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PGM market report

May 2023

Johnson Matthey
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Johnson Matthey defines 'light duty' as cars and light trucks with a gross vehicle weight (GVW) of up to 3.5 tonnes, except in the USA, Canada and Mexico, where vehicles are considered 'light' if they have a GVW of up to 6 tonnes. Automotive production data is taken from S&P Global Mobility, Powertrain Production Forecast, February 2023 (vehicles with a GVW of up to 6 tonnes) and KGP-LMCA Global Commercial Vehicle Powertrain Forecast February 2023 (vehicles with a GVW over 6 tonnes).

The PGM market report is published annually, in May each year.

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Definitions

Europe	EU+ (includes UK and Turkey but excludes Russia)
Japan	Japan only
North America	USA and Canada (excludes Mexico)
China	China only
RoW	Rest of World: all countries not captured in the above
Primary supply	Supply figures represent sales of **primary PGM** by producers and are allocated to the region where mining took place, rather than the region of subsequent processing.
Secondary supply	Secondary supply is the quantity of metal recovered from open-loop recycling (i.e. where the original purchaser does not retain ownership of the PGM). Outside the automotive, jewellery and electronics markets, open-loop recycling is negligible. Automotive recycling represents the weight of metal recovered from end-of-life vehicles and aftermarket scrap. It does not include warranty or production scrap.
Demand	Demand figures for any given application represent the sum of industry demand for new metal in that application, net of any closed-loop recycling (i.e. where industry participants retain ownership of the metal: see page 32). **Automotive demand** is allocated to the region where the vehicle is manufactured and is accounted for at the time of vehicle production. It includes emissions catalysts on vehicles, motorcycles and three-wheelers, as well as fuel cell vehicles. Non-road mobile machinery is counted as industrial demand, in the pollution control category. **Jewellery demand** is allocated to the region where the finished jewellery is manufactured, not sold.
Movements in stocks	This figure gives the overall market balance in any one year and reflects the extent of stocks that must be mobilised to balance the market in that year. It is thus a proxy for changes in stocks held by fabricators, dealers, banks and depositories, but excludes stocks held by primary and secondary refiners and final consumers. A positive figure (market surplus) thus reflects an increase in global market stocks. A negative value (market deficit) indicates a decrease in global market stocks.

PGM summary

Supply and demand in 2022

PGM prices spiked in the first quarter of 2022 on fears of disruption to Russian deliveries

Smelter maintenance and electricity shortages hit PGM supply from South Africa

Auto recycling contracted as end-of-life vehicle intakes fell sharply in the USA and Europe

Automotive PGM consumption rose by 4%, with platinum taking all of the growth

Industrial demand for platinum remained robust, with record sales on the Shanghai Gold Exchange

Palladium and rhodium were hit by price-related substitution in the auto and glass sectors, respectively

For the PGM markets, 2022 was a year of stark contrasts. During the first half, the invasion of Ukraine provoked concerns that disruption to Russian PGM deliveries could precipitate another serious liquidity squeeze. The palladium price spiked to a new record, while the other PGMs also moved higher (despite their more limited exposure to Russian supplies), as consumers and other market participants moved to secure their metal requirements. However, the second half saw a steady improvement in availability, and a general downward movement in prices, despite weakness in primary and secondary supplies. This improved liquidity was a consequence of worsening macro-economic conditions and lacklustre demand, especially for palladium and rhodium, hit by price-related substitution in the automotive and glass sectors, respectively.

"Platinum availability in Western markets tightened as surplus metal was delivered to China, with SGE sales reaching a record 2 million oz"

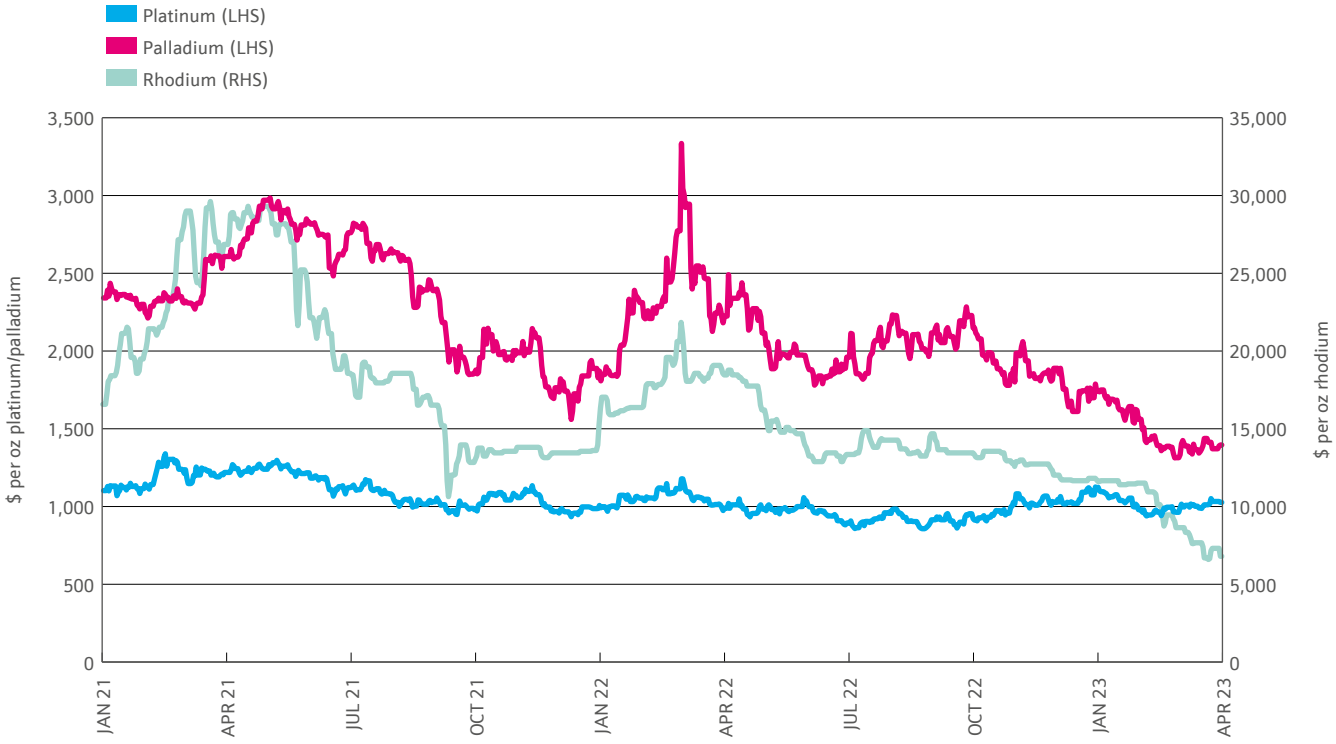


Figure 1 Platinum, palladium and rhodium prices

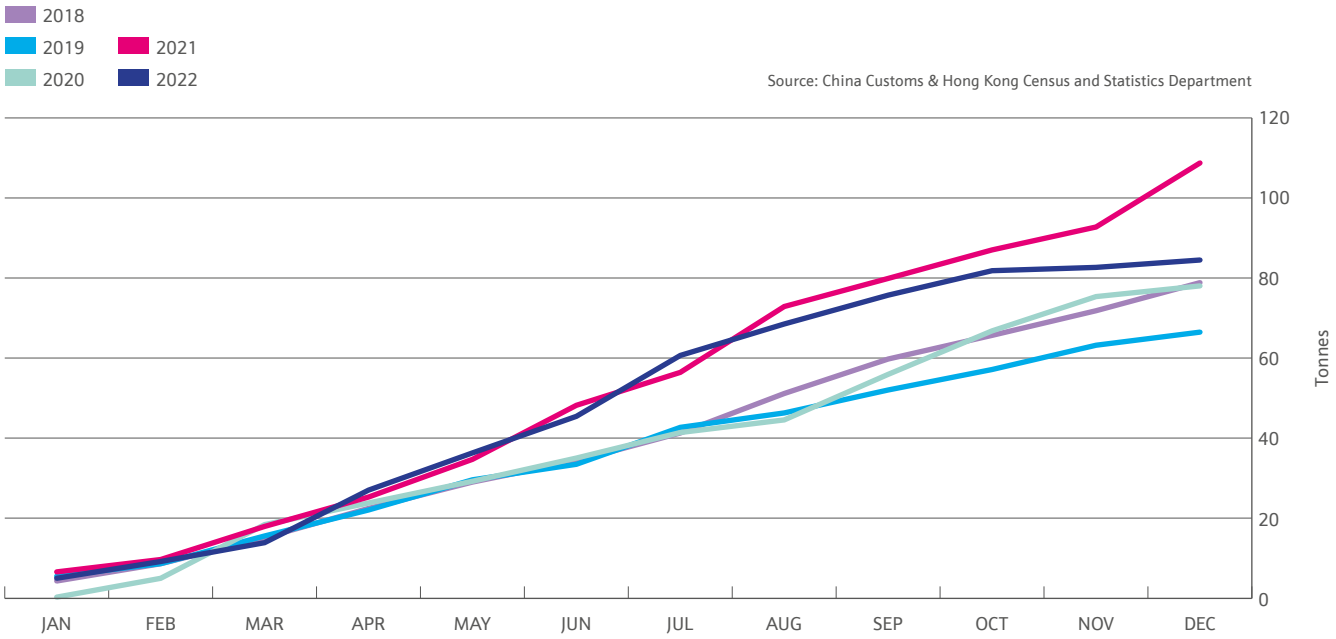


Figure 2 Net imports of platinum into mainland China and Hong Kong

Availability and market balance

The platinum market remained in surplus in 2022, despite weak primary supplies on the back of smelter maintenance in South Africa, and a pronounced downturn in autocatalyst recycling activity. Automotive platinum demand continued its recovery from 2020's low point, as platinum-for-palladium substitution in gasoline autocatalysts gained momentum, and platinum use on heavy diesel vehicles set an all-time high. Industrial purchasing was relatively buoyant: platinum demand from the chemical industry hit a new record, while glass industry requirements were supported by continuing investment in Chinese glass fibre capacity. However, these positive demand trends were offset by another steep decline in Chinese jewellery fabrication (down nearly one-third on 2021), heavy liquidation of ETFs, and sales back to the market by holders of large investment bars in Japan.

While our figures show the platinum market in oversupply, trends in lease rates suggest that availability in Western markets tightened last year. It is likely that much of the surplus metal was acquired by Chinese market participants: SGE sales reached a new high of 2 million oz (this figure includes metal purchased under forward contracts that reached maturity during 2022), while trade data shows that net imports of platinum into China and Hong Kong exceeded 2.7 million oz – well ahead of our estimate of Chinese domestic requirements.

"High used car prices led to a shortfall in end-of-life vehicles entering scrap yards"

Deliveries into China were heaviest between April and July, and were accompanied by spikes in lease rates, as liquidity was drained from Western trading hubs. However, towards the year end, evidence emerged that the Chinese market was approaching saturation: net imports of platinum into China and Hong Kong

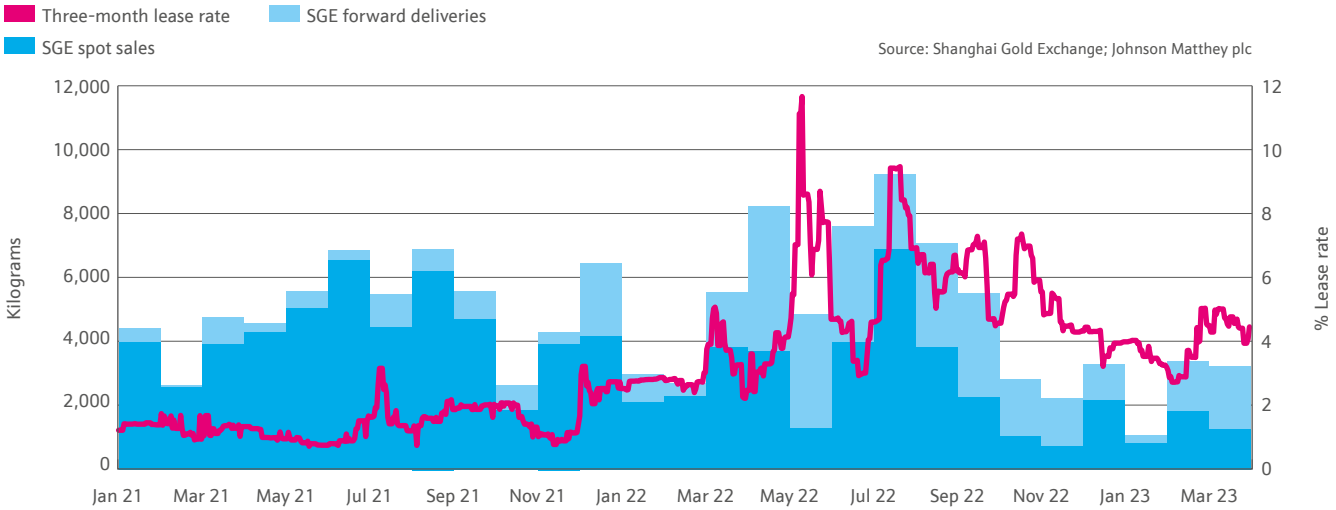


Figure 3 Platinum lease rates and SGE spot sales/forward deliveries

"Glass fibre producers sold significant quantities of unneeded rhodium back to the market"

slowed noticeably, as did SGE sales, and there was an increase in the re-export of platinum bars from Hong Kong to Switzerland.

In contrast, palladium moved back into significant deficit last year, due to a decline in combined primary and secondary supplies. South African shipments were hit by smelter maintenance, electricity shortages and generally difficult operating conditions, while the Ukraine war disrupted Russian deliveries. Autocatalyst scrap volumes were also depressed, with high used car prices leading to a shortfall in end-of-life vehicles entering scrap yards. On the demand side, auto and industrial consumption edged lower, as economic headwinds strengthened, and high palladium prices continued to galvanise efforts to thrift and substitute. Although there was some modest ETF liquidation, this was not enough to balance the market.

This deficit was primarily concentrated in the first half of the year. During this period, the palladium price was unusually high and volatile: the invasion of Ukraine created new geopolitical and logistical obstacles to the delivery of Russian palladium, while consumers and other market participants remained anxious about availability, and some acquired or held metal in excess of their immediate requirements.

However, towards the year end, there were signs of a material improvement in market liquidity. Trade data shows that increased volumes of PGM began to flow direct from Russia to Hong Kong, China and the USA from September onwards. At the same time, industrial and automotive purchasing was running out of steam: the electronics market (which had enjoyed buoyant conditions during the Covid distance-working boom) slowed sharply, while automotive palladium demand was dampened by a combination of increasing electrification, on-going platinum-for-palladium substitution, and elevated PGM inventories at some automakers. This improvement in liquidity was particularly pronounced in China: weak automotive demand, rising imports of Russian metal and a surge in domestic recycling activity left some local market participants holding excess palladium at the year end.

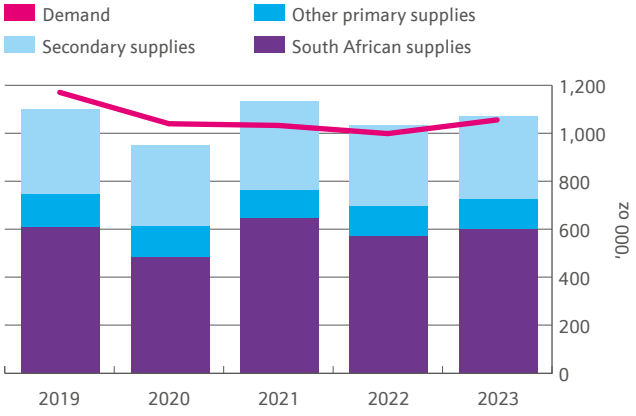


Figure 4 Rhodium supply and demand

Rhodium remained in surplus last year, as substitution efforts in the glass industry continued to accelerate in response to the exceptional price levels of 2021 and early 2022. The rhodium content of platinum alloys used in glass fibre production has fallen further and faster than we had previously anticipated, allowing glass companies to sell significant quantities of unneeded rhodium back to the market. As a result, non-automotive demand for rhodium declined by 43% to just 41,000 oz - less than a quarter of the 2017 peak, and the lowest level for nearly thirty years. Although primary and secondary supplies also fell sharply, this was not enough to bring the market back to balance.

Availability of ruthenium and iridium was adequate last year, despite a fall in South African shipments. Higher prices have helped to support liquidity, by spurring the liquidation of producer stocks of ruthenium (particularly in 2021), improving the economics of 'closed-loop' recycling in the chemicals industry, and stimulating some substitution of iridium in crucibles used to grow crystals for electronics applications.

PGM prices

PGM price movements during the first half of 2022 largely reflected the extent of exposure to Russian supply, with palladium the most affected. Over the past five years, around 28% of combined primary and secondary palladium supplies originated from Russia, whereas this proportion is below 10% for all the other metals.

As 2022 began, palladium moved swiftly through the $2,000 level, spiking above $2,600 when Russian troops entered Ukraine on 24th February. As the situation in Ukraine deteriorated, and widespread economic sanctions were imposed on Russia by the West, concerns about palladium availability intensified, driving the price to new all-time records. It peaked at $3,339 on 7th March, as prices of a range of Russia-exposed commodities surged higher. Although it retreated below $2,200 later that month as concerns about liquidity abated, the delisting of Russian refiners by the LPPM on 8th April reignited availability fears and spurred the price back above $2,500. As a result of the LPPM decision, ingot and sponge produced by Russian refineries since 8th April 2022 has no longer been accepted for 'Good Delivery' into the London and Zurich bullion market.

As availability fears began to ease, palladium fell back to trade between $1,800 and $2,200 for most of the second half. Sentiment was affected by an increasingly gloomy economic picture, with surging inflation, rising interest rates, and slack palladium demand from the automotive sector, although constrained primary and secondary supplies provided some support. The mood turned more negative during December, with palladium falling through $1,800 at the year end.

Platinum and rhodium also reacted to increased supply risks, despite Russia accounting for only a minor share of primary production. Platinum climbed steadily from around $960 in early January to an eight-month high of $1,151 on 8th March, although it subsequently fell back as supply fears eased, trading below $1,000 for most of the April to October

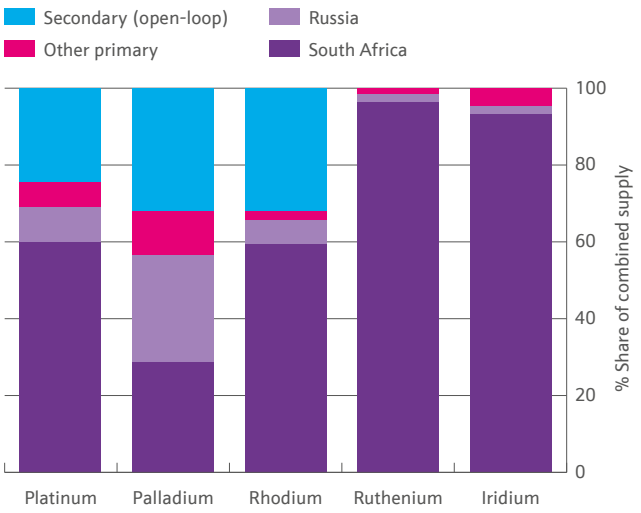


Figure 5 Combined primary and open-loop secondary supply share, 2017–2021

period. The price surged above $1,000 during November, as the US dollar weakened and NYMEX investors added to long positions, but the rally was ultimately short-lived.

Rhodium moved higher during the first quarter: with memories of the extreme supply squeeze of 2021 still fresh, industrial consumers moved to secure their metal needs, spurring the price from $14,500 as the year opened to over $22,000 on 7th March. It gradually gave up these gains, falling back to trade either side of $14,000 between June and November, before sinking to a 27-month low of $12,250 in December. Ongoing sales of rhodium by Chinese glass fibre producers have added liquidity to the market over the past two years, but until recently the price impact had been muted, because Chinese market participants were generally willing to hold surplus rhodium. This willingness evaporated in early 2023, when falling prices prompted Chinese rhodium holders to dispose of their metal, often at a discount to world market prices.

Ruthenium and iridium are much less exposed to Russian supply risk, but prices nevertheless climbed during the first quarter of 2022, as industrial buying in Asia and North America regained momentum. Iridium climbed from a low of $3,900 in February to settle at $5,100 during March, while ruthenium dipped to $525 before rallying to $625. Thereafter, prices for both metals drifted lower, and by October the iridium price had subsided below $4,000, while ruthenium was back below the $500 level. Although the ruthenium price remained subdued during the final quarter, iridium saw another sudden spike in December, jumping to $4,800 on renewed industrial buying.

Russian PGM supplies

While concerns about Russian supplies were a recurring theme in the PGM markets during the first half of 2022, ultimately the Ukraine crisis did not have a significant impact on output at Norilsk Nickel last year. The company reported refined palladium production totalling 2.79 million oz, up 7% on the previous year, while platinum output rose 2% to 651,000 oz, reflecting a recovery in output after 2021's mine flooding incident. There may also have been some release of PGM from the processing pipeline, as supply chain disruption prompted delays in plant maintenance (scheduled outages often result in temporary increases in work-in-progress).

Although PGM refined in Russia after 8th April 2022 no longer qualified for 'Good Delivery' status, preventing delivery into the London and Zurich markets, neither Norilsk Nickel nor Russian PGM generally were subject to formal government sanctions. This meant that there was no legal impediment to the supply of Russian PGM to industrial buyers and

"Palladium set an all-time high of $3,339 following the Russian invasion of Ukraine"

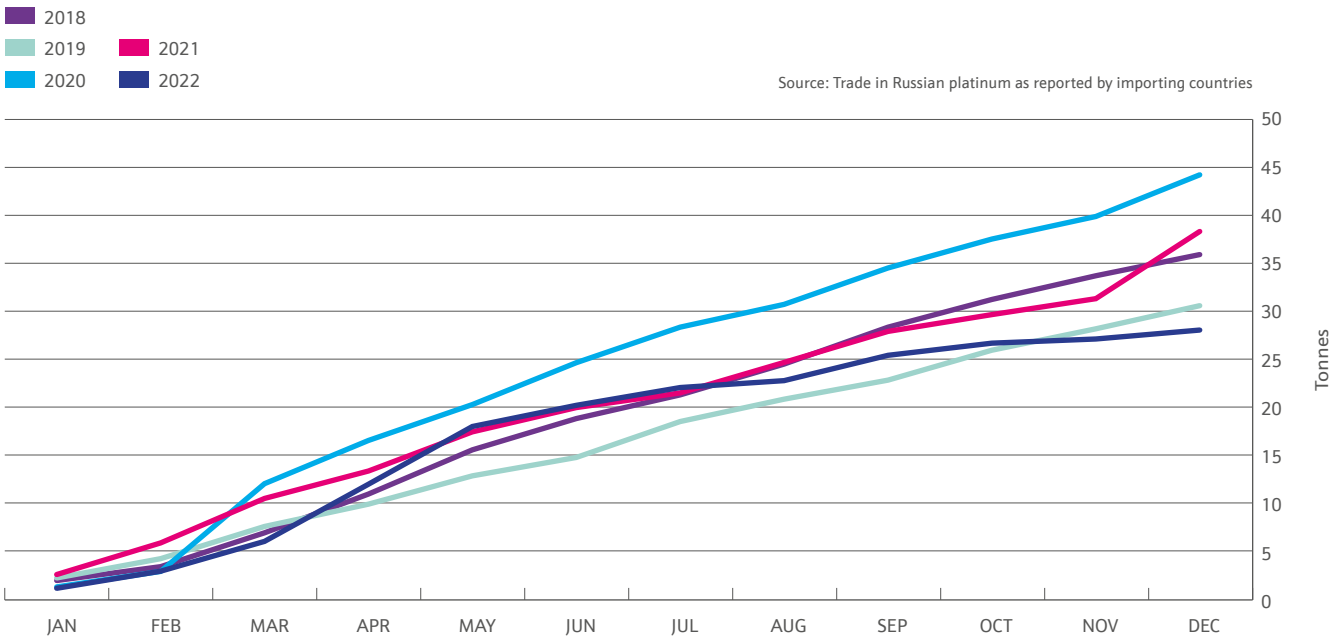


Figure 6 World trade in Russian platinum

other market participants. Nevertheless, it is clear from trade data that customers in some regions have reduced their intakes of Russian metal, while Norilsk Nickel has also reported logistical constraints affecting deliveries.

Russia has suspended publication of PGM export data, but trade statistics published by importing countries show a very significant contraction in world trade in Russian palladium in 2022 – down 32% versus the previous year. Platinum trade was also weak compared with recent years, although the reduction was less marked. This decline should be interpreted with caution. In recent years, the United Kingdom has accounted for a large share of Russian PGM exports, but deliveries of Russian PGM to the UK virtually ceased in mid-2022, in the wake of the LPPM delisting in April and a 35-percentage point increase in duties on Russian PGM in June. As a result, UK imports of Russian platinum and palladium fell by 66% and 82% respectively last year.

"Towards the year end, shipments of Russian palladium increased, probably stimulated by price discounting"

This in turn reduced flows of Russian-branded PGM from London to Asia, where such movements are often counted as 'Russian imports' even if the metal is transhipped via a third country. It is likely that part of the apparent decline in world trade in Russian PGM represents a reduction in double-counting of metal recorded as imports by both the UK and the final destination country. Nevertheless, trade data does suggest that some industrial customers, especially in Europe and Japan, have reduced their intakes of Russian palladium due to metal provenance considerations. It is not yet clear whether this has been fully offset by higher flows into China, although there is evidence of a rise in direct shipments of palladium from Russia to Hong Kong, probably stimulated by price discounting.

We count mine PGM production as 'primary supply' only when it is delivered to the market. Based on company data, Norilsk Nickel's first half platinum and palladium sales fell short of production by 124,000 and 63,000 oz, respectively. Although sales volumes for the full year have not been disclosed, the company's 2022 financial report suggests that some production went unsold. Our supply estimates allow for Russian shipments totalling 2.6 million oz of palladium and 600,000 oz of platinum in 2022, down around 3% year-on-year.

South African and other supplies

After an exceptionally strong year in 2021, South African supplies contracted sharply last year, reflecting a lower contribution from the release of pipeline inventory, along with planned maintenance at processing operations, ongoing operational challenges at many mines, and an increase in the frequency and severity of load-shedding (programmed electricity outages to protect the national grid). However, fears that wage negotiations might trigger industrial action were ultimately unfounded, with new five-year agreements reached at a number of major mines during 2022.

South Africa's two largest PGM producers, Anglo American Platinum and Impala Platinum, both undertook furnace overhauls last year, creating smelting capacity constraints that resulted in a build-up in stocks of semi-processed PGM. These capacity issues were exacerbated by load-shedding, especially during the second half of the year (PGM producers often manage their load curtailment obligations by reducing electricity consumption at their smelters). Sibanye Stillwater also reported a temporary increase in work-in-progress due to electricity shortages; although it was able to treat the backlog in December, it was unable to deliver all the resulting

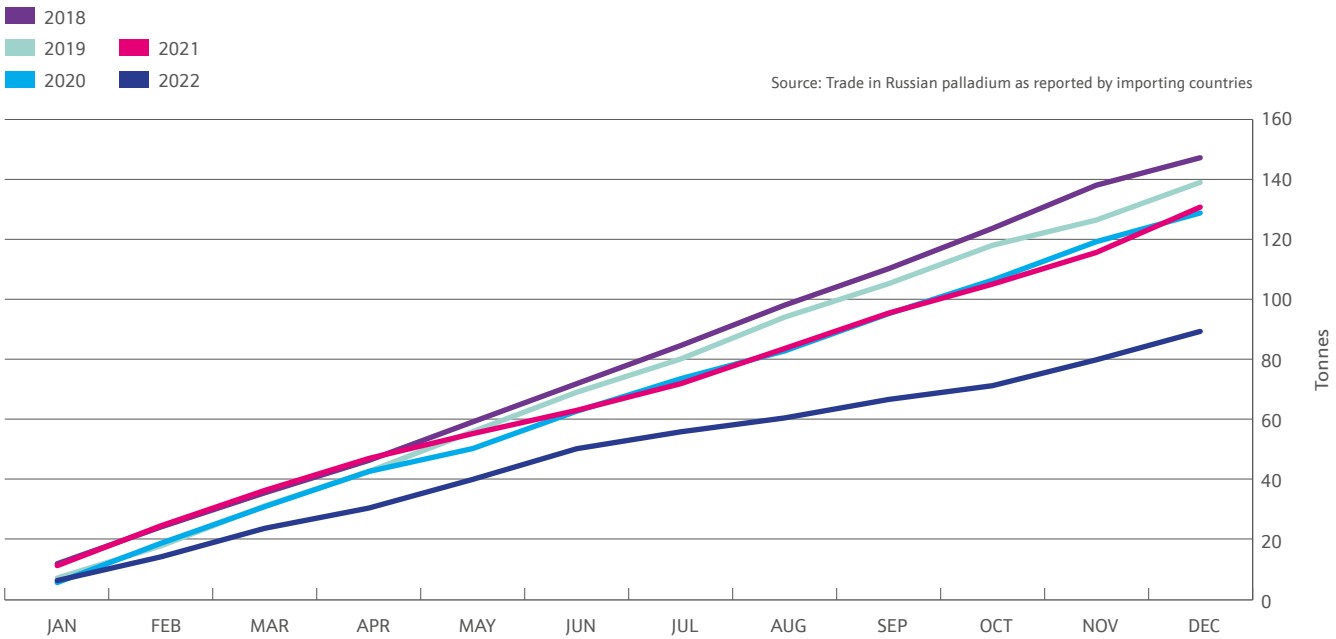


Figure 7 World trade in Russian palladium

refined metal before the year end. The combined impact of these stock movements on 2022 PGM supplies was just over 300,000 oz; this represents production that has been deferred rather than permanently lost. The refining and sale of this metal will add to supplies over the next year or two.

Excluding the impact of these stock movements, we estimate that underlying PGM output at South African mines fell by 6% in 2022. The largest single change was at Anglo's large Mogalakwena mine, where output of PGM in concentrate dropped 16% to 1.03 million oz. This reflected a steep decline in average ore grades, as mining was redirected towards lower-grade areas in the wake of heavy rainfall, equipment shortages, and community protests that led to the resequencing of mining operations.

"South Africa's two largest PGM producers undertook furnace overhauls, creating smelting capacity constraints"

North American PGM output was unusually weak last year. During June, exceptional rainfall in Montana, USA caused widespread flooding and severe damage to local infrastructure, cutting access to the Stillwater mine. Production at Stillwater was suspended for seven weeks, although the nearby East Boulder mine, also operated by Sibanye-Stillwater, was able to continue operations. Total PGM production from the Stillwater mining complex fell by 26% to just over 420,000 oz last year. Output of by-product PGM from Canadian nickel mining also dipped, reflecting a fifteen-week strike at Glencore's Raglan mine in northern Quebec, and a general decline in PGM grades at the Sudbury nickel operations, where some higher-grade shafts are approaching the end of their lives.

Secondary PGM supplies contracted sharply, as impacts from the semiconductor crisis continued to ripple outwards. With availability of new vehicles still limited, used car prices remained unusually high in most major markets, incentivising owners to keep vehicles on the road for longer than in the past. Most Western collectors reported a significant fall in autocatalyst scrap intakes during 2022, with weakness intensifying as the year progressed, despite some signs that the used car market had begun to cool off.

China was an exception to this trend. In this region, recovery of PGM from used vehicles rose by more than 15%, as increasing numbers of catalyst equipped vehicles entered recycling networks, and PGM grades in catalyst scrap rose.

We emphasize that our estimate of Chinese autocatalyst recovery is lower than the actual quantity of PGM treated through Chinese refining facilities in 2022, because our definition of recycling excludes some types of scrap to avoid double-counting. Specifically, we disregard production scrap (because we count demand only when the car is recorded as being produced, so any catalysts scrapped before being fitted to a vehicle are not included in our numbers), as well as catalysts replaced under warranty (on the basis that this is a like-for-like exchange and is broadly neutral for PGM demand). We believe that recycling activity was boosted last year by the processing of excess stock of China 6 catalysts, rendered surplus to requirements due to the rapid electrification of China's car market. The metal recovered from these catalysts is not included in our secondary supply estimates but clearly added to liquidity in the Chinese market during 2022, with some refiners ending the year with unsold palladium and rhodium inventory.

Automotive demand

Global light duty vehicle production rose 8% to 80.9 million units last year, but the post-Covid recovery remained muted, with output still 7% below 2019 levels. There were significant regional contrasts: the Indian and Chinese markets outperformed initial expectations, easily exceeding pre-Covid levels. This was despite periodic lockdowns affecting major Chinese cities and manufacturing hubs, and a huge wave of infections when zero-Covid restrictions were eased towards the year end.

However, the European, Japanese and North American markets saw growth expectations downgraded as the

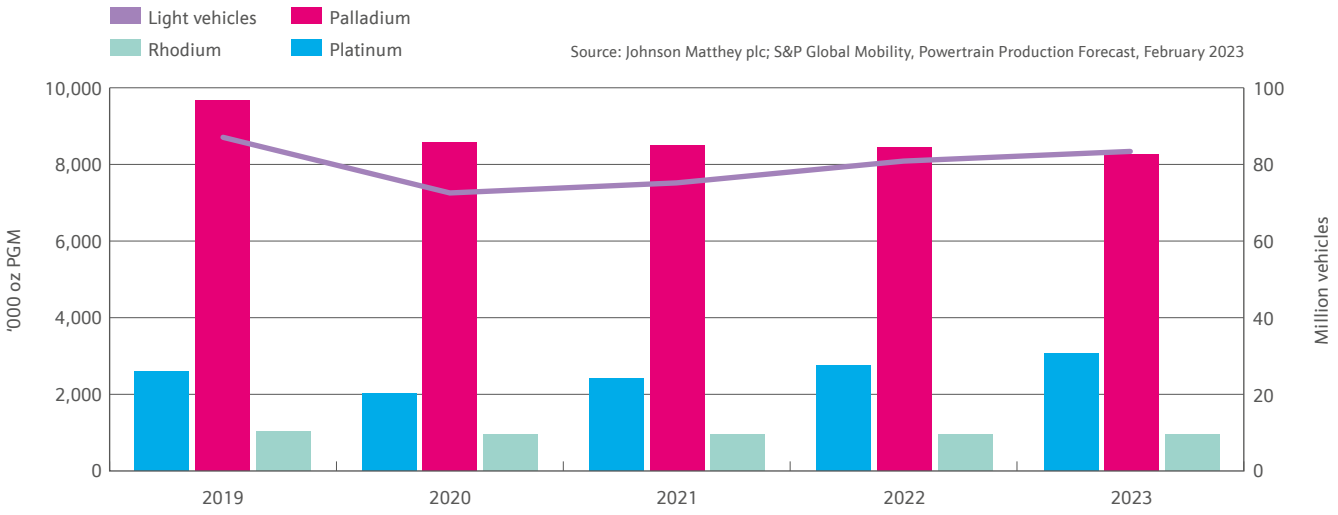


Figure 8 Automotive PGM demand & light vehicle output

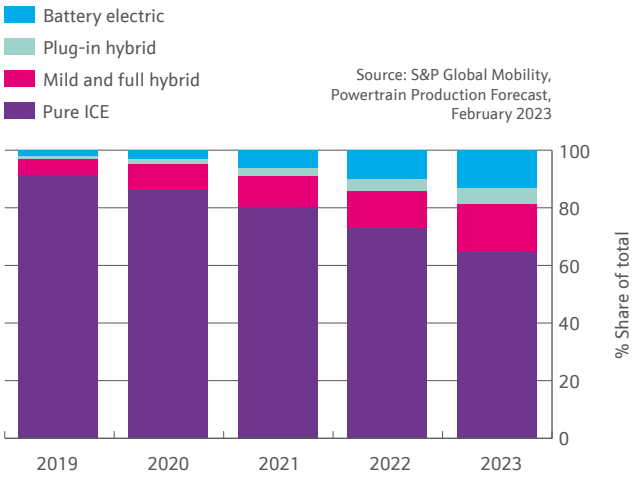


Figure 9 Light duty vehicle market share by degree of electrification

year progressed, mainly due to supply chain tensions that continued to inhibit the recovery in car production. In Europe and Japan, light vehicle output in 2022 was still at or below Covid-hit 2020 levels; the picture in the USA was less stark, but production was nevertheless 12% lower than in 2019.

This weak performance was largely attributable to ongoing semiconductor shortages, which cost the industry an estimated 3 million units of production last year (down from over 9 million in 2021). These losses were concentrated in the large Western and Japanese markets. The war in Ukraine created some additional supply chain challenges, with assembly lines at some German automakers temporarily affected by shortages of wiring harnesses made in Ukraine.

"ICE vehicle share fell, as BEVs gained momentum, especially in China"

From a PGM demand perspective, this relatively lacklustre global picture was compounded by changes in powertrain share, as battery electric vehicles (BEVs) gained momentum, especially in China (other regions saw more modest growth in BEV penetration). Chinese BEV production share leapt from 12% in 2021 to 21% last year, with volumes up 90% to 5.3 million units – far outstripping expectations, and surpassing government targets. Globally, BEV output rose 75% to capture 10% of the light vehicle market, up from 6% in 2021. The share taken by internal combustion engine (ICE) vehicles fell correspondingly; at 72.8 million units, light duty ICE vehicle output was up 3% year-on-year but remained 15% lower than in 2019.

The surge in BEV share in China was stimulated by national and regional government incentives, including subsidies and priority allocation of number plates for 'new energy vehicles' (NEVs) in some big cities. In addition to BEVs, the NEV category also includes fuel cell electric vehicles (FCEV) and plug-in hybrid electric vehicles (PHEV). The latter – which have internal combustion engines but are designed to be driven on battery power alone for shorter trips - enjoyed a particular success in 2022, with Chinese output more than doubling. Although this growth was at the expense of regular (non-hybrid) ICE vehicles, it was broadly positive for PGM demand: PHEVs generally require higher catalyst loadings, to cope with intermittent engine operation and lower exhaust gas temperatures. This partly offset ongoing thrifting of the PGM content of gasoline vehicles in China.

Globally, we estimate that average PGM loadings on light duty gasoline vehicles rose slightly last year, as tightening legislation in the USA, India and some Rest of World countries outweighed thrifting in China. There was a marked trend towards greater platinum use on gasoline cars, usually in the form of tri-metal catalysts, while palladium and rhodium content declined, with high prices encouraging efforts to thrift the more expensive PGM, and stimulating platinum-for-palladium substitution.

Cost-sensitive domestic Chinese automakers were among the first to adopt tri-metal catalysts, but interest in substitution in this region has begun to wane, with car companies preferring to focus R&D efforts on thrifting. In contrast, substitution programmes have progressed rapidly in North America over the past year, targeting some high-volume models with comparatively large engines and heavier PGM loadings.

In line with the above trends, overall PGM demand in the light duty gasoline sector rose by 4% last year, but platinum took virtually all of this growth, leaving palladium and rhodium consumption broadly flat. While platinum accounted for less than 10% of total PGM use on three-way catalysts in 2022, use of this metal on gasoline vehicles was nevertheless at the highest level since 2011.

The heavy duty diesel sector also saw gains in PGM consumption, as the full implementation of China VI emissions legislation on heavy diesel vehicles lifted global average loadings by nearly 30%. This more than offset a decline in world output of diesel trucks, down 20% to 4.1 million vehicles, due to a plunge in commercial vehicle output in China in the wake of heavy pre-China VI buying in 2020–2021. BEV penetration in the heavy duty sector remains very limited, with only around 160,000 battery-powered trucks produced globally in 2022 (representing a market share of less than 4%).

In contrast, PGM demand fell slightly in the light duty diesel segment, reflecting flat production and marginally lower catalyst loadings. Although diesel cars took only 12% of the car market in 2022, this segment remained the largest application for platinum in autocatalysts, accounting for nearly half of automotive demand for this metal.

"PGM loadings on heavy diesel trucks rose strongly, following the implementation of China VI emissions legislation"

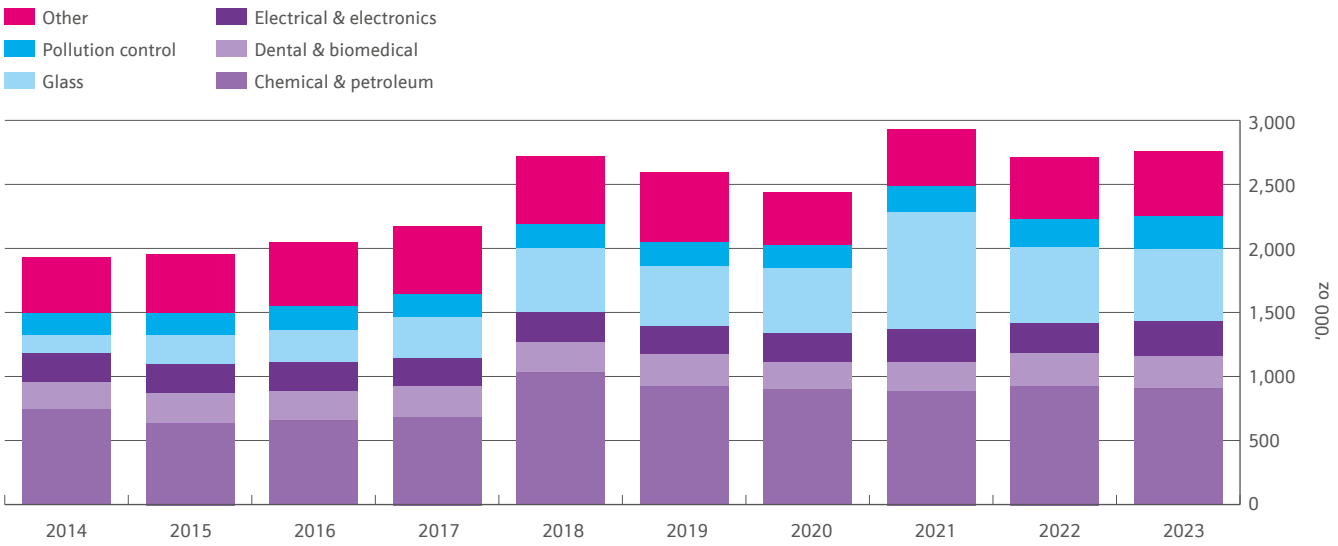


Figure 10 Industrial demand for platinum

Industrial demand

Industrial platinum demand retreated from an all-time high of nearly three million ounces in 2021, but remained unusually robust by historical standards, at over 2.7 million oz. Purchasing by glass companies contracted, because part of the platinum required for fibreglass expansions in 2022 was acquired the previous year. Nevertheless, demand from the glass sector remained close to 600,000 oz, a historically high level, reflecting the role of glass-fibre reinforced materials in applications such as vehicle light-weighting and wind power. Platinum demand also benefited from ongoing price-related changes in alloy composition, towards alloys containing more platinum and less rhodium.

Chemical demand for platinum set a new record of 700,000 oz, with continued strong use in paraxylene and silicones, and further investment in paraxylene units at large integrated petrochemical complexes in China. Construction of these complexes also generated demand for petroleum refining catalysts, although this was partly offset by the closure of some older, less efficient refineries and the resulting sale of metal back to the market.

In contrast, industrial purchasing of palladium and rhodium remained below pre-Covid levels. Record prices accelerated a long-standing trend away from palladium in dental alloys, primarily in favour of non-metallic (ceramic and resin) alternatives. The decline was particularly marked in Japan, the largest market for palladium dental alloys, where dentists have increasingly lost confidence that reimbursements from the government health insurance scheme will cover their metal costs. In the electronics sector, high palladium prices have been driving substitution (with base metals) for many years, but weak demand in 2022 was primarily due to a general downturn in the electronics market rather than an increase in substitution rates.

In the glass sector, efforts intensified to adopt lower rhodium-content alloys in equipment used to produce glass fibre. These fibreglass 'bushings' have traditionally contained up to 20% rhodium, because alloys with a higher rhodium content are

"Chemical demand for platinum set a new record, with further investment in integrated petrochemical complexes in China"

better able to withstand the elevated temperatures involved in glass fibre production. However, at high rhodium prices it can make economic sense for glassmakers to reduce the rhodium content of their alloys, albeit at the price of reduced bushing lifetime and productivity, and a corresponding increase in refining and fabrication costs. Until very recently, a 10% rhodium content was widely regarded as the lower limit, but extreme rhodium prices over the 2020-2022 period drove some fibreglass companies to adopt alloys with even lower rhodium concentrations. The use of advanced (and costly) grain-stabilised platinum technology has facilitated this development.

Alloy replacement programmes are usually rolled out progressively across a company's installed production base. At the end of a production campaign, bushings are removed from service and sent for refabrication, providing an opportunity to adjust alloy composition depending on prevailing prices. Because of the large volumes of PGM employed in glass fibre production (a single large fibreglass plant may contain as much as 30,000 oz of platinum-rhodium alloys), significant quantities of rhodium have been released due to alloy switching over the past two years. Some of this metal has been retained by glass companies to cover future capacity expansions and process losses, but we now believe that much of the surplus rhodium was returned to the market during 2021 and 2022. This resulted in negative rhodium demand from the glass industry, despite unusually high levels of capital investment and exceptionally strong platinum purchasing over this period.

Only in the chemicals sector was demand for palladium and rhodium largely untouched by high prices; in most cases, plants that are already in production or under construction cannot easily

be reconfigured to use alternative process catalyst technologies (even where non-PGM routes exist). Although economic headwinds are beginning to gather, with some bulk chemical markets moving into oversupply, construction of new chemical plants remained strong during 2022, especially in China.

Jewellery and investment

Platinum jewellery demand weakened again in 2022, despite a relatively strong performance in Europe and North America. In these two regions, demand for platinum wedding and engagement bands surged, as marriage rates recovered strongly following pandemic postponements, while Swiss watch makers also saw strong demand for luxury platinum products. However, the large Chinese market saw a ninth consecutive year of decline, with platinum jewellery fabrication dropping to just 470,000 oz, less than a quarter of the 2013 peak. Faced with a prolonged decline in consumer interest in platinum, Chinese jewellery makers have repurposed manufacturing equipment and redeployed or laid off skilled platinum workers. Japanese platinum jewellery fabrication demand was also lacklustre, with marriage rates failing to rebound as much as anticipated, and gold taking market share from platinum in the chain segment. Worldwide, we estimate that jewellery fabrication fell by 8% to 1.34 million oz.

A long period of positive demand for platinum investment products came to an end in 2021, and disinvestment gathered pace last year, despite relatively lacklustre dollar-denominated prices. Platinum ETFs saw sustained liquidation in all regions, with holdings falling from over 3.7 million oz in January to below 3.1 million oz by the year end. Rising interest rates made non-yielding assets generally less attractive, while euro, sterling and rand weakness against the dollar provided investors in these currencies with some profit-taking opportunities. In Japan, holders of large platinum bars also took advantage of high yen-denominated prices to take profits: sales back to the market surged in March and June, as the retail price moved above ¥4,800, and again in October, when platinum topped ¥5,000 for the first time in eight years.

> "Chinese jewellery makers have repurposed manufacturing equipment and redeployed or laid off skilled platinum workers"

> "Rising interest rates and dollar strength stimulated profit-taking by European, South African and Japanese investors"

In total, we estimate that a combination of ETF redemptions and the sale of large bars by Japanese investors resulted in disinvestment of over 700,000 oz of platinum. However, this was partly offset by on-going positive demand for small investment bars and coins such as the US platinum Eagle series and the Chinese platinum Panda. Overall, after accounting for this small investment demand, we estimate that a net 565,000 oz of platinum was returned to the market due to disinvestment in 2022.

Palladium ETFs have seen heavy liquidation in recent years, and by 2021 holdings had fallen below 600,000 oz, from a peak of around three million ounces in 2014–2015. Last year saw some modest further liquidation, pushing remaining ETF holdings down through the half-million ounce level – the lowest since 2008, a year after palladium ETFs were first launched.

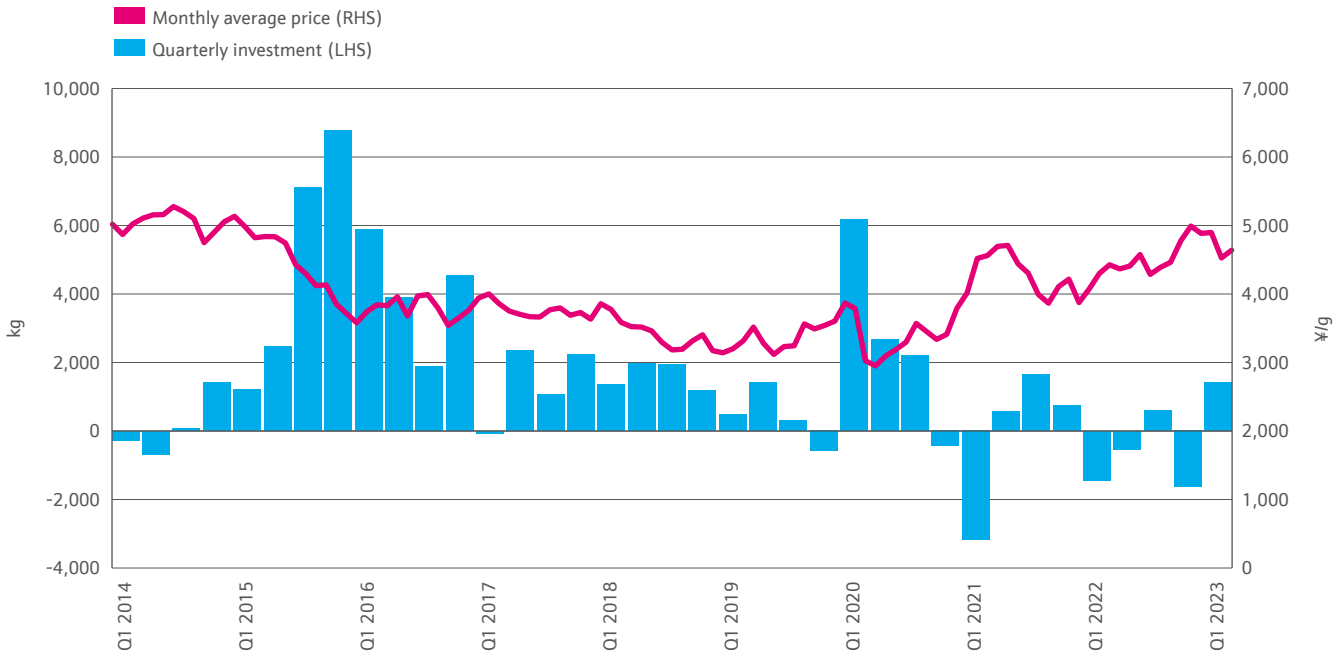


Figure 11 Japanese investment in large platinum bars

PGM outlook

Supply and demand in 2023

Primary PGM supplies should rise this year, with improved smelter availability in South Africa

Russian sales are forecast to be broadly flat, despite an expected fall in mine production

A recovery in US and European car sales should be positive for vehicle scrappage rates

BEVs will capture virtually all the growth in light duty vehicle production

Increased adoption of tri-metal gasoline catalysts will again lift platinum auto demand

Substitution and thrifting of palladium and rhodium is set to continue, despite lower prices

"Although Russian PGM output could fall, we expect Norilsk Nickel to mobilise stocks of metal that were left unsold last year, maintaining shipments at around the 2022 level"

The first quarter of 2023 saw steep falls in palladium and rhodium prices, reflecting subdued demand and ample availability. After a series of liquidity squeezes between 2019 and 2022, both markets are now returning to more normal conditions, with rhodium in a small surplus this year, and the palladium market moving close to balance. In contrast, platinum is forecast to shift into a small deficit in 2023, due to greater adoption of tri-metal catalysts on gasoline vehicles, and robust industrial demand. However, the direction of the platinum market balance remains dependent upon investment: our forecast reflects a return to buying in Japan and South Africa during the first quarter of 2023, but investor interest may prove difficult to sustain in a higher interest rate environment.

Overview and market balance

Our forecasts for all three metals show an increase in primary PGM supplies this year, in line with improved smelter availability in South Africa, and some incremental growth at mines currently implementing expansion programmes. Although Russian PGM output could fall, we expect Norilsk Nickel to mobilise stocks of metal that were left unsold last year, maintaining shipments at around the 2022 level.

Secondary supplies should also show modest gains, in line with a gradual recovery in new vehicle registrations, although there is some downside risk to our estimates if falling palladium and rhodium prices trigger increased 'hoarding' of spent catalytic converters. During the first quarter, scrap flows in China fell steeply, as collectors accumulated stocks in the hope of better

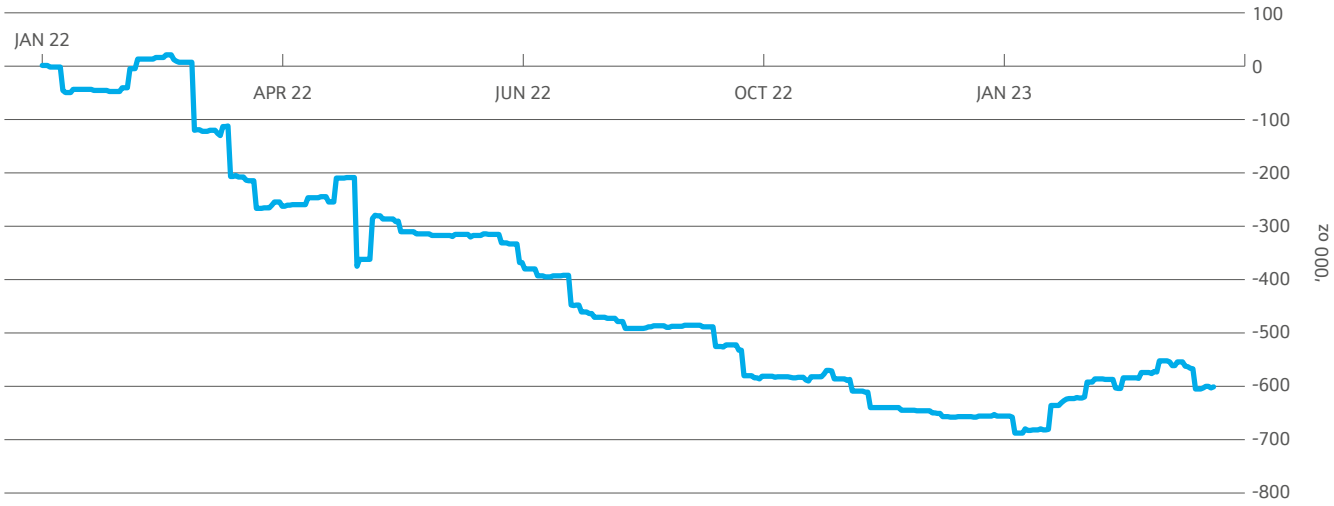


Figure 12 Net change in platinum ETF holdings, January 2022 to March 2023

prices in future; however, we assume that activity will eventually normalise once the market adjusts to lower price levels.

PGM demand is forecast to remain relatively robust, especially for platinum, which could see double-digit gains (assuming investment stays in positive territory for the remainder of the year). Automotive demand for platinum should enjoy another year of strong growth, albeit mainly at the expense of palladium: total PGM consumption on vehicles will rise only marginally, with little-to-no increase in production of ICE vehicles. While several large auto markets will enforce tighter emissions legislation this year, PGM loadings are forecast to rise only modestly.

"Overall, we expect a return to more balanced conditions in the PGM markets this year"

On the industrial front, demand in the chemicals sector is expected to remain buoyant for at least another year, but a downturn in the electronics industry is currently affecting PGM use in electronic components, hard disks and display glass. Our forecasts reflect industry expectations of a recovery in the electronics sector during the second half of 2023; if this does not materialise, there could be some downside to our demand numbers. More broadly, the outlook for major world economies remains clouded by high inflation, rising interest rates, and increased geopolitical instability, increasing the risk that planned capacity expansions in the glass, chemical and petroleum sectors could be delayed or cancelled.

Jewellery demand, primarily for platinum, is forecast to be broadly stable this year. There are signs that the Chinese market could be bottoming out, but manufacturers remain pessimistic about the outlook for platinum jewellery and have redeployed equipment and workers. This means there is little prospect of any material increase in Chinese jewellery demand this year, but there should be some growth in the US and Indian markets.

Our forecast allows for positive investment demand for both platinum and palladium this year. A higher interest rate environment should in theory be negative for non-yielding assets such as PGM, but platinum and palladium nevertheless saw some investor purchasing during the first three months of 2023 (our forecast is based on first-quarter activity and takes a neutral view of investment for the remainder of the year). Platinum benefited from a fall in yen-denominated prices which triggered renewed buying of large bars in Japan, while there was significant investment in South African platinum ETFs as electricity shortages (and the resulting risk to mine production) encouraged a rotation out of mining equities and into underlying commodities. Palladium also saw some modest ETF buying, perhaps reflecting recent falls in the price that have created a more attractive entry point.

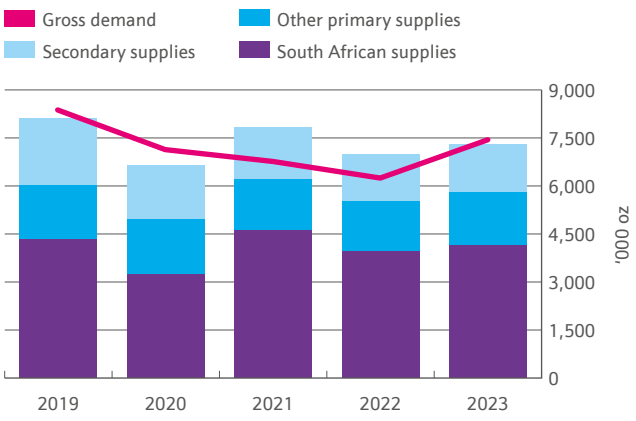


Figure 13 Platinum supply and demand

Supply '000 oz	2021	2022	2023
South Africa	4,609	3,965	4,154
Russia	638	600	630
Others	966	965	1,024
Total primary supply	**6,213**	**5,530**	**5,808**
Secondary supply*	1,645	1,468	1,521
Total combined supply	**7,858**	**6,998**	**7,329**

Demand '000 oz	2021	2022	2023
Automotive	2,405	2,762	3,063
Jewellery	1,468	1,344	1,351
Industrial	2,933	2,717	2,760
Investment	-28	-565	283
Total demand	**6,778**	**6,258**	**7,457**
Movements in stocks	1,080	740	-128

* Secondary supply comprises open-loop recycling from the automotive, jewellery and electronics industries

Table 1 Platinum supply and demand

Overall, we expect a return to more balanced conditions in the PGM markets this year. While we show the platinum market in a small deficit, there are ample market stocks available to meet consumer demand. For palladium and rhodium, the risk of renewed liquidity crises has receded, in view of the subdued outlook for ICE vehicle production, along with platinum-for-palladium substitution in autocatalysts, and technical developments that have released significant quantities of rhodium from the fibreglass industry. With availability concerns having subsided, and prices trending downwards, there is now much less incentive for consumers and other market participants to hold metal surplus to immediate requirements. This change in behaviour has contributed to a significant improvement in liquidity beyond that which is implied by our market balance numbers.

Primary supplies

South African platinum supplies are forecast to rise 5% to 4.15 million oz this year, with palladium and rhodium also expected to see mid-single-digit gains. Some producers began 2023 with excess pipeline inventory, following recent

processing outages; the refining of this metal should support PGM supplies both this year and next. There should also be some incremental growth in PGM output at operations that have recently implemented mine expansion and plant debottlenecking programmes. However, the operating environment remains exceptionally difficult, with PGM miners facing severe pressure from electricity shortages, rising costs, ageing assets, and socioeconomic challenges. While our forecast incorporates an allowance for these factors, there is some downside risk should business conditions deteriorate further.

"South African PGM miners face severe pressures from electricity shortages, rising costs, ageing assets and socioeconomic challenges"

Load-shedding was particularly severe and frequent during the first quarter of 2023. PGM producers can usually meet their load curtailment obligations by reducing power to their processing plants, allowing them to continue mining operations; ore or concentrate that cannot be treated immediately is stockpiled, and processed when sufficient electricity is available. However, at higher stages of load-shedding, it may become unsafe, impractical or uneconomic to send miners underground, leading to shifts being lost and some PGM production being permanently forgone.

To date, the direct impact of load-shedding on production has been limited and our forecast assumes this will continue to be the case. However, if electricity shortages worsen, there is a risk that the number of lost mining shifts will rise. The extent of these losses would of course depend on the severity and duration of load curtailment, with some producers suggesting that between 5% and 15% of PGM output could potentially be at risk.

Output from Norilsk Nickel is expected to drop this year: company guidance suggests that refined PGM ounces could decline by between 7% and 12%, as a furnace is taken offline for maintenance work that was postponed from 2022. The company has reported disruption to procurement of mining equipment and spare parts due to the Ukraine war, following the withdrawal of some Western firms from the Russian market (although it has recently claimed some success in securing new suppliers). Whether this has had any material impact on mining or processing efficiencies is not yet clear: Norilsk Nickel's long processing pipeline means that short-term changes in reported production are not necessarily a good indicator of underlying mining performance.

The fate of proposed expansion projects is also still uncertain, with mid- to long-term guidance currently under review. It was reported in the Russian press in March 2022 that the company will postpone part of its sulphur reduction programme and may reconsider planned mining investments in view of lower palladium and higher nickel prices. This could favour a shift in focus away from the proposed South Cluster expansion, which is relatively rich in PGM, in favour of the underground Talnakh mines, where nickel grades are higher.

Supply '000 oz	2021	2022	2023
South Africa	2,645	2,276	2,442
Russia	2,689	2,600	2,600
Others	1,512	1,431	1,514
Total primary supply	**6,846**	**6,307**	**6,556**
Secondary supply*	3,339	3,099	3,234
Total combined supply	**10,185**	**9,406**	**9,790**

Demand '000 oz	2021	2022	2023
Automotive	8,499	8,449	8,251
Jewellery	88	87	88
Industrial	1,647	1,510	1,469
Investment	17	-109	25
Total demand	**10,251**	**9,937**	**9,833**
Movements in stocks	-66	-531	-43

* Secondary supply comprises open-loop recycling from the automotive, jewellery and electronics industries

Table 2 Palladium supply and demand

Although PGM production at Norilsk is expected to drop in 2023, our view is that sales of Russian metal are likely to be flat to slightly up on last year. Following logistical disruption to shipments in 2022, Norilsk Nickel probably has some unsold stocks of refined PGM, which could be used to maintain deliveries, assuming that buyers can be found for the company's metal.

Trade data suggests that European and Japanese companies reduced their intakes of Russian PGM during 2022. As supply contracts come up for renewal, some of these customers may seek to further limit their reliance on Russian metal. However, since August 2022, increased quantities of Russian PGM have been flowing directly to Hong Kong, presumably for onward delivery to mainland China, while shipments to the USA also picked up during the final quarter of last year.

US PGM imports are likely to fall this year, following a 35-percentage point increase in US import tariffs that was imposed on most PGM products starting on 1st April 2023. The tariff hike applies to unwrought and semi-fabricated Russian platinum, rhodium, ruthenium and iridium, as well as semi-fabricated palladium. However, it excludes unwrought palladium, a category which includes palladium sponge (the form of metal used by the auto industry). In view of the increase in duties, US imports of Russian platinum, rhodium and minor metals are likely to be negligible from April 2023 onwards, but most palladium imports are in the form of sponge and should therefore be less affected.

Russian sales volumes in 2023 may therefore depend upon the ability of Chinese buyers to absorb additional metal, and this in turn will be influenced by automotive and industrial demand, and availability of PGM from other sources (such as autocatalyst

recycling, or metal inventories held by market participants). Pricing is also likely to be an important factor; there is evidence that discounted Russian metal is being offered in some markets.

Supplies of PGM from North American mines should rise this year, as Sibanye-Stillwater's US mining operation recovers from severe disruption due to regional flooding in 2022. However, the pace of recovery will be affected by damage to shaft infrastructure that occurred during maintenance in the first quarter of 2023; this temporarily limited access to deeper sections of the Stillwater West mine and is expected to result in the loss of 25,000–30,000 oz of PGM output this year. In Canada, we expect some moderate gains in PGM by-product volumes from nickel mining, as operations at Glencore's Raglan mine return to normal following a prolonged strike last year.

"Any weakness in Chinese auto recycling should be temporary, in view of the dramatic growth in the vehicle parc in recent years"

Supply '000 oz	2021	2022	2023
South Africa	645	570	597
Russia	53	58	58
Others	65	67	69
Total primary supply	**763**	**695**	**724**
Secondary supply*	369	338	345
Total combined supply	**1,132**	**1,033**	**1,069**

Demand '000 oz	2021	2022	2023
Automotive	962	953	947
Other	70	45	108
Total demand	**1,032**	**998**	**1,055**
Movements in stocks	100	35	14

* Secondary supply comprises open-loop recycling from the automotive industry

Table 3 Rhodium supply and demand

Secondary supplies

There remains significant uncertainty over the near-term outlook for secondary supplies. During 2022, autocatalyst recycling volumes weakened progressively in Europe and North America, and scrap intakes remained unusually depressed during the first quarter of this year. This was directly related to the shortfall in new car sales over the past three years, as pandemic-related challenges followed by severe semiconductor shortages created bottlenecks in vehicle production. The result was that older vehicles are being kept on the road for longer than normal, and the number of end-of-life vehicles entering scrapyards has declined significantly.

There has been some improvement in sales since the final quarter of 2022, and new car registrations in Europe and North America are forecast to rise by 7–8% this year. This should ultimately be positive for vehicle scrappage rates, although it is difficult to predict the timing of any recovery; our forecast assumes that we could see a modest upturn in recycling volumes during the second half of this year.

In contrast, the Chinese auto recycling market saw rapid gains in 2021–2022 but growth could slow this year. Refiners reported a dramatic fall in catalyst scrap intakes during the first quarter of 2023, in response to recent declines in palladium and rhodium prices. Collectors and refiners have adapted their business model to mitigate the downside price risk, offering only a down payment on the contained metal value of catalyst scrap, with the balance being paid when the PGM is refined and sold (previously, payment was made up front). This in turn has altered incentives lower down the recycling chain, with the result that scrap yards and other local operators have been hoarding scrap since late 2022.

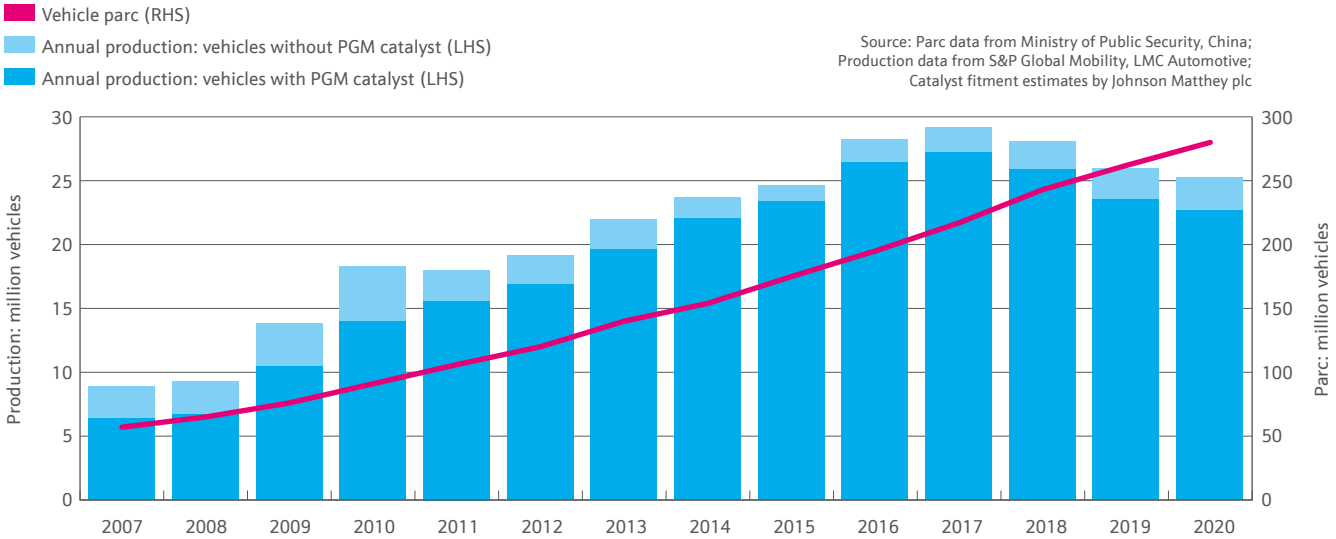


Figure 14 China vehicle parc, production and catalyst fitment 2007-2020

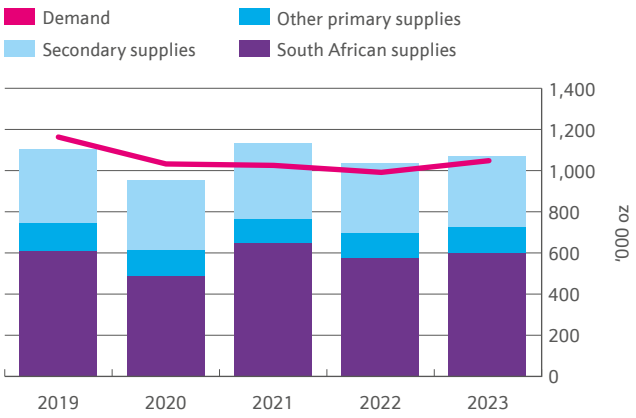


Figure 15 Rhodium supply and demand

Any weakness is likely to be temporary, in view of the dramatic growth in vehicle sales in China between 2008 and 2017 (annual new vehicle registrations rose from under 10 million to over 29 million over this period), and the consequent expansion of the vehicle 'parc'. Going forward, this will result in a surge in the number of cars reaching the end of their operating lives and entering scrap yards. In addition, PGM loadings on end-of-life scrap are rising, as increasing numbers of vehicles meeting China 4 and China 5 emissions legislation enter the recycling network. On balance, we expect a modest increase in Chinese autocatalyst recoveries in 2023, but there is both upside and downside risk to this projection, depending on near-term price trajectories.

Outlook for automotive PGM demand

Consumption of PGM by the automotive industry is expected to see only marginal gains in 2023, as battery electric vehicles once again capture virtually all the growth in the light duty sector. Gasoline car output in China is set to fall by around 5% this year; some other markets should enjoy positive trends (notably India and Japan), leaving world production of gasoline vehicles virtually unchanged. In the light duty diesel segment, production stabilised in 2022 but is expected to resume its long-term decline this year, led by an anticipated 6% fall in European diesel car volumes. The evolution of powertrain shares is discussed in more detail in the 'Focus on automotive PGM demand' section on page 20.

The outlook for the heavy duty sector is one of moderate growth: truck output is forecast to rise by 7% in 2023, primarily due to a recovery in the Chinese market (which contracted sharply last year, following the implementation of China VI legislation on heavy diesel vehicles in July 2021). Diesel powertrains continue to dominate the truck sector: while battery electric share has increased in recent years, electric powertrains are still mainly confined to vans and buses operating over relatively short distances.

Global average PGM loadings will be virtually unchanged in both light and heavy duty applications, despite the implementation of real driving emission (RDE) testing for passenger vehicles in China and India, the phase-in of Euro 6e light duty regulations in Europe, and the roll-out of stricter PROCONVE P-8 limits for heavy duty trucks in Brazil (see page 24 for further discussion of regulatory developments). Many automakers can meet the new Chinese and European standards without any material increases to the PGM content of their vehicles, while higher loadings on Indian cars and South American trucks are being broadly offset by thrifting elsewhere.

Although overall automotive PGM use will be relatively stable, the individual metals are once again expected to see sharply contrasting demand trends, reflecting catalyst fitment decisions taken in response to availability concerns and high palladium prices over the past four years. Platinum-for-palladium substitution continues to gain momentum, with platinum demand forecast to rise by 11% this year, while palladium use will contract by 2%. While palladium prices have fallen in recent months, this is unlikely to have any near-term impact on catalyst fitment programmes.

Rhodium consumption is generally unaffected by substitution decisions, but exceptionally high prices continue to drive some thrifting, despite the ongoing legislative focus on NOx emissions.

Outlook for industrial PGM demand

This year will see a continuation of recent trends in most large industrial applications. PGM demand will be supported by steady investment in the petroleum refining and chemicals sectors in China and the Rest of World region, and further expansion of Chinese fibreglass capacity. However, palladium and rhodium consumption will be affected by ongoing price-related impacts in the dental, electronics and glass sectors. Although prices have fallen in recent months, this is unlikely to have any near-term impact on substitution and thrifting.

Over the past five years, the Chinese petrochemicals sector has seen massive investment in modern integrated refinery complexes that incorporate traditional crude refining capabilities along with capacity to manufacture downstream bulk petrochemicals. This expansion activity was initially stimulated by the 13th Five Year Plan (2016–2020), which emphasised industrial modernisation and domestic self-sufficiency, but demand remains at high levels as projects initiated during this period are completed.

The Chinese fibreglass industry has also undergone remarkable growth in recent years, to meet rapidly expanding demand for lightweight fibre-reinforced materials from the automotive, wind power, construction and electronics sectors. This investment contributed to unprecedented platinum purchasing by glass fibre companies during 2021–2022 and will continue to support consumption this year. However, total platinum use in the glass sector will decline modestly in 2023, as investment in display glass facilities is postponed due to unusually weak LCD requirements in the consumer electronics sector.

"PGM per vehicle will be little changed, despite the introduction of Euro 6e regulations in Europe and RDE testing in China"

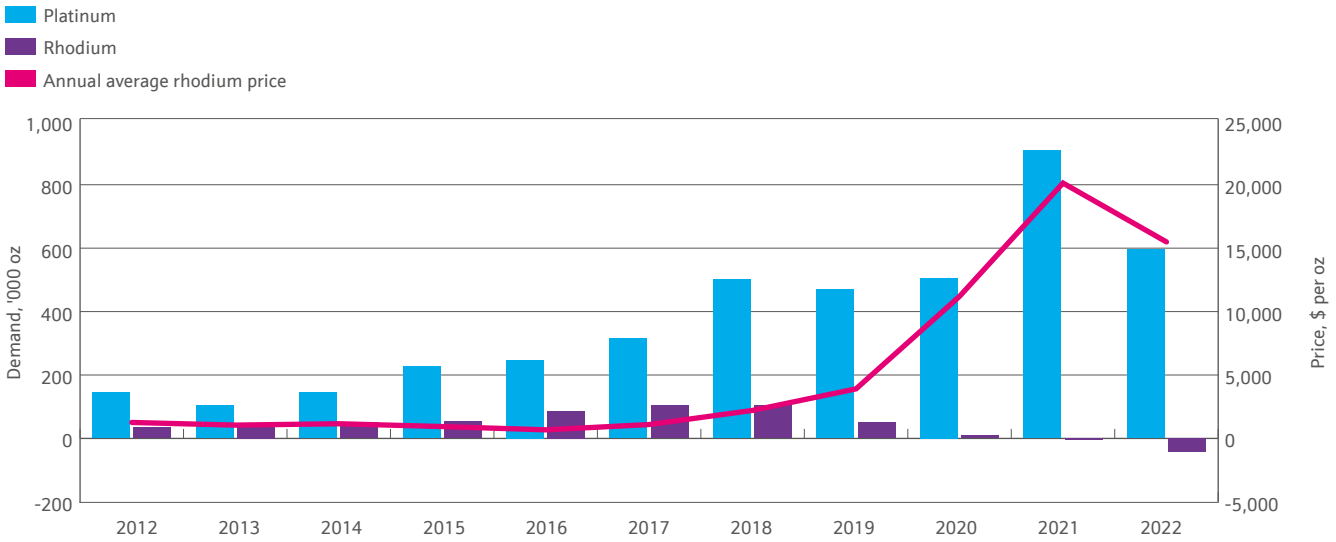


Figure 16 Platinum and rhodium demand in the glass industry

Glass demand for platinum and rhodium has moved in opposite directions over the past two years, because high rhodium prices have encouraged fibreglass producers to adopt alloys with a lower rhodium and higher platinum content. This substitution process applies not only to new plants, but also to installed capacity, with alloy switching being implemented progressively as equipment reaches the end of its productive life and is renewed. This has resulted in the steady release of rhodium from the Chinese glass fibre sector since 2021, with some of this metal being returned to the market. Although rhodium prices declined steadily during late 2022 and the first quarter of 2023, selling activity was significant during this period, as a downturn in the Chinese wind power and construction industries hit profitability, encouraging fibreglass manufacturers to take profits on their rhodium holdings. At the same time, falling prices have made glass companies much less willing than before to hold surplus rhodium inventory to meet their future metal requirements.

Lower rhodium prices could ultimately result in alloy switching programmes being halted or even reversed. Despite technical advances including the use of grain-stabilised alloys, the use of low-rhodium alloys is associated with reduced equipment lifetimes and shorter production campaigns. This means that the economic incentive to substitute rhodium with platinum diminishes well before price parity between the two metals is reached. However, at mid-April 2023 rhodium and platinum prices ($7,500 and $1,050 respectively), the adoption of alloys with a reduced rhodium content is still a cost-effective strategy.

Perhaps the largest source of uncertainty for industrial PGM demand this year is the outlook for the electronics industry. This sector enjoyed exceptionally robust conditions during 2020 and 2021, driven by a dramatic increase in home working and home entertainment during the pandemic. This was positive for PGM demand in a variety of electronics applications, with increased use of platinum in products such as hard disks and thermocouples (used in semiconductor production), and robust demand for palladium plating salts used to coat connectors and lead-frames. There was even a temporary halt in the long-term declining trend in the use of palladium in capacitors and other chip components (where miniaturisation and substitution have been steadily eroding demand for the past two decades). However, growth in the global electronics market ground to a halt in 2022, with a steep fall in sales of personal computers, mobile phones and other personal devices pushing electronic component markets into oversupply. This in turn led to a downturn in new investment (for example, in semiconductor and data centre capacity) and a wave of inventory adjustments.

The downturn in electronics demand is expected to be short-lived, because the long-term drivers of growth remain intact. However, the timing of any turnaround is still very uncertain; our forecast is based on industry expectations of a recovery starting in the second half of this year, but weak economic conditions in many major markets could see this delayed into 2024.

> "At April 2023 rhodium and platinum prices, the adoption of lower-rhodium fibreglass alloys is still a cost-effective strategy"

PGM use in some smaller applications is forecast to rise strongly in 2023. Platinum consumption in non-automotive fuel cells (included in our 'electrical and electronics' category) could exceed 100,000 oz for the first time, reflecting strong investment in fuel cell power plants in Korea, and increased use of fuel cell powered forklift trucks in US warehouses. In the pollution control sector, demand will be boosted by increased fitment of PGM-containing aftertreatment systems to non-road mobile machinery in China, following the implementation of China 4 standards in December 2022. The biomedical industry has also seen a significant upturn in demand over the past year, as procedures that were deferred during the pandemic take place and medical device inventories are rebuilt. Finally, in the 'other' category, a rebound in platinum use in the aerospace industry is underway, as demand for air travel returns to normal and aircraft maintenance schedules are accelerated.

Focus on automotive PGM demand

Chinese emissions legislation is set to tighten, with RDE testing implemented from July 2023

The phase-in of Euro 6e regulations will begin in September this year

Many automakers can meet these new standards without any increase in PGM loadings

Light duty BEV output is set to rise by over one third this year

Gasoline vehicle output could rise slightly this year, but light diesel production is forecast to fall

Proposed Euro 7 standards are set to be enforced on light vehicles from 2025

Overview

Automotive PGM consumption will see only marginal gains in 2023, with battery electric vehicles expected to capture all the growth in light vehicle production. Although emissions legislation is set to tighten again, with the implementation of real driving emissions (RDE) testing in India and China in April and July 2023 respectively, and the phase-in of Euro 6e regulations starting in September, most automakers can meet the new requirements without any material increases to PGM loadings. In the heavy duty sector – where demand has been boosted in the past two years by the enforcement of China 6 limits on heavy diesel trucks – thrifting of PGM loadings will partly offset underlying growth in vehicle volumes. World auto PGM demand is forecast to rise by just 1% to 12.2 million oz this year.

The individual PGM will see divergent demand trends, as platinum-for-palladium substitution on gasoline vehicles gains momentum, reflecting catalyst fitment decisions taken over the past three years when palladium prices were exceptionally high. Platinum automotive demand is forecast to rise by 11%, to exceed 3 million oz for the first time since 2017, while palladium use will contract by 2%. Rhodium consumption is not directly affected by substitution decisions, and will remain flat, with thrifting efforts broadly offset by the on-going legislative focus on NOx emissions under real driving conditions.

"The individual PGM will see divergent demand trends, as platinum-for-palladium substitution on gasoline vehicles gains momentum"

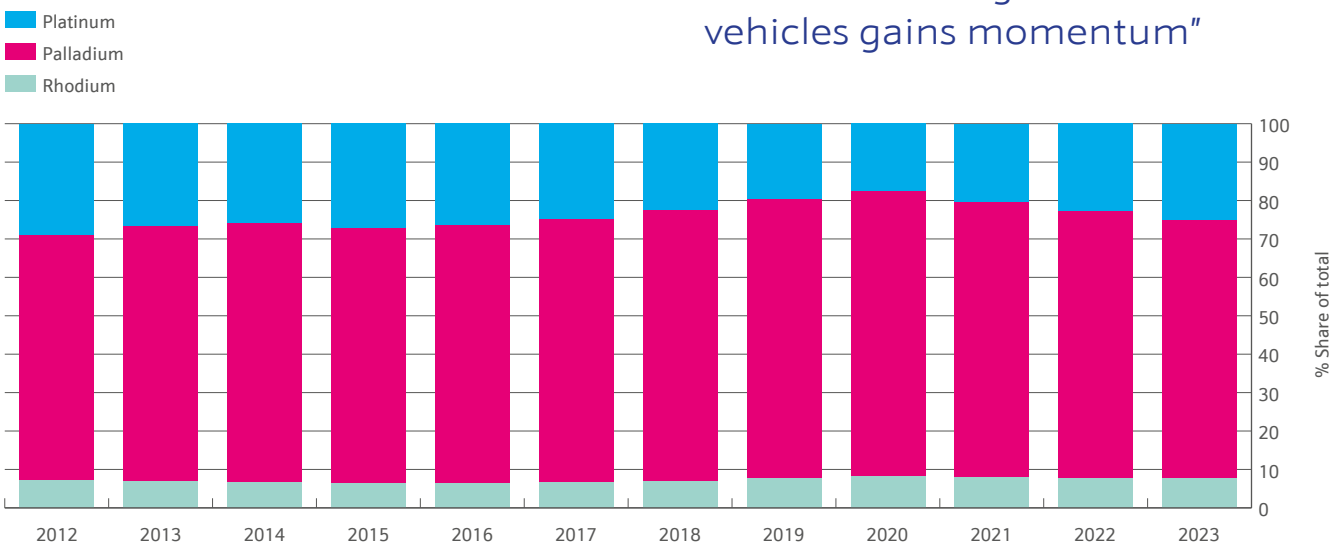


Figure 17 Share of automotive PGM demand by metal

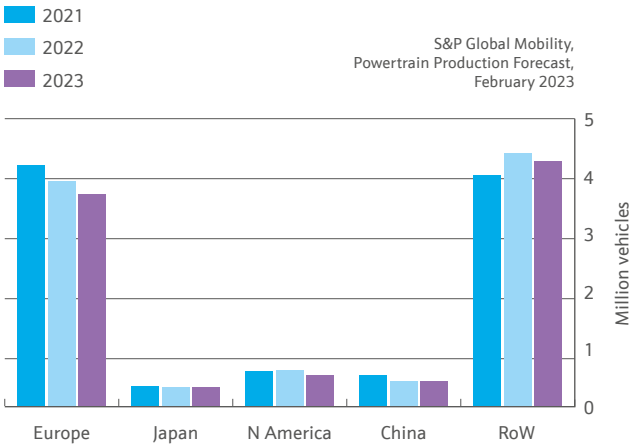


Figure 18 Light duty diesel vehicle production by region

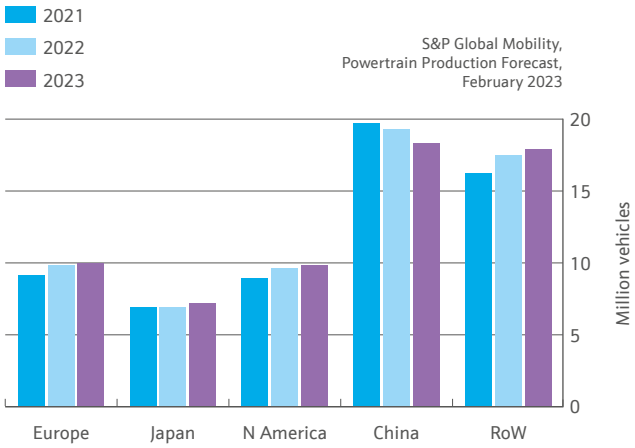


Figure 19 Light duty gasoline vehicle production by region

Light duty vehicle production

With supply chain frictions beginning to subside, light vehicle output in the large, mature markets of Europe, Japan and North America is forecast to rise by 7-8% in 2023. High inflation, rising interest rates, falling disposable incomes, elevated geopolitical risk and increased economic uncertainty have undoubtedly resulted in some demand destruction: industry sales forecasts have been slashed over the past year. However, after three years of exceptionally weak output, there is still enough pent-up demand for vehicles to support a modest recovery in the large, mature auto markets.

In contrast, growth in Chinese light vehicle production could stutter in 2023, following robust gains in 2021 and 2022. The market has been stimulated in recent years by government subsidies for new energy vehicles (NEVs; this category includes battery electric, fuel cell and plug-in hybrid vehicles), along with purchase tax exemptions or discounts, for NEVs and regular internal combustion engine vehicles, respectively. The NEV subsidy programme has now ended (although purchase tax concessions are still available), and at the time of writing, industry forecasts suggest that light vehicle output in China will plateau this year.

However, there may be some upside to the outlook for the Chinese auto market. Stimulus programmes are now being rolled out at the province and city level, to enable manufacturers and dealers to turn over their light vehicle inventory ahead of the implementation of the next stage of emissions legislation in July 2023, and to support local manufacturing and economic activity. Automakers are also cutting retail prices and some are offering large discounts to employees. These local incentives and discounts apply specifically to internal combustion engine (ICE) vehicles.

"A quarter of all ICE vehicles manufactured this year will be hybridised to some extent"

Elsewhere, car production in India enjoyed healthy gains in 2021-2022, and this upward trend is expected to continue for at least another year, supported by robust economic growth and significant pent-up demand for vehicles. Indian light duty output will approach 5.5 million vehicles in 2023, a new all-time record. There should also be a modest increase in car output in Mexico and South America, but many smaller Asian markets are forecast to remain sluggish. There is little prospect of any near-term recovery in the Russian car industry: output plunged from nearly 1.5 million units in 2021 to just 0.5 million last year, following the exit of major Western brands after the Ukraine invasion, and is likely to contract further this year.

Light duty powertrain trends and PGM demand

Overall, light vehicle production is forecast to rise by around 3% to 83.4 million units in 2023; virtually all of this growth will be taken by electric vehicles, with BEV output predicted to rise by over a third. Light duty gasoline volumes are expected to show only marginal gains, as modest increases in other regions are offset by falling output in China. In the light duty diesel sector, production stabilised last year but will resume its decline in 2023, led by an anticipated 6% fall in European diesel car volumes. Diesels will account for only 11% of global light vehicle output this year, down from 17% just five years ago.

While trends in the BEV sector remain strongly positive, growth could decelerate this year, as the Chinese market cools following two exceptional years (during which BEV output rose five-fold from just over 1 million units in 2020 to 5.3 million in 2022). Although BEV production is gathering pace in Europe and North America, these gains will be from a much smaller base than in China.

Electrification (hybridisation) of vehicles with internal combustion engines is also increasing. Worldwide, over a quarter of all ICE vehicles manufactured this year will be hybridised to some extent (i.e., will have an electric motor in addition to an internal combustion engine) – up from 19% in 2022 and under 5% just five years ago. Growth will be particularly strong in the plug-in hybrid (PHEV) segment, especially in China, where local brands have achieved significant market share gains by offering attractively priced vehicles that have excellent fuel economy

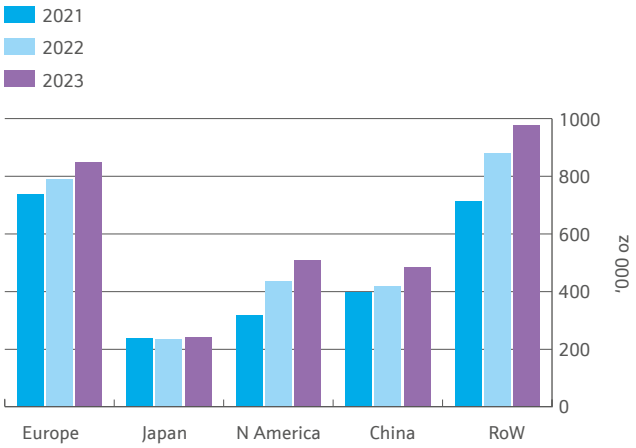


Figure 20 Automotive demand for platinum

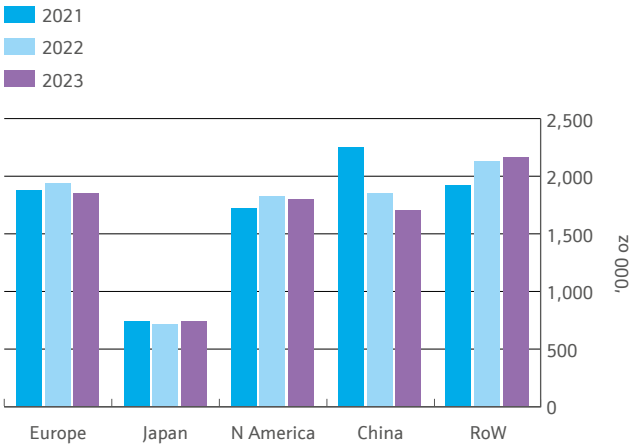


Figure 22 Automotive demand for palladium

and qualify for national and local incentives. These include exemption from purchase tax and the allocation of green number plates, which allow drivers to use their vehicles when traffic restrictions are in place. This year, Chinese output of plug-in vehicles is set to rise by over 50% to approach 2.5 million units.

Outside China, the largest PHEV market is in Europe, with output forecast to reach 1.2 million vehicles this year. However, there are some headwinds developing in this region: under Euro 6e legislation, the calculation of CO_2 emissions from PHEVs will become less favourable, and this could prove negative for future growth in this segment.

In China, increasing PHEV share has been positive for PGM loadings on passenger cars; not only are these vehicles heavier because of the weight of the battery, but intermittent operation of the internal combustion engine also results in lower exhaust gas temperatures, so a higher PGM loading is required to achieve the same catalyst performance.

Chinese loadings will also be supported by the implementation in July 2023 of real driving emissions (RDE) testing, under China 6b legislation (see below for further details). This will limit the scope for PGM thrifting this year. However, PGM consumption on light vehicles in China is nevertheless expected to see a modest decline this year, reflecting the forecast fall in ICE vehicle output. Palladium and rhodium will be most affected, while platinum demand will be boosted by increased use of tri-metal catalysts in the 'close-coupled' position (close to the engine), where PGM loadings tend to be heaviest.

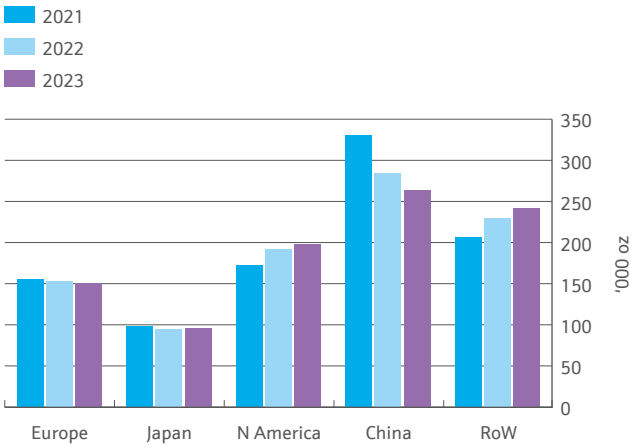


Figure 21 Automotive demand for rhodium

In Europe, PGM loadings on gasoline vehicles will be broadly stable this year, despite the roll-out of a new phase of Euro 6 legislation, known as Euro 6e. These regulations will apply to new models from September 2023 and will be extended to all light vehicles twelve months later. Among other provisions, Euro 6e further increases the stringency of RDE testing, but in practice this will have only a limited influence on PGM requirements, because most aftertreatment systems are already designed to meet or exceed Euro 6e requirements. Total PGM consumption on European light duty vehicles will decline marginally, due to lower diesel car output, but platinum will take a greater share of demand, reflecting rising use of tri-metal catalysts on gasoline vehicles.

North America should see moderate gains in PGM demand on light vehicles this year, in line with a small rise in production and an incremental increase in PGM loadings as more vehicles meet the most stringent category of emissions limits under Federal Tier 3 legislation. Platinum will account for virtually all this growth. US automakers have generally been quicker to adopt tri-metal catalysts than car companies elsewhere, because larger average vehicle sizes and higher overall PGM loadings mean that there is a greater financial incentive to substitute.

India will also see further steady growth in catalyst loadings on light vehicles, following the introduction of RDE testing in April 2023 under Bharat VI legislation. With car output also set to rise, PGM demand in light duty applications in India will climb to more than 600,000 oz this year – up 8% on 2022, and more than 80% higher than in 2019, immediately prior to the introduction of Bharat VI legislation.

"PHEV production in China is growing strongly, with local brands offering attractively priced vehicles that qualify for national and local incentives"

Heavy duty market

Trends in global heavy duty vehicle production have been dominated by the large Chinese market over the past three years. Unlike other regions, the Chinese heavy duty market saw little impact from Covid in 2020-2021 – indeed, truck output in China during these two years was higher than in 2019, due to substantial pre-buying ahead of the implementation of China 6 legislation on heavy duty diesel vehicles in July 2021.

China 6 legislation significantly increased the complexity and cost of aftertreatment systems fitted to Chinese diesel trucks and, since its introduction, production of heavy diesel vehicles in this region has fallen sharply: down from 3.3 million units in 2020 to 1.7 million in 2022. The Chinese market is expected to bounce back in 2023, with growth rates approaching 20%, but output will remain below pre-Covid levels.

In 2020–2021, China accounted for more than three in every five heavy duty vehicles produced globally – with the result that world truck output remained remarkably stable over this period, at 5.4–5.5 million units, despite steep Covid-related declines in other regions. However, the plunge in Chinese production in 2022 saw global HD production fall 19% to just 4.4 million units. The outlook is for moderate growth this year, with truck output forecast to rise by 7% to 4.8 million vehicles, primarily due to a recovery in Chinese output; most other major truck markets remain subdued.

"Diesel powertrains continue to dominate the heavy vehicle sector, although battery electric share is increasing"

While battery electric share is increasing, diesel powertrains continue to dominate the heavy vehicle sector: heavy duty BEVs will account for less than 5% of world truck output in 2023. Even in China, the world leader in vehicle electrification, only 7% of heavy vehicles will be battery powered this year, mainly light commercial vehicles and buses operating over relatively short distances.

"Regulatory measures should boost the rollout of hydrogen infrastructure and reduce hydrogen costs, supporting interest in heavy fuel cell trucks"

Over the past two years, the enforcement of China VI emission limits on heavy duty diesels has had an important impact on PGM consumption. Between 2020 and 2022, average PGM loadings on Chinese trucks more than quadrupled, as these vehicles were fitted with advanced aftertreatment systems for the first time. As a result, growth in world PGM demand in the heavy duty sector saw a temporary disconnect from vehicle production trends, with double-digit growth in PGM consumption in 2021 (despite a flat global vehicle output profile) and stable demand last year (even though truck production fell steeply).

Average loadings will stabilise this year, as modest thrifting in the Chinese market is offset by a sharp increase in the PGM content of Brazilian trucks, following the implementation of PROCONVE P-8 legislation (similar to Euro VI) in January 2023. This means that output will once again become the primary driver of PGM demand. With world truck production forecast to see mid-single-digit growth, PGM consumption on heavy vehicles will rise correspondingly, to set an all-time high.

Across all heavy ICE powertrains (diesel, gasoline and compressed natural gas) we estimate that demand will approach 1 million oz this year, accounting for a record 8% of total automotive PGM use. This proportion is likely to grow in future, because ICE share of the truck market is expected to decline much more slowly than is the case for light vehicles. However, regulatory authorities in Europe and North America are now starting to tighten zero emission mandates for heavy vehicles, and this will ultimately stimulate an acceleration in heavy duty BEV and FCEV uptake in these regions.

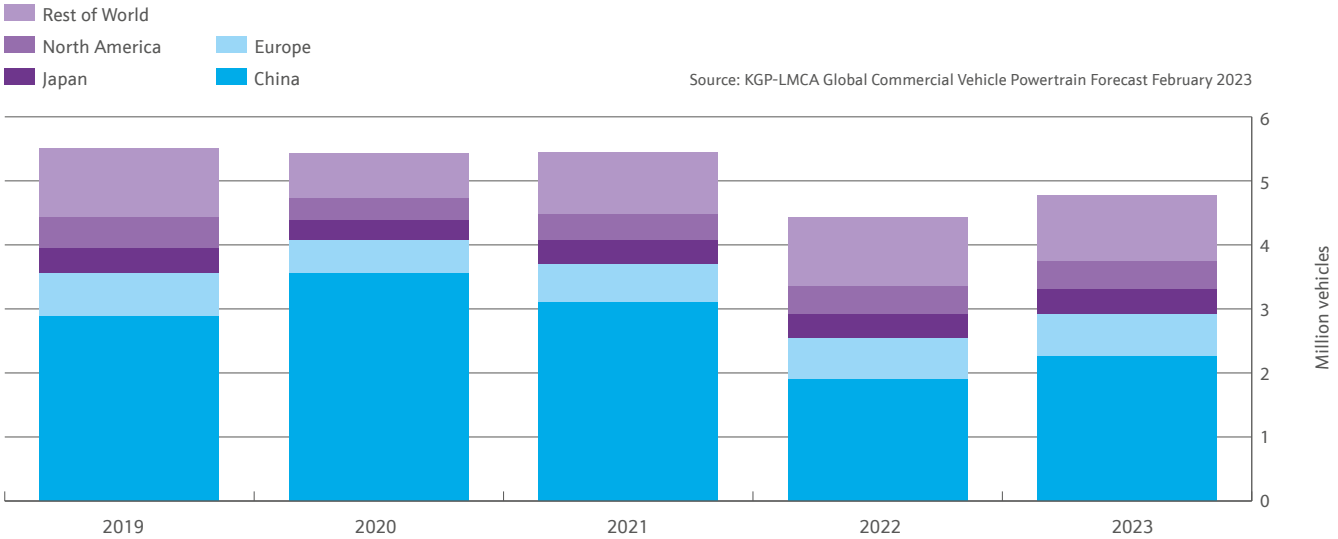


Figure 23 Heavy duty vehicle production 2019–2023

Fuel cell vehicles

Platinum use in fuel cell electric vehicles (FCEVs) should post healthy growth this year (albeit from a low base), driven by strong increases in FCEV output in both the light and heavy duty sectors. While passenger car output continues to grow, focus has shifted to the commercial vehicle sector, where serious consideration is being given to how to achieve 'deep' CO_2 reduction, in line with the regulatory intentions discussed on page 26.

The heavy goods industry is evaluating the use of fuel cell trucks in addition to battery variants, as the shorter refuelling times and longer ranges of FCEV mean that the utilisation rate of each truck is not compromised. In contrast, a fleet comprising purely battery trucks may require additional vehicles to compensate for the impact on individual truck uptime and cargo carrying capacity (which can be reduced by the size and weight of large battery packs).

In the light commercial vehicle segment, similar factors are starting to influence decision making: one large European automaker has announced its intention to mass produce fuel cell vans, targeting use cases where long range, rapid refuelling and maximum cargo carrying capacity are important, or where access to electric charging points is restricted.

Regulatory measures – the Inflation Reduction Act (IRA) in the US and REPowerEU in Europe – are supporting interest in fuel cells for these high-utilisation use cases. Particularly in the case of the IRA, the incentives and other measures are expected to boost the rollout of hydrogen infrastructure and significantly reduce the cost of hydrogen per kilogram. This has a direct impact on the total cost of ownership of fuel cell vehicles, the overriding metric in commercial vehicle purchasing decisions.

Efforts continue to reduce platinum loadings per kilowatt (beyond the >90% reduction already achieved since the 1990s) and are expected to substantially moderate demand growth versus underlying vehicle output growth, ensuring availability of platinum remains sufficient to support the expected growth in vehicle production. With growing concern around the availability of critical raw materials for BEVs, the lower metal intensity and different material requirements of fuel cell vehicles are likely to prove another factor in favour of their uptake.

Emissions legislation in 2023

It was confirmed in July 2022 that another round of amendments to Euro 6 light duty legislation will be phased-in starting in September 2023. This new stage, Euro 6e, further reduces allowable error margins for emissions measured during Real Driving Emissions testing using portable emissions measurement systems ('PEMS error margins', formerly known as 'conformity factors'), to 1.10 for NOx and 1.34 for particulates. (The latter multiple applies to the particle number, PN, and not the total mass of particulate matter, because it is the smallest particles that are most damaging to human health). However, the impact on PGM demand is expected to be small, because most aftertreatment systems are already designed to meet or exceed Euro 6e requirements.

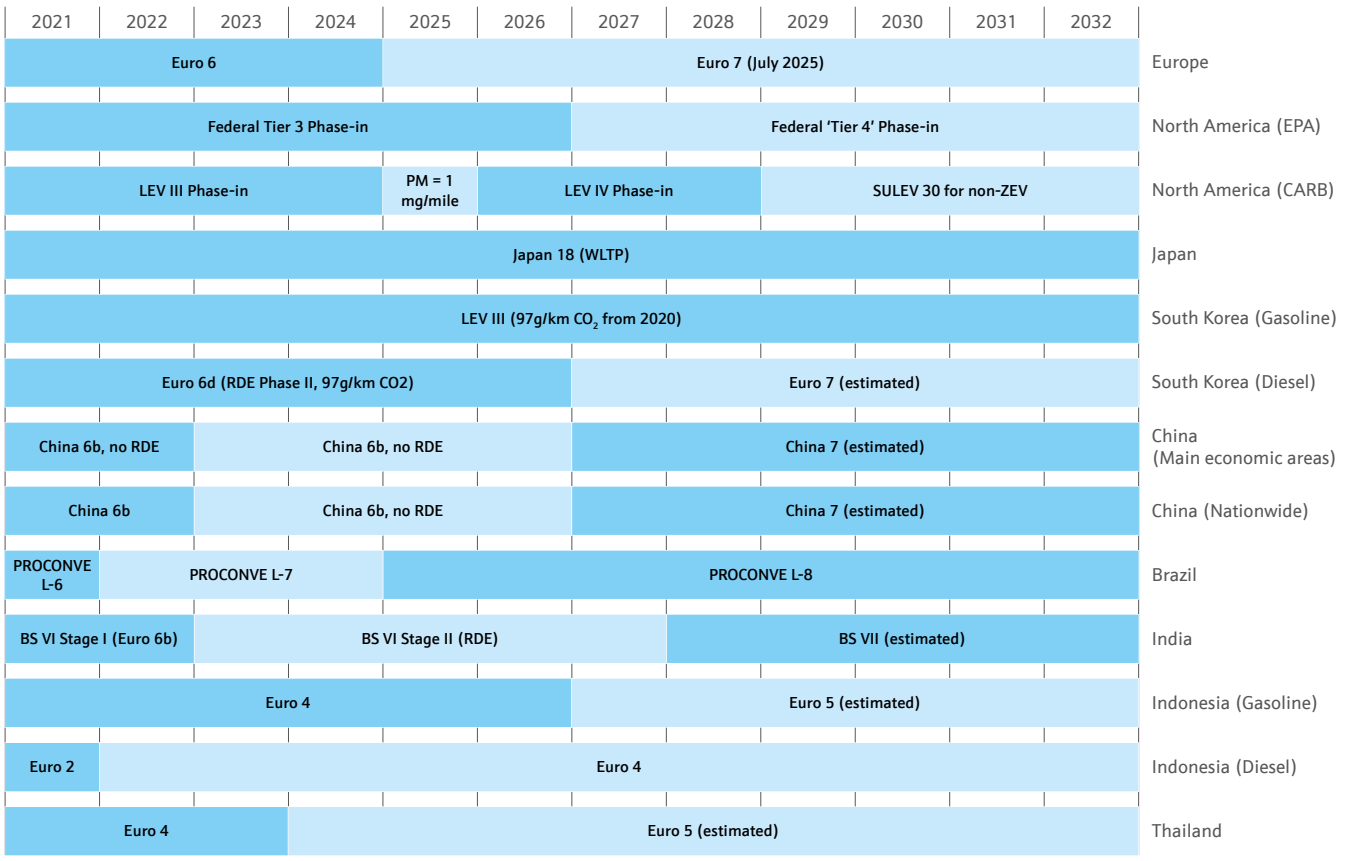


Figure 24 Emissions legislation, light duty

Euro 6e also updates the 'utility factor' (UF) used to calculate CO_2 emissions from plug-in hybrid electric vehicles (PHEVs). Because PHEVs can be driven in either battery or ICE mode, a utility factor must be applied during 'type approval' tests, to account for the proportion of journeys that are powered by electricity alone. Current UFs assume that electric driving accounts for 70-85% of PHEV use, but it has become clear that this is not representative of real driver behaviour in Europe. Not only are electric range and fuel economy lower under real driving conditions than in laboratory testing, but some drivers do not fully charge the battery every day, or regularly travel distances that significantly exceed their vehicle's electric range. This means that PHEVs have much higher real-world fuel consumption and hence CO_2 emissions than type approval data would suggest.

Euro 6e reduces the UF to 50% (from 2025 for private cars and from 2027 for company vehicles) and allows for this figure to be reviewed again in 2024. This change (and the prospect of further amendments) is expected to disincentivise growth of the PHEV market in Europe, with industry forecasts suggesting that European output of these vehicles could peak within the next two years.

In China, the next stage of light duty emissions legislation is due to be enforced starting in July 2023, when cars will be subject to RDE testing for the first time. Like European legislation, China's RDE regulations include 'conformity factors' specifying the multiple by which real driving emissions can exceed type-approval limits: in China, these are set at 2.1 for both NOx and PN. Although underlying China 6 emissions limits are lower than for Euro 6, more relaxed conformity factors and the absence of a cold-start test mean that China 6b RDE is less demanding overall. We do not expect to see any increase in the average PGM content of catalyst systems in China this year; indeed, it is possible that there will be further thrifting, despite the new RDE requirements.

China will also see new heavy duty legislation this year, with China VI-b legislation imposing more stringent emissions testing and monitoring requirements, but we do not expect any significant changes in average PGM content per vehicle. However, heavy duty PGM loadings will rise sharply in Brazil, where the implementation of PROCONVE P-8 legislation in Brazil in January 2023 means that most heavy vehicles built in this country will have Euro VI type aftertreatment systems for the first time. This will contribute to a 15% increase in PGM consumption on heavy duty vehicles in the Rest of World region this year.

"Euro 7 proposals include tougher RDE testing and extended durability requirements, which should be positive for PGM loadings"

Euro 7: light duty

The pace of legislative change in Europe is set to accelerate again over the next few years. Euro 6e will be followed swiftly by the next phase of legislative tightening, Euro 7, proposals for which were published in November 2022. Whereas current emissions limits are different for gasoline and diesel, the new regulations will impose a single set of standards regardless of fuel type or drivetrain. The proposed timeline would see Euro 7 enforced on all new light vehicles from July 2025, with no phase-in period.

"In Europe, proposed heavy duty CO_2 targets could accelerate the move away from diesel engines on trucks and buses"

Under new regulations, cars and vans would be subject to the lowest existing limit (whether for diesel or gasoline); in practice, this represents a tightening of CO limits for gasoline vehicles, while diesel vehicles will be required to meet stricter NOx standards. Diesels will become subject to regulations on total hydrocarbon and non-methane hydrocarbon emissions, which currently only apply to gasoline engines, while all vehicles will be required to comply with new emissions standards for ammonia (NH_3), a previously unregulated pollutant. Finally, although there is no change to the current particle number (PN) limit, it will be widened to apply to all particles larger than 10 nm (previously 23 nm).

Although some aspects of the proposed legislation are likely to prove challenging, especially the accelerated timeframe, the new emissions limits for light duty vehicles are overall somewhat less stringent than the auto industry and other stakeholders had anticipated. This will potentially reduce the need for additional technical complexity in aftertreatment systems. For example, some car companies had intended to add an electrically heated catalyst to their Euro 7 gasoline systems, but now believe that this will be unnecessary. However, the inclusion of tougher RDE testing and an extension of durability requirements (to 200,000 kilometres and/or 10 years) mean that the legislation will still be technically demanding. This is likely to be positive for overall PGM loadings.

Euro 7: heavy duty

The proposals also include a new stage of heavy duty legislation, Euro 7, scheduled for implementation in 2027. Relative to Euro VI, proposed emissions limits are significantly tighter for lorries and buses, reducing permitted NOx emissions by over 80%, and including new standards for nitrous oxide (N_2O) and ammonia, which were previously unregulated. While NOx emissions on heavy duty vehicles are primarily controlled by selective catalytic reduction (SCR), a non-PGM technology, many vehicles will also require additional PGM to meet Euro 7 emissions limits and to comply with tougher durability requirements.

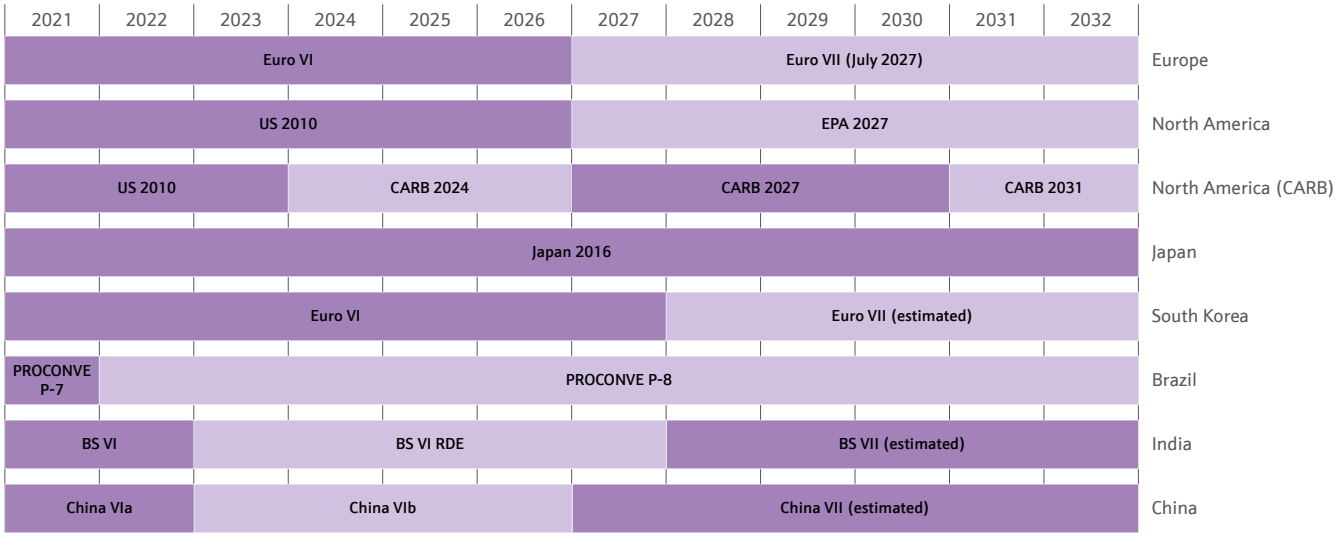


Figure 25 Emissions legislation, heavy duty

Heavy duty vehicles will also become subject to more stringent CO_2 requirements, under proposals published by the European Commission in February 2023. These targets would see a 45% reduction in CO_2 emissions from new heavy vehicles in 2030 (previous target: 30% reduction), rising to 65% in 2035 and 90% by 2040. In addition, the Commission recommends requiring all new city buses to be zero-emission from 2030. The adoption of these targets is expected to accelerate the move away from diesel engines on heavy vehicles, towards powertrains with zero tailpipe CO_2 emissions (principally battery and fuel cell electric vehicles).

"US heavy duty emissions legislations will become significantly more stringent over the next four years"

The zero-carbon category also appears to include internal combustion engines powered by hydrogen, which are being studied by some heavy vehicle manufacturers. Use of hydrogen as a fuel does not emit CO_2, but hydrogen ICE vehicles would emit small amounts of other pollutants and would therefore require some form of catalytic aftertreatment, probably involving small quantities of PGM. However, hydrogen ICE vehicles are not currently in commercial production anywhere in the world, and their future market share (if any) is highly uncertain.

Future legislation in other major auto markets

US heavy duty emissions legislation will also become significantly more stringent over the next four years, as both California state and US federal government regulations tighten. The California Air Resource Board (CARB) Heavy-Duty Low NOx Omnibus regulation comes into effect in 2024, ultimately reducing permitted NOx emissions by 90% once fully implemented (over two stages, in 2024 and 2027). The new rules also include a more challenging certification cycle, tougher in-use emissions requirements, and an extended durability and emissions warranty period.

US federal legislation on heavy trucks is also set to tighten in 2027, under a new Environmental Protection Agency (EPA) rulemaking, updating standards which have been in place since 2010. The new EPA regulation cuts NOx limits by more than 80%, and includes more rigorous durability provisions, although it will be less challenging to meet than the CARB standards. As for Euro VII, lower NOx limits in both the CARB and EPA regulations will mainly be met by increasing SCR catalyst volume, but some additional PGM will be required to improve cold start emissions performance and enhance catalyst durability.

In April 2023, the EPA also announced proposals for new emissions standards for light and heavy duty vehicles, which would be phased over the 2027 to 2032 model years. These 'Tier 4' regulations will involve reductions in emissions of toxic pollutants (NOx, non-methane organic gases, and particulate matter) and will also require progressive cuts to average greenhouse gas emissions across each automaker's fleet. While these federal CO_2 proposals do not go as far as California's Advanced Clean Cars II (ACC2) regulation, which will ban the sale of new ICE cars after 2035, EPA nevertheless believes that the new standards could result in BEV penetration reaching 60-70% in smaller vehicle classes by model year 2032. The new EPA proposals also include new greenhouse gas targets for the heavy duty sector, which could lift BEV share to around 50% in some vehicle classes (such as 'vocational vehicles', including city delivery trucks, local transit vehicles and school buses).

Tighter emissions legislation is also on the horizon in China, for both light and heavy vehicles, but to date there have been no official announcements of specific proposals for China VII. Industry expectations are that the new regulations will focus on more stringent RDE testing. The impact on aftertreatment system design and PGM content will depend upon the extent to which conformity factors are tightened, and the range of driving conditions included in RDE testing (such as ambient temperature, altitude and speed).

Focus on ruthenium and iridium

Strong chemicals demand will boost ruthenium consumption in 2023

Primary ruthenium supply will fall short of industrial demand, but market stocks are ample

Iridium will see growth in electrochemical processes such as copper foil and PEM electrolysis

High prices have triggered some substitution of iridium in crucibles for electronic crystal growing

Primary iridium supply should rise this year, leaving the market in balance

"World supplies of ruthenium have fluctuated in recent years, due to periodic liquidation of producer stocks"

Supply '000 oz	2021	2022	2023
Primary supply	**1,421**	**966**	**999**

Demand '000 oz*	2021	2022	2023
Chemical	329	383	432
Electrical & electronics	443	369	375
Electrochemical	130	131	133
Other	114	140	141
Total demand	**1,016**	**1,023**	**1,081**
Movements in stocks	405	-57	-82

* Industrial demand is net of 'closed-loop' recycling and sales of surplus metal back to the market due to plant closes or technology changes. See page 32 for further information.

Table 4 Ruthenium supply and demand

Over the past five years, prices for the 'minor PGM' – ruthenium and iridium – have risen significantly, reflecting firm demand, constrained supplies, and increasing interest in the use of these metals in the energy transition. Demand is expected to grow strongly in 2023, with increased use of ruthenium in chemical catalysts, and growing consumption of iridium in a variety of electrochemical processes. Following a period of market tightness, availability is currently adequate to meet consumer demand. Higher prices are stimulating efforts to minimise metal consumption, via better efficiencies and improved recoveries from in-process scrap. There has also been some substitution of iridium with platinum in crucibles used to grow electronic crystals.

Supplies and market balance

World supplies of ruthenium have fluctuated significantly in recent years, primarily due to periodic liquidation of producer stocks, especially in 2017–2018 and 2021. We estimate that over a million ounces of ruthenium (roughly equivalent to a year's worth of mine production) were sold from inventories during the six-year period 2017–2022.

Sales out of South Africa were particularly strong in 2021, as miners mobilised stocks to meet strong Chinese demand. While part of this metal was purchased by industrial consumers to meet immediate and longer-term consumption requirements, other market participants – including traders, fabricators and investors – may also have acquired some ruthenium.

As a result of this heavy producer selling, the market was in significant surplus in 2021, so metal was available to meet consumer demand in 2022, even though new supply was slightly below the level of industrial demand. This year, fresh mine production is again expected to be lower than industrial consumption, but market and producer stocks should be adequate to meet consumer requirements.

Ignoring movements in producer stocks, mine production of ruthenium has typically varied in a 0.9–1.0 million oz range over the past decade. It is the third most abundant PGM, after platinum and palladium, and ahead of rhodium: some South African ores are relatively rich in this metal. For example, in UG2 ore (widely mined by platinum producers), ruthenium may account for up to 15% of the six-element (6E) PGM grade, while this figure can be even higher in the chromite seams exploited by Bushveld chrome mining operations. While these chrome ores are not usually mined specifically for PGM, the reprocessing of chrome tailings to extract the PGM has become increasingly widespread in recent years.

Supply '000 oz	2021	2022	2023
Primary supply	**232**	**221**	**240**

Demand '000 oz*	2021	2022	2023
Chemical	25	30	30
Electrical & electronics	50	34	40
Electrochemical	81	91	104
Other	65	64	64
Total demand	**221**	**219**	**238**
Movements in stocks	11	2	2

* Industrial demand is net of 'closed-loop' recycling and sales of surplus metal back to the market due to plant closes or technology changes. See page 33 for further information.

Table 5 Iridium supply and demand

Smaller but significant quantities of ruthenium are also extracted in Zimbabwe (this metal is refined in South Africa). In total, we estimate that around 95% of world ruthenium production comes from these two countries combined.

Iridium supply is also dominated by southern Africa, but this metal is much less abundant than ruthenium. Iridium's share of the 6E grade in South African PGM ores is usually around 2–4%, while deposits outside southern Africa usually contain only trace quantities of this metal. Annual mined output typically varies in a 230,000–250,000 oz range, with southern African producers usually accounting for around 95% of this total.

Producer inventories of iridium are limited, and supplies are therefore much less variable. In recent years, iridium supply has matched demand quite closely, although price movements in 2020–2022 suggest that some additional metal (beyond that which we can confidently identify as industrial demand) may have been acquired by industrial companies, fabricators, traders or other market participants. In 2023, mine production of iridium should rise modestly, as South African producers process excess work-in-progress, and the market should remain balanced.

We do not provide estimates of secondary supplies of ruthenium and iridium. Recycling of these metals almost always takes place inside a 'closed-loop', in which the industrial consumer retains ownership of the metal throughout the refining and refabrication process (see page 33). If surplus 'closed-loop' metal is sold back to the market, for example after plant closure or a change in technology, we count this as negative demand.

"Recycling of iridium and ruthenium almost always takes place within a 'closed loop', in which the industrial consumer retains ownership of the metal"

Minor PGM in chemical process catalysts

The chemicals industry is a major consumer of minor metals, in the form of process catalysts for bulk and speciality chemical manufacturing. It is particularly important for ruthenium, which is employed in the synthesis of a wide range of chemicals; iridium has a more limited range of process catalyst applications, mainly due to its scarcity and price.

Consumption of ruthenium in the chemicals industry is currently enjoying a period of strong growth, with ongoing investment in new capacity for caprolactam and adipic acid, both of which are feedstocks for nylon production (further information is available in the 'Made in China' special feature in the May 2022 edition of the PGM Market Report). While there are non-PGM routes for the synthesis of these chemicals, processes using ruthenium catalysts are widely employed in China. In addition, tighter environmental legislation in China is driving wider use of ruthenium catalysts in industrial wastewater treatment (a process known as catalytic wet air oxidation, CWAO).

As a result, demand for ruthenium in process catalysts rose by 16% to 383,000 oz in 2022, and is forecast to exceed 430,000 oz this year – a new record for consumption in this application. There is potential for at least one further year of growth, before cyclical factors begin to temper purchasing. Chemicals demand is primarily a function of new capacity additions, with large quantities of metal purchased at the time of plant construction; thereafter, only small amounts of PGM are required to 'top-up' losses that occur in the chemical process itself, as well as during the recycling and refabrication of the catalyst charge at the end of its operating life. In the medium term, as the Chinese caprolactam and adipic acid markets move into oversupply, we expect the rate of new capacity additions to fall, and new metal demand to ease.

Iridium demand in process catalysts is also expected to be firm in 2023. Most chemical demand for iridium derives from the Cativa acetic acid process, which employs a ruthenium-iridium catalyst. This is an alternative to the more widely used Monsanto process, which involves a rhodium catalyst. Once the process has been selected (during the plant engineering phase) and plant construction is underway, it is difficult or impossible to switch to an alternative route, so exceptionally high rhodium prices during 2020–2022 have so far had only a limited impact

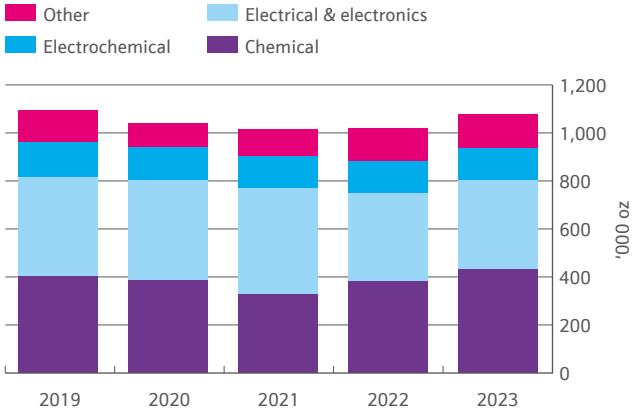


Figure 26 Industrial demand for ruthenium

on PGM use in the acetic acid industry. However, elevated rhodium prices have probably influenced the choice of process route for some plants that are currently under construction.

Minor PGM in electrochemical applications

The minor PGM are employed in a range of electrochemical processes, from long-established technologies such as the production of chlorine and caustic soda using the chlor-alkali process, to more recent applications linked to environmental legislation and the energy transition, including ballast water treatment, production of copper foil used in batteries, and the electrolytic production of hydrogen.

Iridium is a highly attractive electrode material for electrochemical processes, due to its exceptional stability and its suitability in electrolytic applications under high cell potential conditions. These properties are particularly important in some rapidly expanding electrochemical applications, such as the electrolytic deposition of copper foil, where iridium is the primary anode coating material, and water electrolysis using proton exchange membrane (PEM) technology, for which iridium is required as the anode catalyst.

"In China, ruthenium catalysts are widely employed in the production of caprolactam and adipic acid"

Most electrochemical demand for ruthenium derives from older technologies, primarily the chlor-alkali process, where purchasing is largely driven by 'top-up' metal needs (to cover in-use losses, which are relatively significant in this application). Ruthenium is sometimes used in PEM electrolyser anodes (it is a more active catalyst than iridium for the oxygen evolution reaction), but its use is limited by its lack of stability under acidic, high-voltage conditions. Research is underway to address this, which could ultimately allow some iridium to be replaced with ruthenium in PEM electrolysis.

Iridium in copper foil

Copper foil is a thin, continuous layer of copper metal, used in a range of electrical and electronic applications, that can be produced either by physical processes (rolling) or by electrolytic deposition. The electrolytic route currently accounts for the majority of world output of ultra-thin copper foil because production costs are typically lower. This process employs an iridium-coated anode to precipitate copper ions onto a rotating titanium cathode 'drum', producing a very fine, even layer of copper foil.

Traditionally, the main application for copper foil was in printed circuit boards, with demand for foil (and ultimately iridium) driven by trends in the consumer electronics sector. However, in recent years, lithium-ion batteries have become an important end-user of copper foil, which is employed as the anode current collector, conducting electrons liberated during the electrochemical reaction that occurs inside the battery to the exterior. Prior to 2020, the main driver of lithium battery output was the power battery industry (mainly for hand-held domestic and industrial devices), but more recently vehicle electrification has become an important source of growth. Total battery capacity on new vehicles rose five-fold between 2019 and 2022 and is forecast to expand by a further 50% in 2023. This is stimulating significant expansion in electrolytic copper foil capacity.

Green hydrogen and the commercialisation of PEM electrolysis

Iridium is also used in a second major application linked to the energy transition: PEM electrolysis for hydrogen production (if the electricity source is renewable power, then this hydrogen is renewable or 'green'). This technology employs catalyst coated membranes (CCM) to split water into oxygen and hydrogen under an electric current. The reaction is typically promoted by catalysts based on iridium (at the anode) and platinum (at the cathode) – these PGMs are used due to their high activity levels and stability in the acidic conditions of a PEM cell.

Electrolytic hydrogen capacity is currently small, at under 1 GW globally, and is mainly based on liquid alkaline electrolysis – a mature technology that has been commercialised for several decades and uses a nickel catalyst (and sometimes very small amounts of PGM). However, electrolysis capacity is forecast to ramp up steeply over the next few years, in response to government programmes such as the US Inflation Reduction Act and the EU REPowerEu plan, both of which provide incentives for green hydrogen investment.

PEM technology is less mature than alkaline electrolysis but is expected to take significant share of the growing market, as it is particularly suitable for producing hydrogen from renewable power sources, which are inherently distributed and intermittent: PEM electrolysers have a comparatively small footprint, do not require corrosive chemicals, and cope well with variable loads and stop-start operation.

Iridium demand in water electrolysis was virtually non-existent prior to 2020, but has climbed steeply over the last three years, to an estimated 10,000 oz in 2022. Demand is forecast to double again over the next 18–24 months, as major market participants add production capacity for PEM electrolysers. Given the inherently limited availability of iridium, considerable research

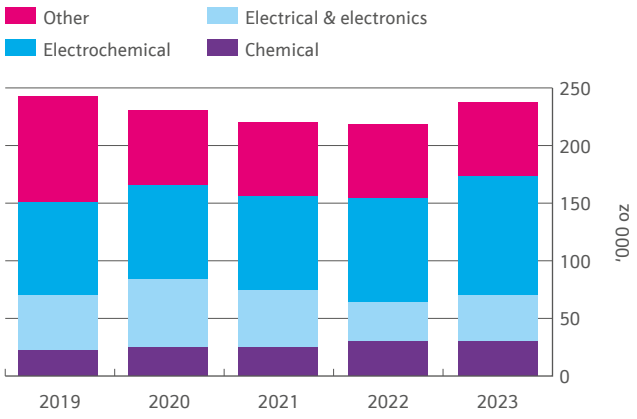


Figure 27 Industrial demand for iridium

and development resources are being devoted to reducing the amount of iridium required per gigawatt of installed capacity. The industry is also focusing on optimising recycling systems, to facilitate the efficient reuse of iridium in new electrolysers in a 'closed loop' recycling process (in which metal is recovered from end-of-life CCMs and returned to its original owner).

"PEM electrolysis technology is particularly suitable for producing hydrogen from renewable power sources"

Ballast water

As noted above, electrochemical use of ruthenium is currently concentrated in older applications. However, there is one recent growth area which uses both iridium and ruthenium electrode coatings: the treatment of ballast water using electrochemical technology. The Ballast Water Management Convention came into effect in September 2017, incorporating legislation by the International Maritime Organisation and the United States Coast Guard; it aims to prevent the spread of harmful aquatic organisms from one region to another by mandating the treatment of ballast water. The Convention already requires new ships to be equipped with water treatment systems; its remit is now being extended to older vessels, most of which require retrofitting.

There are three main methods used to meet the regulations: ultraviolet (UV) water treatment, direct addition of chlorine or peroxide-based chemicals, and electrochemical chlorination. Electrochemical technology is typically employed in larger vessels, and to date has been relatively insensitive to price. PGM demand in this application will remain firm in 2023.

Minor metals in electronics

Ruthenium has numerous applications in the electronics industry, including thick-film ruthenium pastes used as the resistive layers in chip resistors and hybrid integrated circuits, organometallic ruthenium salts for coating applications in next-generation memory chip technology, and magnetic layers and sub-layers on hard disks for data storage applications. Resistors and hard disks currently account for most ruthenium use in electronics.

Demand for ruthenium in chip resistors has been broadly stable in recent years, with growth in the volume and complexity of electronic devices broadly offset by miniaturisation of chip components. However, consumption in this segment fell sharply in 2022, reflecting a significant downturn in sales of consumer electronics, impacted by a combination of semiconductor shortages, Covid disruption, high inflation and falling disposable incomes. This in turn led companies to run down inventories of electronic components, amplifying the impact on PGM demand. There should be a corresponding uptick in ruthenium purchasing once a recovery gets underway, probably from late 2023 or early 2024.

In the hard disk sector, PGM use was supported in 2020–2021 by the explosion of remote working and studying during the Covid pandemic, which in turn drove strong increases in cloud data storage requirements and heavy investment in data centres. However, the hard disk market faltered last year, in line with general weakness in the technology sector, and a slowdown in data centre expansions. A recovery in disk drive shipments is expected to begin during the second half of this year, but is unlikely to have a material impact on ruthenium purchasing until 2024. Total consumption of ruthenium in electronics applications fell by 17% to 370,000 oz in 2022 and is expected to show only marginal gains this year.

In contrast to ruthenium, consumption of iridium in electronics is more limited, with demand mainly derived from the use of solid iridium crucibles to grow crystals used in electronic devices, and iridium complexes used in organic light emitting diodes (OLEDs) for device displays and premium televisions. In 2022, iridium crucible purchasing fell to its lowest level in more than ten years, following two cycles of heavy investment in new capacity that peaked in 2016 and 2020 respectively. These peaks were driven by strong demand for lithium tantalate crystals used in surface acoustic wave (SAW) filters for mobile telephony: the first and largest of these two waves coincided with the roll-out of 4G technology, while more recently demand has been stimulated by the transition to 5G (although the impact on iridium consumption has been much less significant this time around).

This low point has been exacerbated by high prices, which have encouraged crystal manufacturers to investigate alternatives to iridium: some leading Chinese crucible users have begun to employ platinum in lithium tantalate production for the first time. Although platinum has a lower melting point, close to that of lithium tantalate itself, it appears that process modifications have permitted some switching. To date, platinum has only been employed for smaller four-inch diameter crucibles in China; for larger crucibles and in other regions, it is still considered unsuitable due to potential loss of structural integrity and the resulting penalties in terms of processing time, product quality and crucible life. Nevertheless, some Chinese manufacturers have recovered significant quantities of iridium following recent switching programmes, and some of this metal was sold back to the market in 2022.

"Demand for ruthenium in hard disks faltered last year, in response to general weakness in the technology sector, and a slowdown in data centre expansions"

Although OLEDs continue to take share from older display technologies, iridium usage eased in 2022, in line with general weakness in the electronics market. Going forward, iridium demand should be supported by increasing adoption of OLEDs in mobile phones and

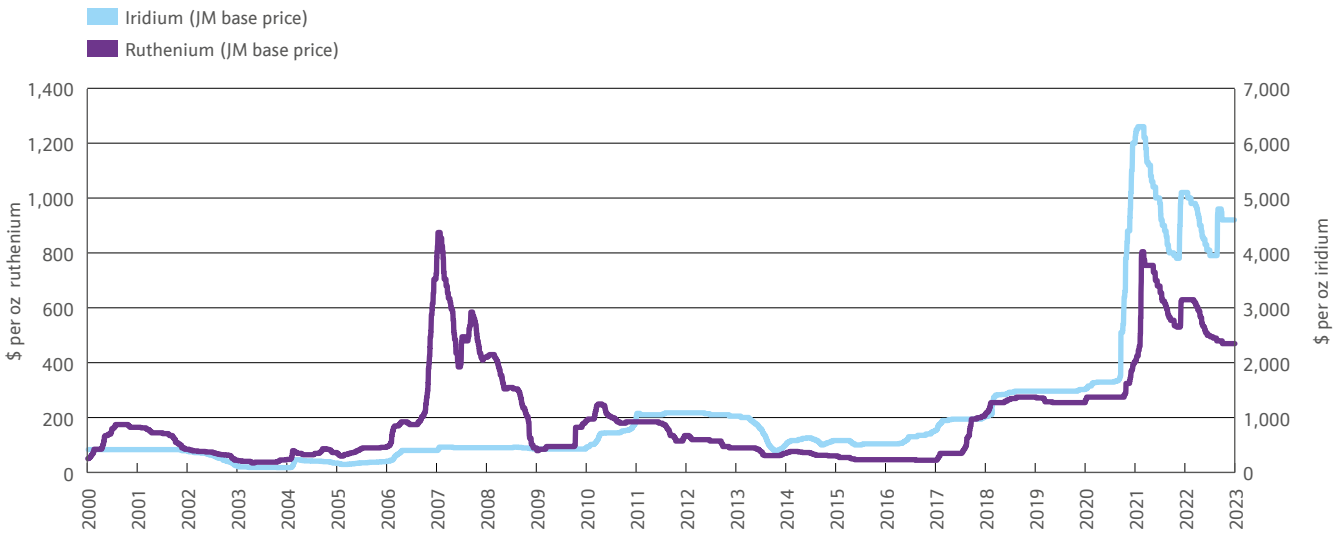


Figure 28 Ruthenium and iridium prices January 2000 to April 2023

premium televisions, but purchasing will be tempered by improved process efficiencies and better recoveries from production scrap, allowing more displays to be manufactured without significant increases in metal consumption.

Minor PGM and the energy transition: using critical raw materials sparingly

Because of their importance in applications such as fuel cells and PEM electrolysis, governments and other authorities have designated PGM as 'critical and strategic raw materials' for the energy transition. Availability of the minor PGM is a particular concern: they are mined only as by-products or co-products of other minerals (mainly platinum and palladium), so their supply profile is relatively price inelastic.

Recently, there has been increasing focus on the ability of primary iridium supply to meet future demand for this metal in the production of green hydrogen. This potential future supply-demand imbalance is being addressed by significant research and investment in the PEM electrolysis sector, to ensure that metal is used as sparingly as possible (by thrifting PEM catalyst loadings and improving electrolyser efficiencies), and to maximise recovery and reuse. This is discussed in Johnson Matthey's recent white paper, available to download here: Recycling and thrifting: the answer to the iridium question in electrolyser growth | Johnson Matthey.

Price considerations are also likely to stimulate thrifting or drive substitution and technology shifts in other applications, to ensure that rare metals are applied only where they provide the most value. Prior to 2020, ruthenium and iridium prices were generally low (with the exception of 2006–2009, when a change in hard disk technology caused a temporary ruthenium shortage). This meant that incentives for thrifting and substitution in established applications were generally limited. However, higher prices are now stimulating efforts to minimise metal use: for example, as discussed above, electronic crystal manufacturers are partly replacing iridium with platinum in crucibles and returning surplus iridium to the market.

"Crucible users in China have begun to use platinum in place of iridium for lithium tantalate crystal production, allowing them to sell some iridium back to the market"

Higher efficiencies, lower losses and improved recoveries should also be achievable in other applications. Interest in the recovery of iridium from spark plugs on end-of-life vehicles is growing, although at present we do not believe that this happens to any material extent. There may also be potential to reduce in-process losses and increase recycling in electrochemical applications such as chlor-alkali, copper foil production and ballast water treatment – all of which currently incur relatively significant permanent losses of PGM due to harsh process conditions.

Special feature

Understanding PGM supply, demand, recycling and availability

Johnson Matthey publishes the PGM Market Report in May each year, to provide PGM stakeholders with an assessment of the current status of the market. As the PGM grow in prominence as critical energy transition metals, they are gaining new stakeholders who may be less familiar with these metals and the structure of the market. This short feature provides some guidance on interpreting our figures, to support the appropriate use of the data in further analysis.

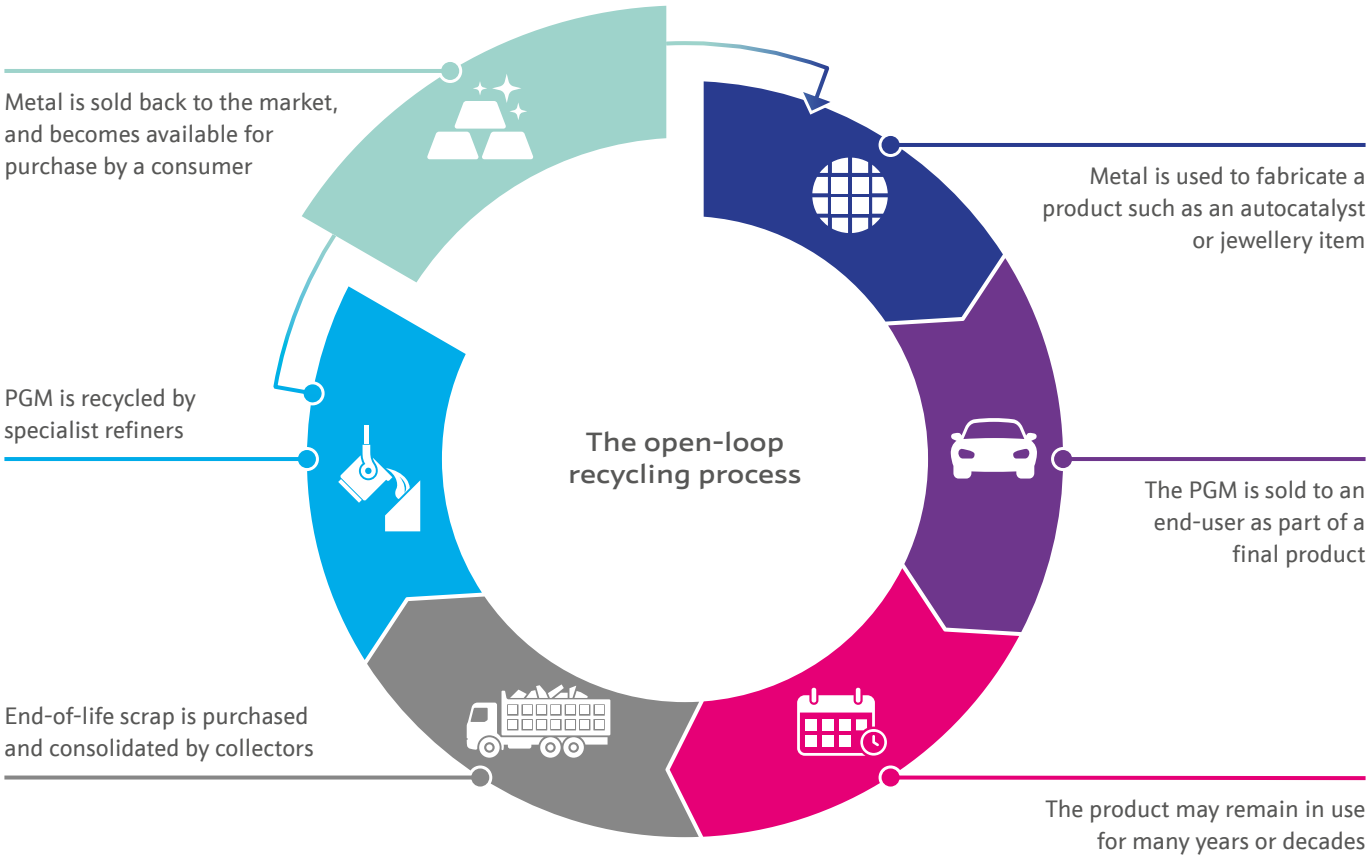
Supply

Primary supply is defined as newly mined metal sold each year by producers. In any one year, it may differ from underlying mine production, because of changes in work-in-progress (pipeline) stocks or due to additional sales by the producers of metal held in refined inventory.

Secondary supply comprises 'open-loop' recoveries from the automotive, jewellery and electronics industries (see below for further information on the different types of PGM recycling). To arrive at a figure for total annual supply, primary supply and open-loop recycling are added together. This combined supply figure represents the total volume of new metal placed on the market in each calendar year.

Open-loop recycling

Our secondary supply estimates include only PGM recovered from open-loop recycling. In this 'open loop', the original purchaser (user) of the PGM – for example, an automaker – does not retain ownership of the metal. Instead, it is sold to an end-user as part of a final product, in the form of an autocatalyst fitted to a vehicle, or an item of platinum jewellery, or a PGM-containing component in an electronic device. Once



the product reaches the end of its life, the PGM is recovered by specialist scrap collectors and sold back to the market.

Many years may elapse between the initial point of PGM consumption and the eventual recovery of the metal. For example, vehicles are typically over fifteen years old by the time they enter the scrapyard, while precious metal jewellery may be kept for decades. There may also be significant losses both during the product's life (for example, due to accidental damage to a vehicle, or loss of a small jewellery item) and once it reaches the end of its life (mainly because of inefficiency in collection networks).

There is one case in which open-loop recycling takes place but is not included in our secondary supply figures: where recycling is directly offset by new demand. For example, when catalytic converters are replaced like-for-like on vehicles in service (usually under warranty or due to a recall or theft), the recovered metal is directly offset by the PGM used in the replacement part. This means that the net effect on demand is close to zero.

Closed-loop recycling

In addition to this open-loop recycling, large amounts of PGM are recycled in a 'closed loop', but are not reported in our secondary supply numbers. The loop is closed because ownership of the metal is retained by the industrial consumer, who returns PGM-bearing materials (such as production scrap, spent chemical catalysts, and old glass-making equipment) to specialist companies for refining and reuse in the same application – thereby attaining true circularity. The closed loop accounts for a significant portion of the metal processed through the refineries operated by Johnson Matthey and other companies worldwide. In applications with a large installed base of metal, the volume of PGM passing through closed-loop recycling each year can be several times the amount of new metal purchased annually.

Closed-loop recycling is a feature of all PGM applications, including those which also give rise to open-loop recycling – for example, production scrap generated during the manufacture of autocatalysts is refined inside a closed loop. This type of recycling is therefore a crucial part of the functioning of the PGM market, but we do not report it, because it does not affect the overall balance of supply and demand.

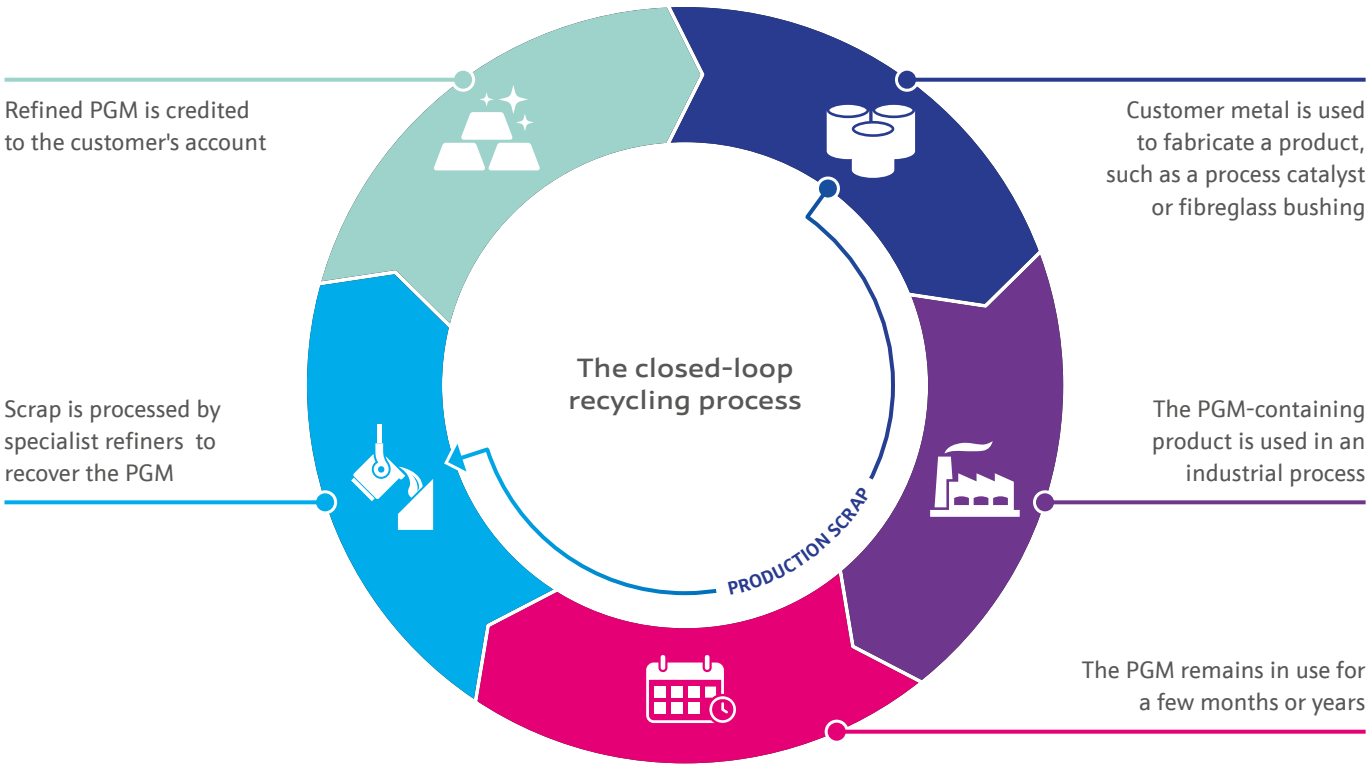
Our published estimates of secondary supply therefore represent only a fraction of total recycling volumes. For ruthenium and iridium, we do not publish any secondary supply estimates at all because open-loop recycling is usually negligible – however, significant quantities of these metals circulate in the closed loop. Because of the value of the PGM and the existence of well-established recycling routes and facilities, recycling is the rule rather than the exception for all these metals.

Demand

Our demand figures represent new metal requirements in each year, after taking closed-loop recycling into account, but before any open-loop recycling.

Demand consists of PGM contained in products purchased by an end-user (such as vehicles, jewellery items, and consumer electronics), and metal purchased for installation in industrial processes, where it is used to make another product. Examples of the latter include PGM catalysts installed in chemical plants and petroleum refineries, 'bushings' used in glass fibre factories, and crucibles for growing electronic crystals.

PGM requirements for these industrial processes are typically greatest when new production capacity is added and an initial charge of PGM is purchased. Thereafter, in-process losses are usually small, and the vast majority of the metal is recovered at the end of a production campaign for reuse in the same



application. Ongoing demand is therefore limited to small amounts of 'top-up' metal. (There are a few exceptions, such as platinum catalyst used to produce silicones, which ends up in the final product in a form that is too dispersed to be recovered, and some electrochemical applications where harsh process conditions result in significant metal losses).

Sometimes, PGM which has been recovered through the 'closed-loop' is no longer required for its original application, due to a plant closure, or because a change in technology has reduced overall metal requirements. In this case, once the recycled metal has been refined and returned to its owner, the latter may choose to retain any excess PGM to cover future 'top-up' demand, or it may sell some or all the spare metal back to the market. In the latter case, we view this as a change in industrial inventory, and it is counted in our numbers as negative demand. A good example of this process is the recent release of rhodium by Chinese fibreglass producers, which pushed rhodium demand in the glass sector into negative territory in 2021–2022.

Market balance

The difference in reported supply and demand is the balance of the market in each year, which we report as a theoretical movement in stocks. If annual supply exceeds annual demand, the balance is positive; the assumption is that the surplus adds to market stocks. Conversely, if annual demand exceeds annual supply, then the negative figure shows what needs to be extracted from market stocks to fill the deficit and satisfy demand.

The balance between annual supply and demand therefore indicates how availability for the PGM has changed in that year, but it is not a measure of availability at any point in time.

Availability and stocks

In addition to new supply, availability in the near term is mainly a function of **market stocks**. These stocks are held by fabricators, dealers, banks and depositories around the world, and are often relatively liquid, because the PGM is either not in use or has been bought purely as a temporary store of value. When these stocks are released, they are not counted as additional supply because they were sourced from metal supplied in previous years.

Where a deficit is projected, this could also be filled by **producer stocks**, if miners have refined PGM inventory available to sell. This inventory is only counted as supply to the market when it is sold by the producer.

The exact extent of both market and producer stocks at any given time is unknown, but they support the functioning of the PGM markets. Recent trends in the palladium market underline the importance of these stocks. Palladium was consistently in deficit between 2012 and 2022, but availability was supported by the existence of substantial market stocks, built up over previous years of annual surpluses. As a result, the market was able to tolerate a large cumulative deficit between 2012 and 2016 without significant upward pressure on price. Only once the most liquid stocks had been mopped up did the palladium price start moving higher.

For the longer term, a broader term applies in a discussion of future availability: '**above-ground stocks**'. Because the PGMs have been in industrial use for decades, and because they are highly recyclable and valuable, substantial amounts of PGM have accumulated around the world in a variety of locations and remain in a useable form. Bank and producer vaults are only a small part of this overall picture; of far more significance is all the metal currently in service in industrial processes.

This metal in service is clearly not available to the market today and is retained within the closed loop. But requirements change over time, due to technological innovation, evolving consumer needs and industrial modernisation. This will certainly be true as the energy transition progresses. Therefore, any discussion of the future PGM supply-demand balance must consider not only trends in mining and secondary supplies, but also the potential evolution of metal in service. For example, will some of the platinum inventory currently being used in petroleum refineries to produce high-octane gasoline one day be released and find its way onto fuel cell vehicles?

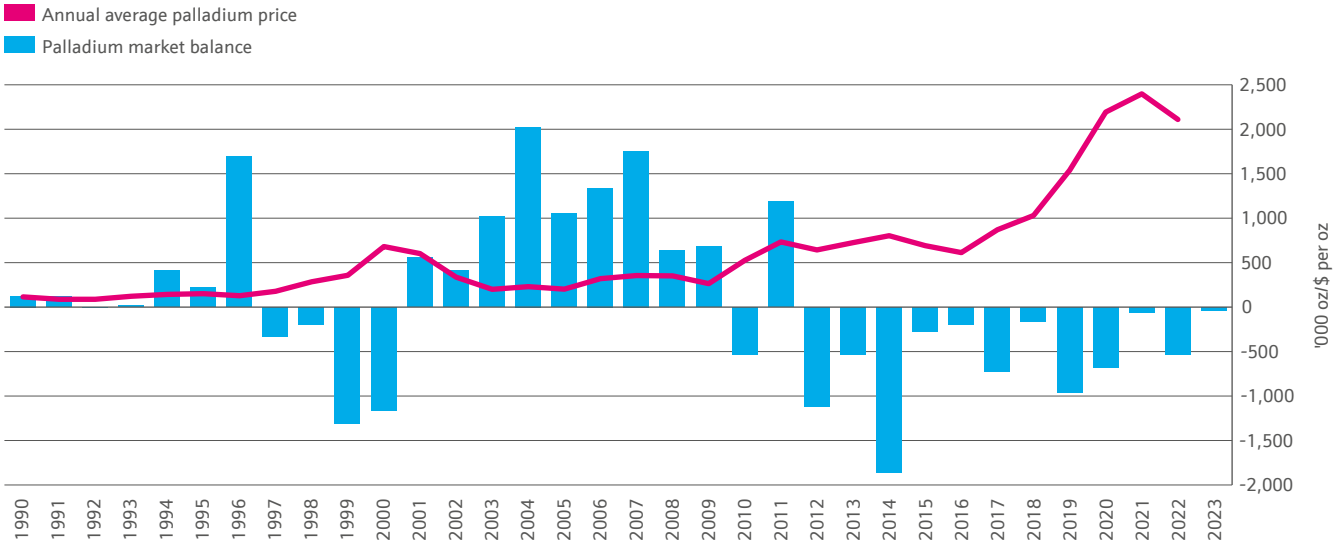


Figure 29 Palladium market balance and price

Platinum supply and demand

Troy ounces

Primary supply '000 oz	2018	2019	2020	2021	2022	2023
South Africa	4,467	4,344	3,243	4,609	3,965	4,154
Russia	687	721	699	638	600	630
North America	370	367	334	279	266	288
Zimbabwe	474	451	482	465	488	529
Others	152	154	205	222	211	207
Total primary supply	**6,150**	**6,037**	**4,963**	**6,213**	**5,530**	**5,808**

Secondary supply '000 oz[1]	2018	2019	2020	2021	2022	2023
Automotive	1,332	1,389	1,154	1,234	1,153	1,200
Electrical & electronics	38	40	38	44	51	56
Jewellery	699	663	506	367	264	265
Total secondary supply	**2,069**	**2,092**	**1,698**	**1,645**	**1,468**	**1,521**
Combined primary and secondary supply	**8,219**	**8,129**	**6,661**	**7,858**	**6,998**	**7,329**

Demand '000 oz[2]	2018	2019	2020	2021	2022	2023
Automotive	2,815	2,589	2,024	2,405	2,762	3,063
Chemical	654	665	615	677	699	697
Dental & biomedical	241	254	218	224	253	257
Electrical & electronics	228	215	226	259	235	266
Glass	501	468	507	908	594	565
Investment	67	1,131	1,022	-28	-565	283
Jewellery	2,258	2,073	1,657	1,468	1,344	1,351
Petroleum	380	262	287	216	230	213
Pollution control	193	190	175	205	223	260
Other	531	542	417	444	483	502
Total demand	**7,868**	**8,389**	**7,148**	**6,778**	**6,258**	**7,457**
Movement in stocks	351	-260	-487	1,080	740	-128

[1]**Secondary supply** comprises 'open-loop' recycling from the automotive, jewellery and electronics sectors. See page 32 for further details.

[2]**Industrial demand** is net of 'closed-loop' recycling and sales of surplus metal back to the market, for example due to plant closures. It represents new metal requirements by industrial consumers in each year. See page 33 for further information.

Platinum demand by region

Troy ounces

Demand '000 oz		2018	2019	2020	2021	2022	2023
Europe	Automotive	1,377	1,193	858	739	790	849
	Chemical	122	122	116	126	137	149
	Dental & biomedical	63	63	54	56	65	66
	Electrical & electronics	12	12	13	14	14	15
	Glass	11	13	14	18	15	12
	Investment	-102	566	308	126	-284	19
	Jewellery	191	195	150	203	238	209
	Petroleum	30	15	-28	-17	-1	-5
	Pollution control	41	41	44	50	53	53
	Other	171	171	128	134	146	151
	Total	**1,916**	**2,391**	**1,657**	**1,449**	**1,173**	**1,518**

Demand '000 oz		2018	2019	2020	2021	2022	2023
Japan	Automotive	291	264	203	237	235	240
	Chemical	40	42	40	41	41	39
	Dental & biomedical	14	14	17	17	19	20
	Electrical & electronics	24	23	25	28	24	24
	Glass	7	27	17	14	11	13
	Investment	220	32	392	-21	-126	48
	Jewellery	293	296	238	246	234	242
	Petroleum	2	2	2	1	1	1
	Pollution control	59	62	55	62	61	61
	Other	55	68	56	58	57	57
	Total	**1,005**	**830**	**1,045**	**683**	**557**	**745**

Demand '000 oz		2018	2019	2020	2021	2022	2023
North America	Automotive	287	289	214	317	435	510
	Chemical	105	100	95	123	121	126
	Dental & biomedical	94	98	65	68	82	83

Demand '000 oz		2018	2019	2020	2021	2022	2023
North America	Electrical & electronics	38	28	24	28	28	38
	Glass	18	21	34	58	26	23
	Investment	66	156	602	115	-69	28
	Jewellery	224	211	210	224	250	260
	Petroleum	15	17	6	27	24	31
	Pollution control	57	53	44	40	42	44
	Other	152	150	95	104	124	132
	Total	**1,056**	**1,123**	**1,389**	**1,104**	**1,063**	**1,275**

Demand '000 oz		2018	2019	2020	2021	2022	2023
China	Automotive	165	158	216	399	420	484
	Chemical	207	274	274	291	306	237
	Dental & biomedical	39	47	34	34	35	35
	Electrical & electronics	45	44	46	50	46	45
	Glass	388	321	382	749	448	447
	Investment	0	0	0	13	15	13
	Jewellery	1,316	1,119	945	665	470	470
	Petroleum	261	163	215	97	127	100
	Pollution control	18	17	14	24	36	70
	Other	69	66	61	62	63	63
	Total	**2,508**	**2,209**	**2,187**	**2,384**	**1,966**	**1,964**

Demand '000 oz		2018	2019	2020	2021	2022	2023
Rest of World	Automotive	695	685	533	713	882	980
	Chemical	180	127	90	96	94	146
	Dental & biomedical	31	32	48	49	52	53
	Electrical & electronics	109	108	118	139	123	144
	Glass	77	86	60	69	94	70
	Investment	-117	377	-280	-261	-101	175
	Jewellery	234	252	114	130	152	170
	Petroleum	72	65	92	108	79	86
	Pollution control	18	17	18	29	31	32
	Other	84	87	77	86	93	99
	Total	**1,383**	**1,836**	**870**	**1,158**	**1,499**	**1,955**
	Grand total	**7,868**	**8,389**	**7,148**	**6,778**	**6,258**	**7,457**

Platinum supply and demand

Tonnes

Primary supply tonnes	2018	2019	2020	2021	2022	2023
South Africa	138.9	135.1	100.9	143.4	123.3	129.2
Russia	21.4	22.4	21.7	19.8	18.7	19.6
North America	11.5	11.4	10.4	8.7	8.3	9.0
Zimbabwe	14.7	14.0	15.0	14.5	15.2	16.4
Others	4.7	4.8	6.4	6.9	6.6	6.4
Total primary supply	**191.2**	**187.7**	**154.4**	**193.3**	**172.1**	**180.6**

Secondary supply tonnes[1]	2018	2019	2020	2021	2022	2023
Automotive	41.5	43.2	36.0	38.4	36.0	37.3
Electrical & electronics	1.2	1.3	1.2	1.4	1.6	1.7
Jewellery	21.7	20.6	15.7	11.4	8.2	8.2
Total secondary supply	**64.4**	**65.1**	**52.9**	**51.2**	**45.8**	**47.2**

Combined primary and secondary supply	**255.6**	**252.8**	**207.3**	**244.5**	**217.9**	**227.8**

Demand tonnes[2]	2018	2019	2020	2021	2022	2023
Automotive	87.5	80.5	63.0	74.9	85.9	95.3
Chemical	20.3	20.6	19.1	21.1	21.8	21.6
Dental & biomedical	7.5	7.9	6.8	6.9	7.9	7.9
Electrical & electronics	7.1	6.8	7.0	8.1	7.2	8.3
Glass	15.6	14.6	15.8	28.2	18.4	17.6
Investment	2.1	35.1	31.8	-0.9	-17.4	8.8
Jewellery	70.2	64.5	51.5	45.7	41.8	42.0
Petroleum	11.8	8.2	9.0	6.7	7.2	6.6
Pollution control	6.1	5.8	5.5	6.3	6.9	8.1
Other	16.5	16.9	12.9	13.8	15.1	15.7
Total demand	**244.7**	**260.9**	**222.4**	**210.8**	**194.8**	**231.9**
Movement in stocks	10.9	-8.1	-15.1	33.7	23.1	-4.1

[1]**Secondary supply** comprises 'open-loop' recycling from the automotive, jewellery and electronics sectors. See page 32 for further details.

[2]**Industrial demand** is net of 'closed-loop' recycling and sales of surplus metal back to the market, for example due to plant closures. It represents new metal requirements by industrial consumers in each year. See page 33 for further information.

Platinum demand by region

Tonnes

Demand tonnes		2018	2019	2020	2021	2022	2023
Europe	Automotive	42.8	37.1	26.7	23.0	24.6	26.4
	Chemical	3.8	3.8	3.6	3.9	4.3	4.6
	Dental & biomedical	2.0	2.0	1.7	1.7	2.0	2.0
	Electrical & electronics	0.4	0.4	0.4	0.4	0.4	0.5
	Glass	0.3	0.4	0.4	0.6	0.5	0.4
	Investment	-3.2	17.6	9.6	3.9	-8.8	0.6
	Jewellery	5.9	6.1	4.7	6.3	7.4	6.5
	Petroleum	0.9	0.5	-0.9	-0.5	0.0	-0.2
	Pollution control	1.3	1.3	1.4	1.6	1.6	1.6
	Other	5.3	5.3	4.0	4.2	4.5	4.7
	Total	**59.5**	**74.5**	**51.6**	**45.1**	**36.5**	**47.1**

Demand tonnes		2018	2019	2020	2021	2022	2023
Japan	Automotive	9.1	8.2	6.3	7.4	7.3	7.5
	Chemical	1.2	1.3	1.2	1.3	1.3	1.2
	Dental & biomedical	0.4	0.4	0.5	0.5	0.6	0.6
	Electrical & electronics	0.7	0.7	0.8	0.9	0.7	0.7
	Glass	0.2	0.8	0.5	0.4	0.3	0.4
	Investment	6.8	1.0	12.2	-0.7	-3.9	1.5
	Jewellery	9.1	9.2	7.4	7.7	7.3	7.5
	Petroleum	0.1	0.1	0.1	0.0	0.0	0.0
	Pollution control	1.8	1.9	1.7	1.9	1.9	1.9
	Other	1.7	2.1	1.7	1.8	1.8	1.8
	Total	**31.1**	**25.7**	**32.4**	**21.2**	**17.3**	**23.1**

Demand tonnes		2018	2019	2020	2021	2022	2023
North America	Automotive	8.9	9.0	6.7	9.9	13.5	15.9
	Chemical	3.3	3.1	3.0	3.8	3.8	3.9
	Dental & biomedical	2.9	3.0	2.0	2.1	2.6	2.6

Demand tonnes		2018	2019	2020	2021	2022	2023
North America	Electrical & electronics	1.2	0.9	0.7	0.9	0.9	1.2
	Glass	0.6	0.7	1.1	1.8	0.8	0.7
	Investment	2.1	4.8	18.7	3.6	-2.1	0.9
	Jewellery	7.0	6.6	6.5	7.0	7.8	8.1
	Petroleum	0.5	0.5	0.2	0.8	0.7	1.0
	Pollution control	1.8	1.6	1.4	1.2	1.3	1.4
	Other	4.7	4.7	2.9	3.2	3.9	4.1
	Total	**33.0**	**34.9**	**43.2**	**34.3**	**33.2**	**39.8**

Demand tonnes		2018	2019	2020	2021	2022	2023
China	Automotive	5.1	4.9	6.7	12.4	13.1	15.0
	Chemical	6.4	8.5	8.5	9.1	9.5	7.4
	Dental & biomedical	1.2	1.5	1.1	1.1	1.1	1.1
	Electrical & electronics	1.4	1.4	1.4	1.6	1.4	1.4
	Glass	12.1	10.0	11.9	23.3	13.9	13.9
	Investment	0.0	0.0	0.0	0.4	0.5	0.4
	Jewellery	40.9	34.8	29.4	20.7	14.6	14.6
	Petroleum	8.1	5.1	6.7	3.0	4.0	3.1
	Pollution control	0.6	0.5	0.4	0.7	1.1	2.2
	Other	2.2	2.1	1.9	1.9	2.0	2.0
	Total	**78.0**	**68.8**	**68.0**	**74.2**	**61.2**	**61.1**

Demand tonnes		2018	2019	2020	2021	2022	2023
Rest of World	Automotive	21.6	21.3	16.6	22.2	27.4	30.5
	Chemical	5.6	3.9	2.8	3.0	2.9	4.5
	Dental & biomedical	1.0	1.0	1.5	1.5	1.6	1.6
	Electrical & electronics	3.4	3.4	3.7	4.3	3.8	4.5
	Glass	2.4	2.7	1.9	2.1	2.9	2.2
	Investment	-3.6	11.7	-8.7	-8.1	-3.1	5.4
	Jewellery	7.3	7.8	3.5	4.0	4.7	5.3
	Petroleum	2.2	2.0	2.9	3.4	2.5	2.7
	Pollution control	0.6	0.5	0.6	0.9	1.0	1.0
	Other	2.6	2.7	2.4	2.7	2.9	3.1
	Total	**43.1**	**57.0**	**27.2**	**36.0**	**46.6**	**60.8**
	Grand total	**244.7**	**260.9**	**222.4**	**210.8**	**194.8**	**231.9**

Palladium supply and demand

Troy ounces

Primary supply '000 oz	2018	2019	2020	2021	2022	2023
South Africa	2,543	2,571	1,975	2,645	2,276	2,442
Russia	2,976	2,987	2,636	2,689	2,600	2,600
North America	1,035	1,042	990	908	813	879
Zimbabwe	393	379	410	392	409	430
Others	135	140	185	212	209	205
Total primary supply	**7,082**	**7,119**	**6,196**	**6,846**	**6,307**	**6,556**

Secondary supply '000 oz[1]	2018	2019	2020	2021	2022	2023
Automotive	2,624	2,916	2,689	2,887	2,634	2,761
Electrical & electronics	475	477	428	443	455	463
Jewellery	12	12	8	9	10	10
Total secondary supply	**3,111**	**3,405**	**3,125**	**3,339**	**3,099**	**3,234**

Combined primary and secondary supply	**10,193**	**10,524**	**9,321**	**10,185**	**9,406**	**9,790**

Demand '000 oz[2]	2018	2019	2020	2021	2022	2023
Automotive	8,837	9,675	8,573	8,499	8,449	8,251
Chemical	605	530	498	593	589	534
Dental & biomedical	364	320	228	209	186	171
Electrical & electronics	768	711	634	647	544	545
Investment	-574	-87	-190	17	-109	25
Jewellery	148	128	85	88	87	88
Pollution control	86	88	76	102	108	123
Other	117	120	93	96	83	96
Total demand	**10,351**	**11,485**	**9,997**	**10,251**	**9,937**	**9,833**
Movement in stocks	-158	-961	-676	-66	-531	-43

[1]**Secondary supply** comprises 'open-loop' recycling from the automotive, jewellery and electronics sectors. See page 32 for further details.

[2]**Industrial demand** is net of 'closed-loop' recycling and sales of surplus metal back to the market, for example due to plant closures. It represents new metal requirements by industrial consumers in each year. See page 33 for further information.

Palladium demand by region

Troy ounces

Demand '000 oz		2018	2019	2020	2021	2022	2023
Europe	Automotive	1,917	2,095	1,795	1,873	1,936	1,847
	Chemical	65	71	53	73	108	74
	Dental & biomedical	52	43	29	32	31	28
	Electrical & electronics	91	85	73	74	63	61
	Investment	-141	-56	-17	-17	-58	11
	Jewellery	49	42	28	29	29	29
	Pollution control	22	26	27	29	30	30
	Other	18	12	10	10	10	10
	Total	**2,073**	**2,318**	**1,998**	**2,103**	**2,149**	**2,090**

Demand '000 oz		2018	2019	2020	2021	2022	2023
Japan	Automotive	880	917	776	737	711	735
	Chemical	17	17	16	17	16	16
	Dental & biomedical	156	140	102	89	75	67
	Electrical & electronics	198	180	162	158	128	129
	Investment	-1	1	3	2	1	3
	Jewellery	52	45	31	32	30	30
	Pollution control	13	14	13	14	13	13
	Other	6	6	4	6	6	6
	Total	**1,321**	**1,320**	**1,107**	**1,055**	**980**	**999**

Demand '000 oz		2018	2019	2020	2021	2022	2023
North America	Automotive	2,069	2,058	1,701	1,722	1,825	1,799
	Chemical	76	84	35	76	70	73
	Dental & biomedical	130	112	77	70	64	61
	Electrical & electronics	113	103	91	93	79	78
	Investment	-87	-5	-35	34	-25	16
	Jewellery	27	21	13	13	14	14
	Pollution control	15	13	10	13	14	15
	Other	36	37	27	30	29	29
	Total	**2,379**	**2,423**	**1,919**	**2,051**	**2,070**	**2,085**

Demand '000 oz		2018	2019	2020	2021	2022	2023
China	Automotive	2,097	2,700	2,631	2,246	1,848	1,703
	Chemical	272	252	289	320	286	260
	Dental & biomedical	7	6	6	5	5	5
	Electrical & electronics	141	131	118	123	103	104
	Investment	0	0	0	0	0	0
	Jewellery	2	1	0	0	0	0
	Pollution control	34	31	22	36	40	53
	Other	38	43	38	34	24	27
	Total	**2,591**	**3,164**	**3,104**	**2,764**	**2,306**	**2,152**

Demand '000 oz		2018	2019	2020	2021	2022	2023
Rest of World	Automotive	1,874	1,905	1,670	1,921	2,129	2,167
	Chemical	175	106	105	107	109	111
	Dental & biomedical	19	19	14	13	11	10
	Electrical & electronics	225	212	190	199	171	173
	Investment	-345	-27	-141	-2	-27	-5
	Jewellery	18	19	13	14	14	15
	Pollution control	2	4	4	10	11	12
	Other	19	22	14	16	14	24
	Total	**1,987**	**2,260**	**1,869**	**2,278**	**2,432**	**2,507**
	Grand total	**10,351**	**11,485**	**9,997**	**10,251**	**9,937**	**9,833**

Palladium supply and demand

Tonnes

Primary supply tonnes	2018	2019	2020	2021	2022	2023
South Africa	79.1	80.0	61.4	82.3	70.8	75.9
Russia	92.6	92.9	82.0	83.6	80.9	80.9
North America	32.2	32.4	30.8	28.2	25.3	27.3
Zimbabwe	12.2	11.8	12.7	12.2	12.7	13.4
Others	4.2	4.4	5.8	6.6	6.5	6.4
Total primary supply	**220.3**	**221.5**	**192.7**	**212.9**	**196.2**	**203.9**

Secondary supply tonnes[1]	2018	2019	2020	2021	2022	2023
Automotive	81.7	90.7	83.6	89.8	81.9	85.9
Electrical & electronics	14.8	14.9	13.3	13.8	14.1	14.4
Jewellery	0.3	0.3	0.2	0.3	0.3	0.3
Total secondary supply	**96.8**	**105.9**	**97.1**	**103.9**	**96.3**	**100.6**

Combined primary and secondary supply	**317.1**	**327.4**	**289.8**	**316.8**	**292.5**	**304.5**

Demand tonnes[2]	2018	2019	2020	2021	2022	2023
Automotive	274.8	301.0	266.5	264.4	262.8	256.7
Chemical	18.8	16.4	15.6	18.4	18.4	16.7
Dental & biomedical	11.2	10.0	7.1	6.6	5.8	5.4
Electrical & electronics	23.9	22.1	19.7	20.1	17.0	16.9
Investment	-17.8	-2.7	-5.9	0.6	-3.4	0.7
Jewellery	4.6	4.0	2.7	2.7	2.6	2.7
Pollution control	2.8	2.7	2.3	3.1	3.3	3.8
Other	3.7	3.8	2.8	3.0	2.5	2.9
Total demand	**322.0**	**357.3**	**310.8**	**318.9**	**309.0**	**305.8**
Movement in stocks	-4.9	-29.9	-21.0	-2.1	-16.5	-1.3

[1]**Secondary supply** comprises 'open-loop' recycling from the automotive, jewellery and electronics sectors. See page 32 for further details.

[2]**Industrial demand** is net of 'closed-loop' recycling and sales of surplus metal back to the market, for example due to plant closures. It represents new metal requirements by industrial consumers in each year. See page 33 for further information.

Palladium demand by region

Tonnes

Demand tonnes		2018	2019	2020	2021	2022	2023
Europe	Automotive	59.6	65.2	55.8	58.3	60.2	57.4
	Chemical	2.0	2.2	1.7	2.3	3.4	2.3
	Dental & biomedical	1.6	1.3	0.9	1.0	1.0	0.9
	Electrical & electronics	2.8	2.6	2.3	2.3	2.0	1.9
	Investment	-4.4	-1.7	-0.5	-0.5	-1.8	0.3
	Jewellery	1.5	1.3	0.9	0.9	0.9	0.9
	Pollution control	0.7	0.8	0.8	0.9	0.9	0.9
	Other	0.6	0.4	0.3	0.3	0.3	0.3
	Total	**64.4**	**72.1**	**62.2**	**65.5**	**66.9**	**64.9**

Demand tonnes		2018	2019	2020	2021	2022	2023
Japan	Automotive	27.4	28.5	24.1	22.9	22.1	22.9
	Chemical	0.5	0.5	0.5	0.5	0.5	0.5
	Dental & biomedical	4.8	4.4	3.2	2.8	2.3	2.1
	Electrical & electronics	6.2	5.6	5.0	4.9	4.0	4.0
	Investment	0.0	0.0	0.1	0.1	0.0	0.1
	Jewellery	1.6	1.4	1.0	1.0	0.9	0.9
	Pollution control	0.4	0.4	0.4	0.4	0.4	0.4
	Other	0.2	0.2	0.1	0.2	0.2	0.2
	Total	**41.1**	**41.0**	**34.4**	**32.8**	**30.4**	**31.1**

Demand tonnes		2018	2019	2020	2021	2022	2023
North America	Automotive	64.3	64.0	52.9	53.6	56.8	56.0
	Chemical	2.4	2.6	1.1	2.4	2.2	2.3
	Dental & biomedical	4.0	3.5	2.4	2.2	2.0	1.9
	Electrical & electronics	3.5	3.2	2.8	2.9	2.5	2.4
	Investment	-2.7	-0.2	-1.1	1.1	-0.8	0.5
	Jewellery	0.8	0.7	0.4	0.4	0.4	0.4
	Pollution control	0.5	0.4	0.3	0.4	0.4	0.5
	Other	1.1	1.2	0.8	0.9	0.9	0.9
	Total	**73.9**	**75.4**	**59.6**	**63.9**	**64.4**	**64.9**

Demand tonnes		2018	2019	2020	2021	2022	2023
China	Automotive	65.2	84.0	81.8	69.9	57.5	53.0
	Chemical	8.5	7.8	9.0	9.9	8.9	8.1
	Dental & biomedical	0.2	0.2	0.2	0.2	0.2	0.2
	Electrical & electronics	4.4	4.1	3.7	3.8	3.2	3.2
	Investment	0.0	0.0	0.0	0.0	0.0	0.0
	Jewellery	0.1	0.0	0.0	0.0	0.0	0.0
	Pollution control	1.1	1.0	0.7	1.1	1.3	1.6
	Other	1.2	1.3	1.2	1.1	0.7	0.8
	Total	**80.7**	**98.4**	**96.6**	**86.0**	**71.8**	**66.9**

Demand tonnes		2018	2019	2020	2021	2022	2023
Rest of World	Automotive	58.3	59.3	51.9	59.7	66.2	67.4
	Chemical	5.4	3.3	3.3	3.3	3.4	3.5
	Dental & biomedical	0.6	0.6	0.4	0.4	0.3	0.3
	Electrical & electronics	7.0	6.6	5.9	6.2	5.3	5.4
	Investment	-10.7	-0.8	-4.4	-0.1	-0.8	-0.2
	Jewellery	0.6	0.6	0.4	0.4	0.4	0.5
	Pollution control	0.1	0.1	0.1	0.3	0.3	0.4
	Other	0.6	0.7	0.4	0.5	0.4	0.7
	Total	**61.9**	**70.4**	**58.0**	**70.7**	**75.5**	**78.0**
	Grand total	**322.0**	**357.3**	**310.8**	**318.9**	**309.0**	**305.8**

Rhodium supply and demand

Troy ounces

Primary supply '000 oz	2018	2019	2020	2021	2022	2023
South Africa	618	606	483	645	570	597
Russia	69	68	58	53	58	58
North America	22	24	22	17	18	19
Zimbabwe	43	40	43	42	43	44
Others	5	7	6	6	6	6
Total primary supply	**757**	**745**	**612**	**763**	**695**	**724**

Secondary supply '000 oz[1]	2018	2019	2020	2021	2022	2023
Automotive	331	356	338	369	338	345
Total secondary supply	**331**	**356**	**338**	**369**	**338**	**345**

Combined primary and secondary supply	**1,088**	**1,101**	**950**	**1,132**	**1,033**	**1,069**

Demand '000 oz[2]	2018	2019	2020	2021	2022	2023
Automotive	900	1,035	965	962	953	947
Chemical	63	56	55	56	66	82
Electrical & electronics	4	6	7	7	5	6
Glass	103	51	7	-4	-41	5
Other	-13	22	5	11	15	15
Total demand	**1,057**	**1,170**	**1,039**	**1,032**	**998**	**1,055**
Movement in stocks	31	-69	-89	100	35	14

[1]**Secondary supply** comprises 'open-loop' recycling from the automotive, jewellery and electronics sectors. See page 32 for further details.

[2]**Industrial demand** is net of 'closed-loop' recycling and sales of surplus metal back to the market, for example due to plant closures. It represents new metal requirements by industrial consumers in each year. See page 33 for further information.

Rhodium supply and demand

Tonnes

Primary supply tonnes	2018	2019	2020	2021	2022	2023
South Africa	19.2	18.9	15.0	20.1	17.7	18.6
Russia	2.1	2.1	1.8	1.6	1.8	1.8
North America	0.7	0.8	0.7	0.5	0.6	0.6
Zimbabwe	1.3	1.2	1.3	1.3	1.3	1.4
Others	0.2	0.2	0.2	0.2	0.2	0.2
Total primary supply	**23.5**	**23.2**	**19.0**	**23.7**	**21.6**	**22.6**

Secondary supply tonnes[1]	2018	2019	2020	2021	2022	2023
Automotive	10.3	11.1	10.5	11.5	10.5	10.7
Total secondary supply	**10.3**	**11.1**	**10.5**	**11.5**	**10.5**	**10.7**

Combined primary and secondary supply	**33.8**	**34.3**	**29.5**	**35.2**	**32.1**	**33.3**

Demand tonnes[2]	2018	2019	2020	2021	2022	2023
Automotive	28.0	32.2	30.0	29.8	29.7	29.5
Chemical	1.9	1.7	1.7	1.7	2.0	2.5
Electrical & electronics	0.1	0.2	0.2	0.2	0.1	0.2
Glass	3.2	1.6	0.2	-0.1	-1.3	0.2
Other	-0.4	0.7	0.2	0.5	0.5	0.5
Total demand	**32.8**	**36.4**	**32.3**	**32.1**	**31.0**	**32.9**
Movement in stocks	1.0	-2.1	-2.8	3.1	1.1	0.4

[1]**Secondary supply** comprises 'open-loop' recycling from the automotive, jewellery and electronics sectors. See page 32 for further details.

[2]**Industrial demand** is net of 'closed-loop' recycling and sales of surplus metal back to the market, for example due to plant closures. It represents new metal requirements by industrial consumers in each year. See page 33 for further information.

Ruthenium demand

Troy ounces

Demand '000 oz	2018	2019	2020	2021	2022	2023
Chemical	356	401	385	329	383	432
Electrical & electronics	433	416	419	443	369	375
Electrochemical	139	144	137	130	131	133
Other	187	137	103	114	140	141
Total demand	**1,115**	**1,098**	**1,044**	**1,016**	**1,023**	**1,081**

Tonnes

Demand tonnes	2018	2019	2020	2021	2022	2023
Chemical	11.1	12.5	12.0	10.3	11.9	13.4
Electrical & electronics	13.5	12.9	13.0	13.8	11.5	11.7
Electrochemical	4.3	4.5	4.3	4.0	4.1	4.1
Other	5.8	4.2	3.2	3.5	4.3	4.4
Total demand	**34.7**	**34.1**	**32.5**	**31.6**	**31.8**	**33.6**

Iridium demand

Troy ounces

Demand '000 oz	2018	2019	2020	2021	2022	2023
Chemical	21	22	25	25	30	30
Electrical & electronics	46	48	59	50	34	40
Electrochemical	72	81	82	81	91	104
Other	104	92	65	65	64	64
Total demand	**243**	**243**	**231**	**221**	**219**	**238**

Tonnes

Demand tonnes	2018	2019	2020	2021	2022	2023
Chemical	0.7	0.7	0.8	0.8	0.9	0.9
Electrical & electronics	1.4	1.5	1.8	1.5	1.1	1.2
Electrochemical	2.3	2.5	2.6	2.5	2.8	3.3
Other	3.2	2.9	2.0	2.0	2.0	2.0
Total demand	**7.6**	**7.6**	**7.2**	**6.8**	**6.8**	**7.4**

Glossary

ACC2	Advanced Clean Cars II regulation
BEV	Battery electric vehicle
CARB	California Air Resources Board
CCM	Catalyst coated membrane
CF	Conformity factor
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CWAO	Catalytic wet air oxidation
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EC	European Commission
ELV	End-of-life vehicle
EPA	Environmental Protection Agency
ETF	Exchange traded fund
FCEV	Fuel cell electric vehicle
GPF	Gasoline particulate filter
GVW	Gross vehicle weight
HDD	Heavy duty diesel
ICE	Internal combustion engine
ISC	In-service conformity
IRA	Inflation Reduction Act
LCD	Liquid crystal display
LDG	Light duty gasoline
LDD	Light duty diesel
LED	Light emitting diode
LEV	Low emission vehicle
LPPM	London Platinum and Palladium Market
MLCC	Multi-layer ceramic capacitor
NEV	New energy vehicle (BEV, PHEV or FCEV)
NH_3	Ammonia
NO_x	Oxides of nitrogen
NRMM	Non-road mobile machinery
NYMEX	New York Mercantile Exchange
N_2O	Nitrous oxide
OLED	Organic light emitting diode
PEM	Proton exchange membrane
PEMS	Portable emissions measurement system
PGM	Platinum group metals
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter or soot
PMR	Perpendicular magnetic recording
PN	Particle number
RDE	Real driving emissions
RoW	Rest of World region
SAW filter	Surface acoustic wave filter
SCR	Selective catalytic reduction
SGE	Shanghai Gold Exchange
UF	Utility factor
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
ZEV	Zero emission vehicle
4E grade	Combined content of four elements: platinum, palladium, rhodium and gold
6E grade	Combined content of six elements: platinum, palladium, rhodium, gold, ruthenium and iridium