supply crisis poses near-term challenges to the industry's ability to maintain reliable supply, which in time, although likely coming at a significant cost to the industry, can be resolved. Longer term, the future closure of older and higher-cost mines combined with the lack of investment in maintaining, let alone growing, mine capacity could result in a declining profile for South African production, and hence primary supplies of these key materials for the hydrogen economy. Therefore, continued efforts in the efficient use and thrifting of these scarce and precious future facing metals are key to keeping these markets sustainable.

Hydrogen metals primary production by region, 2023 forecast



Source: SFA (Oxford)

Full throttle thrifting

Dr. Detlef Gaiser, in his article **HYdrogen, Pharmaceuticals, Environment: Not just a HYPE for PGMs**, describes Heraeus's progress in catalysts for the energy transition, then takes us through the roles of PGMs in catalysing chemical reactions to produce pharmaceuticals. After all, we will need a healthy population to continue innovating with PGMs to look after our planet. He highlights the pivotal role of iridium in the ramp-up of hydrogen production and the apparent gap between limited iridium primary supply and burgeoning demand for green hydrogen. The teams at Heraeus have made significant progress in thrifting, delivering the performance and durability needed in PEM (proton exchange membrane) electrolysers. Of course, recycling the catalyst at the end of its operating lifetime is the last link in the circular economy, and he outlines some of the approaches to recovering these valuable PGMs from challenging substrates.

Detlef sets out the gains for the pharmaceutical industry from using highly specialised, PGM-based catalysts. Hydrogen features again, but this time in so-called asymmetric hydrogenation reactions in which iridium, ruthenium and rhodium catalysts enable chemists to build complex, three-dimensional, biologically active molecules via high yield reactions without the need for costly separation and purification steps.

Financing the future

Kevin Eggers, in his article **The Role of Hydrogen in Reaching Global Net-Zero**, sets the scene for AP Ventures' portfolio companies, many based around PGMs and seeking to scale up the hydrogen economy. APV is currently invested in 25 companies, of which 18 use PGMs directly as part of their technology. While the roles of PGMs as catalysts in PEM electrolysers and PEM fuel cells is well known, he points out that there are many more opportunities for platinum, iridium and ruthenium, plus palladium too, though to a much lesser extent for rhodium.

Kevin highlights some of the attractive options for PGMs in the mid-stream of the hydrogen value chain: transport and storage are the vital link between the upstream electrolytic production of green hydrogen via renewables and the downstream use of hydrogen as an energy carrier, including but not solely in transport. Liquid organic hydrogen carriers (LOHCs) enable hydrogen to be stored and transported in a similar way to petroleum fuels, thus utilising existing infrastructure. Platinum and palladium show great promise as catalysts in the processes for hydrogenation and dehydrogenation of the LOHCs.

PGMs and hydrogen in symbiosis

We trust this year's edition of *The Platinum Standard* leaves you in no doubt that while the technologies adopted on the path to a decarbonised future will be many and varied, and perhaps experience the occasional misstep, we remain confident that hydrogen needs PGMs and PGMs need hydrogen.

HYDROGEN, PHARMACEUTICALS, ENVIRONMENT: NOT JUST A HYPE FOR PGMS

HYdrogen, Pharmaceuticals, Environment: Not just a HYPE for PGMs

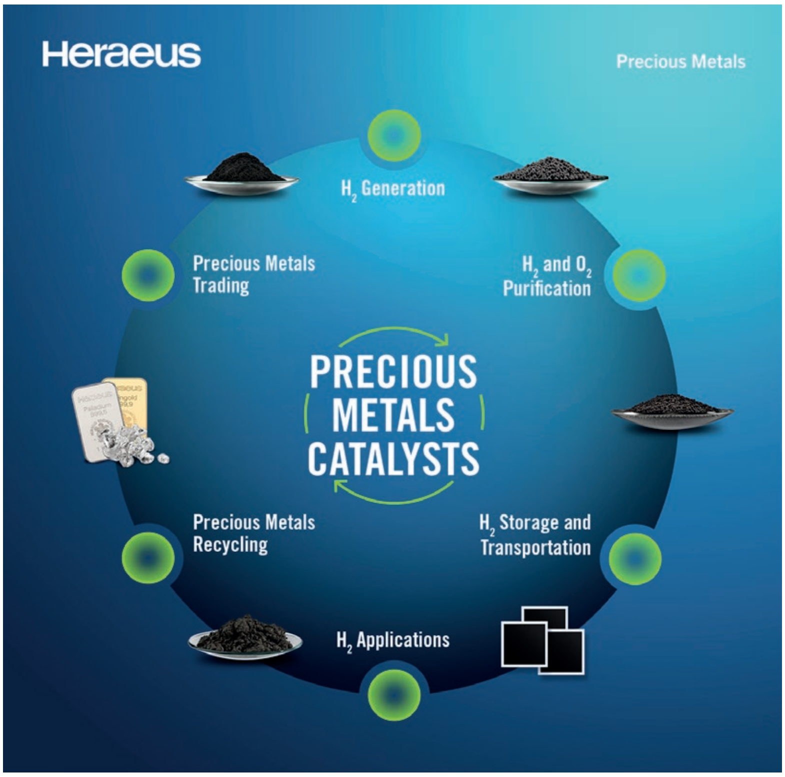
Dr. Detlef Gaiser, Technical Sales Manager, Heraeus Precious Metals

New fields for PGMs

As the automotive industry moves towards fossil-free options, demand for precious metals such as platinum, palladium and rhodium for catalytic converters, currently the largest application of PGMs, is expected to decrease. However, the declining demand in this field does not mean the end of significant demand for these valuable metals. On the contrary, new fields are emerging, such as hydrogen technologies and the synthesis of pharmaceuticals, which require precious metal-based catalysts. Additionally, the circular use of precious metals through recycling is becoming increasingly important to reduce the carbon footprint and enhance supply security. This article will explore these growth areas for precious metals and highlight their promising future.

The future of PGM demand is bright, despite declining use in the automotive sector

Heraeus Precious Metals catalysts



Source: Heraeus Precious Metals

Part 1: The hydrogen economy

Precious metals come into play at almost every step of the hydrogen economy: from precious metal-based electrocatalysts in proton exchange membrane electrolysis (PEM-EL) to produce hydrogen, to gas purification, storage and transport, to industrial applications or fuel cells.

Hydrogen's wide range of potential end-uses makes it key for the energy transition

Why is hydrogen so interesting in the energy transition?

Whoever has seen an oxyhydrogen experiment in chemistry lessons at school has literally been able to ***hear*** the energy contained in a mixture of hydrogen and oxygen. The German name "Knallgas", which means "gas that burns with a loud bang", is not without reason as a lot of energy is released. But the energy ***content*** is only one aspect. For the energy ***transition***, two other aspects make it so interesting:

1) *when hydrogen is burned, the reaction product is only water, not CO_2 and;*

2) *the reaction of hydrogen and oxygen can proceed in such a way that the chemical energy can be transformed directly to electricity.*

Vice versa, electrical power can be transformed into hydrogen and oxygen in the water electrolysis process. This interchangeability makes hydrogen so pivotal for storing electrical energy.

Where do precious metals come into play and what is the challenge?

PEM-EL is pivotal for producing green hydrogen from renewable energy and is based on precious metals, specifically platinum and iridium. It is the technology of choice for storing energy from renewable, fluctuating resources such as solar and wind power in the form of hydrogen. PEM-EL can handle naturally occurring power fluctuations due to a faster response time, it works at higher current densities and it delivers hydrogen at high pressure and purity.

PEM-EL is best suited for harnessing renewable power

Experts estimate that by 2030, 40% of electrolyser capacity will be based on PEM-EL, which translates to 70 GW out of the expected total capacity of 175 GW. It could even be more, as this is only the announced total capacity.

40% of global electrolyser capacity will be PEM by 2030

Therein lies the challenge: iridium is extraordinarily scarce. Only about 9 tons (~290 koz) of the primary metal is extracted from mines each year, and it is unlikely that this amount will significantly increase. Today, most of this iridium is used in other applications which are not expected to decrease their demand significantly. So of these 9 tons, around 1.5 tons (~48 koz) can be expected to be freed up for PEM-EL.

Primary iridium supply amounts to~9 t each year

The iridium gap for the hydrogen ramp-up can be closed by thrifting

The required amount of iridium per gigawatt in PEM-EL currently averages 400 kg/GW of electrolyser capacity. To build 70 GW would require about 28 tons (~900 koz) of iridium. However, between now and 2030, only about 12 tons (~386 koz) is expected to be available.

28 t of iridium is required by 2030, only 12 t is available

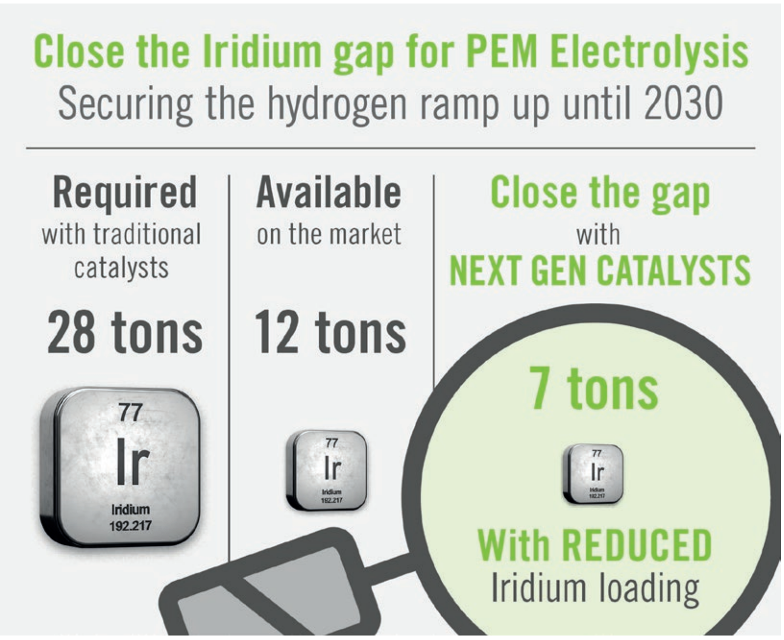
So how can this gap be closed? **With thrifting!**

Heraeus's next-generation iridium catalysts can lower the use of iridium down to 100 kg/GW in the application. Thus, for building 70 GW, now only 7 tons of iridium are required. If about 12 tons can be made available (see above), this opens a buffer for up to 120 GW of electrolyser capacity to 2030.

Further developments are expected to enable even lower loadings in the future. Heraeus's mixed oxide catalysts are aiming for an iridium loading of only 30 kg/GW.

Iridium use can be reduced by >90% to 30 kg/GW

How can we solve the iridium supply shortfall?



Source: Heraeus Precious Metals

Stability and cost-competitiveness

Developing materials that show the required mass activity is only one side of the coin. A typical electrolyser should run for at least 10 years. Therefore, it is critical that the components and materials used in the electrolyser stacks are of high durability and long-term stability. Thus, long-term studies are important to show that a new material will match the requirements over time.

The stack can represent up to 25% of the total cost of an electrolyser

Heraeus's low load catalysts have been validated for long-term stability and performance within the Kopernikus P2X project and by industrial clients. It has been proven that the next-generation catalysts from Heraeus are suitable to accompany the hydrogen ramp-up.

To ensure the cost competitiveness of PEM electrolysers, it is important to recycle precious metals from end-of-life stacks. These stacks can represent between 5% and 25% of the total cost of an electrolyser stack, depending on the precious metal price and the catalyst generation used. Heraeus has sufficient capacity and state-of-the-art technologies to process the increasing volumes of membrane materials from PEM-EL (and also PEM fuel cells).

Lower PGM loadings can accentuate economies of scale

Part 2: Pharmaceutical efficiency

The role of precious metal catalysts in the development of new pharmaceutical syntheses

Precious metal catalysts have become increasingly important in the field of pharmaceutical synthesis owing to their unique properties such as high catalytic activity and selectivity. Pharmaceutical syntheses are complex processes that aim to produce active pharmaceutical ingredients (APIs), the basis for drugs. The use of catalysts in these processes is crucial as it can significantly reduce the time and cost required to produce APIs. The market size of precious metals for pharmaceutical and agriculture end-uses is estimated to be in the range of 7-14 tons (225-550 koz) each year, with moderate growth expected in the coming years.

Precious metal catalysts improve efficiency in drug production

Soluble homogeneous PGM catalysts

The platinum-group metals – platinum, palladium, rhodium, iridium, ruthenium and osmium – are widely used as catalysts because of their unique properties. Homogeneous PGM catalysts allow for the highest usage of the contained metal since virtually every single metal atom is available for the reaction. They have been used in various reactions such as hydrogenation, isomerisation, and oxidation, which are critical in the synthesis of complex molecules such as APIs. Through a careful choice of ligands, the electron density and the space directly at the PGM can be modified in such a way as to allow access to the catalytic centre from only one side. This allows the reaction to run only in one direction, which prevents the formation of unwanted side products.

Iridium, rhodium and ruthenium complexes for asymmetric hydrogenation

Asymmetric hydrogenation is an important reaction as it enables the production of chiral molecules, which is one of the major challenges in pharmaceutical synthesis. Chiral molecules are molecules that exist in two forms, known as enantiomers, which are mirror images of each other but cannot be superimposed. In many cases, only one of the enantiomers is biologically active, while the other is either inactive or may even have negative effects on the body.

The use of iridium, rhodium and ruthenium complexes results in a surplus of the required enantiomer, eliminating the need for costly separation and purification steps. It thus leads to lower production costs, increased efficiency and reduced waste products. Substitution between PGMs is challenging in the case of asymmetric hydrogenation reactions as the metals are not easily interchangeable. One metal often catalyses one specific asymmetric hydrogenation best.

Minor PGMs aid production of useful molecules

Osmium compounds for the synthesis of hormone-like molecules

Osmium compounds have gained attention in the pharmaceutical industry because of their ability to catalyse so-called dihydroxylations (a reaction that introduces two -OH groups at the same time). This reaction can be used in the synthesis of hormone-like molecules, which are useful for the treatment of, for example, post-menopausal discomfort.

Palladium complexes for C-C coupling reactions

Carbon-carbon (C-C) coupling reactions are very useful in the synthesis of APIs as they allow the direct formation of carbon-to-carbon bonds between building blocks. Instead of long linear syntheses with low overall yields, researchers can now use convergent syntheses starting from two or more building blocks, almost like building a house with Lego bricks.

These palladium catalysts have been used in the synthesis of various drugs such as antivirals, antibiotics and anti-cancer drugs.

Palladium is also used in vital drug production

Precious metal catalysts play a major role in the development of new syntheses for the pharmaceutical industry. They are an ideal choice for synthesising complex molecular structures with high purities and yields. As a result, they are vital to the development of new drugs and the efficient production of existing ones.

Precious metals compounds for pharmaceutical uses

Source: Heraeus Precious Metals

Part 3: Sustainable use of PGMs through recycling

The importance of the recycling of used precious metals cannot be overstated. One of the major advantages is the significantly lower carbon footprint of up to 98% compared to primary metals from mines. This also holds true for PGMs used in the hydrogen economy.

Moreover, precious metals are limited in supply and can be difficult and expensive to mine. Primary metals account for roughly 67-76% of annual precious metal (Pt, Pd, Rh) supply while 24-33% comes from recycled metals. Increasing the recycling rates of these metals offers an opportunity to reduce the demand for primary metal extraction.

Up to a third of PGM supply is from recycling

Present and future fields of application of PGM recycling – catalysts, catalytic converters and CCMs

Heraeus has been recycling spent homogeneous and heterogeneous PGM catalysts at its sites for several decades using a multi-step process. This process typically involves thermal treatment of liquid or wet residues to reduce the material to a PGM-rich ash, which is also used to precisely determine the PGM content. A wet chemical treatment is then used to separate the PGMs and refine them into metal sponge or compounds. This recycling process allows the recovery of valuable PGMs and extends their useful life.

Another major stream is end-of-life catalytic converters, which contain several grams of precious metals and are recovered in a multi-stage process. The process typically starts with dismantling and "de-canning" the converter to remove the housing, followed by grinding up the PGM-coated monolithic honeycomb ceramic. Next, the ceramic powder is melted in an electric arc furnace and separated into a slag phase and a metal phase. The metal phase is then concentrated in a converter before the precious metals are extracted from it, again using the wet chemistry process mentioned above.

PGM catalysts from different industries represent a portion of recycling

The expected decrease in exhaust catalysts as a result of the declining importance of combustion engines not only poses risks in terms of demand for precious metals, but also opens new opportunities. Owing to the simultaneous ramp-up of the hydrogen economy, which also cannot do without precious metals, interesting new recycling streams are developing.

Volumes of recycled autocatalysts will begin to decline...

End-of-life electrolyser or fuel cell stacks typically contain hundreds of catalyst-coated membranes (CCMs) which are coated with precious metals. These membranes are often made of fluorinated polymers which need special treatment. However, suitable technologies are already available.

Currently, there are technologies at hand for processing CCMs, including total incineration – an established technology – as well as new methods that can recycle both the catalyst and the fluoropolymer from the membrane. These new methods involve mechanical removal of the catalyst coating or chemical separation of the membrane and coating.

...but new streams will open as technologies mature

By developing effective methods to recycle precious metals from CCMs, it is not only waste that can be reduced, but also reliance on primary sources as well as the environmental impact of precious metal extraction.

In conclusion, precious metals' recycling is an indispensable aspect of sustainable resource management. It offers significant environmental, economic, and social benefits, and is essential for meeting the high demand for these valuable metals while ensuring their conservation for future generations.

THE ROLE OF HYDROGEN IN REACHING GLOBAL NET-ZERO

The role of hydrogen in reaching global net-zero

Kevin Eggers, Founding Partner, AP Ventures

Introduction

Hydrogen is a versatile and clean energy carrier that will play an important role in decarbonising the world in which we live. Presently, the majority of hydrogen is produced from fossil fuels, such as natural gas and coal, and used for industrial applications such as the production of ammonia and refining petrochemical products. However, we are seeing an increased global interest in low-emission hydrogen. According to a study conducted by the International Energy Agency (IEA), approximately 94 million tonnes (Mt) of hydrogen was produced in 2021, of which only 1 Mt was low-emission hydrogen. The IEA has calculated that by 2030, 100 Mt of low-emission hydrogen production per year will be required to meet international 2050 Net-Zero emissions targets.[1] Research groups have varying perspectives on how much of the world's energy demand will be supplied by hydrogen: IRENA's (International Renewable Energy Agency) World Energy Transitions Outlook 2022 estimates that hydrogen will make up as much as 12% of global energy demand, whereas the Hydrogen Council suggests that renewable and low-carbon hydrogen could account for up to 22%.[2, 3]

Low-emission hydrogen was ~1% of all hydrogen production in 2021

By replacing the existing hydrogen supply with low-emission hydrogen which is produced either by splitting water with renewable electricity using electrolysers or from fossil fuel sources with carbon capture, there is significant potential to reduce the carbon emissions of industries which have historically consumed hydrogen from unabated natural gas and coal. For example, ammonia production from fossil fuel-based hydrogen accounts for 1.3% of global energy demand and around 1% of energy-related CO_2 emissions; bringing this to zero will have a significant impact on reaching the net-zero target by 2050.

Growing this percentage has potential to significantly contribute to decarbonisation

The potential of hydrogen, however, extends beyond its current applications. The hard-to-abate sectors, such as aviation and maritime, will likely be reliant on the use of clean hydrogen or its derivatives such as sustainable aviation fuel, ammonia or methanol. According to a 2021 report by the Hydrogen Council,[4] if we consider the decarbonisation potential of all existing and new hydrogen applications, hydrogen has the potential to abate 80 gigatons of cumulative CO_2 from now through to 2050, with an annual abatement potential of 7 gigatons in 2050 (around 20% of the total abatement needed to meet 2050 targets).

The world has started to recognise the importance of hydrogen and its potential contribution to net-zero in 2050. According to an IEA report published in September 2022,[5] 25 countries (and the European Commission) have developed a hydrogen strategy so far. Recently, India also announced ambitious plans to promote renewable energy-sourced hydrogen in a bid to reduce emissions and become a major exporter of hydrogen. This global adoption shows that the emergence of the hydrogen economy is no longer a question of 'if', but 'when' – and it is in the hands of key industries, investors, policy-makers and technology developers to come together to drive this global hydrogen transformation.

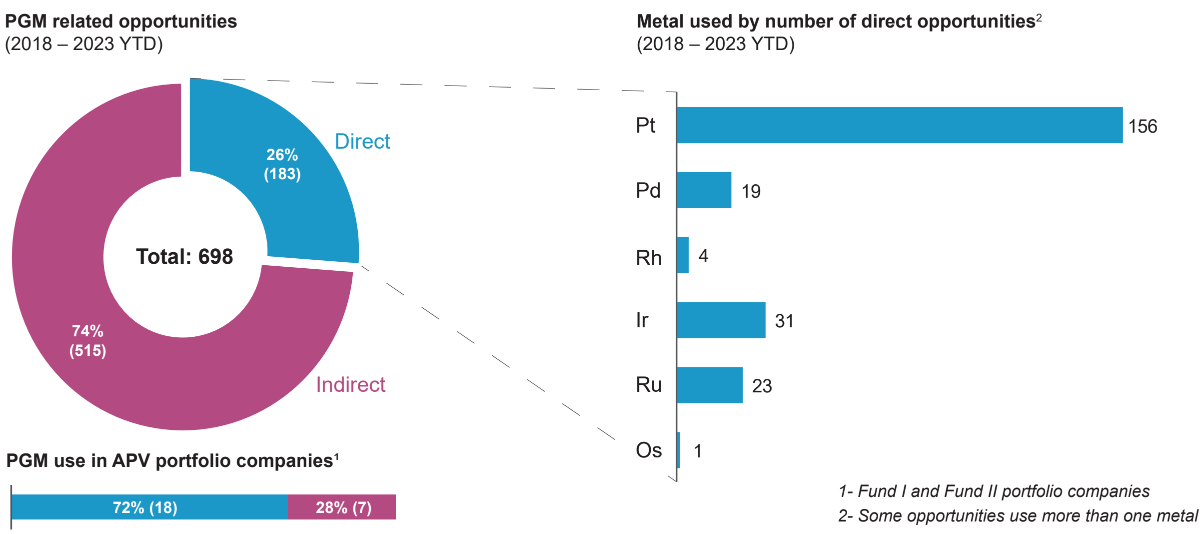
AP Ventures: A venture pioneer in the hydrogen space

AP Ventures (APV) was established in July 2018 as an independent venture capital fund to support early-stage technology companies in the hydrogen value chain. The history of APV predates 2018, as it was formerly a corporate venture capital business unit within Anglo American, which remains an investor and significant supporter of the fund. APV was originally founded with a vision to invest in technologies which use or enable the future use of platinum-group metals (PGMs), with a significant focus on hydrogen and decarbonisation. In order to increase its reach and impact, APV was spun-out in 2018 and since then has welcomed 11 new Limited Partners to date. APV currently manages 25 portfolio companies across the hydrogen value chain, from production, storage, transport and end-use applications.

APV is helping to fund the development of future PGM end-uses

Figure 1: APV pipeline themes — PGMs' use

Since its inception, the Fund has seen 2,064 opportunities, of which 698 (33.8%) are PGM-related opportunities and 18 (72%) of our portfolio companies are direct users of PGMs.



Source: AP Ventures

Despite the global surge of interest in the hydrogen sector, many obstacles remain before the hydrogen economy becomes a reality. Lack of infrastructure, safety concerns, limited availability of renewable energy sources, lack of policy support, high cost of hydrogen production, immaturity of the hydrogen technologies, and supply chain concerns are some of the bottlenecks that are often raised. No one company can address all these issues and collaboration across various industries, academia, governments and financial institutions will be needed.

The hydrogen economy faces many hurdles before it can be fully realised

APV supports the development of disruptive technologies by providing risk capital to early-stage technology companies, often from universities and research institutions, until they are fully commercial and adopted by the industry at large. In our endeavours to find disruptive technologies, we have reviewed over 2,000 deals to date. We have invested in 25 of those companies, carefully selecting those that we believe will have significant impacts on the hydrogen technology landscape. While our focus is on hydrogen, we remain close to our PGM roots: nearly 700 of our assessed deals were associated with the PGM theme and 18 of our portfolio companies use PGMs as part of their technology.

Unlocking the hydrogen value chain with PGMs

It is no industry secret that PGMs have a unique relationship with hydrogen as a catalyst, most notably for the oxygen reduction reaction in proton exchange membrane (PEM) fuel cells and for the oxygen and hydrogen evolution catalysts for PEM electrolysers. Their ability to conduct electricity, catalyse temperamental reactions and resist harsh acidic environments makes them ideal catalysts. According to a recent report by the Hydrogen Council,[6] the cumulative demand of iridium and platinum for PEM electrolysers could be approximately 175-300 t and 100-150 t, respectively, by 2050. PEM fuel cells are also estimated to consume between 2,000 t and 9,000 t of platinum on a gross demand basis by 2050.

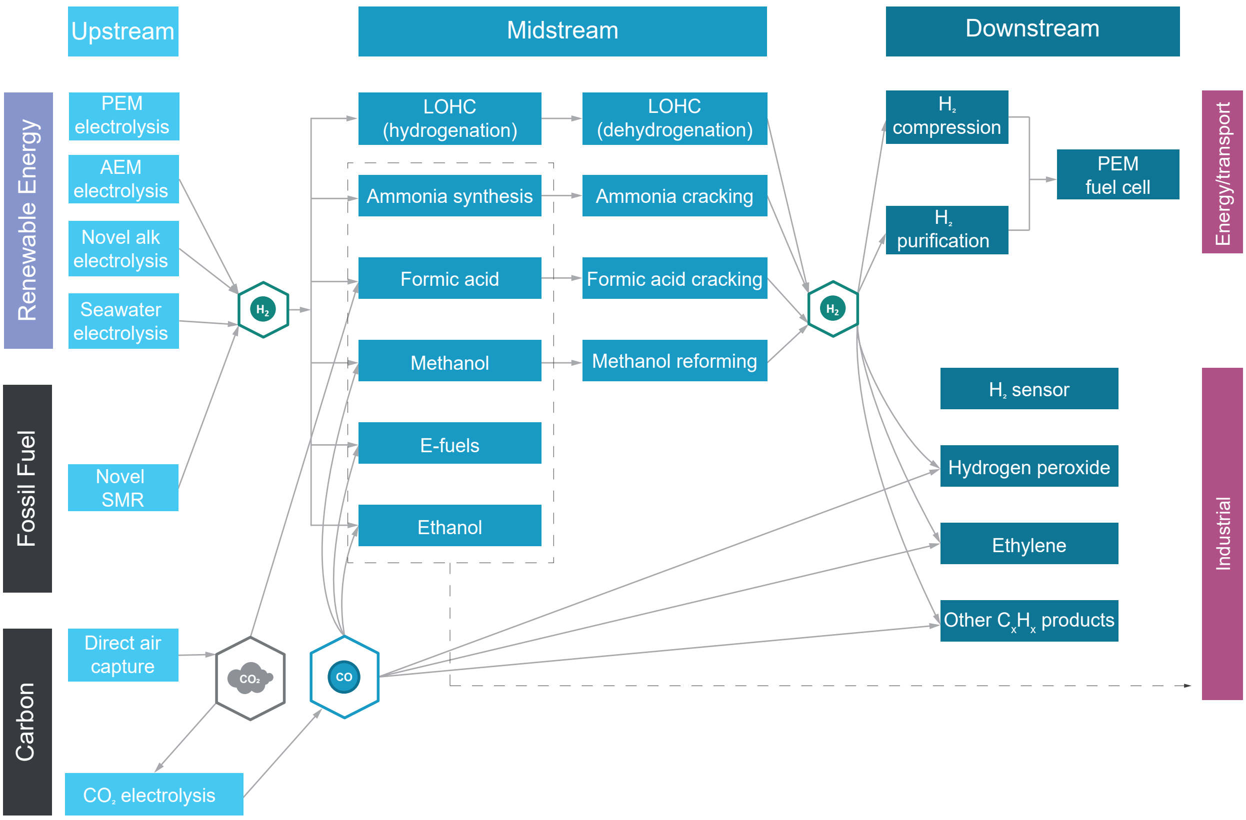
Hydrogen catalysts are avenue of significant future PGM demand

While the criticality of PGMs for PEM fuel cells and PEM electrolysers is relatively well-documented, other parts of the hydrogen value chain may also require PGMs. The graphic below shows a value chain mapping of the hydrogen applications (non-exhaustive) which may require the catalytic properties of PGMs based on APV's research.

Figure 2 shows how extensively PGMs are used across the hydrogen value chain. However, this is only a snapshot of the present landscape, which is susceptible to change based on factors such as the progress of technologies, price and availability of PGMs, market, and regulations.

PGMs — not just for PEM!

Figure 2: Use of PGMs in the hydrogen value chain



Source: AP Ventures

Taking hydrogen compression as an example – hydrogen is typically produced at relatively low pressures and must be compressed before its transport, storage and use. Traditionally, mechanical compressors such as reciprocating compressors are used; however, they are often costly and fragile. Some of the less developed alternatives to mechanical compression include the use of electrochemical reactions, amongst others, which has the potential to be a less expensive and more stable alternative to the incumbent technology. Electrochemical compressors have a very similar structure to PEM fuel cells where the PEMs are sandwiched by platinum-coated electrodes, and therefore have the potential to be a significant contributor to future PGM demand.

However, the development of electrochemical compressors has several technical challenges to overcome, as well as potential market risks such as the emergence of competing technologies and demand (or lack thereof) for high-performing compressors. It is only when these challenges have been fully addressed that we will know the true impact of hydrogen compression on the demand for PGMs.

Similar analysis can be made of other early-stage technologies in the hydrogen value chain. While there is a huge potential for the PGM industry to benefit from the establishment of the hydrogen economy, as shown in Figure 2, its overall impact is still to be determined, given the immaturity of the technologies and the uncertainties around the market adoption of such new technologies. Some of the factors to consider in assessing the impact of emerging hydrogen technologies on the PGM industry are included in Figure 3 below.

Figure 3: Assessing the impact on the PGMs market — key considerations

Potential Impact On PGMs Demand	Timing
✔ What is the expected future loading of the PGMs on the technology, relative to the supply?	✔ What is the technology readiness level?
✔ What is the technology competitive landscape? ✔ Is PGMs based-technology the mainstream?	✔ Are there any regulations or government incentives that support the commercialisation of the technology?
✔ How likely is this technology to take-off? ✔ Is there regulatory support? ✔ Is there support from the industry to onboard this technology	✔ Is there support from the industry to onboard this techology?

Source: AP Ventures

Considering the factors in Figure 3, APV has created an analysis of the potential impacts that various technologies in the hydrogen value chain will have on PGM demand. Note, for this assessment, only direct uses of PGMs were considered, and we do not take into account the indirect impact of applications on PGM demand (for example, any low-cost hydrogen production technologies will enable the hydrogen economy, therefore it can be argued that its impact on PGM demand is high, though in this assessment we considered only the direct impact of technologies on the PGM industry).

The hydrogen value chain carries weight in influencing PGM demand

Figure 4 is not intended to provide a precise estimate of PGM usage in each of the sectors, but to summarise our current view on the sectors that may be relevant to the PGM industry in the next several years to a decade.

Figure 4: Some sectors support PGM demand more than others

	Sector	Potential impact on PGMs	Timing	Integrated Assessment
Upstream	PEM-EL*	High	Near-term	
	Novel AEL** (Incl. AEM-EL***)	Low	Near-term	
	Seawater electrolysis	Medium	Long-term	
	Novel SMR	Low	Long-term	
	Direct air capture	Low	Long-term	
	CO_2 electrolysis	High	Medium-term	
Midstream	LOHC****	High	Medium-term	
	Ammonia synthesis	Medium	Medium-term	
	Ammonia cracking	Medium	Near-term	
	Formic acid	Medium	Long-term	
	Methanol synthesis	Low	Long-term	
	Methanol reforming	High	Medium-term	
	E-fuels	Low	Near-term	
Downstream	H_2 compression	Medium	Medium-term	
	H_2 purification	Medium	Medium-term	
	PEM fuel cell	High	Near-term	
	H_2 sensor	Low	Long-term	
	Hydrogen peroxide	Medium	Medium-term	
	Ethylene	Medium	Long-term	

*Source: AP Ventures. *PEM electrolyser, **Alkaline electrolyser, ***Anion exchange membrane electrolyser, ****Liquid organic hydrogen carrier.*

Outlined below are two specific sectors and their impacts on the PGM industry:

Liquid organic hydrogen carrier (LOHC)

LOHC is a disruptive technology which enables hydrogen to be stored and transported in a similar way to oil. The ability to easily and safely store and transport hydrogen is becoming increasingly critical as low-carbon hydrogen replaces traditional carbon-emitting products as an energy source and feedstock. To establish an interconnected global hydrogen economy, low-carbon hydrogen needs to be transported in large volumes from low-cost sources to end-uses in a storage medium that is safe, utilises existing familiar global infrastructure, and is cost competitive. LOHC technologies ensure that existing fossil-fuel infrastructure can be repurposed and used to transport vast quantities of hydrogen via rail, sea and land, utilising oil pipelines, crude oil tankers, petrol trucks and storage facilities.

Through the adoption of LOHC, hydrogen can piggy-back on established fossil fuels infrastructure

Why is this of interest to the PGM industry?

For the hydrogenation and dehydrogenation of LOHCs, platinum and palladium are used as catalysts. There are several projects underway to demonstrate the feasibility of LOHC technologies, and large amounts of PGMs may be consumed once the technology is fully commercialised.

Ammonia cracking

Ammonia is a stable and non-flammable substance with high energy density that can be easily transported and stored. It is therefore a candidate to replace fossil-based fuel for transportation, such as in the maritime sector. It is also seen as a potential future hydrogen carrier technology, which can be used for the safe long-haul transport of hydrogen from places of abundant renewable energy (e.g. Chile) to energy-constrained countries (e.g. Japan). To make use of the hydrogen contained within ammonia, it is necessary to decompose the ammonia into its constituent elements of nitrogen (N_2) and hydrogen (H_2). There has been a surge in innovation to find the optimal way to crack the ammonia to support the use of green ammonia as an energy carrier.

Ammonia is highly energy dense, but requires cracking to extract hydrogen

Why is this of interest to the PGM industry?

The cracking of ammonia to hydrogen and nitrogen requires a high-temperature and high-pressure environment. In order to lower the temperature and pressure to optimise the energy requirement, a PGM-based catalyst is often used.

The potential for PGM-based technologies in the hydrogen value chain is immense; however, the sheer volume of potential hydrogen technologies can be overwhelming. In order to ensure the success of PGM-based hydrogen technologies, the PGM industry needs to be strategic and focus on technologies which are impactful in a relatively short timeframe. In the next section, we discuss the actions that the PGM industry can take to support the emerging hydrogen economy.

The role of the PGMs industry in scaling up the global hydrogen economy

Global hydrogen adoption has the potential to drive global PGM demand but, equally, the PGM industry must play a part in driving hydrogen adoption forward. While often used only in small quantities, the cost implications of sourcing PGMs are significant for some of the technologies. More concerning is the availability of the metals, especially as some of the technologies are heavily reliant on the properties of PGMs. The PGM industry can take an active role in addressing challenges surrounding PGM prices and supply in a number of different ways:

Cost and availability of metals are concerns

1. Showing a strong commitment to supplying PGMs to certain applications/sectors.
2. Investing sufficient capital in the expansion of primary production of PGMs to ensure sufficient future supply against rising demand.
3. Continuing research and development to thrift PGMs.
4. Developing recycling technologies (or supporting the development of PGM technologies which are easily recyclable), to ensure faster circulation of the metals.
5. Introducing PGM financing models (leases and hedges) to enable price risk management.

Early support from the PGM industry will be very valuable for early-stage technology companies to fight off PGM sceptics, allowing them to focus on their core task of innovating new technologies which, in turn, will accelerate the development of new disruptive technologies in the value chain.

Conclusion: call for action

Hydrogen and PGMs have a unique relationship, and we are convinced that the emergence of the global hydrogen economy will have a significant impact on the PGM market. In turn, this means that the PGM industry has an important role to play in meeting 2050 decarbonisation targets. To unlock the potential of the nascent global hydrogen sector in the next decade, the PGM industry will need to work with other key industries, investors, governments and technology developers in the hydrogen value chain to build confidence, capital and resources.

The role of PGMs in global decarbonisation is significant

1 *IEA, 'Global Hydrogen Review', September 2022.*

2 *IRENA, 'World Energy Transitions Outlook 2022', March 2022.*

3 *Hydrogen Council, 'Hydrogen for Net-Zero', November 2021.*

4 *Hydrogen Council, 'Hydrogen for Net-Zero', November 2021.*

5 *IEA, 'Global Hydrogen Review', September 2022.*

6 *Hydrogen Council, 'Sufficiency, sustainability, and circularity of critical materials for clean hydrogen', December 2022.*

THE PGM MARKETS IN 2022/23

The PGM markets in 2022/23

Dr. Ralph Grimble, SFA (Oxford)

The platinum market

Last year was another year of shocks for the PGM markets. The Russian invasion of Ukraine led to concerns about PGM supply which pushed the palladium price to a record high in March, with the platinum and rhodium prices also rising sharply. However, no sanctions have been placed directly on Nornickel or PGMs and with a gradually weakening economic outlook as the year progressed, the prices retreated over the rest of the year. Meanwhile, South African producers had to contend with increasingly constrained power supplies.

Platinum demand was supported by the more widespread use of gasoline autocatalysts with higher platinum loadings and growth in light-vehicle production. However, Russia's invasion of Ukraine disrupted automotive production and supply chains, as did Covid restrictions in China. The semiconductor chip shortage remained a constraint on light-vehicle manufacture and BEVs continued to gain market share, capping the recovery in automotive demand. Industrial platinum requirements edged up, but with significant Covid restrictions in China consumer spending was hit and platinum jewellery demand fell further. This left the platinum market with a 135 koz surplus (excl. investment).

Platinum's substitution into gasoline autocatalysts is supporting demand

In 2023, the platinum market is predicted to move into a deficit of 195 koz, owing to a combination of supply shortfalls and rising demand. Primary supply is projected to recover in South Africa as stocks that built up last year are processed. This is expected to outweigh a drop in Russian production as smelter maintenance constrains output this year. Secondary supply is estimated to be slightly lower this year as recessions are anticipated in the US and Europe which typically result in fewer old vehicles being scrapped.

In 2023, the platinum market moves into deficit

Overall platinum demand is set to expand this year, driven by stronger automotive demand from further expansion of light-vehicle production and the increasing use of gasoline autocatalysts with higher platinum loadings. Industrial requirements are edging upward but this is expected to be offset by a slight decline in jewellery demand. Investment demand has reversed course so far in 2023, after shrinking last year, with some expansion of ETF holdings.

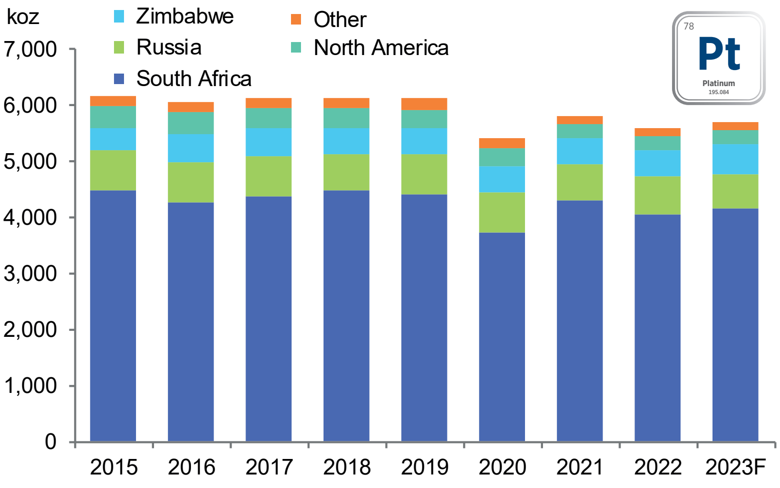
Mine supply

Primary platinum supply fell by 11% to 5,500 koz last year. In 2021, South African output was boosted by stockpiled material being processed, whereas there was a build-up in work-in-progress stocks last year, resulting in a 16% drop in refined output to 3,980 koz. Supply was modestly higher from Russia and Zimbabwe at 495 koz and 655 koz, respectively, but a flooding incident in North America cut output there to 250 koz.

This year, global platinum production is forecast to increase by 2% to 5,615 koz. South African output is predicted to expand by 3% to 4,105 koz in 2023, as some work-in-progress stocks that were built up last year are processed. During 2022, the mining companies had to contend with increasingly frequent and more severe load-shedding as power plant breakdowns compounded the shortfall in power supply from plants closed for scheduled maintenance. The situation remains precarious and should it deteriorate further then refined output could be at risk. Nornickel delayed scheduled smelter maintenance so that it now falls completely in 2023 and is anticipated to cut Russian output to 610 koz. North American production is estimated to rebound to 260 koz, as Stillwater's output recovers from the interruption caused by the flooding that prevented access to the mine. Zimbabwe's platinum supply is expected to increase by 4% to 515 koz owing to the ramp-up of yield at Zimplats.

Platinum supply rises 2% in 2023 despite a drop in Russian output

Platinum supply by region



Source: SFA (Oxford)

Recycling

Secondary supply of platinum fell by 17% to 1,545 koz in 2022 as both jewellery and autocatalyst recycling experienced tough conditions. The difficult trading conditions amid lockdowns in China that hit jewellery sales also impacted jewellery recycling. The lack of semiconductor chips that held back new vehicle production meant that second-hand cars were more sought after and fewer were scrapped than under more typical conditions. The impact became more pronounced as the year progressed and declining PGM prices were also a factor. This year, platinum recycling is forecast to slip by a further 2% to 1,520 koz. Jewellery recycling is expected to be little changed but automotive recycling is likely to decline further as recessions are anticipated in Europe and the US which will limit the number of vehicles being scrapped.

Secondary supply is declining

Demand

Global platinum demand (excl. investment) rose by 2% to 6,910 koz last year, as robust growth in automotive demand and a modest increase in industrial demand outweighed a sharp decline in jewellery demand, which was significantly impacted by Covid lockdowns in China.

Platinum demand rises to 7.3 moz this year

This year, platinum consumption is forecast to improve by 6% to 7,330 koz. Automotive demand continues to expand, benefitting from substitution of some platinum into gasoline autocatalysts which are being more widely used. A small increase in industrial usage is offset by a further decline in jewellery demand.

Automotive demand

Automotive platinum demand is forecast to rise by 13% to 3,330 koz in 2023, driven by the more widespread use of gasoline autocatalysts in which some platinum has been substituted to replace some palladium. The semiconductor chip shortage remains a factor, but it should be much less of a constraint on new light-vehicle production which is projected to grow by 3% to over 84 million units. Diesel car production continues its decline in Western Europe and diesel's market share is estimated to fall below 15%. Global HDV demand is predicted to increase as production rises by 5%, with a strong rebound in China as the economy operates without Covid restrictions.

Platinum automotive demand growing owing to greater light-vehicle production and substitution into gasoline autocatalysts

Jewellery demand

Platinum jewellery demand slumped by 17% to 1,650 koz last year. Much of the contraction was a result of the Covid restrictions in China which locked down significant parts of the country at various points during the year and hit consumer spending. India saw a recovery from the Covid impacts of the previous year and the US also had another strong year.

This year, platinum jewellery demand is forecast to dip by 2% to 1,620 koz. Platinum jewellery sales in China are projected to slip further, despite the economy no longer being impacted by Covid restrictions, as gold is more favoured. After two very strong years, demand in the US is expected to ease. Growth is anticipated in India, with Japan and Europe also seeing modest gains.

Jewellery demand is still contracting

Industrial demand

Industrial platinum demand edged up 1% to 2,235 koz in 2022. Chemical sector usage fell owing to the high natural gas price impacting nitric acid production in Europe, and electrical demand also contracted owing to a decline in hard disk drive shipments. Offsetting that, net petroleum usage rebounded and glass requirements rose, mainly due to continuing capacity expansions in China and the RoW.

In 2023, industrial requirements are predicted to rise by 2% to 2,275 koz. A rebound in chemical sector demand is anticipated now that natural gas prices have retreated, and further capacity expansions lift glass demand, which more than outweighs a drop in usage in the petroleum sector, while other end-uses remain more or less stable.

Industrial demand expands 2% in 2023

Platinum use in the hydrogen economy is expected to see continued growth this year from both PEM fuel cell vehicles and electrolysers, taking it to 110 koz.

Investment and movement of above-ground stocks

Investment demand was exceedingly weak in 2022. Coin purchases remained solid but physical bar investment and ETF holdings both declined, returning bars to the market. The platinum price exceeded the psychological ¥4,000/g level several times during the year and Japanese investors took the opportunity to take profits, with the result that there was a net supply of bars to the market. ETF investors significantly reduced their holdings, selling a net 566 koz during the year, which left global ETF holdings at just over 3 moz, the lowest level since 2018.

Platinum investment may be positive this year

The outlook for platinum investment has brightened so far in 2023, with ETFs gaining 190 koz in the first four months of the year. However, as long as the price holds above ¥4,000/g, bar investment in Japan is likely to be subdued.

The palladium market

The palladium market had a 520 koz deficit in 2022, owing to supply underperformance and modest demand growth. The Russian invasion of Ukraine led to concerns about palladium supply which pushed the palladium price to a record high in March. With no sanctions placed directly on Nornickel or PGMs, Russian metal still reached end-users, and, with a gradually weakening economic outlook as the year progressed, the price retreated over the rest of the year. Meanwhile, South African producers were dealing with more frequent load-shedding events and a flooding incident in North America hit output there. Overall consumption improved, as the semiconductor chip shortage became less severe, enabling light-vehicle production to increase by around 5 million units, lifting automotive demand and outweighing a dip in industrial demand.

This year, the palladium market is predicted to remain in deficit at 565 koz. Refined supply is set to retreat as output from Russia is limited by smelter maintenance. Gains in North America, where production should recover from last year's flooding incident, and South Africa, where some stockpiled material is expected to be processed, are insufficient to make up for the shortfall from Russia. Global demand is forecast to be slightly lower owing to dips in industrial and automotive demand, where increasing global light-vehicle production is offset by further gains for BEVs, curbing gasoline vehicle production, and the use of gasoline autocatalysts with platinum substituted for some palladium.

Underperforming supply keeps the market in deficit in 2023

Global palladium supply fell by 6% to 6,460 koz in 2022, as output in South Africa contracted by 19% to 2,240 koz, after being boosted by stocks being processed in the previous year, and flooding in the US temporarily reduced yield. Production in Russia increased by 8% to 2,790 koz, as output returned to normal following flooding at two mines in 2021.

Primary palladium production is forecast to slip by 3% to 6,275 koz this year. Nornickel delayed smelter maintenance into 2023 which has resulted in Russian refined palladium supply being forecast to fall by 14% to 2,405 koz. Processing of some stockpiled material is expected to add to South African output, lifting it by 7% to 2,390 koz. Incremental growth in Zimbabwe continues, with production reaching 440 koz, and a recovery in US output helps to lift North American supply by 4% to 770 koz.

Processing plant maintenance cuts Russian production

Secondary palladium supply is projected to expand by 4% to 2,625 koz in 2023. Automotive recycling is expected to contract in the US and Europe as recessions are anticipated in both regions which typically result in fewer vehicles being scrapped. However, growing numbers of vehicles are projected to reach the end of their lives in China which, along with some slight growth in other regions, results in an overall increase.

Secondary supply held back as fewer old vehicles are scrapped

Automotive demand for palladium is estimated to drop slightly to 7,685 koz. Although global light-vehicle production is predicted to increase by around 3 million units, BEV market share gains and ongoing substitution of platinum into gasoline autocatalysts at the expense of some palladium result in slightly lower automotive demand.

BEV sales crimp palladium automotive demand

Industrial demand is predicted to slip to 1,540 koz as modest gains in the chemical sector are offset by ongoing declines in electrical and dental usage.

The rhodium market

The rhodium market is forecast to have a deficit of 45 koz in 2023, widening from a 15 koz deficit in 2022, as supply contracts slightly and demand improves moderately. Last year, rhodium supply contracted sharply to 735 koz owing to less stockpiled material being processed in South Africa. Meanwhile, automotive demand rebounded along with the recovery in light-vehicle production as the chip shortage eased somewhat.

Rhodium market deficit expands to 45 koz in 2023

Refined rhodium production is predicted to dip by 2% to 720 koz this year. Even with a small amount of rhodium expected to be produced from processing stockpiled material, output in South Africa is estimated to slip by 2% to 585 koz. Russia's output is also likely to be slightly lower owing to smelter maintenance. Secondary supply is forecast to be little changed but should the recessions in the US and Europe be worse than anticipated, autocatalyst recycling could contract this year.

Rhodium supply dips by 2%...

Rhodium demand is projected to rise by 1% to 1,075 koz in 2023. Automotive demand is set to edge lower owing to growth in the BEV market share outpacing growth in the overall market. Industrial demand is forecast to expand this year, mostly owing to a rebound in the chemical sector. Chemical demand is predicted to experience a revival in 2023 after high natural gas prices prompted some temporary shuttering of ammonia production which impacted the nitric acid industry last year. Rhodium usage in the glass industry is also likely to improve owing to capacity additions, as the thrifting induced by the high price has mostly run its course.

...whereas demand increases by 1% this year

The price outlook for the next six months

Platinum $1,000/oz

The platinum market looks set to move into deficit this year. In South Africa, the power supply situation has not improved and it is assumed that some production will be lost owing to power curtailments. That said, with some work-in-progress stock expected to be processed, primary supply is predicted to rise modestly this year.

Light-vehicle production is on a rising trend and platinum substitution into gasoline autocatalysts is also helping to lift automotive demand back above 3 moz. Industrial demand remains robust, but jewellery demand could ease owing to weaker economic growth in Europe and the US and platinum jewellery being somewhat out of favour in China, although China's reopening after Covid restrictions could lift platinum jewellery sales too.

Weak economic outlook to weigh on the platinum price

With plentiful above-ground stocks and a weakening economic outlook, as interest rates rise and credit contracts, a modest deficit for platinum may not be sufficient to keep the price on an upward trajectory. The price is forecast to average $1,000/oz over the next six months. A prolonged period of even more severe power shortages in South Africa is possible and is an upside price risk.

Palladium $1,350/oz

Gross palladium demand is forecast to decline slightly in 2023. Although light-vehicle production is growing as the semiconductor chip shortage finally eases, BEV market share gains, particularly in China, and the substitution of platinum into gasoline autocatalysts mean that automotive demand is projected to be marginally lower than last year. Industrial palladium demand is also predicted to slip lower.

Palladium demand slips this year

Smelter maintenance in Russia and power curtailments in South Africa are expected to result in a drop in primary supply, although secondary supply could improve as increasing numbers of end-of-life light vehicles are scrapped in China.

The palladium market is set to have a deficit this year as both palladium demand and supply are predicted to contract. However, the palladium price is still trying to find a floor as it retreats from its record high. Without robust demand growth, the price is estimated to keep sliding lower and average $1,350/oz during the next six months.

Price retreating from record high

Rhodium $7,625/oz

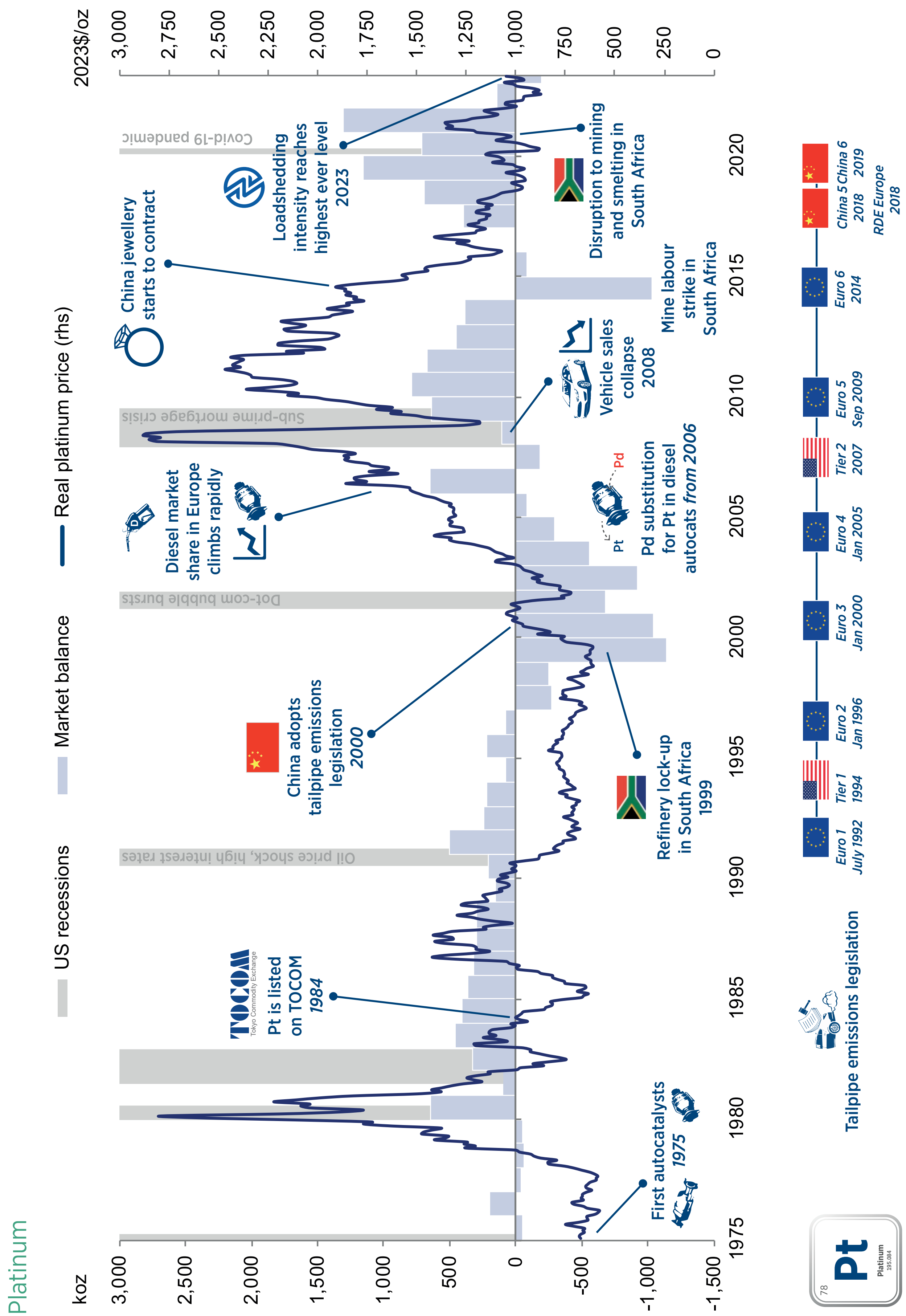
Rhodium supply is projected to shrink slightly this year. Although some stockpiled material is expected to be processed in South Africa during 2023, this modest boost to refined production is set against ongoing power curtailments which are impacting productivity. Meanwhile, smelter maintenance in Russia is limiting output there.

Demand for rhodium is predicted to be modestly higher, as a slight drop in automotive requirements is more than offset by a rebound in industrial uses as the nitric acid industry recovers from last year's natural gas price shock in Europe.

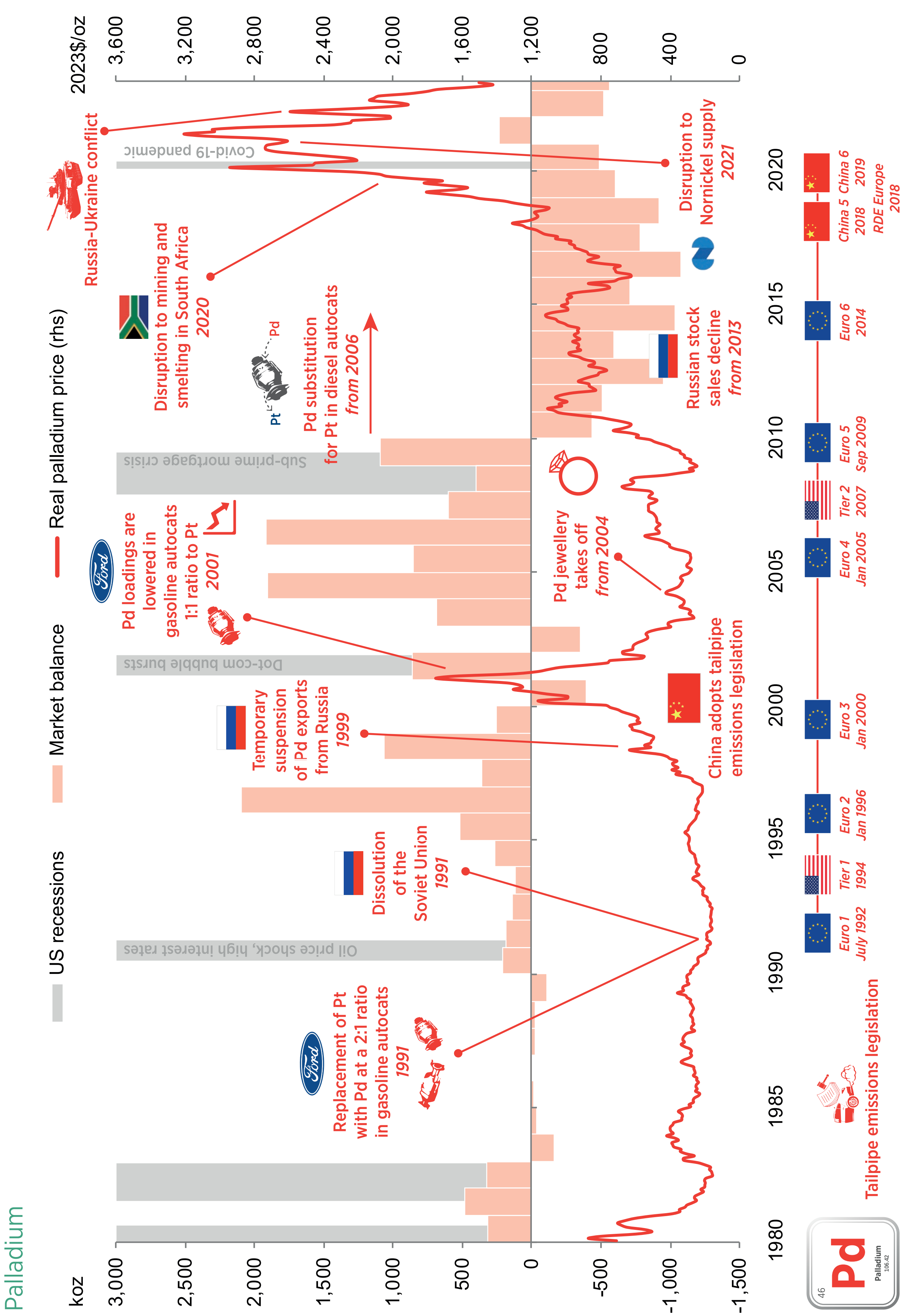
Marginally higher demand will not be sufficient to sustain the rhodium price

Although the rhodium market is likely to stay in deficit this year, this has not been supporting the price as it continues to fall back from its record high. Sales of stock from the glass industry have also weighed on the price. With the economic outlook weakening, the price is forecast to average $7,625/oz over the next six months.

PGM PRICE HISTORY

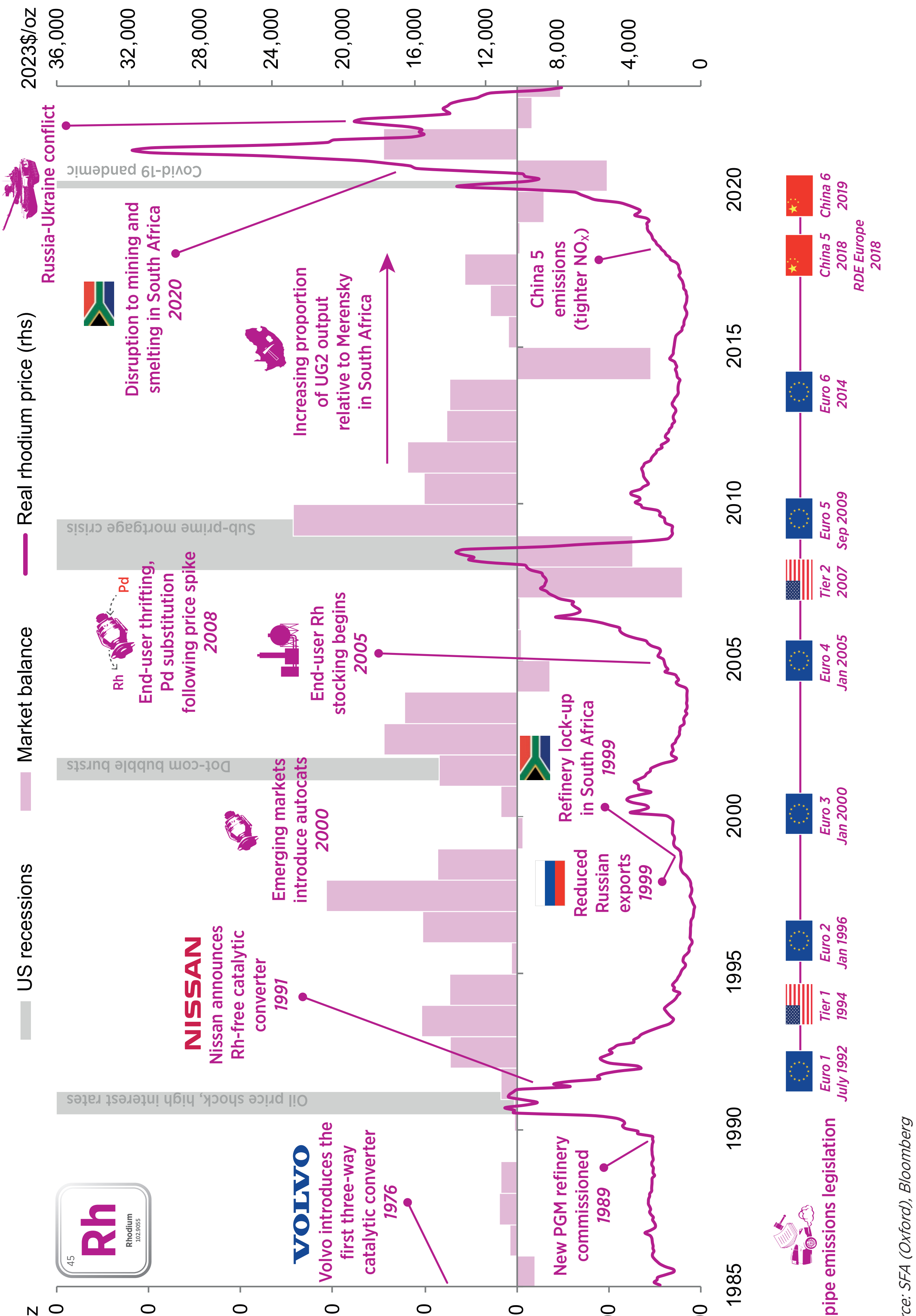


Source: SFA (Oxford), Bloomberg

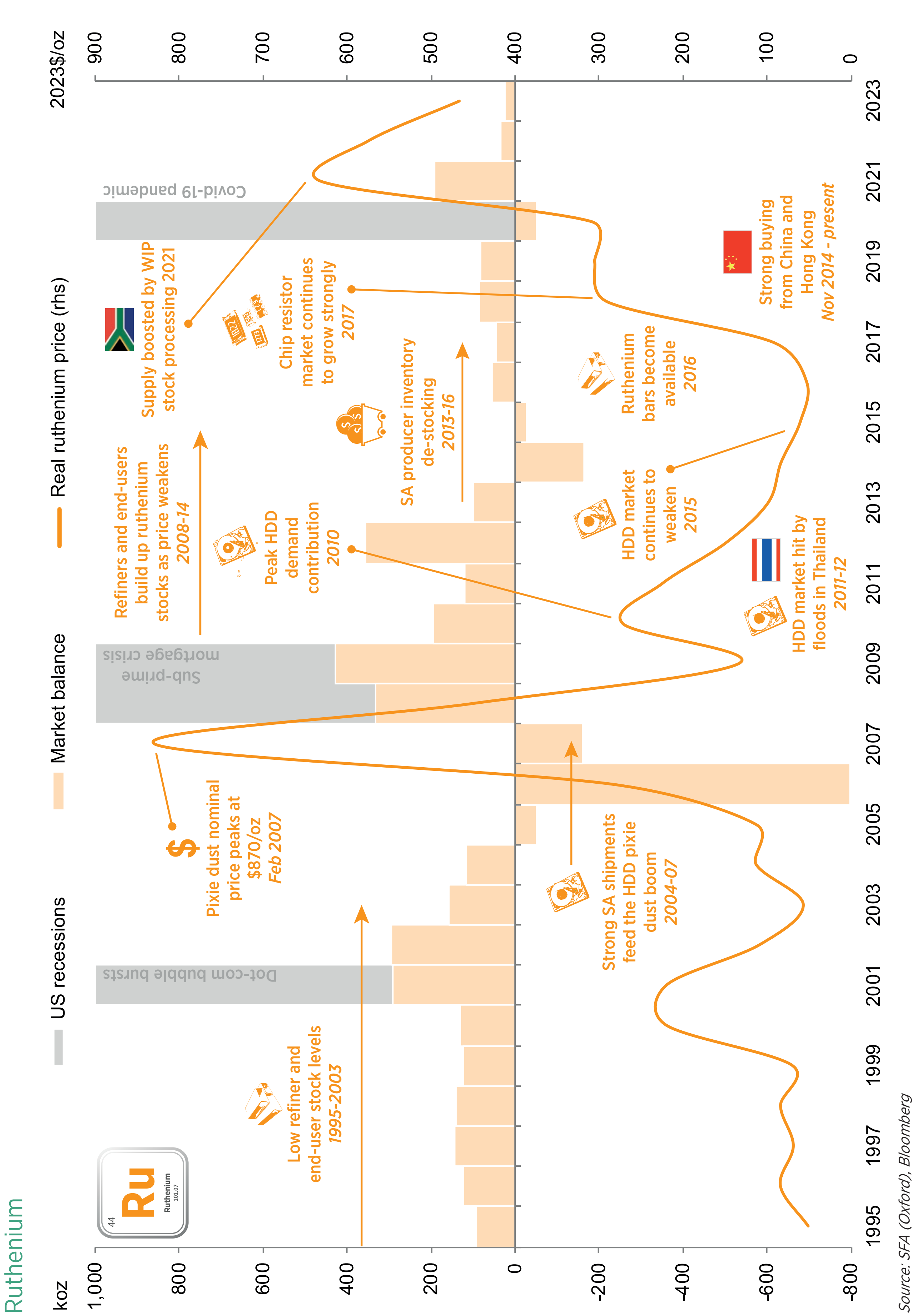


Source: SFA (Oxford), Bloomberg

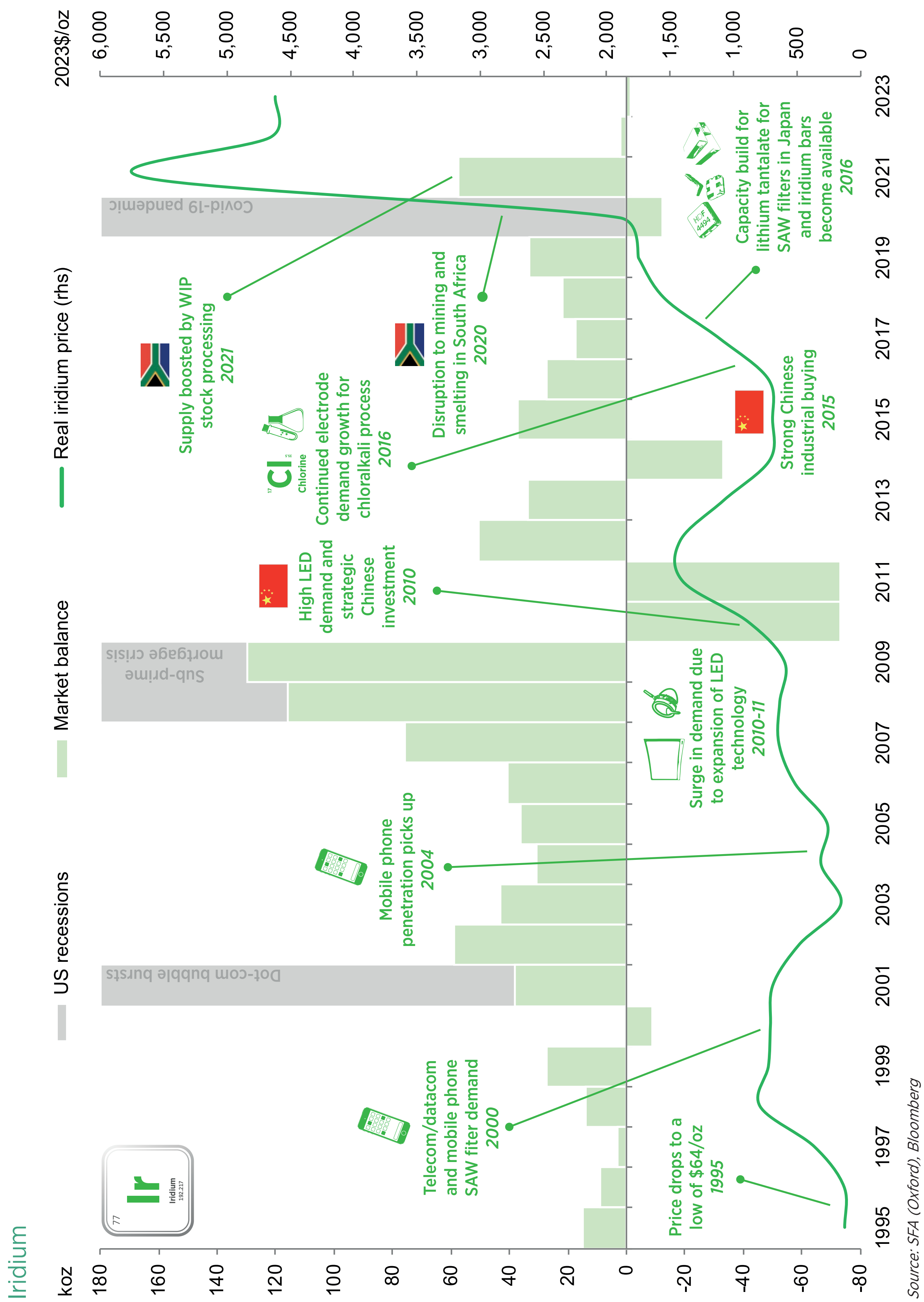
Rhodium



Source: SFA (Oxford), Bloomberg



Source: SFA (Oxford), Bloomberg


Iridium
US recessions
Market balance
Real iridium price (rhs)
koz
2023$/oz
Dot-com bubble bursts
Sub-prime mortgage crisis
Covid-19 pandemic
Price drops to a low of $64/oz 1995
Telecom/datacom and mobile phone SAW fiter demand 2000
Mobile phone penetration picks up 2004
Surge in demand due to expansion of LED technology 2010-11
High LED demand and strategic Chinese investment 2010
Continued electrode demand growth for chloralkali process 2016
Chlorine
Strong Chinese industrial buying 2015
Disruption to mining and smelting in South Africa 2020
Capacity build for lithium tantalate for SAW filters in Japan and iridium bars become available 2016
Supply boosted by WIP stock processing 2021
Iridium 192.217
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
6,000
5,500
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
Source: SFA (Oxford), Bloomberg

APPENDIX

Platinum supply-demand balance

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Primary supply									
Regional									
South Africa	4,480	4,265	4,385	4,470	4,405	3,260	4,715	3,980	4,105
Russia	710	715	720	665	710	700	640	655	610
Zimbabwe	405	490	480	465	460	480	470	495	515
North America	365	390	360	345	350	330	255	250	260
Other	200	185	185	180	185	175	125	125	130
Total	**6,165**	**6,045**	**6,125**	**6,130**	**6,105**	**4,950**	**6,210**	**5,500**	**5,615**
Demand & recycling									
Autocatalyst									
Gross demand	3,260	3,365	3,305	3,110	2,830	2,390	2,715	2,940	3,330
Recycling	1,185	1,210	1,325	1,420	1,495	1,300	1,415	1,160	1,135
Net demand	2,080	2,150	1,980	1,690	1,335	1,090	1,295	1,780	2,195
Jewellery									
Gross demand	2,835	2,510	2,450	2,245	2,090	1,560	1,780	1,650	1,620
Recycling	515	625	560	505	500	410	400	345	345
Net demand	2,325	1,885	1,890	1,740	1,595	1,150	1,380	1,305	1,275
Industrial demand	**1,840**	**1,970**	**1,845**	**1,965**	**2,010**	**1,990**	**2,215**	**2,235**	**2,275**
Hydrogen	**25**	**45**	**50**	**70**	**45**	**45**	**50**	**90**	**110**
Other recycling	**25**	**25**	**30**	**30**	**30**	**30**	**45**	**40**	**40**
Gross demand	**7,960**	**7,890**	**7,650**	**7,385**	**6,975**	**5,985**	**6,760**	**6,910**	**7,330**
Recycling	**1,720**	**1,860**	**1,915**	**1,955**	**2,020**	**1,745**	**1,860**	**1,545**	**1,520**
Net demand	**6,240**	**6,030**	**5,735**	**5,435**	**4,950**	**4,235**	**4,900**	**5,365**	**5,810**
Market balance									
Balance (before ETFs)	-75	15	390	695	1,155	710	1,310	135	-195
ETFs (stock allocation)	-240	-10	100	-240	995	505	-265	-565	
Balance after ETFs	165	20	295	935	160	210	1,575	705	

Source: SFA (Oxford)

Platinum demand and recycling summary

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Autocatalyst									
North America	480	410	390	390	375	285	375	470	520
Western Europe	1,450	1,630	1,555	1,340	1,150	810	750	780	850
Japan	510	450	435	425	395	300	285	275	295
China	145	195	230	220	245	485	695	710	880
India	180	170	175	200	155	115	180	220	225
RoW	500	505	520	540	510	395	430	480	560
Total	**3,260**	**3,365**	**3,305**	**3,110**	**2,830**	**2,390**	**2,715**	**2,940**	**3,330**

Source: SFA (Oxford)

Platinum demand and recycling summary (continued)

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Jewellery									
North America	250	265	280	280	275	210	255	265	235
Western Europe	235	240	250	255	260	175	190	175	180
Japan	340	335	340	345	330	245	260	265	270
China	1,765	1,450	1,340	1,095	945	755	875	740	710
India	180	145	175	195	210	120	135	160	165
RoW	70	70	75	75	75	55	60	50	60
Total	**2,835**	**2,510**	**2,450**	**2,245**	**2,090**	**1,560**	**1,780**	**1,650**	**1,620**
Industrial									
North America	260	390	350	350	300	230	280	340	340
Western Europe	270	280	275	295	285	260	255	280	260
Japan	95	85	65	100	105	120	100	100	100
China	650	725	645	550	620	820	1,015	940	980
RoW	560	490	505	665	700	560	565	575	595
Total	**1,840**	**1,970**	**1,845**	**1,965**	**2,010**	**1,990**	**2,215**	**2,235**	**2,275**
Hydrogen									
North America	5	10	10	15	10	10	10	10	10
Western Europe	0	5	0	0	0	0	0	10	10
Japan	15	25	30	35	15	20	25	30	30
China	0	0	0	0	0	0	0	25	40
RoW	5	5	5	20	15	10	10	15	15
Total	**25**	**45**	**50**	**70**	**45**	**45**	**50**	**90**	**110**
Total gross demand									
North America	995	1,075	1,030	1,035	965	735	920	1,080	1,110
Western Europe	1,955	2,160	2,085	1,895	1,690	1,240	1,195	1,245	1,300
Japan	955	890	870	900	845	690	675	665	695
China	2,565	2,375	2,215	1,870	1,810	2,060	2,585	2,415	2,610
RoW	1,490	1,390	1,455	1,690	1,665	1,255	1,380	1,500	1,615
Total	**7,960**	**7,890**	**7,650**	**7,385**	**6,975**	**5,985**	**6,760**	**6,910**	**7,330**
Recycling									
Autocatalyst									
North America	505	535	585	640	645	575	580	450	420
Western Europe	370	400	440	465	505	425	500	365	360
Japan	95	95	100	110	110	100	115	110	115
China	55	40	40	35	40	30	35	40	45
RoW	155	150	160	170	190	170	185	190	195
Total	**1,185**	**1,210**	**1,325**	**1,420**	**1,495**	**1,300**	**1,415**	**1,160**	**1,135**
Jewellery									
North America	5	5	5	5	5	5	5	5	5
Western Europe	5	5	5	5	5	5	5	5	5
Japan	160	150	160	145	140	110	115	105	115
China	335	460	385	340	340	285	265	220	215
RoW	5	5	5	5	10	10	10	10	10
Total	**515**	**625**	**560**	**505**	**500**	**410**	**400**	**345**	**345**
WEEE	**25**	**25**	**30**	**30**	**30**	**30**	**45**	**40**	**40**

Source: SFA (Oxford)

Platinum demand and recycling summary (continued)

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Recycling									
Total recycling									
North America	520	545	600	650	660	585	595	465	435
Western Europe	380	410	450	480	520	440	515	380	375
Japan	255	245	265	260	255	210	235	220	230
China	395	500	425	380	385	320	305	265	265
RoW	165	165	175	185	205	190	210	210	220
Total	**1,720**	**1,860**	**1,915**	**1,955**	**2,020**	**1,745**	**1,860**	**1,545**	**1,520**

Source: SFA (Oxford)

Palladium supply-demand balance

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Primary supply									
Regional									
South Africa	2,560	2,375	2,530	2,500	2,555	1,845	2,755	2,240	2,390
Russia	2,605	2,555	2,740	2,670	2,870	2,810	2,585	2,790	2,405
Zimbabwe	325	395	395	380	385	405	395	420	440
North America	995	1,065	985	1,035	975	950	840	740	770
Other	455	420	415	395	395	385	265	270	270
Total	**6,940**	**6,810**	**7,065**	**6,975**	**7,180**	**6,395**	**6,845**	**6,460**	**6,275**
Demand & recycling									
Autocatalyst									
Gross demand	7,575	7,925	8,140	8,300	8,445	7,435	7,595	7,730	7,685
Recycling	1,605	1,710	1,920	2,035	2,175	2,010	2,380	2,095	2,205
Net demand	5,970	6,210	6,220	6,265	6,270	5,430	5,220	5,635	5,480
Jewellery									
Gross demand	245	240	215	215	215	200	215	225	235
Recycling	80	80	60	60	60	55	60	65	70
Net demand	165	165	155	155	155	145	155	160	165
Industrial demand	**1,930**	**1,900**	**1,840**	**1,840**	**1,715**	**1,640**	**1,655**	**1,550**	**1,540**
Other recycling	**430**	**390**	**380**	**370**	**365**	**335**	**415**	**365**	**350**
Gross demand	**9,755**	**10,065**	**10,195**	**10,355**	**10,375**	**9,280**	**9,470**	**9,505**	**9,460**
Recycling	**2,115**	**2,180**	**2,360**	**2,465**	**2,600**	**2,395**	**2,855**	**2,525**	**2,625**
Net demand	**7,640**	**7,890**	**7,835**	**7,890**	**7,780**	**6,880**	**6,615**	**6,980**	**6,835**
Market balance									
Balance (before ETFs)	-700	-1,080	-775	-910	-600	-485	235	-520	-565
ETFs (stock allocation)	-665	-640	-375	-560	-90	-115	50	-90	
Balance after ETFs	**-35**	**-440**	**-400**	**-350**	**-515**	**-370**	**185**	**-430**	

Source: SFA (Oxford)

Palladium demand and recycling summary

46 Pd 106.42 Palladium

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Autocatalyst									
North America	1,855	1,935	1,850	1,860	1,815	1,460	1,475	1,520	1,620
Western Europe	1,790	1,685	1,705	1,720	1,675	1,255	1,195	1,170	1,100
Japan	745	775	800	840	870	760	730	705	650
China	1,725	1,985	2,055	2,035	2,255	2,445	2,565	2,575	2,565
India	185	225	240	260	240	205	280	355	380
RoW	1,280	1,320	1,490	1,580	1,590	1,305	1,355	1,405	1,370
Total	**7,480**	**7,590**	**7,935**	**8,140**	**8,300**	**8,445**	**7,405**	**7,500**	**8,240**
Jewellery									
North America	35	35	35	35	35	35	35	40	40
Western Europe	55	55	55	55	55	50	50	55	55
Japan	50	50	50	50	50	45	45	50	50
China	75	75	50	50	50	50	55	60	65
RoW	25	25	25	25	25	25	25	25	25
Total	**245**	**240**	**215**	**215**	**215**	**200**	**215**	**225**	**235**
Industrial									
North America	2,275	2,345	2,225	2,200	2,150	1,740	1,760	1,805	1,900
Western Europe	2,160	2,065	2,070	2,070	2,015	1,570	1,505	1,480	1,420
Japan	1,220	1,225	1,215	1,225	1,220	1,060	1,020	985	925
China	2,175	2,435	2,520	2,570	2,720	2,980	3,130	3,100	3,105
RoW	1,925	1,995	2,165	2,285	2,270	1,930	2,050	2,135	2,110
Total	**1,930**	**1,900**	**1,840**	**1,840**	**1,715**	**1,640**	**1,655**	**1,550**	**1,540**
Total gross demand									
North America	2,275	2,345	2,225	2,200	2,150	1,740	1,760	1,805	1,900
Western Europe	2,160	2,065	2,070	2,070	2,015	1,570	1,505	1,480	1,420
Japan	1,220	1,225	1,215	1,225	1,220	1,060	1,020	985	925
China	2,175	2,435	2,520	2,570	2,720	2,980	3,130	3,100	3,105
RoW	1,925	1,995	2,165	2,285	2,270	1,930	2,050	2,135	2,110
Total	**9,755**	**10,065**	**10,195**	**10,355**	**10,375**	**9,280**	**9,470**	**9,505**	**9,460**
Recycling									
Autocatalyst									
North America	895	960	1,060	1,135	1,190	1,130	1,300	1,015	995
Western Europe	270	260	305	330	335	300	380	285	270
Japan	125	125	145	180	200	185	205	195	205
China	115	160	165	155	165	150	180	245	330
RoW	205	205	245	240	290	240	315	350	405
Total	**1,605**	**1,710**	**1,920**	**2,035**	**2,175**	**2,010**	**2,380**	**2,095**	**2,205**
Jewellery									
Japan	20	20	20	20	20	15	15	20	20
China	60	60	40	40	40	40	45	45	50
Total	**80**	**80**	**60**	**60**	**60**	**55**	**60**	**65**	**70**
WEEE									
North America	85	80	75	70	70	60	70	60	55
Western Europe	80	75	80	80	75	70	75	70	65
Japan	170	135	130	125	120	110	120	110	100
China	25	35	35	40	45	45	60	55	60
RoW	65	60	60	60	60	55	90	70	70
Total	**430**	**390**	**380**	**370**	**365**	**335**	**415**	**365**	**350**
Total recycling									
North America	980	1,040	1,130	1,205	1,255	1,190	1,370	1,075	1,050
Western Europe	350	335	385	410	410	370	455	355	335
Japan	315	280	295	325	335	310	345	325	325
China	195	255	240	235	250	235	285	350	440
RoW	270	265	305	295	345	295	405	425	475
Total	**2,115**	**2,180**	**2,360**	**2,465**	**2,600**	**2,395**	**2,855**	**2,525**	**2,625**

Source: SFA (Oxford)

Rhodium supply-demand balance

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Primary supply									
Regional									
South Africa	620	615	620	625	640	475	670	595	585
Russia	70	70	75	75	80	80	75	75	70
Zimbabwe	35	45	45	40	40	45	40	45	45
North America	30	25	25	20	20	20	20	15	15
Other	10	10	10	10	10	10	5	5	5
Total	**765**	**765**	**775**	**770**	**790**	**630**	**815**	**735**	**720**
Demand & recycling									
Autocatalyst									
Gross demand	865	835	870	900	1,010	925	920	940	930
Recycling	260	280	305	335	355	330	365	310	305
Net demand	605	555	565	565	655	590	550	630	625
Industrial demand	**155**	**180**	**155**	**210**	**170**	**135**	**125**	**125**	**140**
Other recycling	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**3**	**2**
Gross demand	**1,020**	**1,015**	**1,025**	**1,110**	**1,180**	**1,060**	**1,040**	**1,065**	**1,075**
Recycling	**265**	**280**	**305**	**340**	**355**	**335**	**370**	**310**	**310**
Net demand	**755**	**735**	**720**	**775**	**820**	**725**	**670**	**755**	**765**
Market balance									
Balance (before ETFs)	10	30	55	0	-30	-100	145	-15	-45
ETFs (stock allocation)	-5	5	-20	-50	-15	-10	-5	0	
Balance after ETFs	**15**	**25**	**75**	**45**	**-15**	**-90**	**150**	**-15**	

Source: SFA (Oxford)

Rhodium demand and recycling summary

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Autocatalyst									
North America	240	235	230	225	220	175	170	185	190
Western Europe	250	210	215	230	290	225	215	220	225
Japan	125	125	125	130	130	110	100	100	95
China	110	130	150	155	205	275	285	275	260
India	15	20	20	20	20	15	20	30	30
RoW	120	115	130	145	150	125	125	130	135
Total	**865**	**835**	**870**	**900**	**1,010**	**925**	**920**	**940**	**930**
Industrial									
North America	15	20	15	20	20	15	15	15	15
Western Europe	10	10	10	20	15	10	5	10	15
Japan	10	10	10	10	10	10	10	10	10
China	80	95	75	90	70	65	65	65	70
RoW	40	45	40	70	55	30	25	25	30
Total	**155**	**180**	**155**	**210**	**170**	**135**	**125**	**125**	**140**
Total gross demand									
North America	255	255	245	245	240	190	185	200	205
Western Europe	260	225	225	245	300	235	220	230	240
Japan	135	135	135	140	140	120	115	110	105
China	190	225	225	245	275	340	345	340	330
RoW	175	180	190	235	220	170	175	185	190
Total	**1,020**	**1,015**	**1,025**	**1,110**	**1,180**	**1,060**	**1,040**	**1,065**	**1,075**
Recycling									
Autocatalyst									
North America	150	160	165	180	190	180	200	155	150
Western Europe	45	50	55	60	65	60	70	50	50
Japan	30	35	35	45	45	40	45	40	45
China	10	5	5	5	5	5	10	15	20
RoW	25	30	35	45	50	45	45	45	45
Total	**260**	**280**	**305**	**335**	**355**	**330**	**365**	**310**	**305**

Source: SFA (Oxford)

45 Rh 102.91 Rhodium

GLOSSARY OF TERMS

APIs
Active pharmaceutical ingredients.

Basket price
Collective revenue of metals divided by 4E oz.

BEV
Battery electric vehicle.

CCM
Catalyst coated membrane.

ESG
Environmental, social and governance.

Eskom
South Africa's public energy producer and supplier.

ETF
Exchange-traded fund.

Gigatonne
One billion tonnes.

Gross demand
A measure of intensity of use.

GWh
Gigawatt hour.

HDV
Heavy-duty vehicle.

Hydrogenation
A chemical reaction between molecular hydrogen and another compound or element, usually in the presence of a catalyst.

ICE
Internal combustion engine.

Isomerisation
The process in which a molecule, polyatomic ion or molecular fragment is transformed into an isomer with a different chemical structure.

koz
One thousand troy ounces.

LOHC
Liquid organic hydrogen carrier.

Merensky Reef
A PGM-bearing horizon within the Bushveld Igneous Complex, South Africa. Also contains nickel and copper sulphides that are mined as by-products.

moz
One million troy ounces.

Mt
One million tonnes.

Net demand
A measure of the theoretical requirement for new metal, i.e. net of recycling.

Net supply
Proxy supply of metal surplus to requirements.

oz
Troy ounce.

PEM
Proton exchange membrane.

PEM-EL
Proton exchange membrane electrolysis.

PGMs
Platinum-group metals.

Primary supply
Mine production.

Secondary supply
Recycling output.

Thrifting
Using less metal in order to reduce costs.

TOCOM
Tokyo Commodity Exchange.

UG2 Reef
A PGM-bearing horizon within the Bushveld Igneous Complex, located stratigraphically below the Merensky Reef. One of the main chromite-bearing reefs of the Bushveld Igneous Complex. Typically comprises lower base metals contents than the Merensky Reef.

WEEE
Waste electrical and electronic equipment.

4E
Platinum, palladium, rhodium and gold.

Currency symbols:

ZAR	South African rand.
£	British pound sterling.
$	US dollar.
¥	Japanese yen.

METHODOLOGY

Primary supply is calculated from actual mine production and excludes the sale of stock in order to provide pure production data. Stock sales are treated separately in SFA's database as movement of stocks. Therefore, state stock sales from Russia are excluded in tabulations.

Gross demand is a measure of intensity of use.

Net demand is a measure of the theoretical requirement for new metal, i.e. net of recycling.

Automotive demand is based on vehicle production data not sales.

ACKNOWLEDGEMENTS

SFA (Oxford) would like to thank all those whose hard work contributed to turning what began as an ambitious idea into the finished report you now see in front of you.

In particular, we would like to acknowledge our team:

Adele Rouleau
Alison Clapton
Carol Lu
David Mobbs
Emilio Soberón
Gyubin Hwang
Jamie Underwood
Jo Holmes
Kimberly Berman
Louis Scott
Ralph Grimble
Thomas Chandler
Yoshimi Mizoguchi Owen
Alex Biddle
Beresford Clarke
Daniel Croft
Eknoor Arora
Fahad Aljahdali
Henk de Hoop
Jenny Watts
Joel Lacey
Lakshya Gupta
Oksan Atilan
Sandeep Kaler
Tuğçe Ayvali

We should also mention a team of Associate Consultants, without whom this publication would not have been possible.

A special mention should also be given to Jeremy Coombes and Andy Smith whose combined knowledge of and expertise in compiling such an ambitious PGM industry review helped to fashion a report of which we could all be thoroughly proud.

We thank Janice Hurst and Karen Darley for proofreading *The Platinum Standard* throughout its production.

Then there are our third-party data suppliers: LMC Automotive, a GlobalData company, Oxford Economics, Bloomberg, and Trade Data Monitor whose data form the basis of many of the charts in this report.

Finally, to our clients and all those who have supported us throughout our time in business, we would like to dedicate this report as a mark of our gratitude for your continuing support.

ABOUT HERAEUS

Heraeus Precious Metals Trading Desks

Europe, Middle East, Africa & other regions
Phone: +49 6181 35 2750
edelmetallhandel@heraeus.com

South East Asia
Phone: +852 2773 1733
tradinghk@heraeus.com

USA
Phone: +1 212 752 2180
tradingny@heraeus.com

China
Phone: +86 21 3357 5658
tradingsh@heraeus.com

The Heraeus Group is a broadly diversified and globally leading family-owned technology company, headquartered in Hanau, Germany. The company's roots go back to a family pharmacy started in 1660. Today, the Heraeus group includes businesses in the environmental, electronics, health and industrial applications sectors. Customers benefit from innovative technologies and solutions based on broad materials expertise and technological leadership.

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 recycling. It has extensive expertise in all platinum group metals as well as gold and silver.

Heraeus Deutschland GmbH & Co. KG
Heraeus Precious Metals
Heraeusstrasse 12–14
63450 Hanau, Germany
www.heraeus-precious-metals.com

SFA (Oxford) Ltd
United Kingdom
Phone +44 1865 784366
www.sfa-oxford.com
The Oxford Science Park,
Oxford, United Kingdom, OX4 4GA

Disclaimer

This document is being supplied to the recipient only, on the basis that the recipient is reasonably believed to be a professional market participant in the precious metals market. It is directed exclusively at entrepreneurs and especially not intended for the use of consumers.

The material contained in this document has no regard to the specific investment objectives, financial situation or particular need of any specific recipient or organization. It is not provided as part of a contractual relationship. It is not and should not be construed as an offer to sell or the solicitation of an offer to purchase or subscribe for any investment or as advice on the merits of making any investment.

This report has been compiled using information obtained from sources that Heraeus and SFA (Oxford) Ltd ("SFA") believe to be reliable but which they have not independently verified. Further, the analysis and opinions set out in this document, including any forward-looking statements, constitute a judgment as of the date of the document and are subject to change without notice.

There is no assurance that any forward-looking statements will materialize. Therefore, neither SFA nor Heraeus warrants the accuracy and completeness of the data and analysis contained in this document.

Heraeus and SFA assume no liability for any losses or damages of whatsoever kind, resulting from whatever cause, through the use of or reliance on any information contained in this document. However, in so far as a liability claim exists under German law, Heraeus and SFA shall have unlimited liability for willful or grossly negligent breach of duty.

Unless expressly permitted by law, no part of this document may be reproduced or distributed in any manner without written permission of Heraeus. Heraeus specifically prohibits the redistribution of this document, via the Internet or otherwise, to non-professional or private investors and neither Heraeus nor SFA accepts any liability whatsoever for the actions of third parties in reliance on this document.