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PGM market report

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Automotive production data is taken from IHS Markit, Global Production-based Powertrain Forecast, April 2022. 2022 figures are a forecast and subject to change. In line with regional emissions legislation, 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.

The PGM market report is published annually,
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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
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.
Recycling	Recycling figures represent **secondary PGM supplies** and are 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. It is allocated to the region where the vehicle was originally sold (but not necessarily scrapped).
Gross demand	Gross demand figures for any given application represent the sum of industry demand for new metal in that application; that is it is net of any **closed-loop recycling** (i.e. where industry participants retain ownership of the metal: an example would be recycling of spent chemical catalysts where the metal is retained to be used on fresh catalyst that replaces the spent charge). Gross demand also includes any changes in unrefined metal stocks in the sector. Increases in unrefined stocks lead to additional demand, while reductions in stocks (including any metal released from industry, e.g. in the case of chemical plant closures) lead to negative demand. **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 under industrial demand). **Jewellery demand** is allocated to the region where the finished jewellery is manufactured, not sold.
Net demand	Gross demand less open-loop recycling.
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 2021

Temporary mismatches between supply and demand caused dramatic PGM price movements

Primary supplies were constrained in early 2021, but improved as backlogs were refined

Industrial PGM use was robust, with strong chemicals demand and record purchasing by glassmakers

Auto PGM demand was hit by semiconductor shortages, lower loadings, and growth in BEV market share

PGM investment was weak, with liquidation of platinum ETFs and limited investor interest in palladium

Platinum jewellery demand fell to a 30-year low, as Chinese fabrication contracted again

Following dramatic falls in both supply and demand in 2020, initial expectations of a rapid return to pre-pandemic business conditions proved overly optimistic. PGM demand in 2021 was hit by global supply-chain disruption, especially in the auto industry, where the impact of semiconductor shortages was amplified by changes in consumer preference in favour of electric vehicles. While industrial buying was robust, except in a handful of highly price-sensitive applications, net demand for PGM in investment and jewellery contracted sharply. Primary PGM supplies were constrained during early 2021, following process plant outages in South Africa the previous year, but improved as backlogs were processed, pushing all the PGM into fundamental surplus for the calendar year. Nevertheless, temporary mismatches between supply and demand caused dramatic price movements during the early part of 2021, before increasing availability and faltering demand drove prices downwards from mid-year.

"During early 2021, all the PGM except platinum traded significantly above historical levels, as constrained supplies and an improvement in demand created acute liquidity squeezes"

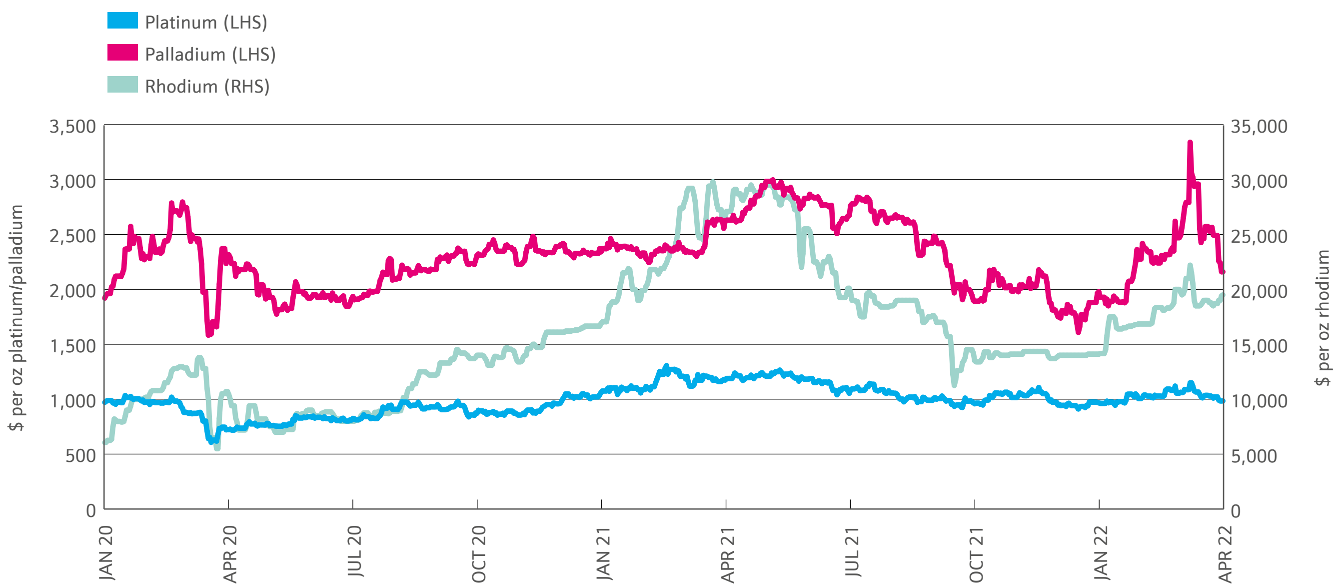


Figure 1 Platinum, palladium and rhodium prices

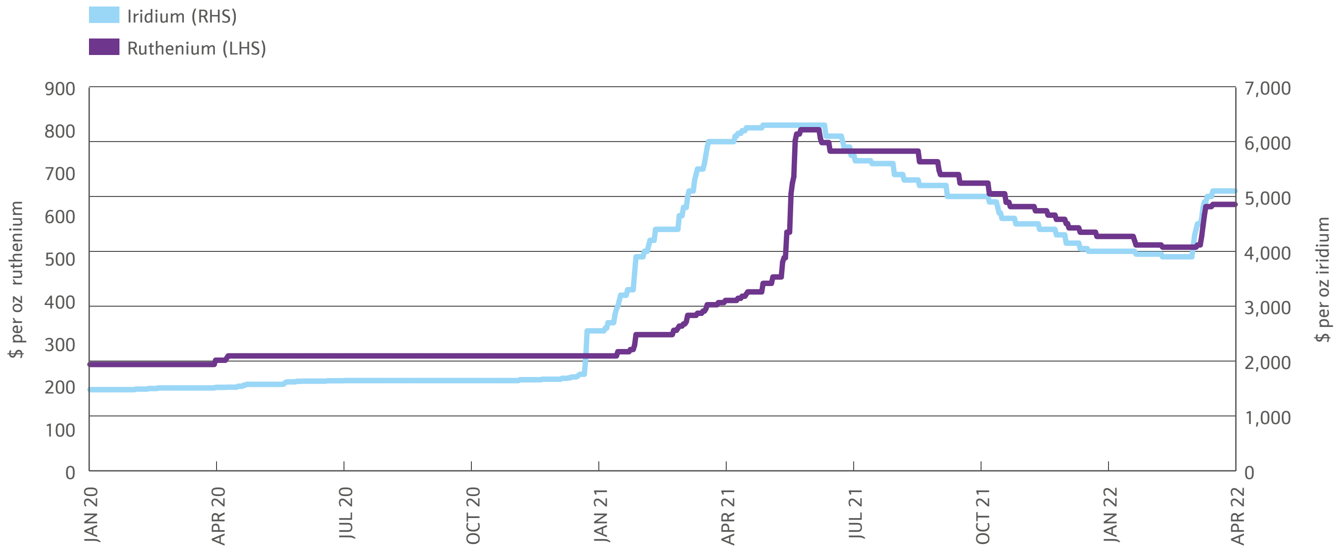


Figure 2 Ruthenium and iridium prices

During the first four months of 2021, all the PGM except platinum traded significantly above historical levels, as constrained supplies and an improvement in demand created acute liquidity squeezes and unusual price volatility (Figures 1 and 2). Rhodium was the most severely affected: the price surged repeatedly to highs of around $30,000, reflecting extreme shortages of availability following outages at Anglo American Platinum's converter plant (ACP) during 2020, which created a backlog containing around one million ounces of PGM. Iridium also experienced extreme price pressure, climbing to a peak of $6,300 in April – by far the highest price ever seen for this metal – while ruthenium reached a fourteen-year high of $800 during May.

Supply of these 'minor' PGM is dominated by South Africa, so they were more severely affected by the ACP outage than platinum and palladium, which have a somewhat more geographically diverse primary supply base (Figure 3). Although the ACP resumed production in December 2020, the 'insoluble' PGM (rhodium, ruthenium and iridium) are technically complex to refine and have long processing lead-times.

Price volatility was exacerbated by unusual purchasing patterns, particularly for iridium, as consumers concerned about future availability purchased metal ahead of their actual requirements. Speculative buying may also have contributed to price movements, with strong investor interest in potential iridium demand in the production of 'green' hydrogen (see our special feature on hydrogen on page 32 of the May 2021 edition of this report, available on our website).

"Iridium consumers concerned about future availability purchased metal ahead of their actual requirements"

While less dependent upon South African supplies, the palladium market also experienced another bout of unusual tightness during early 2021, with sponge moving to a large premium over ingot, signalling a shortage of metal in the form usually

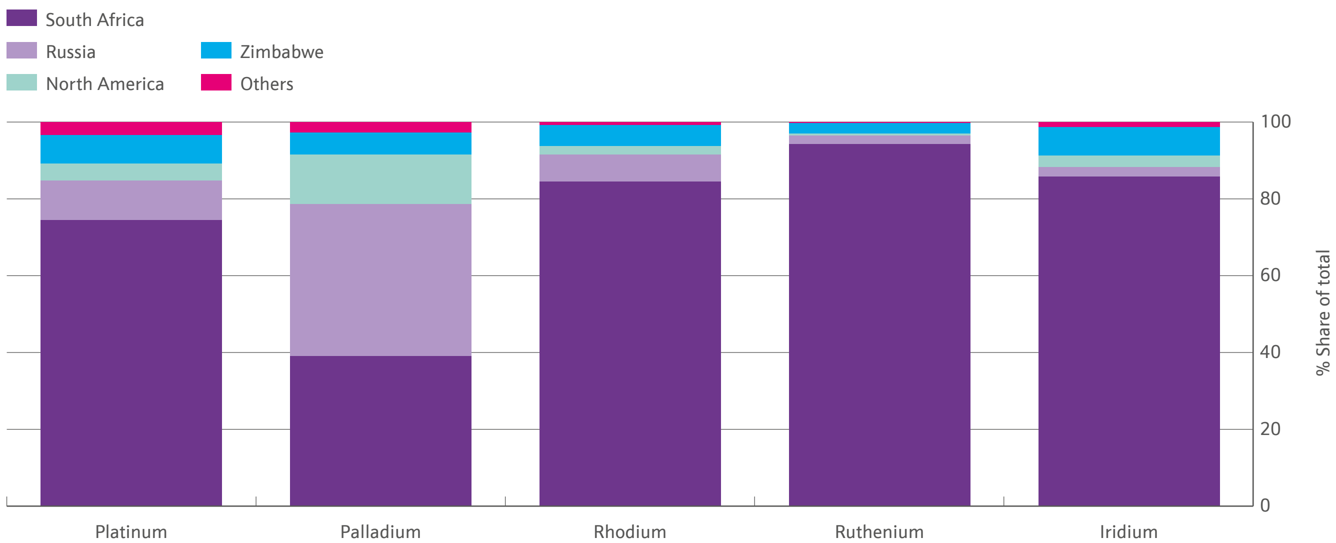


Figure 3 Primary supply share by region, 2021

required by Western industrial consumers. The price surged to $3,000 in April, following news that Norilsk Nickel expected to lose a significant quantity of annual PGM production in the wake of an accident at a processing plant and the temporary closure of two large mines due to underground flooding.

Platinum was less volatile than its sister metals during early 2021: it is a large, relatively liquid market, making it somewhat less vulnerable than the other PGM to any temporary disruption in deliveries from South Africa and Russia. Nevertheless, the price ascended to a six-year high of just over $1,300 in mid-February 2021, and then traded either side of $1,200 until early June. Supply risks probably played a role in this relative price strength, while investor sentiment was bolstered by the near-term prospect of additional demand in gasoline autocatalysts and longer-term potential for platinum to play a key role in the hydrogen economy.

As the year progressed, semiconductor shortages intensified, cutting short the recovery in automotive production, while high prices stimulated thrifting in some industrial applications. PGM demand faltered, while the release of most of the ACP backlog bolstered supplies and improved availability. This sent PGM prices spiralling downwards: palladium fell to a 21-month low of under $1,600 in December, while rhodium collapsed to $11,000 in September before stabilising at around $14,000 for the remainder of the year. Iridium and ruthenium also eased progressively from June onwards, to $4,000 and $550 respectively at the year end, although prices for these metals remained significantly above pre-2021 levels. Platinum, meanwhile, descended gradually to pre-pandemic levels of around $900.

"As the year progressed, semiconductor shortages cut short the recovery in automotive production"

Overview and market balance

Following deficits in 2019–2020, all the autocatalyst PGM were adequately supplied last year. Demand for palladium and rhodium was hit by weak consumption in automotive applications: after starting the year strongly, PGM purchasing began to ebb as gasoline vehicle production slid lower and Chinese automakers thrifted PGM loadings. Our automotive numbers are based on an estimate of actual PGM consumption on vehicles built in 2021 – by this measure, demand for palladium and rhodium fell below the pandemic-hit 2020 total (Figure 4). However, because some automakers purchase their PGM via regular monthly contracts, we believe that the auto industry ended the year with excess stocks of metal; this is difficult to quantify and therefore not included in our demand numbers.

"Industrial demand for platinum set an all-time high, with exceptionally strong purchasing by glassmakers"

High palladium and rhodium prices impacted industrial consumption, limiting the post-lockdown bounce: dental companies continued to adopt alternatives to palladium, while glass manufacturers reduced the rhodium content of platinum-rhodium alloys used in glass fibre 'bushings'. Combined automotive and industrial demand for palladium and rhodium was slightly below the lockdown-hit 2020 total, and 12% lower than the all-time peak in 2019.

In contrast, industrial demand for platinum reached a new all-time high of 2.9 million oz. Last year saw exceptionally strong purchasing by the Chinese glass industry, which required platinum both for a new wave of glass fibre capacity expansions, and to replace rhodium that was removed from glass-making alloys on cost grounds (see page 33). There were also modest gains in automotive platinum consumption, due to tightening heavy duty emissions legislation in China and an increase in platinum-for-palladium substitution in gasoline autocatalysts. Combined industrial and automotive platinum consumption rose by 17% to 5.3 million oz.

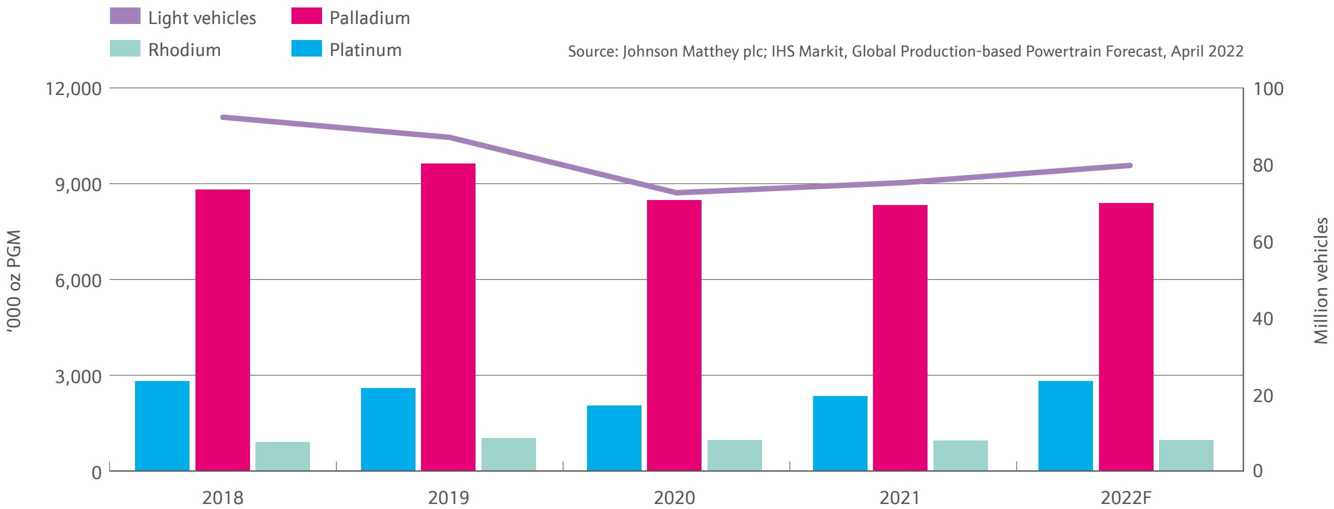


Figure 4 Automotive PGM demand & light vehicle output

However, overall platinum demand was dented by ongoing weakness in the Chinese platinum jewellery sector, and a steep fall in purchasing of investment products. With platinum jewellery fabrication in China falling by a quarter to just 705,000 oz, world consumption of platinum in jewellery dropped below 1.5 million oz for the first time since 1991. Meanwhile, the platinum investment market moved into negative territory, down from over 1 million oz in 2020. Overall, gross platinum demand slumped to 6.75 million oz, a twenty-year low.

"Primary PGM supplies were boosted by the processing of a backlog at Anglo American Platinum's converter plant"

PGM supplies

Primary supplies of platinum and rhodium rose by a quarter in 2021, as most of the backlog at Anglo American Platinum's converter plant was refined and sold. Palladium shipments rose by only 10%, reflecting the different geographical distribution of primary palladium supply, which is less dependent upon South Africa (Figure 3). While there was some disruption to Russian mine output – due to a processing plant collapse and the temporary closure of two mine shafts at the world's largest palladium producer, Norilsk Nickel – this ultimately had only a limited impact on supplies in 2021. Norilsk Nickel has estimated that production losses last year totalled around 470,000 oz of combined platinum and palladium, but shipments remained close to 2020 levels due to the release of metal from the processing pipeline and the sale of some palladium from refined stocks.

Autocatalyst PGM recycling rose by 8% but fell short of the 2019 level. The year started strongly, as a backlog of end-of-life scrap that had accumulated during 2020 moved through the recycling network, and high PGM prices encouraged the swift movement of material through the value chain. However, scrappage activity declined during the second half and especially in the final quarter of the year. With auto production constrained by semiconductor shortages, and strong pent-up consumer demand for cars, prices for used vehicles rose steeply. This created an incentive to keep older cars on the road for longer, reducing the number of end-of-life vehicles entering scrap yards and depressing spent catalyst volumes.

The ruthenium and iridium markets were also well-supplied, despite early-year tightness in the wake of the ACP outage. There is evidence that producers sold metal (particularly ruthenium) from their refined inventories during the first half of 2021, when trade data indicates that unusually large shipments were made to China (Figure 5). Last year's Chinese imports of ruthenium and iridium exceeded our estimates of demand in this region; we believe that there may have been some speculative purchasing in response to growing interest in critical materials for the future hydrogen economy.

"World consumption of platinum in jewellery fell below 1.5 million ounces for the first time since 1991"

Auto production and demand

While hydrogen-related applications show great promise for future PGM demand, catalytic converters remain by far the largest single PGM application at present. Automotive demand peaked in 2019, when total PGM use in vehicles reached 13.3 million oz, as the early implementation of China 6 legislation boosted the average PGM content of a gasoline vehicle.

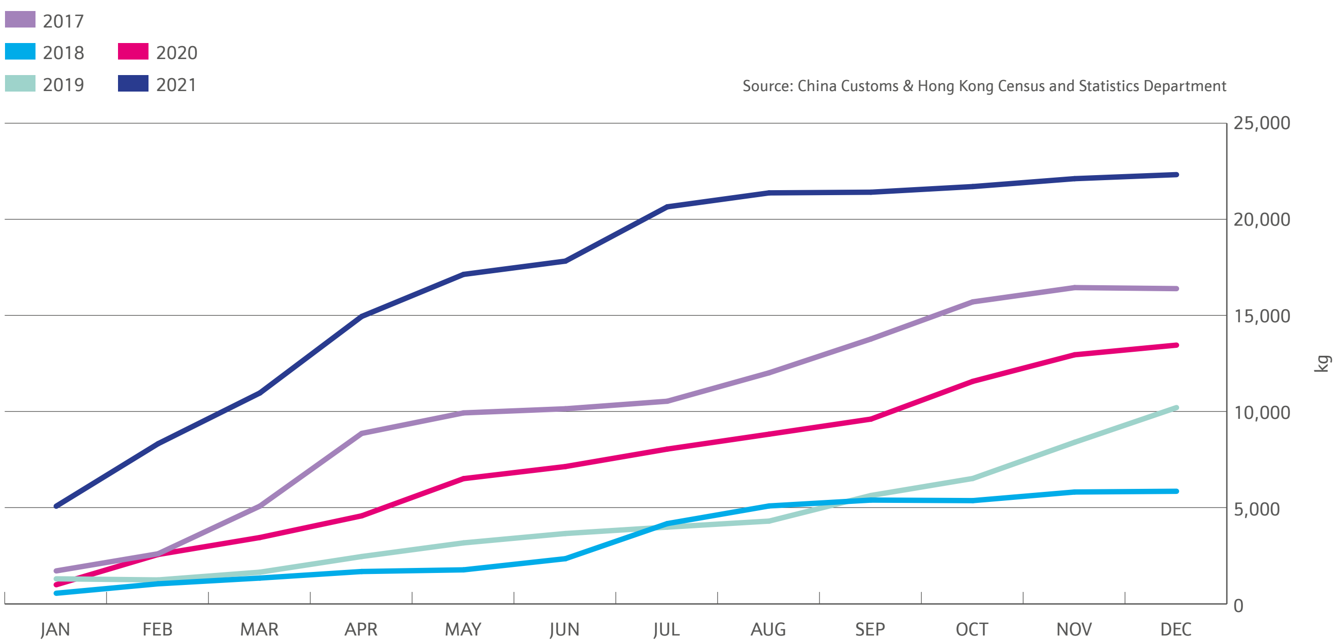


Figure 5 Net imports of ruthenium and iridium into China and Hong Kong

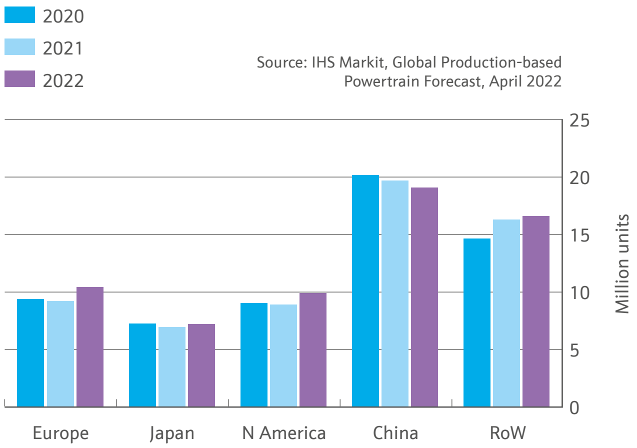


Figure 6 Light duty gasoline vehicle production by region

Since then, average PGM loadings have stabilised at the global level – with thrifting in China largely offset by legislation-driven gains in Europe and North America (see page 30) – leaving demand primarily determined by vehicle production volumes.

Auto sales and production were severely affected in 2020 by Covid lockdowns and extended plant closures, but by the year end, there were signs that pent-up consumer demand would support a resurgence in light vehicle sales and production. Global car sales in the final quarter of 2020 exceeded those of a year earlier, and by the beginning of 2021, auto industry analysts were predicting that vehicle production volumes would return to pre-pandemic levels as early as 2022.

"Battery electric vehicles captured almost all the growth in global light vehicle production"

However, vehicle output forecasts were repeatedly slashed as shortages of semiconductor chips worsened, and car companies were obliged to revise their production plans and periodically halt their assembly lines. In January 2021, light vehicle output for the year was expected to be close to 83 million units; ultimately, according to the IHS Markit Global Production-based Powertrain Forecast issued in early April 2022, only 75.3 million were produced. (Our light duty category includes cars and light trucks with a gross vehicle weight of up to 3.5 tonnes, except in the USA, Canada and Mexico, where – in line with regional emissions legislation – vehicles are considered 'light' if they have a GVW of under 6 tonnes). This represented an improvement of only 3.6% compared to the previous, lockdown-hit year, with most of these gains taken by battery electric vehicles. Only in the Rest of World region was there any growth in production of internal combustion engine (ICE) vehicles.

The heavy duty market was less affected by semiconductor shortages, with production volumes rising strongly in all regions except China. While Chinese truck output contracted by 13%, it remained above 2019 levels, following a dramatic expansion the previous year, when volumes were boosted by pre-buying ahead of China VI emissions legislation.

These new emissions limits applied to all heavy duty diesel trucks from July 2021 and, unlike previous regulations, cannot be met without PGM catalysts. As a result, there was a sharp increase in the proportion of Chinese-made trucks fitted with PGM-containing aftertreatment systems, which in turn led to a significant increase in average loadings in the Chinese market. This was the main contributor to last year's growth in platinum demand, although demand also benefited from some platinum-for-palladium substitution in gasoline catalysts.

"From July 2021, all Chinese heavy duty diesel trucks were fitted with PGM catalysts"

In contrast, palladium and rhodium demand faced much stronger headwinds, with demand affected by changes in the vehicle mix, substitution, and ongoing PGM thrifting in China. Last year, battery electric vehicles captured the vast majority of overall growth in global light vehicle production, leaving gasoline car output up less than 1% to 61 million units (and 15% below the 2019 level). Only the Rest of World recorded higher gasoline car production volumes than in 2020 (Figure 6).

Meanwhile, the average palladium and rhodium content of a gasoline vehicle dropped slightly, as platinum took a larger (although still minor) share of the gasoline PGM mix, and domestic Chinese automakers sought to reduce the overall PGM cost of their catalysts. These domestic OEMs had increased their PGM loadings significantly when they first launched China 6 models in 2019, but high PGM prices have stimulated aggressive thrifting, while improvements in engine technology have enabled strict emissions limits to be met with smaller quantities of PGM.

Palladium demand has also been hit by – and platinum has benefited from – a move away from palladium-rhodium catalyst technology to tri-metal formulations on some vehicle models. In 2021, substitution primarily affected the lower-loaded 'underfloor' catalysts, which are further from the engine and therefore experience lower temperatures than 'close-coupled' catalysts, facilitating platinum use. However, there was some early adoption of platinum in the close-coupled position, and this is expected to gather pace during 2022.

A brief guide to

The semiconductor crisis

The semiconductor crisis has its origins in early 2020, as the first Covid wave extended around the world, and lockdowns triggered temporary shutdowns of car production lines. Anticipating a prolonged impact on consumer demand for vehicles, automakers and their component suppliers cancelled orders for parts, including semiconductor chips used extensively in modern vehicles for applications such as engine management, driver assistance, safety and connectivity features.

At the same time, a shift towards working, studying and consuming entertainment at home meant that electronics manufacturers were enjoying booming demand for products such as laptops, mobile devices and games consoles. The roll-out of 5G technology was also generating substantial growth in demand for chips, with some premium 5G phones requiring twice as many chips as predecessor models. Semiconductor manufacturers diverted their spare production capacity towards these larger and more profitable end-markets, leaving them with little flexibility to meet demand from the auto industry when vehicle sales rebounded faster than anticipated, and car companies raced to place new chip orders.

Shortfalls in chip output were compounded by a series of outages at semiconductor plants. Fires halted production at major producers in Japan and Germany, while climate disruption caused plant closures in Texas, USA (following a severe winter storm in February 2021) and at the world's largest semiconductor manufacturer in Taiwan (due to extreme drought that restricted water supplies). Chip makers also had to contend with successive waves of Covid, which hit chip testing and packaging operations in some South East Asian countries during the third quarter of 2021.

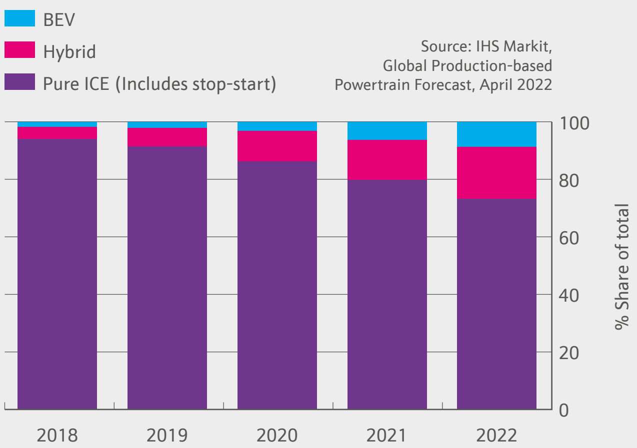


Figure 7 Light duty vehicle market share by degree of electrification

Chip companies have announced significant capital investment in new facilities, but a single semiconductor fabrication plant (also known as a 'fab' or 'foundry') may cost several billion dollars and take several years to complete. In addition, capital spending tends to focus on the latest generation of chips, whereas the auto industry primarily uses more mature semiconductor technology.

The consequence has been a wave of vehicle assembly line shutdowns, with the impact matching or exceeding that of Covid lockdowns in some countries. As well as pausing production, automakers have also reduced the electronic content of some models, for example, by replacing digital speedometers with analogue versions, removing wireless charging, or forgoing some advanced driver assistance features. In addition, some companies may have accumulated inventory of near-complete vehicles, placed in storage while awaiting the fitment of electronic components. It is possible that the completion and shipment of these unfinished vehicles contributed to an improvement in reported vehicle output in some regions in late 2021.

While pandemic disruption and plant outages were the main causes of semiconductor shortages, underlying trends in automotive chip consumption have exacerbated the crisis. According to IHS Markit, the number of chips per vehicle nearly doubled between 2017 and 2021, reflecting changes in the vehicle segmentation mix and growing adoption of electronic features outside luxury segments, compounded by significant increases in vehicle electrification since 2019.

Hybrid vehicles accounted for around 14% of world light-duty vehicle production in 2021, compared to 6% in 2019, while the market share taken by battery electric vehicles (BEVs) has trebled over the past two years to 6% in 2021 (Figure 7). The chip content of a vehicle is strongly linked to its degree of electrification: BEVs typically consume more than twice as many semiconductor chips as a 'pure' (non-hybrid) internal combustion engine (ICE) vehicle of a similar size and vehicle class. Hybrids have a chip content closer to that of BEVs than to pure ICE models.

The war in Ukraine could add to tensions in the automotive supply chain, due to disruption to supplies of neon (of which Ukraine is a major producer): gas mixtures including neon are required for excimer lasers, employed in photolithography in the semiconductor industry. However, lack of underlying foundry capacity is likely to remain the fundamental constraint on both semiconductor production and vehicle output for the next year or two.

PGM outlook

Supply and demand in 2022

War in Ukraine has created significant uncertainty over PGM shipments from Russia

South African supplies will fall in 2022, as plant maintenance and operational challenges hit output

Auto recycling volumes are set to contract, with vehicle scrappage rates hit by weak car sales

Recovery in auto PGM demand could be compromised by supply chain constraints and Covid disruption

Industrial platinum demand should remain robust, but high prices have hit palladium and rhodium use

Investor interest in PGM appears limited, despite elevated risks to supplies

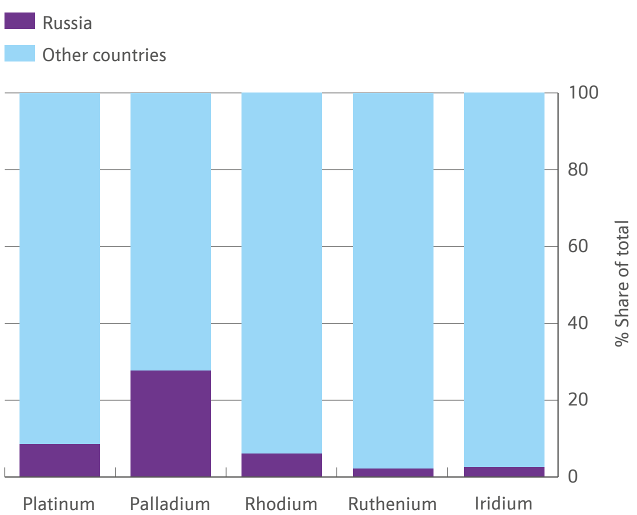


Figure 8 Russian share of combined primary & secondary PGM supplies in 2021

The outlook for PGM supply and demand in 2022 is highly uncertain. War in Ukraine has created significant risks to supply, due to Russia's position as the world's largest primary palladium supplier, and a significant producer of platinum and rhodium. While Russia is not a major PGM consumer, there are wider risks to PGM demand, with the crisis expected to exacerbate existing difficulties in supply chains, augment inflation, and depress economic growth. Covid also continues to create downside risks for PGM consumption, especially in China, where some major cities experienced lockdowns during March and April as the country fought to contain the spread of the Omicron variant.

PGM price movements during the first quarter of 2022 largely reflected the degree of exposure to Russian supply, with palladium the most affected. Last year, around 28% of combined primary and secondary palladium supplies were sourced from Russia, whereas the proportion was under 10% for platinum and rhodium, and below 5% for ruthenium and ruthenium (Figure 8).

As the year opened, palladium moved swiftly from below $2,000 to trade either side of $2,300, spiking above $2,600 when Russian troops entered Ukraine on 24th February. As the situation in Ukraine degraded, and widespread economic sanctions were imposed on Russia by the West, concerns about palladium availability intensified, driving the price to new all-time records. Palladium 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 palladium from Norilsk Nickel continued to reach the market and concerns about liquidity abated, the delisting of Russian refiners by the LPPM reignited availability fears and spurred the price back above $2,500. The LPPM decision means that ingot and sponge produced by Russian refineries after 8th April will no longer be accepted for 'Good Delivery' into the London and Zurich bullion market.

"In 2021, around 28% of combined primary and secondary palladium supplies came from Russia"

Platinum and rhodium also responded to increased supply risks, despite Russia accounting for a much smaller share of supply. Platinum climbed steadily from around $960 as the year opened to an eight-month high of $1,150 in early March, although it subsequently fell back as supply fears eased, ending the first quarter below $1,000. It saw only a limited rebound following the LPPM announcement on 8th April.

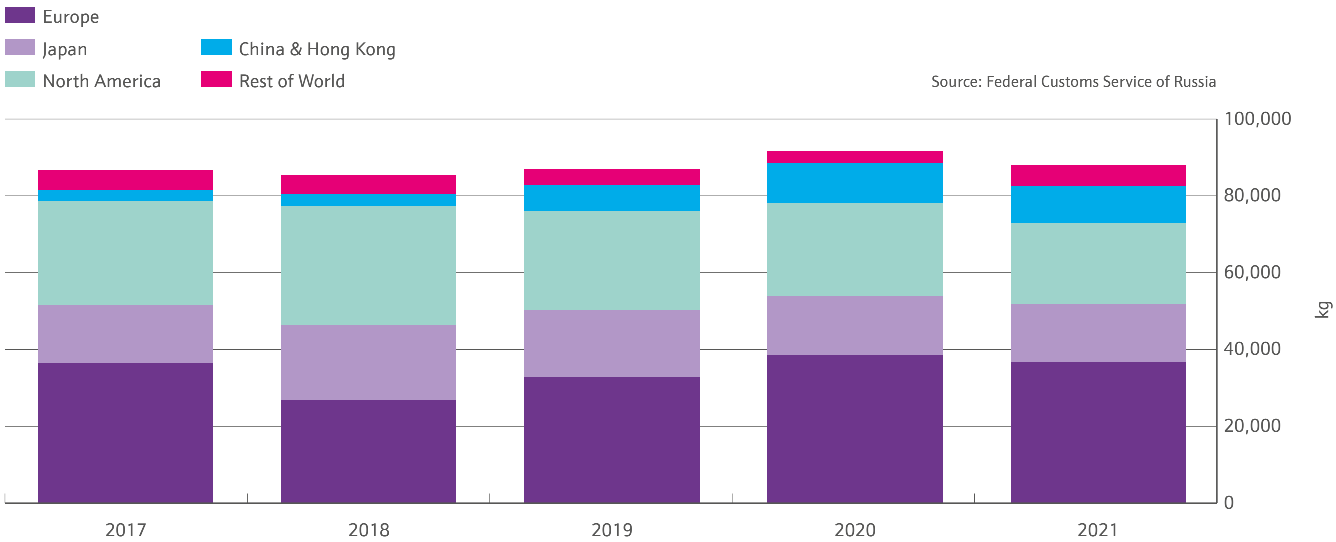


Figure 9 Russian palladium exports by destination region

Rhodium also moved higher during the first quarter: with memories of the extreme supply squeeze of 2021 still fresh, consumers moved to secure their metal needs, spurring the price from $14,500 at the start of 2021 to over $22,000 on 7th March. It continued to trade above $18,000 for the remainder of the month.

> "There are unusually large uncertainties surrounding Russian supplies in 2022"

Ruthenium and iridium are much less exposed to Russian supply risk, as over 95% of primary supplies come from South Africa and Zimbabwe. Prices for both metals fell steadily during the second half of 2021, but the downward trend flattened and then reversed during the first quarter of this year, as industrial buying in Asia and North America returned. 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.

PGM supply

There are unusually large uncertainties surrounding Russian PGM supplies in 2022. The Russian PGM producer Norilsk Nickel was not subject to sanctions at the time of writing, and during the immediate aftermath of the invasion of Ukraine, it continued to ship metal, despite logistical hurdles. Air links from Russia to Europe and North America were largely severed, but PGM was able to reach the market via hubs to the East. However, the removal of Russian refineries from the LPPM 'Good Delivery' list on 8th April will affect deliveries of metal to Western customers going forward. It is difficult to anticipate the size of the impact, so we have chosen not to show a forecast of Russian PGM supplies this year.

Europe and the USA have accounted for over two-thirds of Russian palladium exports in recent years (Figure 9), but a combination of metal provenance considerations and the removal of 'Good Delivery' status (for metal refined after 8th April 2022) means this is likely to change in future. Supplies may ultimately be diverted to other destinations, possibly at a discount, but it will take some time for new contracts to be negotiated.

Mining and processing activities in Russia will ultimately be affected by economic sanctions and the withdrawal of Western businesses, but the extent and timing of the impact is difficult to quantify at this stage. Ability to procure spare parts for mining equipment and other consumables may be impaired, while there will be obstacles for Russian companies seeking access to Western technology and plant for capital projects. In the short term, these supply chain impacts could reduce mine production efficiencies, while in the longer term, we may see delays to expansion projects.

Norilsk Nickel's most recent guidance (issued in April 2022) was for PGM output to be flat to slightly down this year, in the wake of disruption to mining and concentrating activities at its Polar mine site in 2021. The two mines that were temporarily shut due to underground flooding had returned to full capacity by the end of last year, but maintenance at the Nadezhda smelter (scheduled to take place in 2022–2023) will extend processing lead-times and result in an increase in work-in-progress. The company expects to produce 2.45–2.71 million oz of palladium and 605,000–667,000 oz of platinum this year, but for the reasons discussed above it may be unable to deliver all its production to the market.

After an exceptionally strong year in 2021, South African supplies are forecast to contract this year, in line with a lower contribution from the release of pipeline (work-in-progress) stocks, along with planned maintenance at processing operations, and ongoing operational challenges at many mines. With wage negotiations due to take place this year at several major producers, there is also a heightened risk of industrial action, especially during the second half. Our forecast assumes that the operating environment will remain difficult but does not allow for any prolonged strike action.

South Africa's two largest PGM producers, Anglo American Platinum and Impala Platinum, are both undertaking major furnace overhauls this year. Implats' Number 3 furnace was taken off-line for repairs during the first quarter, while Anglo's Polokwane smelter will undergo a rebuild during the second half. At the same time, programmed maintenance will also take place at the Mogalakwena South concentrator (which supplies PGM concentrate to Polokwane). While processing plant maintenance does not affect the volume of PGM mined, it usually results in a temporary increase in work-in-progress inventories, which may take some time to draw down. As a result, both companies have reduced their production guidance for their 2022 financial years.

Although refined PGM output is set to fall, we expect underlying mine production in Southern Africa – including PGM mined in Zimbabwe and refined in South Africa – to be broadly stable this year, assuming there is no serious labour disruption. While there are a small number of projects in the ramp-up phase, these gains are being offset by depletion at some older shafts, and difficult operating conditions generally. In recent months, many mines have experienced higher-than-usual levels of operational disruption with a wide range of causes: safety stoppages, inconsistent power supplies (caused both by national 'load-shedding' programmes, and by local incidents such as cable theft), community unrest, Covid outbreaks, sporadic illegal labour stoppages, and unusually heavy rains.

North American PGM output is expected to remain weak versus historical levels, following disruption at mining operations. Vale's Totten mine – part of its Sudbury nickel operation – was closed between September 2021 and February 2022 due to damage to the shaft, while Sibanye-Stillwater's Montana mining operation has reduced its production outlook in the wake of operational challenges.

Secondary PGM supplies are forecast to contract this year, as impacts from the semiconductor crisis ripple outwards. With new car sales constrained by availability of new vehicles, rather than by lack of consumer demand, we expect prices for used cars to remain high, and vehicles to be kept on the road for longer than in the past. This is likely to act as a near-term constraint on autocatalyst scrap volumes, especially in Europe and North America, although there is still potential for some growth in recycling in other regions.

Reduced availability of catalysts in Western markets could result in a limited increase in the processing of 'difficult to treat' materials such as diesel particulate filters, as backlogs that have accumulated due to lack of processing capacity are gradually drawn down. As a result, we could see platinum recycling outperform palladium and rhodium this year.

Gross demand '000 oz	2020	2021	2022
Europe	2,791	2,716	2,956
Japan	1,091	1,071	1,131
North America	2,082	2,219	2,521
China	3,227	2,896	2,627
Rest of World	2,316	2,737	2,958
Total	**11,507**	**11,639**	**12,193**

Table 1 Combined platinum, palladium and rhodium automotive demand

Automotive production and demand

Auto industry forecasts have been downgraded in response to the war in Ukraine, and light vehicle output is now expected to remain below 80 million units this year. The direct impact of the Ukraine conflict will be relatively small: Russian light vehicle production was around 1.5 million units in 2021, while Ukraine produces only a few thousand cars and light trucks annually. However, the war has intensified risks to supply chains that were already under severe tension. In addition, Covid lockdowns in China during March and April have resulted in the temporary closure of some vehicle assembly plants, creating significant additional downside for auto production forecasts.

> "Covid lockdowns in China have hit supply chains and cut vehicle output"

Semiconductor supply remains a major source of uncertainty for automotive output in 2022. During the first quarter, there was some disruption to semiconductor finishing operations in Malaysia, due to flooding last December, while a large earthquake in Japan caused some production outages in March. The ongoing surge in Omicron infections in China has caused temporary interruptions at semiconductor manufacturers, while there are concerns that an interruption in supplies of neon gas from Ukraine might hit chip production from mid-year. Any unscheduled semiconductor plant downtime, or delays in bringing on planned new foundry capacity, would create renewed downside risks for car and truck output.

The Ukraine conflict has created other supply chain challenges for the auto industry, with production at some German automakers paused in March due to shortages of wiring harnesses made in Ukraine. At the time of writing, disruption appears to be easing, but there is clearly potential for sporadic component shortages to result in assembly lines being halted temporarily, particularly in Europe. Although most of these stoppages will be short, the cumulative impact could ultimately become material.

Over the past year, availability of vehicles has been the primary factor limiting car sales. Consumer demand for vehicles has been strong, as evidenced by steep rises in used car prices and long lead-times for new orders – suggesting that had automakers been able to make more vehicles, they would have found ready buyers. While the outbreak of war in Europe could temper consumers' willingness to spend on high-ticket items, and high inflation will leave individuals with reduced spending power, severe constraints on auto production mean that this is unlikely to have a significant further impact on global vehicle sales in 2022.

Our current forecast is for an increase in automotive PGM consumption this year (Table 1), although much will depend on how the production picture evolves. Demand in light duty applications will primarily be driven by vehicle volumes: the average PGM content of a gasoline catalyst system is expected to remain stable for a third consecutive year, as thrifting in China is balanced by higher loadings in Europe and North America. In the heavy duty sector, the average PGM content of a heavy duty diesel truck will rise by a further 30%, following a 50% rise last year, with all heavy diesel vehicles sold in China this year being fitted with China VI compliant aftertreatment systems incorporating PGM catalysts.

We expect automotive use of platinum to outperform that of palladium and rhodium, as platinum increases its demand share for a second consecutive year (Figure 10). Heavy duty diesel catalysts are platinum-rich, while platinum consumption will also benefit from further substitution in light duty gasoline applications. While platinum accounts for only a small proportion of total gasoline PGM demand, the average platinum content of a gasoline car in 2022 is forecast to rise by around two-thirds compared with last year. In particular, by the end of this year we expect European and North American automakers to begin fitting tri-metal catalysts in much greater numbers, reflecting substitution decisions taken over the past two-to-three years. In the US, these substitution programmes often target high-volume models with comparatively large engines and heavier PGM loadings, whereas in Europe substitution to date has primarily been on lower-cost, lower-margin vehicles. We also expect substitution to ramp up in China, with automakers that have already used platinum-containing formulations in the underfloor position increasingly adopting tri-metal close-coupled catalysts as well.

Last year, signs emerged that automakers' interest in further platinum-for-palladium substitution had begun to wane, as palladium and rhodium prices fell by around 50% from their peaks. Some car companies, especially in China, shifted their focus away from substitution towards thrifting the overall PGM content of the catalyst, often with considerable success (see page 9). It is possible that the Ukraine war will reignite interest in platinum-containing (usually tri-metal) gasoline vehicle catalysts, for price, availability and metal provenance reasons, but there is no direct evidence of this yet.

Industrial demand

Industrial platinum demand is forecast to retreat from last year's all-time record of nearly three million ounces but should remain unusually robust by historical standards. In particular, purchasing by glass companies is forecast to contract, because part of the platinum required for this year's fibreglass expansions was acquired in 2021. Nevertheless, demand from the glass sector should remain at or close to half a million ounces (a historically high level), reflecting the growing role of glass-fibre reinforced materials in reducing carbon emissions, in applications such as vehicle light-weighting and wind power.

Chemical demand for platinum is also forecast to be at or close to record levels, with ongoing strong use in nitric acid and silicones, and further investment in large integrated petrochemicals complexes in China. Construction of these complexes is also creating demand for petroleum refining catalysts, although this will be partly offset by the closure of some older, less efficient refineries.

In contrast, industrial purchasing of palladium and rhodium is forecast to remain below pre-Covid levels. Record prices have accelerated a long-standing trend away from palladium in dental alloys, while glass companies continue to adopt lower rhodium-content alloys for glassmaking equipment. Only in the chemicals sector has demand for palladium and rhodium been largely untouched by high prices; although some companies temporarily delayed 'top-up' purchases (to replace in-process losses) during 2021, this is only a timing issue and does not affect underlying consumption.

It is too early to judge the impact of the Ukraine crisis on industrial PGM demand. Russia consumes modest amounts of PGM in its nitric acid and petroleum refining industries but is otherwise a minor user of PGM in industrial applications. This means that the direct risk to industrial demand is small. However, indirect damage to the world economy will ultimately be negative for PGM consumption, with some capacity expansions likely to be delayed or cancelled.

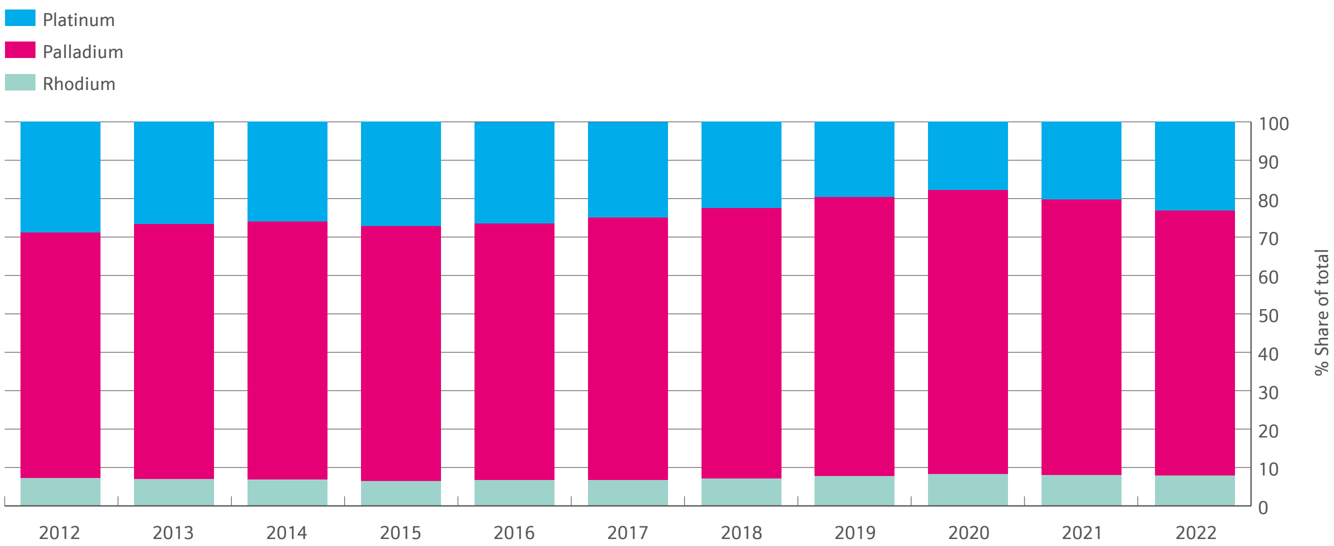


Figure 10 Share of automotive PGM demand by metal

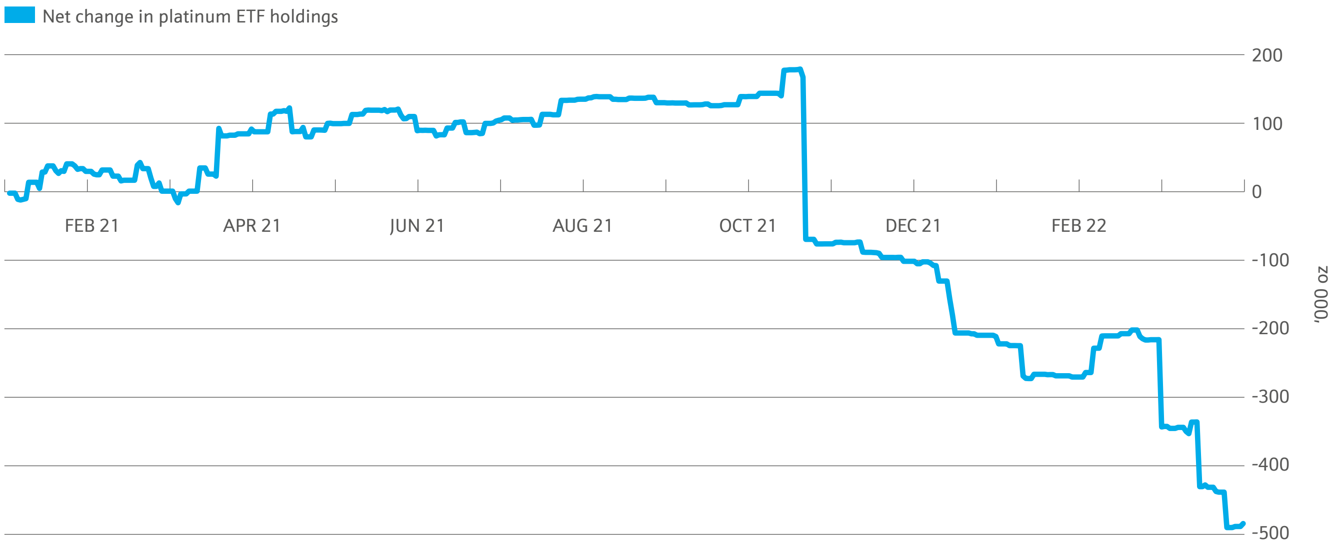


Figure 11 Net change in platinum ETF holdings, January 2021 to March 2022

PGM investment

With geopolitical tensions rising during the first quarter of 2022, PGM price volatility created both buying and selling opportunities for investors. Steadily rising platinum prices during January and February incited modest disinvestment by Japanese holders of large platinum bars, although this selling was more moderate than during the same period of 2021. As is often the case, Western investment in ETFs moved in the opposite direction: there was a limited increase in platinum ETF holdings over the January–February period.

In March, as the platinum price peaked at $1,150 and then dropped steeply back below $1,000, the situation reversed. There was heavy profit-taking in platinum ETFs in Europe, and to a lesser extent in other regions (Figure 11), while Japanese retail investors sold actively into the price peak early in the month.

Palladium ETF holdings rose marginally during the first quarter, as investors first added to their holdings, and then took profits as the price peaked at over $3,000. There have also been some very limited redemptions of rhodium ETF holdings (which are now minimal, at below 12,000 oz).

We take a neutral view of investment in ETFs and Japanese large bars for the remainder of the year (although we allow for continued positive demand in small platinum investment products). Despite elevated risks to PGM supplies, there appears to be limited appetite for fresh investment in PGM ETFs, perhaps reflecting a decrease in attractiveness of non-yielding assets in a context of rising interest rates. On the other hand, there remains potential for price movements to trigger disinvestment, more so for platinum than palladium.

Remaining palladium ETF holdings are relatively small (below 600,000 oz at the end of March 2022), and much of this metal has been held through three distinct price peaks during 2020–2022, suggesting that significantly higher prices would be required to trigger substantial new liquidation. In contrast, just under 3.5 million oz of platinum was held in ETFs at the end of March 2022; while prices remain weak, redemptions are likely to be limited, but there is potential for further profit-taking should prices rally again. The current environment is somewhat more positive for investment in Japan – low platinum prices and a tense geopolitical environment should be broadly favourable for fresh large bar purchasing by retail investors – but this market is extremely price sensitive, so any significant price gains could be met by further liquidation.

> "Japanese retail investors sold actively into the March 2021 price peak"

Market balance

Compared to recent years, investment appears less likely to play a determining role in the direction of market balance in 2022. Instead, Russian supply volumes and automotive demand trends are the key sensitivities this year.

Vehicle production forecasts have already seen cuts since the start of the year, based on continuing semiconductor shortages and supply-chain disruption aggravated by the war in Ukraine. The current Covid wave in China could trigger further downgrades, with lockdowns hitting supply chains and some automakers halting operations at their Chinese factories in April. It is possible that lower vehicle output will help mitigate the impact of a fall in PGM shipments, although this will depend on the degree of supply disruption. For palladium and rhodium, there is a risk of a move back into deficit; in contrast, platinum is expected to remain well-supplied, but there is potential for the market to be closer to balance this year than in 2021.

Special feature

Made in China

How the 13th Five Year Plan boosted industrial demand for PGM

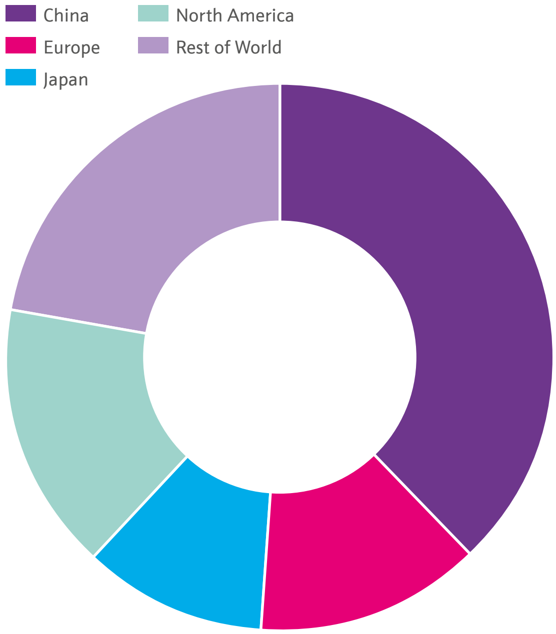


Figure 12 Regional share of industrial PGM demand, 2021

Introduction

Since the late 1990s, China has become an increasingly important market for PGM: purchasing by Chinese consumers accounted for over 30% of total world PGM demand in 2020–2021, up from around 5% in 1998. The rise of China as a major PGM user began in the late 1990s, when young Chinese consumers began to buy platinum fashion jewellery in unprecedented quantities. Platinum jewellery demand peaked in 2013, but by then China was also becoming a major user of PGM in autocatalysts, as car sales took off and emissions legislation tightened. Automotive demand in turn reached a high point in 2020, when China accounted for 28% of all PGM use on vehicles worldwide, but has since begun to recede, due to PGM thrifting and rapid growth in the market share of battery electric vehicles.

Industrial PGM use was small until the early 2000s, when the rapid development of China's economy saw steady growth in PGM requirements, especially in the chemical, glass and electronics industries. By 2011, total PGM demand in industrial applications in China had reached one million ounces annually. Demand stabilised over the next three years – in a context of lacklustre performance in the global markets served by Chinese industry – but began to regain momentum around the middle of the decade. Then, as Chinese industry entered a period of massive capacity expansion and modernisation, industrial PGM demand took off again. In 2021, Chinese purchasing of PGM for industrial applications reached 2.24 million oz, and accounted for a remarkable 38% of total world industrial demand (Figure 12).

These recent gains have been stimulated by the Chinese government's industrial policy, which is articulated in a series of Five Year Plans (5YPs). These 5YPs set broad overall goals, within which policy and objectives are developed for individual sectors such as the petroleum and chemical industry. The 13th 5YP (2016–2020) emphasised industrial modernisation, science and technology innovation, and support for emerging industries. In the petrochemicals sector, this stimulated extensive modernisation of the country's oil refining and processing base, and a drive for increased self-sufficiency in basic 'building-block' chemicals that are essential feedstocks for China's industrial production. The fibreglass industry also focussed on upgrading its production base (which had previously used older, less efficient technology), while also expanding output to meet demand from growing industries such as wind power.

PGM in petrochemical processes

The impact of the 13th 5YP on PGM demand has perhaps been most visible in the petroleum refining and chemicals industries, where there has been massive investment in modern integrated refinery complexes that incorporate traditional oil refining capabilities along with capacity to manufacture downstream bulk petrochemicals. This has driven significant demand for all the PGM, particularly platinum (Figure 13). In total, nearly 5 million oz of PGM were purchased by the Chinese petroleum refining and chemicals sectors during 2016–2020 – up from 3 million oz in the previous five-year period. While the 14th 5YP is not expected to generate massive growth on the scale of its predecessor, we expect these industries to continue to consume large quantities of PGM: demand in chemical and petroleum applications during 2021 and 2022 alone is estimated at nearly 2.2 million oz PGM, largely due to the completion of projects initiated during the previous 5YP period.

Petroleum refining

China's total crude oil processing capacity grew by 5% annually between 2015 and 2020: during this period, there was significant rationalisation at older small-to-medium sized refineries (leading to the recovery of some platinum from installed petroleum refining catalyst), but this was greatly offset by massive investment in modern integrated refineries, mainly around the Bohai Sea and the Yangtze and Pearl River deltas. These capacity expansions were required not just to supply fuels for transport and industrial uses, but also to provide feedstocks for downstream chemical processes, producing bulk chemicals for end-use applications such as plastics and textiles. This modernisation and expansion process has generated very significant demand for PGM, especially platinum, in catalytic reforming and isomerisation catalysts, with demand hitting two separate peaks: in 2018 and again in 2020 (when low prices encouraged some advance purchasing for future projects).

Bulk chemicals

While China's oil refining capacity has risen relatively moderately since the start of the 13th 5YP, growth in downstream production of bulk chemicals has been much larger. In 2016, China's chemical industry remained comparatively under-developed and highly dependent on imports. Although the country had adequate capacity for some low-value chemicals such as caustic soda and calcium carbide, it was highly reliant on external supplies of important feedstocks such as paraxylene (PX) and mono-ethylene glycol (MEG). This structural imbalance was highlighted in the 'Petrochemical and Chemical Industry Development Plan (2016–2020)', published in September 2016, and correcting this was made a primary objective of the 13th 5YP for the chemicals sector.

Multiple chemical processing steps are required to convert oil into synthetic polymers (plastics) for end-uses such as packaging, consumer and industrial textiles, and components for construction and automotive applications. Figure 14 shows how a variety of oil- or gas-based bulk chemicals are used as feedstocks for these end-products, and the PGM catalysts that are required in the manufacturing processes. There are, broadly speaking, three chemical process 'streams' in plastics production that involve a PGM catalyst for at least one production step: polyethylene terephthalate (PET), nylon and polypropylene (PP).

PGM for plastics: the polyethylene terephthalate process stream

Polyethylene terephthalate is a clear, lightweight plastic that is widely used in polyester textiles and food-grade packaging. It is made by combining mono-ethylene glycol and purified terephthalic acid (PTA) to form a polymer chain; strands of PET are then extruded, cooled, and cut into small pellets that can later be heated to melting point and moulded into virtually any shape. Palladium catalysts are used to make PTA, while production of MEG may also involve a PGM catalyst (China produces some of its MEG using coal as a feedstock, in a process that involves palladium – see below).

In addition, platinum catalysts are required to make paraxylene, a feedstock for PTA. Although China was relatively self-sufficient in PTA by 2016, it remained highly reliant on imports for its paraxylene needs. This was an important consideration in the development of new integrated petrochemical complexes, which generally incorporate large paraxylene units. Capacity for this chemical doubled over the 13th 5YP period, and by 2020 China was the world's largest paraxylene producer. At the same time, the downstream PTA industry also expanded, stimulated by growing consumer demand for plastics and synthetic textiles. By the end of the 13th 5YP, paraxylene import dependence had been reduced to about 45%, but the commissioning of additional projects should reduce this figure to around 30% by the end of 2022.

This activity stimulated strong demand for platinum and palladium in paraxylene and PTA, especially over the 2018–2020 period, as large integrated refinery projects began to be delivered (catalyst lead times are generally slightly ahead of actual project start-up times). Demand should remain robust at the start of 14th 5YP, as further paraxylene expansions come on-line. Worldwide, over the past five years (2016–2020), more than 80% of new paraxylene capacity and more than 90% of new PTA capacity has been concentrated in China.

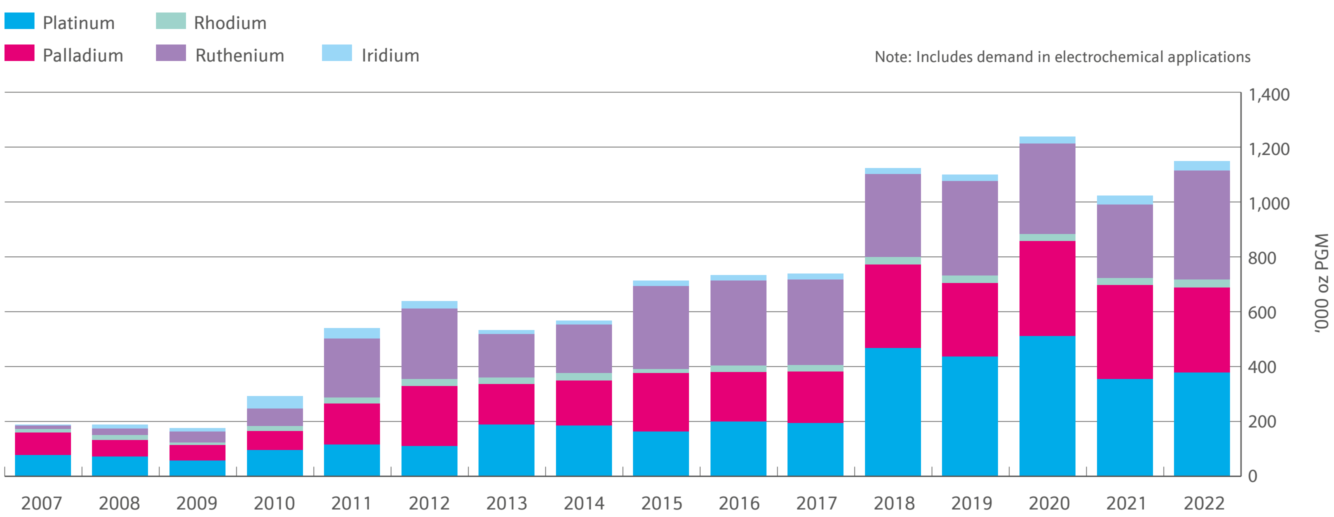


Figure 13 PGM demand in chemicals and petroleum refining in China

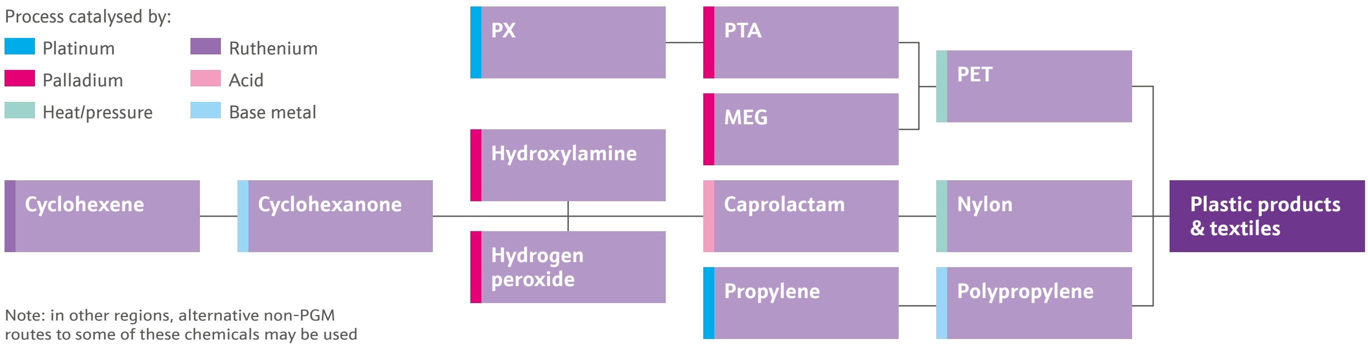


Figure 14 Typical Chinese routes to PET, Nylon and Polypropylene

PGM for plastics: the polypropylene process stream

Polypropylene is a synthetic polymer that is made by polymerising a propylene monomer. It is used in a very diverse range of applications: its relatively high melting point makes it suitable for heat-resistant food packaging, while its durability and strength make it appropriate for use in components for the electrical, construction and automotive industries.

Petroleum refineries are the primary source of the propylene used to make polypropylene: it is a by-product formed during refinery processes known as steam cracking and catalytic cracking, during which large hydrocarbon molecules are broken down into smaller molecules such as ethylene. However, since the advent of cheap shale gas in 2009 (which led to consistently low natural gas prices in the 2010–2020 period), some Chinese refineries have adopted natural gas as a feedstock for ethylene production via ethane dehydrogenation, a process which is less conducive to the formation of propylene by-product. This in turn led to the increased adoption of 'on-purpose' propylene processes, in order to meet rising domestic demand for this chemical.

One 'on-purpose' route to propylene is via the dehydrogenation of propane gas (propane dehydrogenation, PDH), a process which has also been favoured by low gas prices in recent years. The most widely used PDH technology uses a platinum catalyst. Chinese PDH capacity developed rapidly during the 13th 5YP period, growing from under 3 million tonnes per annum (tpa) in 2015 to nearly 7 million tpa in 2020. This has generated significant demand for platinum, particularly in 2020, when large amounts of platinum were purchased at low prices for use in future PDH plants. While rising gas prices have since reduced margins for on-purpose propylene production, companies appear to be continuing with the development of PDH projects, with six new plants commissioned in 2021 and many others still at the planning or development stage.

PGM for plastics: the nylon process stream

Nylon is a generic term for a family of synthetic polymers that are widely used in textiles, moulded parts, and films for food packaging. The manufacturing process route depends on the type of nylon: nylon 6 (widely used in apparel and household textiles) is formed using caprolactam as a feedstock, while nylon 66 (a more rigid, durable fibre often used in industrial applications) is produced via a reaction involving adipic acid.

PGM catalysts are not used directly in the production of these two chemicals, but are involved in a number of upstream processes. Notably, a ruthenium catalyst is widely used in China for the selective dehydrogenation of benzene to cyclohexene, a precursor for the manufacture of both caprolactam and adipic acid (outside China, plants are typically older and use alternative, non-PGM routes). This has given rise to very significant demand for ruthenium in process catalysts in recent years, with the Chinese caprolactam industry accounting for up to 20% of global demand for this metal in some years, and we expect demand to continue at relatively high levels during the 14th 5YP period.

Caprolactam has a particularly long and complex production route, involving numerous intermediate chemical steps. Some of these processes require feedstocks, such as hydrogen peroxide, that are typically produced using palladium catalysts. The development of downstream caprolactam production has therefore been a significant driver for capacity additions for these chemicals since 2016, although the impact of caprolactam capacity additions has been much less significant for palladium than for ruthenium.

What role for coal?

Oil is usually the most cost-efficient feedstock for most chemical processes, but economic and other considerations can sometimes drive the adoption of alternative inputs such as natural gas and coal. China does not have enough oil and gas production to meet its own needs, but is well-endowed with coal reserves. This has created a strong incentive for the use of alternative coal-based routes to certain bulk chemicals, partly on cost grounds but also with the objective of reducing import dependence and improving security of supply. During the 13th 5YP period, technology breakthroughs enabled the development of a coal-to-chemicals industry in China, with coal used as the feedstock for a number of bulk chemicals. One of these processes, coal-to-mono ethylene glycol (CTMEG), uses a palladium catalyst.

Some limited investment in CTMEG had already been seen prior to 2016, stimulated by very high reliance on imported ethylene glycol, but the 13th 5YP period saw massive capacity growth for this process, adding significantly to palladium demand. However, in recent years, CTMEG plants in China have sometimes been impacted by low oil prices, periodically rendering coal-derived MEG marginal or uneconomic. This has affected capacity utilisation rates and has tempered expansion plans.

Higher oil prices in the wake of the Ukraine crisis should make CTMEG more attractive, but there is still some doubt over the construction of planned new plants. While the 14th 5YP explicitly supports the coal-to-chemicals industry, many of these processes consume large amounts of energy, which may be incompatible with energy policy imperatives: since 2020, energy-intensive processes have been subject to a more stringent government approval process. It remains to be seen how many additional CTMEG projects will be approved and developed, so future palladium demand in this application is subject to particular uncertainty.

Glass fibre

After the petroleum and chemicals industry, the other large beneficiary of the 13th 5YP was the glass sector: cumulative PGM consumption during 2016–2020 reached 1.5 million oz, versus 700,000 oz in the previous five-year period. The glass industry makes extensive use of equipment made of platinum-rhodium alloys, capable of resisting the extremely high temperatures and corrosive environment involved in glassmaking (pages 33 and 34).

Growth in PGM demand during the 13th 5YP was driven by the modernisation and large-scale expansion of the country's fibreglass industry, to meet rapidly growing demand for lightweight fibre-reinforced materials from the automotive, wind power and electronics sectors. This sustained investment lifted China's glass fibre output from 3.6 million tpa in 2016 to 5.4 million tpa in 2020.

Expansion of fibreglass capacity has accelerated again during the early part of the 14th 5YP, with Chinese glass companies purchasing record amounts of platinum in 2021, for current and future expansion projects. While the approvals process for energy-intensive industrial projects was tightened in 2020 (in line with China's net zero objectives and to improve energy security), it was announced in November 2021 that the fibreglass industry would be temporarily excluded from the new measures.

Made in China: what next for PGM demand?

2021 was the first year of the 14th Five Year Plan (2021–2025), although much of the PGM demand that occurred last year was a result of expansions that were initiated in the previous five-year period. The new plan once again sets ambitious objectives for PGM-using industries: for the chemical industry, there will be increased focus on process and product innovation, enhancing safety, and optimising the geographical location of Chinese production; in the petroleum sector, the emphasis moves away from massive expansion towards right-sizing, and a focus on producing valuable chemical building blocks, rather than fuels. Green and low-carbon objectives are also a key element of the plan, with a focus on green hydrogen and the use of biomass as a feedstock for bulk chemicals.

The high-performance glass fibre and composite sector has also been singled out as a target for further development, creating a favourable environment for further investment in new glass fibre plants. There is also policy support for current initiatives to reduce the rhodium content of glass fibre bushings, reflecting the extremely high price of this metal and its limited domestic availability.

It is too early to fully anticipate the impact of industrial policies developed under the 14th 5YP, but we currently expect 2021–2025 to be a period of consolidation for Chinese PGM demand. Industrial PGM consumption in China is forecast to remain at historically elevated levels, albeit below the exceptional levels of 2021, in line with continued investment in the glass and chemicals industries. However, it is likely that PGM demand in petroleum refining has now peaked and will decline going forward (ultimately, as demand for conventional fuels falls away, we could even see some release of PGM currently installed in petroleum refineries). In its place, we would expect to see growing investment in energy-transition technologies, involving increased use of PGM in hydrogen-related applications, and potentially in new applications in the biofuels and biochemicals sectors, and for the conversion of plastic waste into chemical feedstocks. The use of PGM process catalysts often facilitates more energy-efficient reactions, with fewer unwanted by-products and reduced water consumption, so process routes involving PGM are likely to be favoured by energy and environmental imperatives.

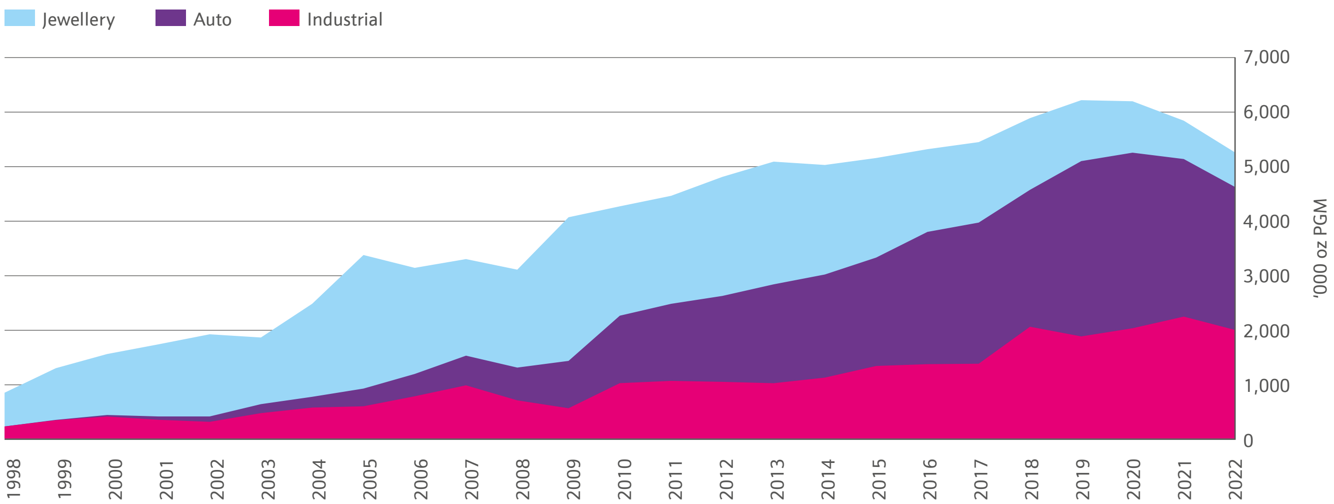


Figure 15 Chinese PGM demand by sector (excludes investment demand)

Platinum

Review of 2021

Platinum moved into surplus in 2021, as supplies recovered and investment purchasing collapsed

South African shipments surged, as the industry recovered from Covid disruption and processing outages

Industrial purchasing was at record levels, with exceptionally heavy buying from glassmakers

Auto demand was boosted by tighter truck legislation in China and higher platinum use on gasoline cars

Platinum jewellery fabrication contracted, with persistent weakness in the Chinese market

Heavy ETF liquidation in the final quarter pushed investment demand into negative territory

The platinum market moved into surplus in 2021, as supplies recovered from Covid disruption and processing outages, investment purchasing collapsed into negative territory, and jewellery fabrication contracted once again. In contrast, automotive and industrial consumption enjoyed strong growth. The auto sector benefited from buoyant heavy duty demand and an increase in platinum-for-palladium substitution in gasoline catalysts, while industrial purchasing soared to a new all-time record on the back of exceptionally strong activity in the glass sector. While our figures show a market in oversupply, trends in lease rates suggest that availability in Western markets may have tightened somewhat during 2021. We believe that much of last year's platinum surplus was acquired by Chinese market participants, who purchased platinum at low prices in anticipation of future demand, and perhaps to add to strategic holdings.

In total, 1.7 million oz of platinum were sold on the Shanghai Gold Exchange (SGE) in 2021 (Figure 16), up from 1.35 million oz in 2020 (already an exceptionally strong

"Sales of platinum on the Shanghai Gold Exchange easily eclipsed the previous all-time high"

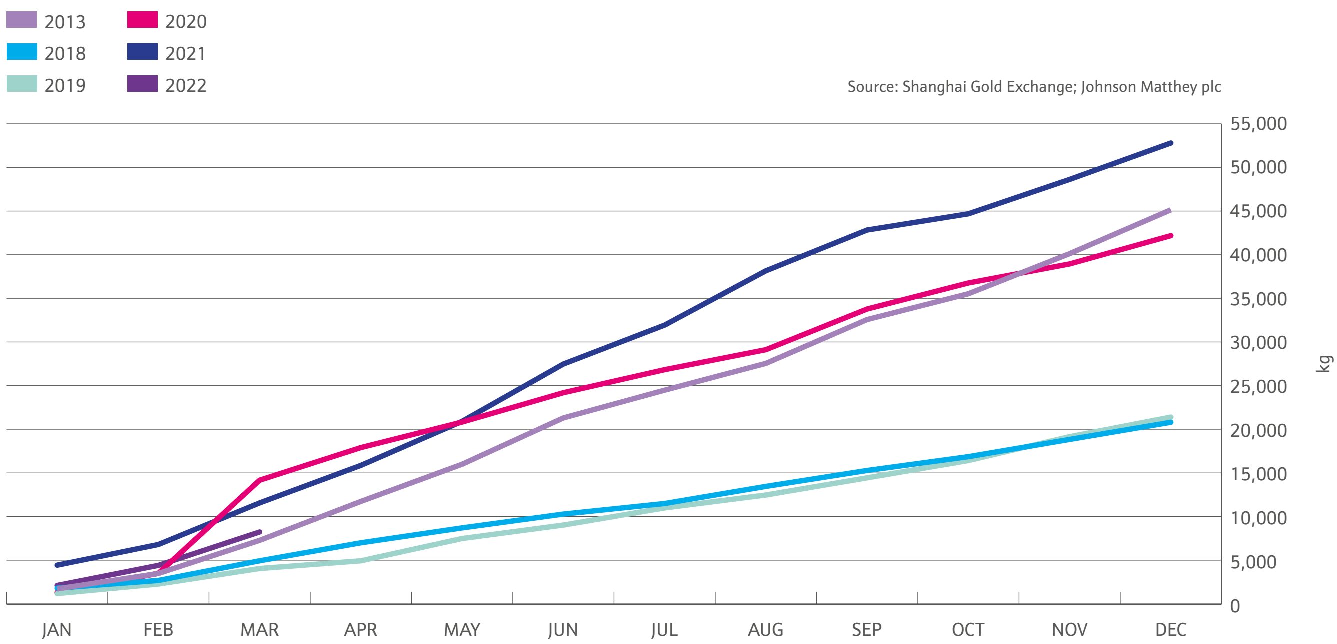


Figure 16 Cumulative SGE platinum sales

Supply '000 oz	2020	2021	2022
South Africa	3,222	4,611	4,204
Russia	699	638	-
Others	1,015	948	1,018
Total primary supply	**4,936**	**6,197**	**-**

Demand '000 oz	2020	2021	2022
Automotive	2,045	2,353	2,820
Jewellery	1,656	1,478	1,447
Industrial	2,474	2,949	2,627
Investment	1,022	-28	-92
Total gross demand	**7,197**	**6,752**	**6,802**
Recycling	-1,702	-1,659	-1,628
Total net demand	**5,495**	**5,093**	**5,174**
Movements in stocks	-559	1,104	-

Table 2 Platinum supply and demand

year). Sales easily eclipsed the previous high, set in 2013, when jewellery demand peaked at 2.1 million oz. Last year's record was set despite persistent weakness in the jewellery market, where fabrication has contracted to around a third of the 2013 peak, and where net demand (after allowing for recycling) was less than half a million ounces last year.

Trade statistics also show unusually high flows of metal from Western suppliers to Hong Kong and China (Figure 18). Cumulative net imports were well above the levels seen in recent years, and exceeded measured demand, suggesting that some degree of stock building has occurred in China.

"South African supplies recovered from Covid disruption and processing outages in 2020"

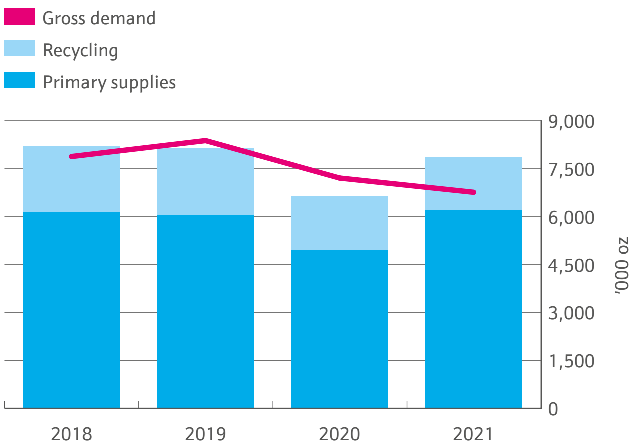


Figure 17 Platinum supply and demand

Industrial applications now dominate Chinese consumption of platinum, with industrial users in China requiring an estimated 1.27 million oz last year. Demand in industrial applications more than quadrupled between 2011 and 2021, with most of the growth coming in the last four years. This has largely been driven by state industrial policy, which has seen China invest massively in expanding domestic capacity for key industrial products. Industrial demand is discussed in more detail on page 26, while our Special Feature on page 16 takes a wider look at the impact of Chinese government policy, and in particular the 13th (2016–2020) and 14th (2021–2025) Five Year Plans, on industrial PGM consumption in China.

Outside China, demand for platinum was lacklustre in 2021, failing to regain the 2019 level. Nevertheless, lease rates remained persistently above pre-2020 levels, suggesting that availability has tightened as surplus metal has headed east.

Primary and secondary supplies

Primary platinum supplies rebounded strongly last year, climbing more than 25% to 6.2 million oz, as the industry recovered from Covid disruption and processing plant outages in 2020. Almost all of this gain came from South Africa, where shipments surged by 43% from the previous year's quarter-century low.

Anglo American Platinum had ended 2020 with a backlog of around one million ounces of PGM, following temporary shutdowns at its converter plant (ACP) that year. Much of this excess work-in-progress was released and sold during 2021, with small amounts of platinum being put to refined stocks ahead of an expected fall in output this year.

Refined output at other South African producers also rose, primarily due to a recovery in mining activity from Covid-related impacts the previous year. Overall, we estimate that underlying mine production of platinum in South Africa rose by 13%, regaining the 2019 level, with a ramp-up at newer operations (such as Northam's Booysendal mine) offsetting depletion at older shafts on the western Bushveld.

Russian platinum supplies declined by 9% to 638,000 oz. Norilsk Nickel reported the loss of around 470,000 oz of combined platinum and palladium production following the temporary closure due to flooding of two large underground mines at its Talnakh site operations, but this was partly offset by the refining of some additional PGM from the processing pipeline.

Platinum shipments from North America contracted by 17%, primarily due to very weak production of PGM by-products from Canadian nickel mines. Output at Vale was hit by a prolonged mid-year strike at its Sudbury processing operations, and by the temporary closure of the Totten mine following damage to its vertical shaft in September. More generally, PGM output from the Sudbury nickel mines has been decreasing in recent years, with average grades falling as shafts that mined relatively high PGM values reach the end of their productive lives. US platinum output also fell, due to operational difficulties at Sibanye-Stillwater's Montana mine following a fatal accident in mid-year.

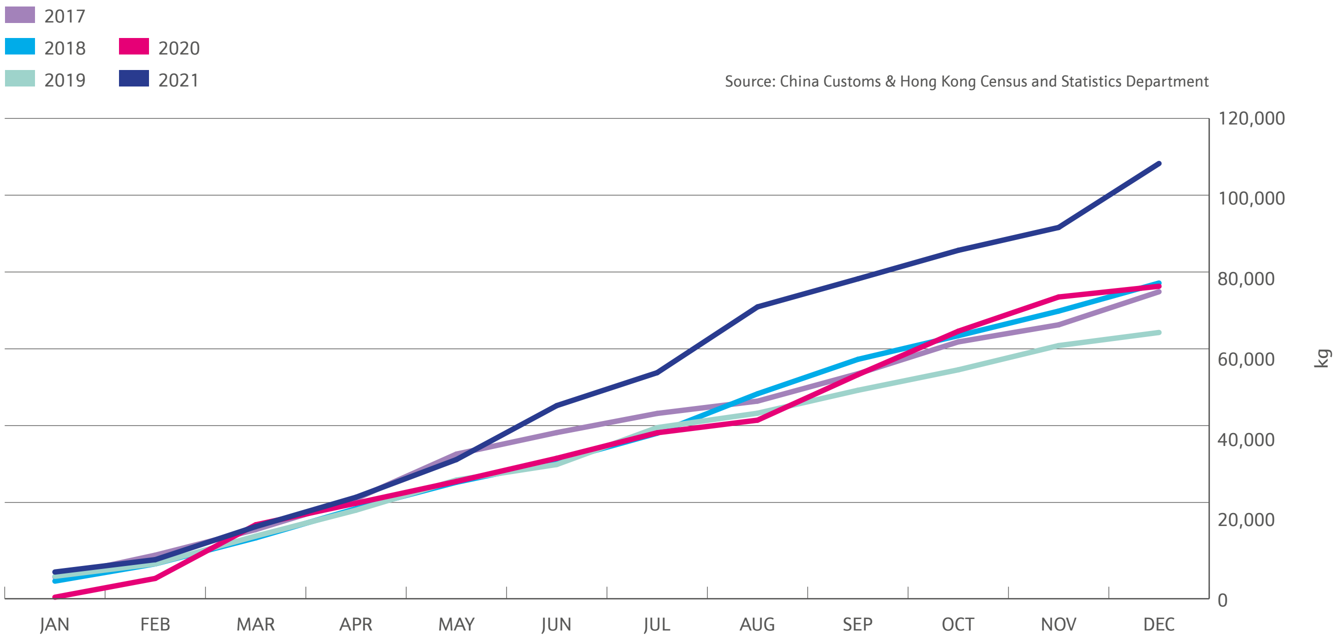


Figure 18 Net imports of platinum into China and Hong Kong

> "High prices in early 2021 prompted Japanese investors to sell platinum bars back to the market"

Secondary platinum supplies – derived from the reprocessing of jewellery, electronic and autocatalyst scrap – fell by 3% in 2021, as lower jewellery recycling in China offset higher recoveries elsewhere. Recovery of platinum from end-of-life vehicles had fallen steeply in 2020, as the Covid pandemic caused a fall in vehicle scrappage rates and created logistical difficulties for collectors. At the same time, a combination of PGM price differentials and technical considerations had made the processing of gasoline catalysts more attractive relative to diesel scrap, causing a backlog of diesel material to accumulate at various points in the scrap collection network. As a result, platinum recoveries fell much faster than those of palladium and rhodium in 2020, and recovered more slowly during the first half of last year.

As 2021 progressed, continued weakness in new vehicle sales and rising demand for used cars resulted in fewer end-of-life vehicles arriving at scrap yards, especially in the large European and North American markets. Towards the end of the year, following the sharp drop in rhodium and palladium prices and with availability of scrap increasingly constrained, there was some evidence that higher quantities of platinum-rich scrap were beginning to work through the system. We expect this trend to continue in 2022, in view of ongoing supply chain difficulties that will restrict new car deliveries and reduce the number of vehicles being scrapped.

Investment

Platinum investment demand retreated into negative territory in 2021, following two exceptionally strong years during which investors added over 2 million oz to platinum holdings. This sustained surge in investment was driven by several distinct factors, including an overspill from 'safe haven' buying in gold, concerns over supply following electricity shortages, plant outages and Covid disruption to mining in South Africa, and a perception that platinum represented 'value for money' in view of its near-term potential in gasoline autocatalysts and longer-term prospects in the hydrogen economy.

By the end of 2020, investor holdings were at historically high levels: nearly 4 million oz of platinum was held in exchange traded funds (ETFs) globally, while Japanese retail investors had accumulated more than 2 million oz of platinum bars over the previous decade. Between 2017 and 2020, the price had rarely exceeded $1,000, so when platinum ascended to a six-year high of just over $1,300 in mid-February 2021, and subsequently traded above $1,000 for much of the year, it was inevitable that some investors would seize the opportunity to take profits.

During the first half of the year, selling was particularly pronounced in the Japanese market, where investor behaviour is highly responsive to short-term movements in yen-denominated metal prices (Figure 19). The retail platinum price moved sharply higher during January and February, trading as high as ¥5,000 per gram (nearly twice the previous year's low), prompting private investors to return large quantities of platinum bars to the market. With prices remaining consistently elevated, there was also some modest liquidation of Japanese ETFs during the second quarter. However, from mid-June, the yen platinum price drifted lower, stimulating sustained new demand for platinum bars, while there was also some renewed purchasing in Japanese ETFs. Overall, Japanese platinum holdings ended 2021 only modestly lower than a year previously.

In contrast, liquidation in other regions was mainly concentrated in the final quarter of the year, when there were heavy redemptions of South African ETFs and more moderate liquidation in the European and North American funds. By the year end, platinum ETF holdings had fallen to just over 3.7 million oz.

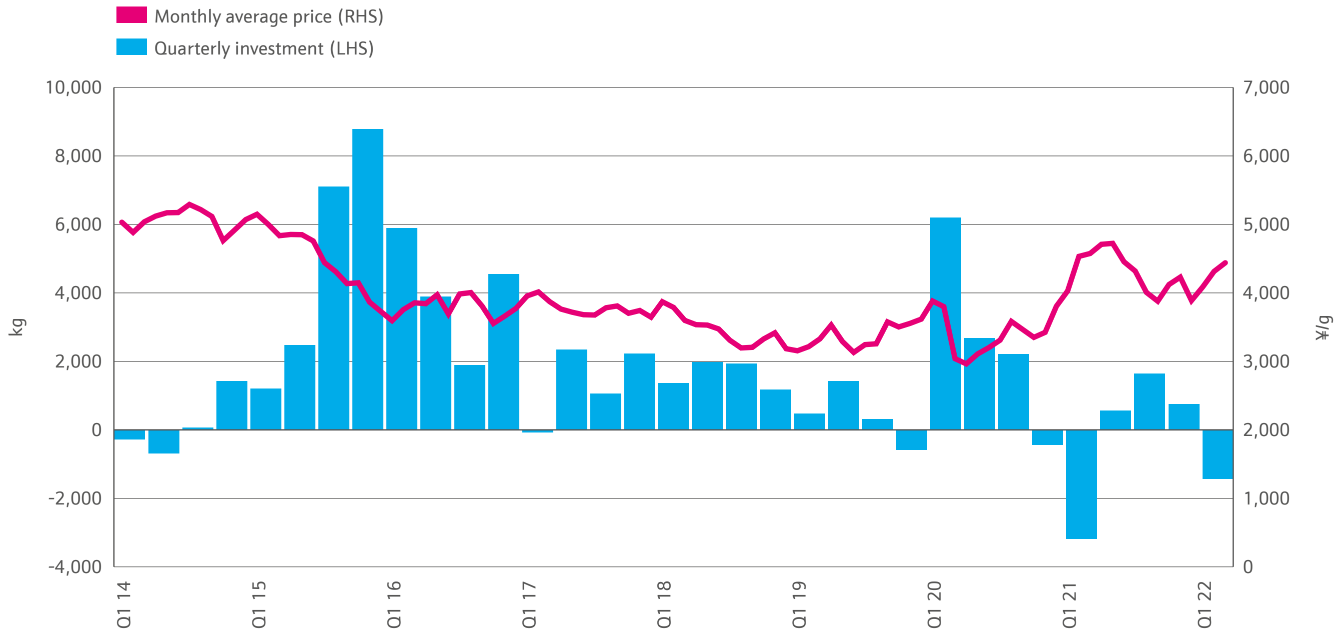


Figure 19 Japanese investment in large platinum bars

Our investment numbers include an estimate of platinum in the form of coins, small bars and wafers, sold to private investors outside Japan. Demand for these investment products was unusually strong in 2021: production of the US Mint's one-ounce bullion Platinum Eagle coin was up by a third on the previous year, while the People's Bank of China issued platinum Panda coins for the first time since 2005. This strong coin demand helped offset net disinvestment in ETFs and Japanese large bars, leaving overall investment only slightly negative.

Jewellery

Gross demand for platinum in jewellery contracted again in 2021, sliding below 1.5 million oz for the first time in thirty years, as Chinese fabrication shrank by a quarter versus the previous year.

We previously reported a surge in Chinese platinum jewellery manufacturing during the third quarter of 2020, when a steep rise in the gold price encouraged retailers to devote more counter space to platinum jewellery. However, the consumer response to increased retail stocking of platinum was lacklustre, with the result that both retail outlets and jewellery manufacturers were carrying excess inventory at the start of 2021. It has taken time to draw down this stock, dampening platinum fabrication demand.

Resurgent consumer demand for gold jewellery has contributed to platinum being side-lined: retailers have increased the amount of counter space devoted to gold, with platinum often relegated to a less prominent location in the store. Gold fashion jewellery has also become more cost competitive: the industry has switched to weight-based pricing (as opposed to per-piece pricing) for some important 'speciality' segments, including 'antique' gold and a specially hardened 24 karat product known as '5G gold'. These competitively priced products have proved very attractive to consumers, further eroding platinum's market share.

> "In China, resurgent demand for gold jewellery has led to platinum being side-lined"

In contrast, Western platinum jewellery markets showed signs of bouncing back from Covid impacts. With spending on travel and other services limited during successive pandemic waves, and government stimulus packages helping to support incomes, many consumers have redirected their discretionary spending towards luxury goods. In addition, marriage rates have rebounded from the Covid lows seen in 2020: in the USA, for example, the number of weddings rose by around 50% in 2021, boosting demand for platinum bridal rings.

Automotive demand

Our estimates of automotive demand have been restated to include platinum use in fuel cell electric vehicles (FCEV). The use of PGM in catalysts for non-road vehicles such as agricultural equipment and industrial machinery was previously included in our estimates of autocatalyst demand, but is now shown separately in a new 'pollution control' category. This latter category also includes catalysts used in small engines (for mobile generators, pumps and garden tools such as lawnmowers), and stationary source emissions control in factories. All these applications use technology similar to that used in autocatalysts.

Automotive demand for platinum rebounded from a twenty-year low seen the previous year, with all regions except Europe recording increases (Figure 20), and platinum taking a larger share of total automotive PGM consumption (Figure 10, page 14). There was an uptick in consumption of platinum in gasoline catalysis, as platinum-for-palladium substitution began to gather pace, while platinum use in the heavy duty diesel sector leapt by 50% as China implemented stricter emissions limits. However, this was partly offset by the continuing slide in global diesel car output: volumes fell a further 2.4% from the lockdown-hit 2020 total.

Demand '000 oz	Gross 2020	Gross 2021	Gross 2022	Recycling 2020	Recycling 2021	Recycling 2022	Net 2020	Net 2021	Net 2022
Europe	150	173	179	-5	-5	-5	145	168	174
Japan	237	250	259	-130	-141	-139	107	109	120
North America	210	224	231	-10	-11	-11	200	213	220
China	945	705	635	-362	-220	-200	583	485	435
Rest of World	114	126	143	-3	-3	-3	111	123	140
Total	**1,656**	**1,478**	**1,447**	**-510**	**-380**	**-358**	**1,146**	**1,098**	**1,089**

Table 3 Platinum demand: Jewellery

The light duty diesel market has traditionally been dominated by Europe: as recently as 2016, diesel car output exceeded 9 million vehicles per annum and made up nearly half of all new car production in the region. Diesel market share began to slip in 2017, as fallout from the 'Dieselgate' scandal eroded consumer confidence, and some cities announced restrictions on older diesel vehicles. Since then, there have been double-digit falls in European diesel production volumes every year, with the rate of decline accelerating in 2020–2021. Last year, light duty diesel output in Europe was just 4.15 million vehicles (Figure 21), the lowest for 25 years; production share fell below 30% for the first time since 2000. While overall light duty output was constrained by semiconductor chip shortages, diesel volumes were harder hit than gasoline or BEV, as automakers ceased offering diesel variants of some models.

The other major market for diesel cars, India, has also seen diesel market share plunge, from a high point of over 50% ten years ago, to around a quarter of light vehicles built in 2020 and 2021. The price differential between diesel and gasoline fuel has narrowed in recent years, making diesels less attractive to consumers than in the past; in addition, the introduction of Bharat VI (BSVI) legislation in 2020 significantly increased the complexity and cost of diesel aftertreatment systems, making it uneconomic to manufacture smaller diesel vehicles. Many Indian automakers have rationalised their diesel offerings over the past two-to-three years, and some have exited this segment completely.

Globally, platinum demand in the light duty diesel sector contracted by 5%, in line with the fall in production volumes. Following a period of falling diesel loadings in 2017–2018, when the use of non-PGM selective catalytic reduction (SCR) technology for NOx control gradually replaced PGM-rich NOx traps and it became increasingly common to combine the functionality of the SCR and diesel particulate filter in a single (non-PGM) catalyst brick, the average PGM content of a diesel car has been broadly stable over the last three years. It has been supported by tighter emissions limits (in particular, the adoption of BSVI legislation in India), along with changes in the diesel vehicle mix in favour of larger engines as European and Indian automakers cease producing small diesel models. In addition, the North American diesel market has been more robust than elsewhere, although diesel production here remains small in absolute terms; in this region, diesel engines tend to be reserved for the largest pick-up trucks, and PGM loadings are significantly higher than elsewhere.

"Automotive platinum demand rebounded from the twenty-year low seen in 2020"

Demand for platinum in gasoline emissions control accelerated in 2021, although platinum's share of the gasoline PGM mix remained small. Prior to 2020, platinum use in gasoline aftertreatment was largely confined to Japanese automakers (and their transplants in other regions). These companies never fully transitioned to palladium-rhodium technology, retaining some platinum in their gasoline catalyst systems based on strategic considerations such as PGM availability and the 'mine mix'.

While these Japanese car companies remain some of the heaviest users of platinum on gasoline vehicles, last year saw the first material impact from the roll-out of platinum-containing systems at automakers in regions where there was previously little or no platinum in the gasoline PGM mix. This substitution activity has mainly been cost-driven; it has therefore been most pronounced at price-sensitive domestic Chinese automakers and in the USA, where average vehicles are larger and PGM loadings significantly higher than elsewhere.

Chinese domestic automakers were among the first to adopt substituted parts, initially in the cooler 'underfloor' position where PGM loadings are comparatively light, and more recently in the 'close-coupled' location, close to the engine, where

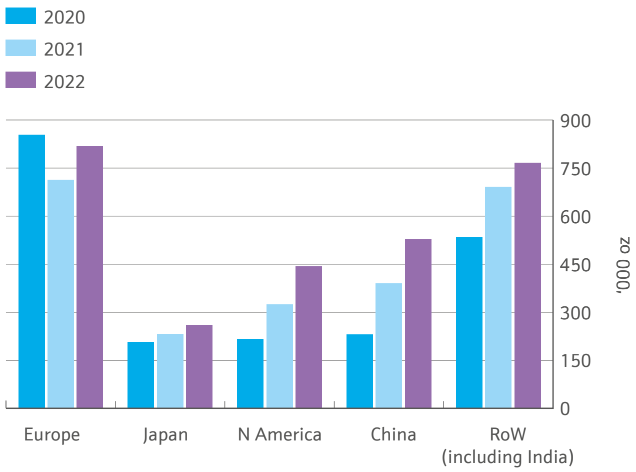


Figure 20 Automotive demand for platinum (gross)

catalyst bricks have a much higher PGM content. The process of rolling-out new catalyst formulations is much more rapid in China than elsewhere, partly because automakers (especially domestic companies) are highly responsive to cost pressures, and partly because they are permitted to self-certify emissions compliance. As a result, there was a marked acceleration in Chinese use of platinum in gasoline catalysts during 2021.

While China has so far been at the forefront of platinum-for-palladium substitution, there has been a noticeable reduction in enthusiasm for further substitution at Chinese automakers over the past year. Improvements in engine technology and greater experience with China 6 aftertreatment systems have enabled car companies to achieve dramatic reductions in the PGM content of their vehicles, substantially reducing overall metal costs. At the same time, steep falls in palladium and rhodium prices during the second half of 2021 reduced the financial incentive to substitute. Nevertheless, we still expect platinum use to rise in 2022, reflecting substitution programmes that are already being implemented.

"China and North America saw a marked acceleration in the use of platinum in gasoline catalysts"

Some US automakers were also early adopters of tri-metal technology, and platinum use in gasoline applications rose strongly in 2021, albeit from a low base. In North America, the accelerated-ageing protocols employed in catalyst testing (to simulate catalyst performance over the lifetime of the vehicle) are relatively conducive to the use of platinum-containing catalysts. These ageing protocols vary between regions, and to some extent between automakers; in China and the USA they tend to be comparatively benign for catalyst durability, with lower testing speeds limiting the peak temperatures to which the catalyst is exposed. This facilitates the use of platinum.

In Europe, ageing protocols are harsher, to reflect higher real-world driving speeds in this region. This means catalysts are exposed to higher temperatures for longer periods, making substitution with platinum more technically challenging.

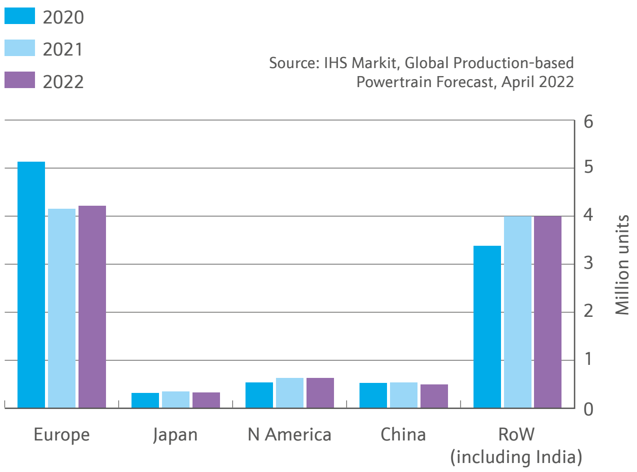


Figure 21 Light duty diesel vehicle production by region

Gross demand '000 oz	2020	2021	2022
Europe	856	715	820
Japan	208	232	261
North America	216	324	444
China	231	390	528
Rest of World	534	692	767
Total	**2,045**	**2,353**	**2,820**

Table 4 Platinum demand: Automotive

European automakers also have to contend with strict real driving emissions (RDE) and in-service conformity requirements, making them more risk-averse and less willing to change catalyst formulations. Although there was some very limited replacement of palladium with platinum in this region during 2021, the impact on demand was negligible. However, we expect European platinum use in gasoline applications to accelerate this year, with platinum being adopted in underfloor catalysts at some volume automakers.

While the gasoline sector saw the largest percentage increase in platinum demand in 2021, the largest gains in absolute terms came from the heavy duty diesel sector, which uses platinum and palladium in diesel oxidation catalysts (DOC) and diesel particulate filters (DPF). Typically, platinum accounts for between two-thirds and three-quarters of the total PGM loading on diesel aftertreatment systems.

Outside China, all regions saw growth in platinum use in the heavy duty sector, in line with a recovery in truck production from Covid disruption the previous year. Meanwhile, Chinese heavy duty demand trebled, as the full enforcement of China VI legislation from July 2021 compelled the fitment of platinum-containing aftertreatment systems on all heavy diesel trucks. Earlier legislation could usually be met using SCR technology (often without any PGM bricks at all), but the new standards require more extensive use of both DOCs and DPFs. While light duty diesels are often equipped with a combined SCR and particulate filter (SCRF) that does not contain PGM, heavy diesel vehicles are almost always equipped with a platinum-rich particulate filter.

Our automotive numbers now include platinum used in light and heavy duty FCEVs (platinum used in other fuel cell applications is reported in our electronics demand estimate). Platinum demand more than doubled in 2021. While light duty vehicles remained the largest source of fuel cell demand, last year also saw material demand from the heavy duty sector for the first time, and this is expected to become an increasingly important driver of demand in fuel cell vehicle applications going forward.

As discussed in our last report, fuel cell buses and commercial vehicles have emerged as a key part of China's New Energy Vehicle strategy. Hydrogen fuel cells are considered by Chinese policy makers to offer a practical solution to the need for zero-emissions vehicles in heavy duty segments where the use of batteries alone is not optimal. This assessment has also informed the thinking of prominent Western vehicle manufacturers and their key suppliers in the commercial truck sector, with several companies actively developing fuel cell powertrains for use in long-haul heavy duty vehicles.

See page 32 of our May 2021 PGM market report for a special feature focusing on the future development of the hydrogen market and the role of PGM technologies.

Industrial demand

Industrial platinum demand set a new record of nearly 3 million oz (Figure 22), with the glass industry accounting for nearly a third of that total – by far the highest single-year demand total ever seen in this sector.

Expansion activity in China's fibreglass industry moved into top gear, reflecting rising needs for strong, lightweight glass-fibre reinforced materials in the wind power, telecommunications, construction and automotive industries. In addition to buying metal for fibreglass plants constructed during 2021, glass companies made advance purchases ahead of capacity expansions that will be delivered in 2022.

Platinum demand in the fibreglass sector has also benefited from price-driven changes in the composition of alloys used in 'bushings' (solid metal recipients with multiple nozzles through which molten glass is extruded to form fibres). These alloys have traditionally contained between 10% and 20% rhodium (the balance being platinum), but some glass companies have begun to adopt alloys with a lower rhodium content, in response to exceptionally high prices. Because rhodium is less dense than platinum, each ounce of rhodium removed must be replaced by approximately 1.7 ounces of platinum, assuming that bushing dimensions remain unchanged (in practice, changes in alloy composition may also necessitate the redesign of bushings, typically reducing their weight slightly). Over the past two years, this process has resulted in a significant increase in the average platinum content of the installed base of glassmaking alloys.

"Fibreglass expansions moved into top gear, lifting platinum purchases by glass companies above 900,000 oz"

Sales of platinum to chemical and petroleum companies were robust last year, although demand did not quite recover to 2019 levels. This was partly because of some advance buying during 2020, when Chinese petrochemicals companies took advantage of weak prices to acquire metal for future expansions.

Globally, chemical demand is underpinned by platinum catalysts used to produce speciality silicones widely employed in food-grade packaging, medical and automotive applications. Unlike most other chemical processes (where PGM catalyst is recovered and refined at the end of a production campaign), the platinum used in silicone manufacture is entirely consumed during the process. Demand is therefore directly linked to production volumes, which recovered strongly in 2021 following Covid disruption the previous year.

Nitric acid is the other mainstay of global platinum demand in the chemicals sector. Although platinum in spent catalyst gauze is recovered at the end of each production campaign, in-process losses are higher than in most other chemical processes (except silicones), meaning that annual demand is significant even in the absence of capacity expansions.

Demand for platinum process catalysts used in the manufacture of bulk petrochemicals remained above historical levels, with demand once more concentrated in China. Purchases of platinum process catalysts in China have been exceptionally elevated over the last four years: a focus on increasing domestic self-sufficiency in key bulk chemicals in the 13th Five Year Plan (2016–2020) has stimulated massive expansion of domestic Chinese petrochemicals capacity. Our special feature on page 16 examines the impact of Chinese industrial policy on PGM demand.

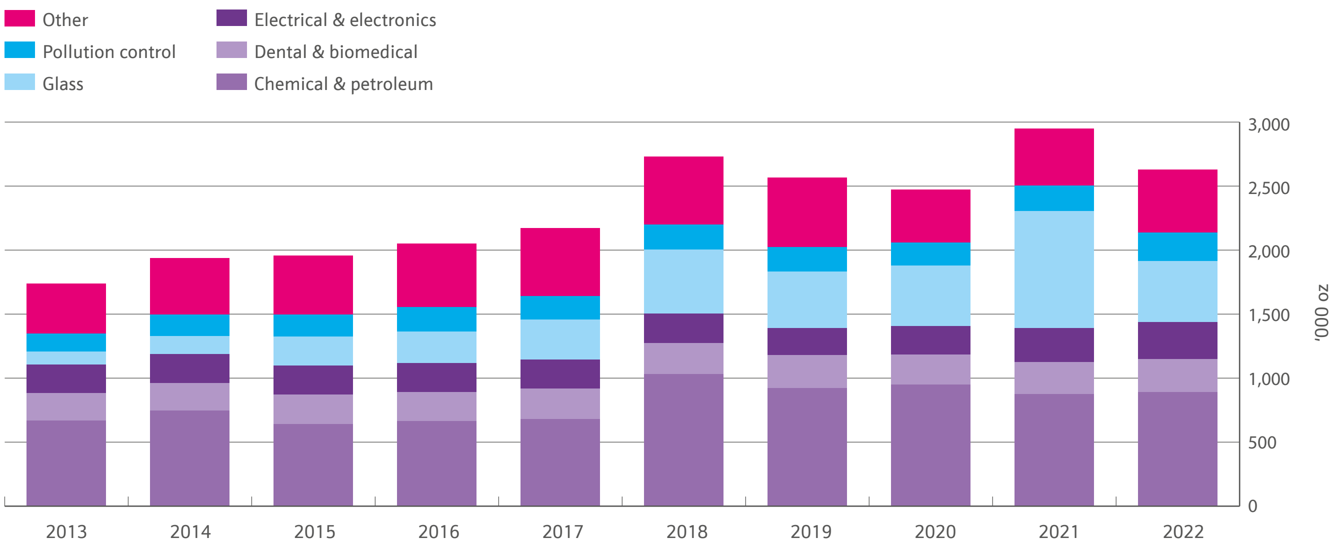


Figure 22 Industrial demand for platinum

Demand '000 oz	2020	2021	2022
Chemical	616	638	662
Dental & biomedical	233	251	256
Electrical & electronics	221	266	289
Glass	476	913	475
Petroleum	335	236	231
Pollution control	176	199	224
Other	417	446	490
Total	**2,474**	**2,949**	**2,627**

Table 5 Platinum demand: Industrial

These integrated petrochemicals complexes incorporate traditional petroleum refining units, so their construction has also been positive for platinum consumption in naphtha reforming catalysts. Nevertheless, global platinum demand from the petroleum sector contracted last year, partly because Chinese companies had already bought much of the metal they needed when prices fell to multi-year lows in 2020, and partly because of refinery closures in other regions.

"Large fuel cell systems were deployed for power generation in Korea"

Demand for platinum in electrical and electronics applications rose by over 20% last year. This category includes consumption in electronic plating, thermocouples, non-automotive fuel cells, and hard disks, with the latter accounting for the largest share of demand. While the hard disk industry faces some headwinds, notably from the adoption of solid-state drives in most consumer electronic devices, this has been more than offset by rapid expansion of the cloud storage industry. Hard disks are still the dominant technology used in data centres, and these facilities continue to add to their storage capacity, in line with global trends in favour of increased home-working and greater consumption of online entertainment.

Platinum demand in stationary fuel cells also enjoyed strong growth, with increasing deployment of large fuel cell systems in Korea for power generation. The South Korean Government announced a Hydrogen Portfolio Standard (HPS) in 2020 for full implementation by this year; this is distinct from the Renewable Portfolio Standard and is intended to accelerate the hydrogen economy. Electricity generated by fuel cells falls under the HPS and is subject to specific targets and support for increased deployment. A variety of fuel cell technologies will be employed, but platinum-containing technologies are taking a material share of this market.

Our new 'pollution control' category captures PGM use in emissions control in non-automotive applications. In recent years, tightening emissions legislation in Europe, North America and Japan has resulted in catalyst fitment to all non-road mobile machinery with internal combustion engines, although gradual thrifting of PGM loadings and modest increased use of batteries has tended to dampen the growth in demand. In China, demand for PGM in non-road emissions control remains small, with catalyst use mainly confined to very small engines. However, the fitment of PGM-containing aftertreatment systems to larger mobile equipment has begun to rise, ahead of the introduction of new China IV regulations, which are scheduled to be enforced from December 2022.

Palladium

Review of 2021

A shortage of liquidity drove palladium to a peak of $3,000 in May 2021

The price fell below $1,600 in December, as South African supplies recovered strongly

Russian shipments rose slightly, despite the temporary closure of two large mines

Secondary supplies increased, as a backlog of auto scrap was recycled

Auto palladium demand was hit by weak gasoline car output, substitution, and thrifting by Chinese automakers

Industrial demand saw a modest recovery, with strong purchasing by the chemicals sector

Following unusual market tightness in early 2021, availability of palladium improved progressively, as South African supplies recovered from processing outages the previous year, and automotive demand slid by 2%. With severe semiconductor shortages acting as a constraint on vehicle production, automakers increased their output of battery electric vehicles (BEV) at the expense of gasoline and diesel models. The impact on demand was exacerbated by thrifting programmes at Chinese domestic car companies, where palladium loadings were reduced for a second consecutive year.

Availability and market balance

Last year saw extreme contrasts in palladium availability: unusual tightness during the first half of the year gave way to increasing liquidity from mid-year onwards, driving the price down from a peak of $3,000 in May to a low of under $1,600 in December. This reflected a progressive recovery in South African shipments, as Anglo American Platinum processed the backlog from its 2020 converter outages, combined with intensifying weakness in world automotive markets. Car makers facing severe semiconductor shortages chose to shift resources into BEV production, in response to strong consumer demand for zero emission vehicles and to meet carbon emissions targets: the result was a fall in gasoline vehicle output in all regions except the Rest of World.

With PGM purchasing by the auto industry flagging just as supplies were returning to normal levels, palladium market liquidity improved significantly. While our estimates show a market close to balance (i.e. supply and demand closely matched), it is likely that other mechanisms also contributed to an improvement in availability. In particular, there were net imports into the two major market clearing locations, Switzerland and the UK during 2020–2021 (Figure 24). This suggests that a combination of sustained high prices, periodically elevated lease rates, and persistent sponge premiums over ingot may have encouraged the mobilisation and delivery of market stocks, and the conversion of some ingot into sponge.

"Automakers facing severe semiconductor shortages shifted resources into BEV production"

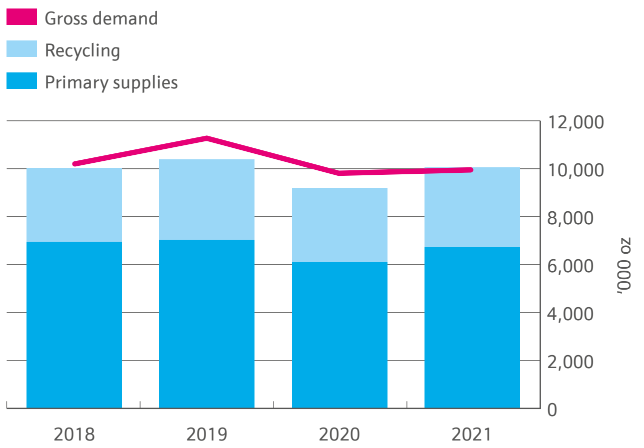


Figure 23 Palladium supply and demand

Palladium supplies

Primary supplies of palladium rose by 10% in 2021, as South African deliveries surged higher following processing plant outages at Anglo American Platinum the previous year. Compared to other South African producers, Anglo's PGM production split is palladium-rich, due to the large contribution from the Mogalakwena open-cast operation that mines over half a million ounces of palladium annually. The company's palladium sales rose by over 75% last year, as the bulk of the ACP backlog was processed.

Russian shipments rose slightly, despite the temporary closure of two Norilsk Nickel mine shafts that resulted in the loss of an estimated 470,000 oz of PGM output. The company was able to maintain its supplies to the market by reducing its refining pipeline and selling some stocks of refined palladium that had been put aside the previous year.

"High prices incentivised scrap yards and collectors to expedite the dismantling and reprocessing of palladium-rich catalysts"

There was also an increase in secondary supplies, primarily from autocatalyst recycling. During the early months of the year, the auto scrap industry saw strong volumes, as a backlog of scrap and semi-processed materials that had accumulated during 2020 worked through the recycling network. At the same time, high prices incentivised scrap yards and collectors to expedite the dismantling and reprocessing of palladium-rich catalysts.

However, from mid-year onwards, European and North American collectors reported a gradual reduction in volumes of autocatalyst scrap, primarily due to a shortfall in new auto production, which has driven up used-car values and has resulted in older vehicles being kept in service for longer. Availability of spent catalyst – especially palladium-rich gasoline catalysts – worsened significantly during the final quarter, but because of long processing pipelines the impact on recoveries will primarily be seen in 2022.

Automotive demand

Automotive palladium demand declined by 2% to 8.34 million oz in 2021, in the wake of a 12% drop the previous year. World gasoline vehicle production rose marginally, but the average palladium content of a vehicle dropped slightly, due to a combination of thrifting in China, increased use of platinum-containing formulations (displacing some palladium), and a

Supply '000 oz	2020	2021	2022
South Africa	1,975	2,652	2,486
Russia	2,636	2,689	-
Others	1,551	1,453	1,521
Total primary supply	**6,162**	**6,794**	**-**

Demand '000 oz	2020	2021	2022
Automotive	8,503	8,340	8,411
Jewellery	85	91	93
Industrial	1,556	1,649	1,642
Investment	-190	17	0
Total gross demand	**9,954**	**10,097**	**10,146**
Recycling	-3,145	-3,363	-3,211
Total net demand	**6,809**	**6,734**	**6,935**
Movements in stocks	-647	60	-

Table 6 Palladium supply and demand

change in the regional share of production. Gasoline car output rose strongly in the Rest of World region, where the average PGM content of a catalyst system tends to be lower, but fell in Europe and North America, where loadings are highest.

There were wide regional disparities in thrifting and substitution activity. In China, domestic automakers have made significant progress in reducing the PGM content of their gasoline catalysts, to the extent that thrifting appears to have displaced substitution as the primary mechanism by which car companies intend to

"In China, domestic automakers significantly reduced the PGM content of their gasoline catalysts"

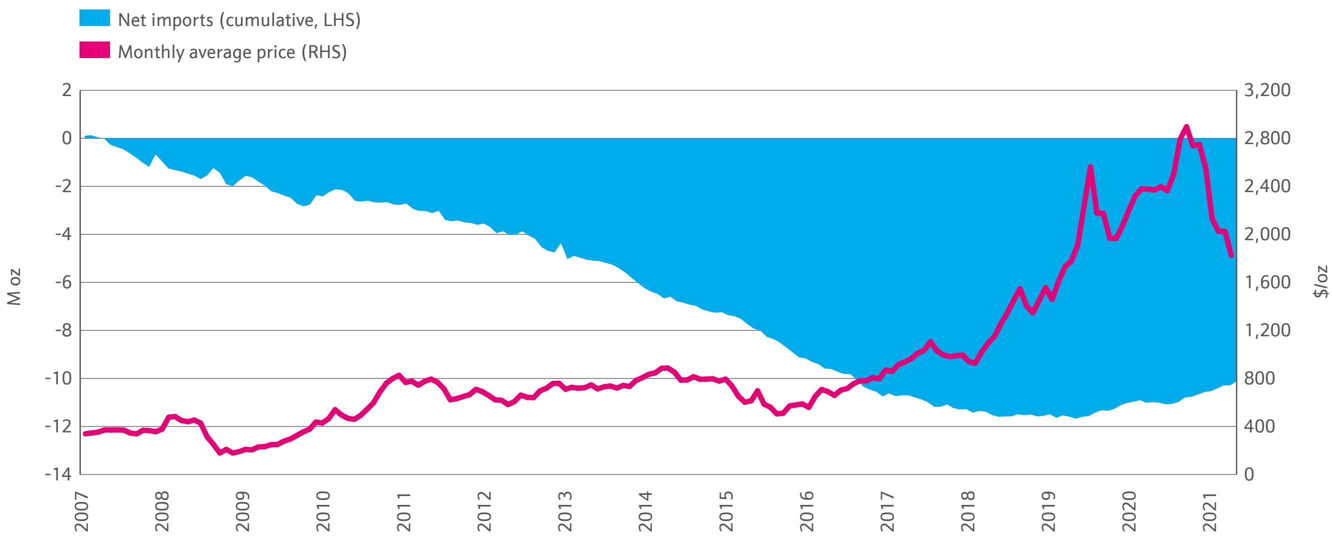


Figure 24 Cumulative net imports of palladium into the UK and Switzerland since 2007

Gross demand '000 oz	2020	2021	2022
Europe	1,786	1,849	1,971
Japan	777	740	768
North America	1,701	1,723	1,880
China	2,631	2,186	1,821
Rest of World	1,608	1,842	1,971
Total	**8,503**	**8,340**	**8,411**

Table 7 Palladium demand: Automotive

reduce their PGM costs. With the first phase of China 6 light duty emissions legislation fully enforced since July 2020 – and the next stage not due for implementation until mid-2023 – the industry has had some breathing space to focus on improving engine performance and cutting engine-out emissions. This means that catalysts have less work to do, and facilitates the removal of some PGM from aftertreatment systems. Overall, we estimate that average PGM loadings on Chinese gasoline vehicles were trimmed by more than 10% in 2021.

This reduction disproportionately affected palladium, because last year also saw the first material impact of platinum-for-palladium substitution on Chinese gasoline vehicles. Last year, platinum-containing catalysts were adopted on some domestic car models in China, primarily in the 'underfloor' position where loadings are relatively low, and this modestly reduced palladium's share of the gasoline PGM mix.

"All new cars registered in Europe in 2021 were required to meet the full Euro 6d standards"

While further substitution is expected this year, as the use of platinum in the higher-loaded 'close-coupled' position becomes more widespread, recent successes in thrifting could contribute to a slower pace of substitution going forward. Although emissions legislation will tighten again in July 2023 – when China 6b limits will be imposed and real driving emissions (RDE) testing will come into force – the new standards are expected to be somewhat easier to meet than the equivalent European regulations. In particular, the China 6b RDE protocol does not include a cold-start requirement, while NOx 'conformity factors' (CF: the allowance by which real driving emissions may exceed laboratory test limits) are expected to be significantly less onerous than in Europe. As a result, automakers may be able to meet China 6b RDE standards without increasing loadings, and there may even be scope for further thrifting. This is likely to reduce car companies' appetite for new substitution programmes.

In contrast, legislation in Europe and North America is still tightening, so thrifting programmes have yet to have a material impact on average PGM loadings. Where automakers have implemented cost-saving initiatives targeting PGM, they have to date been more focussed on substitution, although this is still in its early stages and uptake of platinum-containing catalyst formulations varies widely between companies.

European demand for palladium on gasoline cars enjoyed moderate growth in 2021, despite semiconductor shortages that depressed vehicle output below the previous-year level, and some limited adoption of tri-metal catalyst formulations. All new passenger cars registered in 2021 were required to meet the full Euro 6d standards, under which conformity factors applied during RDE testing are reduced from 2.1 (under Euro 6d-temp) to 1.43. This was the primary driver of double-digit growth in average PGM loadings, which hit a new record (and probably the peak in the current emissions legislation cycle). Although platinum took some of that growth, substitution has been slower to get off the ground in Europe than in some other regions.

The average palladium content of a US gasoline vehicle also rose in 2021, as an increasing proportion of new registrations met very strict SULEV standards under US Federal Tier 3 legislation. However, this gain was largely offset by lower output of gasoline vehicles, leaving palladium use little changed. Adoption of tri-metal formulations is proceeding somewhat more quickly in North America than in Europe, and this had a modest but material impact on US palladium consumption last year.

With BEVs, substitution and thrifting chipping away at demand in more mature markets, it was the Rest of World region that saw the strongest gains in automotive palladium use in 2021. Light vehicle production rebounded by 9%, and most of these gains were concentrated in the gasoline sector (BEV market share remains very small in most Rest of World markets). Palladium demand growth was particularly strong in India: Bharat VI legislation was fully enforced from April 2020, and has contributed not only to higher catalyst loadings, but also to a move away from diesel in favour of gasoline engines in the light duty sector. Gasoline cars accounted for around three-quarters of production in 2021, versus 60% just three years earlier.

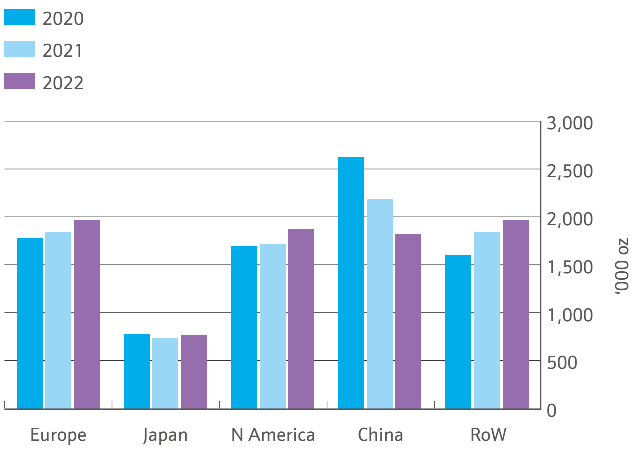


Figure 25 Automotive demand for palladium (gross)

Industrial applications

Industrial demand for palladium is increasingly dominated by the relatively price-insensitive chemicals sector. Consumption in this sector has been unusually elevated over the past four years, and remained close to all-time highs in 2021, with Chinese industrial

Demand '000 oz	2020	2021	2022
Chemical	524	589	614
Dental & biomedical	228	210	191
Electrical & electronics	634	655	644
Pollution control	76	96	109
Other	94	99	84
Total	**1,556**	**1,649**	**1,642**

Table 8 Palladium demand: Industrial

policy continuing to support strong investment in the production of bulk chemicals (see our special feature on China on page 16).

Consumption of palladium in electronics has been in steady decline for many years, with palladium being progressively supplanted by nickel in multi-layer ceramic capacitors (MLCC), once a million-ounce application but now accounting for less than 200,000 oz annually. However, substitution in MLCC appears to be slowing, with palladium use now concentrated in speciality applications such as medical and military where it can be more challenging to qualify new materials and where cost pressures are less significant. With a post-Covid recovery in capacitor production last year, palladium use in MLCC showed some modest gains for the first time in fifteen years.

The use of palladium to plate electronic components such as connectors and lead-frames also increased, in line with strong consumer demand for end-products. Palladium is used alongside gold in this application, and while there are theoretically some opportunities to switch metals in response to price incentives, in practice there are technical hurdles to overcome. With both metals trading close to record levels during 2021, there was limited economic impetus to drive new palladium thrifting programmes.

"Chinese industrial policy supported palladium use in the Chinese chemicals sector"

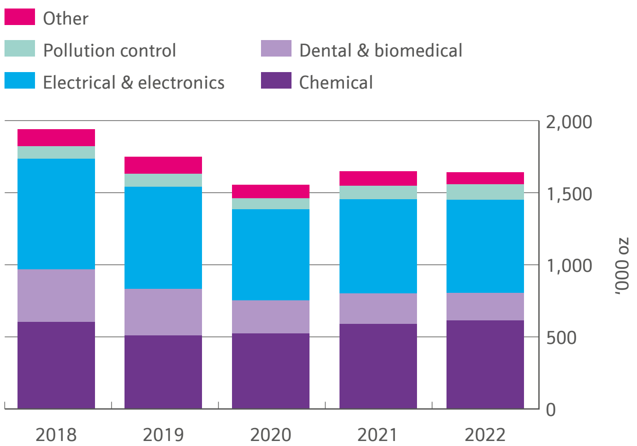


Figure 26 Industrial demand for palladium

In contrast, the destruction of dental demand continued last year, with high prices pushing dentists to adopt alternative materials (either cheaper metal products, such as base metal alloys, or alternative materials such as ceramics and resin). Japan remains the largest dental market, mainly because the government has historically subsidised the use of 'Kinpala' alloy, which has a palladium content of 20%. While procedures using 'Kinpala' alloy continue to be covered by the state health insurance scheme, reimbursement levels are determined by an alloy price that is usually fixed at quarterly intervals. In recent years, unusual volatility in the palladium price has meant that the actual cost of 'Kinpala' alloy has frequently been above the level of reimbursement, with the result that dentists must cover the shortfall. As a result, Japanese dentists are increasingly turning to alternative materials and the market share of 'Kinpala' alloy has declined sharply over recent years.

Investment

Following continuous liquidation of palladium ETFs between 2015 and 2020, total holdings had fallen from a peak of nearly 3 million oz to less than 600,000 oz by the start of 2021. Despite record prices, there was limited further profit-taking last year; indeed, some limited net ETF buying emerged for the first time since 2014. Overall, however, investor interest in palladium appears to have virtually dried up. This is due to a combination of factors, including elevated prices and wide spreads (which limit the upside for investors), along with widespread recognition of the risk posed by BEVs to future palladium demand. Over the last eighteen months, there has been only a very muted investor response to two separate threats to Russian supplies: the temporary closure of two large mines at Norilsk Nickel in February 2021, and the invasion of Ukraine a year later. Instead, precious metal investors have turned to gold, the traditional safe-haven asset.

"Despite supply risks, investor interest in palladium ETFs has virtually dried up"

ETFs have usually accounted for the majority of palladium investment, but over the years mints have periodically issued bullion coins, typically purchased by retail investors and collectors. During 2021, the US Mint issued over 20,000 oz of proof and bullion palladium Eagle coins, but this was offset by the return of older coins and bars to the market in response to high prices.

Rhodium

Review of 2021

The rhodium market moved into surplus following two years of significant deficit

Extreme contrasts in availability saw rhodium peak at $30,000 then plunge to $11,000

Supplies from South Africa normalised progressively, following processing plant outages in 2020

Exceptionally high prices stimulated reductions in the rhodium content of glassmaking alloys

Auto demand fell, as thrifting by Chinese automakers outweighed tightening legislation elsewhere

"A severe liquidity squeeze saw the price climb to an all-time high of $30,000 in March 2021"

Rhodium consumption fell slightly in 2021, hit by a combination of weak gasoline car production, thrifting of PGM loadings at Chinese automakers, and changes in the composition of glassmaking alloys. In contrast, combined primary and secondary supplies rose strongly: a backlog of PGM was refined in South Africa, while recycling of spent autocatalysts staged a modest recovery after Covid disruption the previous year.

Although the market moved into surplus on an annual basis, the year was one of extreme contrasts. During the first four months of 2021, demand outstripped supply, as vehicle production staged a modest recovery and primary supply remained constrained in the wake of mining disruption and processing outages during 2020. This created a severe liquidity squeeze which saw the price climb steadily from $17,000 in January to an all-time high of $30,000 in March.

Thereafter, the price moved into reverse, falling back below $20,000 in June (Figure 27), as the outlook for automotive production became steadily gloomier, and supplies from South Africa normalised. In September, rhodium plunged briefly below $12,000, as auto industry forecasters sharply downgraded vehicle production outlooks, before stabilising around $14,000 for the remainder of the year.

While rhodium lost over half its value between April and September, the price remained extremely elevated by historical standards: the September 2021 low point was above the pre-2020 record of $10,000 set in June 2008. While liquidity improved significantly during the second half of the year, and the market moved into oversupply, our figures probably overstate

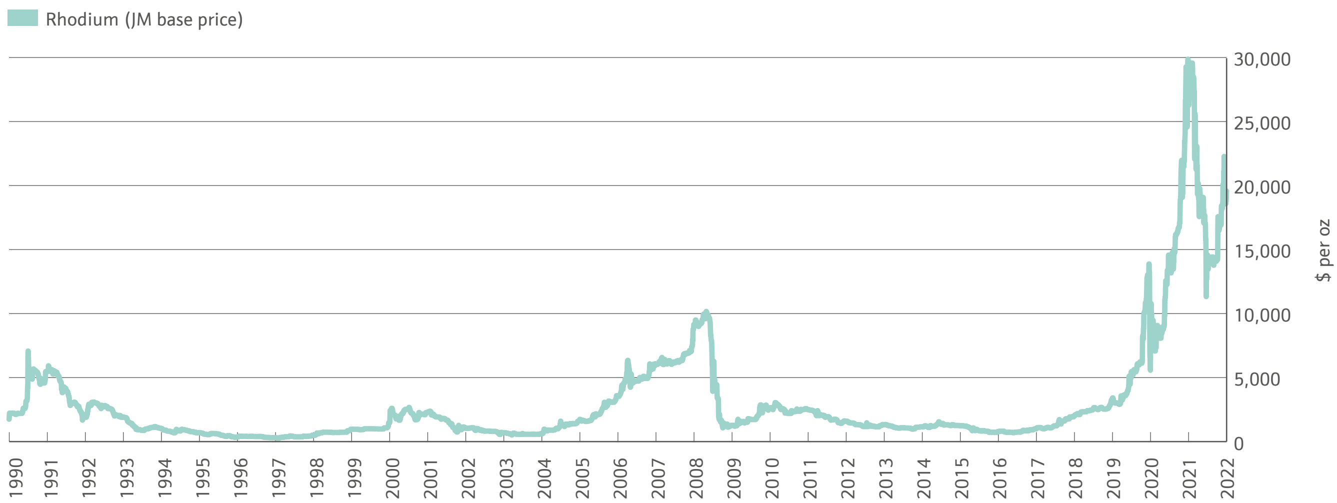


Figure 27 Rhodium prices 1990–2022

Supply '000 oz	2020	2021	2022
South Africa	484	646	575
Russia	58	53	-
Others	69	65	69
Total primary supply	**611**	**764**	**-**

Demand '000 oz	2020	2021	2022
Automotive	959	946	962
Other	75	86	120
Total gross demand	**1,034**	**1,032**	**1,082**
Recycling	-338	-369	-351
Total net demand	**696**	**663**	**731**
Movements in stocks	-85	101	-

Table 9 Rhodium supply and demand

the degree of excess liquidity in the market. In particular, the auto industry continued to take and hold contracted metal, despite weak consumption due to lower-than-anticipated vehicle output; some car companies may have ended the year with higher than usual metal inventories. This is not reflected in our automotive demand numbers, which are based on estimates of the amount of PGM used on vehicles last year.

Rhodium supplies rebounded strongly in 2021, due to the processing of a backlog that accumulated during outages at Anglo American Platinum's converter plant (ACP) the previous year. The ACP resumed operations in December 2020, but because of the long refining pipeline for the minor PGM, refined rhodium output only returned to normal levels during the second quarter of 2021. For the full year, primary supplies in 2021 jumped by a quarter compared to 2020.

In contrast, demand retreated slightly. This was largely due to underlying trends in vehicle production: a severe shortage of semiconductors periodically halted assembly lines, while the last two years have seen gasoline cars lose market share to battery electric vehicles. However, price has undoubtedly begun to have a negative impact on demand.

Rhodium demand is usually relatively price inelastic: due to this metal's long history of extreme price movements (Figure 27), its use has retrenched to those applications in which there are no economically or technically viable alternatives. Consumption is now heavily dominated by the autocatalyst sector, which requires rhodium for NOx emissions aftertreatment and accounted for over 90% of gross demand in 2020–2021 (a historically high proportion). Remaining demand mainly comes from the chemical and glass sectors, which require rhodium for process catalysts and glassmaking equipment. In these applications, most demand occurs at the time of new plant construction, although smaller amounts of 'top-up' metal are purchased periodically to cover in-process losses.

"Rhodium supplies rebounded strongly, due to refining of Anglo's ACP backlog"

Previous price spikes in 1990–1991 and 2007–2008 stimulated technical innovations that enabled companies to use rhodium more efficiently. For example, between 2008 and 2016, car companies in North America and Europe implemented development programmes aimed at reducing the rhodium content of their catalysts: average rhodium loadings on gasoline vehicles fell by a third over this period, despite successive waves of tightening emissions legislation. (Loadings have since increased, due to extremely strict NOx limits in most major markets, along with more challenging test cycles, and 'real driving emissions' legislation in Europe – see page 30).

The past two years have seen the rhodium price set new all-time highs, far exceeding previous peaks. Despite a steep descent during the second half of 2021, it remains extremely elevated compared to historic price levels – the 2008 high, considered extreme at the time, was just over $10,000. Most consumers have limited short-term ability to react to very high prices by adjusting their consumption (except by deferring purchases); the one exception is the glass industry, which can flex its rhodium usage by adjusting the rhodium content of platinum alloys used in 'bushings' for glass fibre manufacture.

The glass sector saw unusually high levels of capital investment during 2021, triggering exceptionally strong platinum purchasing for plant expansions (see page 26). This would ordinarily have boosted rhodium usage – but instead, demand remained very weak, at just 16,000 oz, due to changes in alloy composition at glass fibre producers (Figure 29).

Alloys used in fibreglass manufacturing have traditionally contained between 10% and 20% rhodium, with the rhodium content varying within this range depending upon metal prices. Bushings with a higher rhodium content are better able to withstand the extremely high temperatures involved in glass fibre production. This allows for longer production campaigns, improves productivity, and reduces the cost of recycling and refabricating bushings.

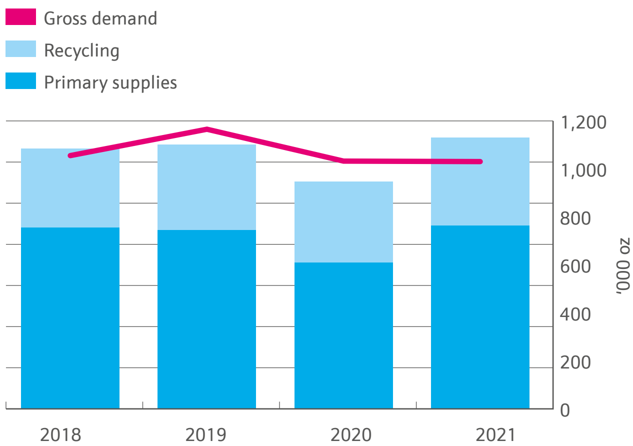


Figure 28 Rhodium supply and demand

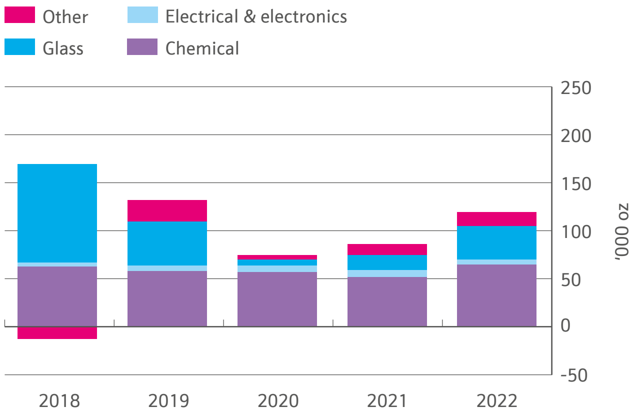


Figure 29 Industrial demand for rhodium

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 a corresponding increase in refining and fabrication costs. Until very recently, a 10% rhodium content was widely considered the lower limit, but exceptionally high rhodium prices during 2020 and 2021 have driven some fibreglass companies to adopt alloys with an even lower rhodium concentration.

This alloy replacement process does not apply exclusively to new plants, but is usually rolled out progressively across a company's entire installed production base: a single large fibreglass plant may contain as much as 30,000 oz of platinum-rhodium alloys. At the end of a production campaign, usually lasting one-to-two years, bushings are removed from service and sent for refining and refabrication, providing an opportunity to adjust alloy composition depending on prevailing prices.

Over the past two years, this process has resulted in a significant decrease in the average rhodium content of the installed base of glassmaking alloys. Some of the recovered rhodium has been retained by glass companies to cover capacity expansions and process losses, while some has been returned to the market. As a result, net rhodium requirements in the glass fibre sector were minimal in 2020–2021, despite significant capacity expansion and record platinum demand.

The display glass industry also uses equipment made from platinum-rhodium alloys, but opportunities to thrift rhodium are much more limited. Production campaigns are much longer, so there are fewer opportunities to change alloy composition, while the exceptionally tight specifications for flat glass tend to discourage the use of lower-performance alloys.

Outside the glass sector, industrial users have much more limited scope to reduce rhodium usage in the short term. While chemical purchasing fell slightly in 2021, this was not a result of rhodium being thrifted or substituted in chemical processes, but due to companies deferring 'top-up' purchases of rhodium to replace in-process losses.

Automotive demand for rhodium fell by 1% last year, as thrifting outweighed the impact of tightening emissions legislation in Europe and North America, and a recovery in gasoline car production in Rest of World (the only region to see gains in light duty gasoline vehicle production last year).

Rhodium plays an essential role in treating NOx emissions from gasoline engines. Most automakers have sought to minimise their rhodium consumption over the years, thrifting metal content where this was possible without compromising catalyst performance. However, all gasoline aftertreatment systems still use small amounts of rhodium, because it is by far the most effective catalyst for NOx.

In recent years, NOx limits have tightened in all major auto markets, while there has been greater focus on ensuring vehicles meet the emissions limits under real world driving conditions, especially in Europe. Starting in 2017, the EU phased-in real driving emissions (RDE) regulations, requiring vehicles to meet strict NOx limits not just in the laboratory but under an extremely wide range of on-road driving conditions. These factors have combined to drive global rhodium loadings up by more than 40% from a low point in 2016.

In 2021, rhodium loadings continued to rise in Europe and North America, reflecting the full enforcement of Euro 6d legislation, and the phasing-in of Tier 3 US Federal regulations. In these regions, automakers have mainly concentrated on meeting tightening emissions limits, rather than on thrifting, but in any case, the introduction of a new catalyst formulation usually requires at least twelve to eighteen months. As the current cycle of legislative tightening comes to an end, we expect automakers to devote more attention to reducing the rhodium content of their catalyst systems.

In China, the lead-time for introducing new catalysts is much shorter: since April 2020, car companies have been allowed to self-certify that their aftertreatment systems comply with emissions legislation. With no further legislative tightening expected until July 2023 (when China 6b regulations are scheduled to be enforced nationwide) Chinese automakers have taken the opportunity to focus on reducing their PGM use. As a result, the average rhodium content of a Chinese gasoline car fell by more than 10% in 2021, bringing to an end a four-year streak of rising global average loadings.

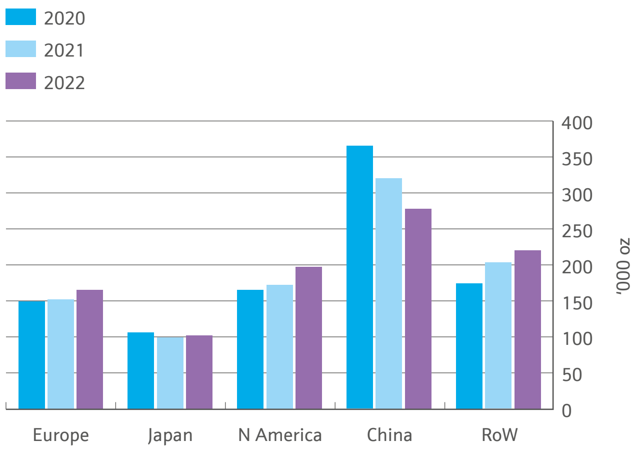


Figure 30 Automotive demand for rhodium (gross)

Ruthenium & iridium

Review of 2021

Iridium set an all-time high of $6,300, while ruthenium rose to a fourteen-year peak of $800

The ballast water treatment and copper foil sectors contributed to strong electrochemical demand for iridium

Iridium spark plug demand fell, on weak gasoline car output and increased substitution activity

Chemical demand for ruthenium slowed, following advance purchasing by caprolactam producers in 2020

Chinese ruthenium imports surged, with some speculative purchasing by private investors

"Sales from producer inventory were absorbed by heavy purchasing from Chinese buyers"

Demand for iridium and ruthenium contracted slightly in 2021. With prices climbing steeply during the first half of the year, there were some early signs of impacts on demand, especially in the iridium spark plug sector, and in the use of ruthenium in water purification. However, elsewhere the decline in demand was largely unrelated to price. Purchasing of ruthenium chemical catalysts retreated, as did demand for iridium crucibles – in both cases, this was primarily due to a slow-down in purchasing for capacity expansions for caprolactam and electronics crystal-growing, respectively.

Prices, supplies & trade

Iridium is a very rare metal, typically accounting for less than 3% of the 'six-element' (6E: platinum, palladium, rhodium, gold, ruthenium and iridium) grade of ores mined in South Africa and Zimbabwe (outside Southern Africa, production is small). Ruthenium is much more abundant, often accounting for over 10% of the 6E PGM grade mined by South African mines. Both metals have a history of wide fluctuations in demand, usually as a result of technological developments. For example, ruthenium was once widely used in plasma displays, which briefly dominated the flat-screen television market around the turn of the century before they were displaced by LCDs (which do not require any ruthenium). Ruthenium subsequently saw extremely strong purchasing by the computer hard drive industry in 2006–2007, as disk manufacturers adopted a new technology ('perpendicular magnetic recording', PMR) which involved the use of small amounts of ruthenium in between the magnetic layers that are used to store data. Likewise, massive uptake of LED technology in 2010–2011, and then the roll-out of 4G

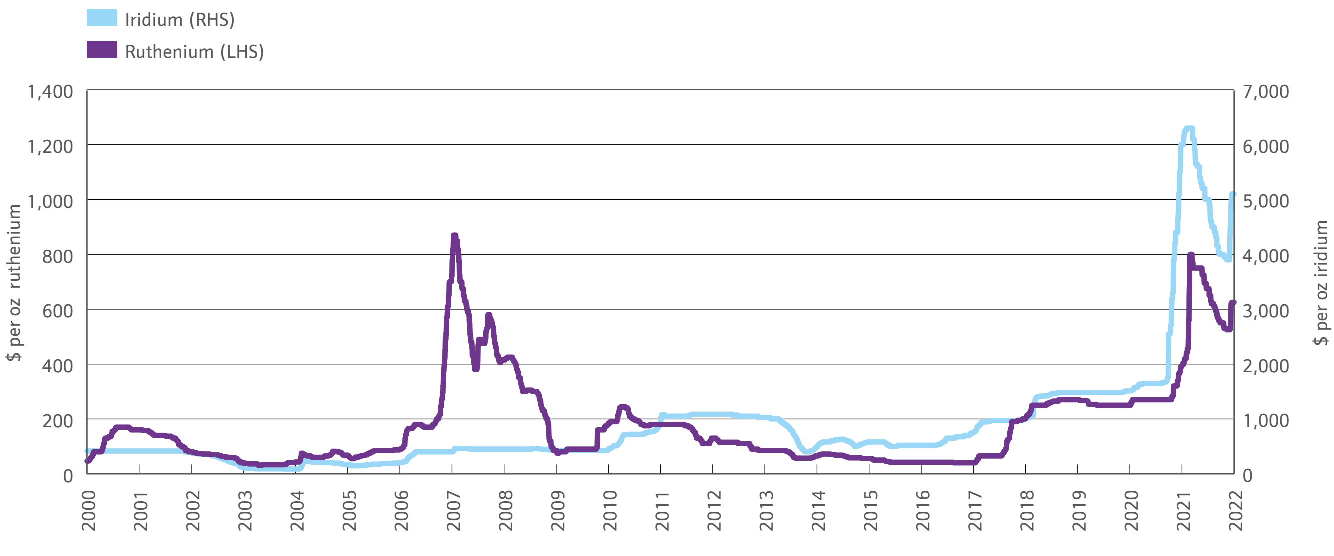


Figure 31 Ruthenium and iridium prices January 2000 to March 2022

mobile technology in 2015–2016 triggered two short periods of unusually heavy demand for iridium crucibles, used to grow specialist crystals used in electronics. However, between these peak purchasing periods, it is common for demand for these metals to fall below the level of annual primary production. In the past, this resulted in producers accumulating some above-ground stocks, particularly of the more abundant ruthenium.

Producer inventory has gradually been drawn down over the past five years, with some of this metal finding its way to China. This was particularly true last year, when Chinese trade statistics recorded usually high imports (primarily of ruthenium), significantly exceeding our estimates of Chinese consumer requirements in 2021. It is possible that there was some advance buying ahead of chemical plant expansions planned for 2022, but we believe that significant quantities of ruthenium were purchased by Chinese private investors. This investment is thought to have been primarily of a speculative nature, and is not included in our estimates of demand.

Despite this mobilisation of producer stocks, prices saw extreme volatility: ruthenium reached a fourteen-year high of $800 in May 2021, while iridium climbed to a peak of $6,300 – by far its highest ever price. Iridium in particular was the subject of some additional purchasing by Western industrial consumers, in advance of actual requirements, while there may also have been some build-up of work-in-progress at fabricators, in view of positive demand trends in some newer applications.

Iridium demand

Although overall iridium demand fell slightly in 2021, this metal is currently seeing growing consumption in several of its newer electrochemical applications, mainly driven by ecological and environmental considerations. For example, last year saw strong growth in demand for iridium used to coat anodes used in the treatment of ballast water. This application is being driven by International Maritime Organisation (IMO) and United States Coast Guard (USCG) legislation which requires ships to be fitted with ballast water treatment equipment to prevent the spread of harmful aquatic organisms from one region to another. The regulations have applied to newly built ships since 2017, and are currently being phased-in for older vessels, which will need to be retrofitted by September 2024.

Iridium is also widely used to coat electrodes used in the electrochemical deposition of copper to form a thin, continuous layer of metal foil. The main user of copper foil

Demand '000 oz	2020	2021	2022
Chemical	25	25	30
Electrical & electronics	59	53	61
Electrochemical	86	88	99
Other	65	65	65
Total	**235**	**231**	**255**

Table 10 Iridium demand

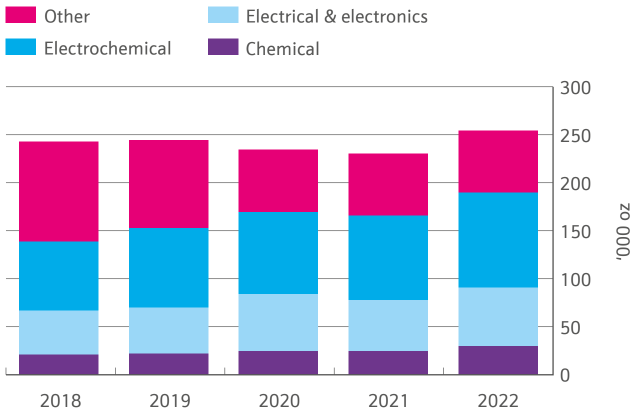


Figure 32 Industrial demand for iridium

> "Iridium reached a peak of $6,300, by far its highest ever price"

has traditionally been the printed circuit board industry, but in recent years, lithium battery production has begun to consume significant volumes of copper, both in power batteries (for consumer equipment such as lawnmowers, power tools and vacuum cleaners) and increasingly in battery electric vehicles. Electric vehicle batteries require particularly large quantities of copper foil, and this is becoming a key driver of iridium demand in this application.

The use of iridium electrodes in proton exchange membrane (PEM) electrolysers for the production of hydrogen is currently very small, but 2021 saw measurable quantities of demand in this application for the first time, as well as some increase in work-in-progress in the supply chain. Looking forward, net zero commitments are expected to drive strong growth in the green hydrogen sector, where PEM is one of a small number of technologies currently in commercial use (see our special feature on hydrogen on page 32 of the May 2021 PGM market report). This has the potential to generate significant demand for iridium in future, although as the technology matures, we expect iridium loadings to be reduced significantly, while the development of a closed recycling loop will ensure that iridium is recovered efficiently from end-of-life electrolysers.

Demand in iridium's other industrial applications was lacklustre in 2021. Purchasing of iridium process catalysts (mainly for acetic acid plants) was flat, while there was a decline in iridium sales to crystal manufacturers (included in our electrical and electronics category) and to spark plug makers (included in 'other' applications). While this was primarily influenced by wider industry trends, high prices have begun to have a limited impact on demand.

Purchasing of iridium for crucibles used in electronic crystal growing occurs mainly during capacity expansions; although some losses occur when the crucible is recycled and refabricated at the end of its working life, 'top-up' demand is relatively small. As 4G mobile technology became widely adopted from around 2015, there was heavy investment in capacity for lithium tantalate crystals used in surface acoustic wave (SAW) filters for mobile telephony. The rate of capacity expansion has slowed markedly since 2017, although the roll-out of 5G technology continues to be broadly supportive of demand, especially in China.

There are now some signs that crystal manufacturers are evaluating ways to reduce their reliance on iridium. The temperatures involved in growing lithium tantalate crystals can exceed 2,000 °C, so pure iridium is by far the best crucible material, because of its exceptionally high melting point of 2,446 °C. We believe that some companies have begun to test crucibles made of platinum-iridium alloys, but these are still at the research and development stage. Even if the use of alternative alloys proves feasible, any reduction in the iridium content of crucibles is likely to be accompanied by a significant shortening of crucible lifetime.

Demand for iridium in spark plugs is also beginning to see some price impacts. Over the past decade, iridium alloys have been widely adopted in electrodes for spark plugs installed as original equipment in gasoline vehicles. Iridium is attractive due to its extremely high arc resistance, which helps to delay deterioration of the electrode surface, and enables manufacturers to equip vehicles with plugs that will last for much of the vehicle's lifetime.

The main factor influencing iridium use in spark plugs is gasoline vehicle output, which was weak during 2020–2021. However, exceptionally high iridium prices have now begun to stimulate substitution activity in this application. Some manufacturers are simply replacing iridium with platinum (which has a long history of use in premium spark plugs for modern vehicles), but there has been increased interest in alloys containing other PGM, including ruthenium.

Ruthenium demand

Gains in ruthenium prices in 2021 were less extreme than for rhodium and iridium, so there has been correspondingly less pressure for industrial consumers to invest in thrifting and substitution activities. Indeed, as noted above, ruthenium has gained very modestly from some early adoption of ruthenium-containing alloys as an alternative to iridium in spark plugs.

However, higher prices have nevertheless had a modest impact on industrial demand. In the chemicals sector, the use of ruthenium in catalytic wet air oxidation (CWAO) for the treatment of industrial wastewater is sensitive to price. Although there has been some continued uptake of CWAO systems, adoption has been slower than previously anticipated due to the high up-front cost of the ruthenium catalyst. Elevated prices have also had an impact on metal purchasing by the Chinese caprolactam industry, due to increased recycling of ruthenium process catalysts. At low prices, the recovery of ruthenium from this application is uneconomic, but since 2018 there has been a gradual increase in the processing of spent catalyst. In the electrochemical sector, swimming pool purification systems using ruthenium electrocatalysts compete with a range of alternative technologies, such as UV purification and the direct addition of chlorine-based chemicals. Because much demand comes from private swimming pools owned by individual households, this sector is relatively price sensitive and ruthenium-based technology has lost market share.

Demand '000 oz	2020	2021	2022
Chemical	385	329	455
Electrical & electronics	404	432	448
Electrochemical	136	131	134
Other	102	124	153
Total	**1,027**	**1,016**	**1,190**

Table 11 Ruthenium demand

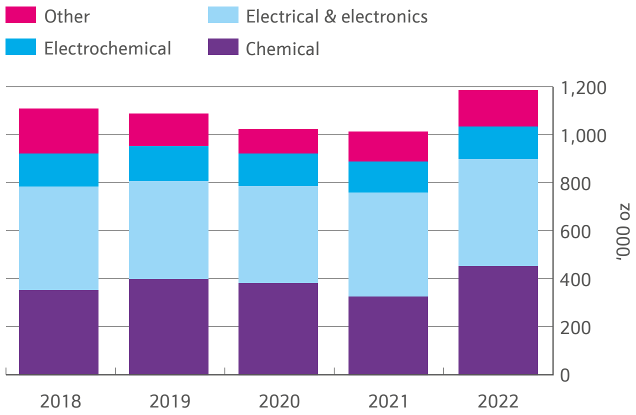


Figure 33 Industrial demand for ruthenium

"Higher ruthenium prices have stimulated an increase in recycling of chemical catalysts in China"

Elsewhere, demand for ruthenium has primarily been influenced by broader economic and industrial trends. Purchasing of ruthenium chemical catalysts slowed in 2021: while some new caprolactam capacity came on-stream early last year, we think that the metal for these plants was acquired in 2020. In contrast, electrical and electronics demand rebounded from pandemic-related disruption, with ongoing strong consumer demand for electronic devices underpinning the use of ruthenium pastes in components such as chip resistors, and growth in data storage requirements supporting ruthenium purchasing by hard disk manufacturers. It was also a positive year for a variety of applications that employ ruthenium-containing alloys, including extremely hard tungsten carbide alloys used in the machine tool industry, and corrosion-resistant alloys for the oil, gas and chemicals industries (these are included in our estimate of demand in 'other applications').

Understanding Johnson Matthey's supply and demand figures

Supply: mined (or primary) supply, i.e. metal sold each year by producers. 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.

Recycling: open-loop recycling only – in other words, secondary metal supplied to the market each year. Because recycling can also be seen as 'negative demand', our recycling figures are quoted in negative numbers.

Demand: the annual requirement for new metal in each application (so it is net of any closed-loop recycling). Because this figure is quoted before any open-loop recycling is considered, JM refers to it as gross demand. (See definitions on page 4).

2022 figures are a forecast and subject to change.

Working with the figures in our tables:

- Total market supplies comprise mined supply plus open-loop recycling.
- Total recycling of PGM comprises open-loop plus closed-loop recycling. As JM does not publish the latter figure, care should be taken not to misinterpret the recycling figure in our table as equivalent to all recycling.
- Adding the open-loop recycling figure (in negative numbers) to demand gives net demand. Subtracting net demand from mined supply gives the total market stocks that must be mobilised to balance the market each year.
- Alternatively, adding our supply and recycling figures (ignoring the negative sign for recycling) gives total annual supply. Subtracting gross demand from total annual supply gives the total market stocks that must be mobilised to balance the market each year.
- If total supplies exceed gross demand in a given year, the market balance is positive, denoting a surplus, and the surplus metal is added to total market stocks. If, however, gross demand exceeds total supplies, the market balance is negative in that year, denoting a deficit and market stocks are drawn upon to meet the shortfall.

Notes to tables

[1]**Supply** figures represent estimates of sales by the mines of primary PGM and are allocated to where the initial mining took place rather than the location of refining.

[2]Our **Russian supply** figures represent the total PGM mined in Russia and the CIS. Demand in Russia is included in the Rest of the World region.

[3]Supplies from **Zimbabwe** have been split from Others' supplies. Platinum group metals mined in Zimbabwe are currently refined in South Africa, and our supply figures represent shipments of PGM in concentrate or matte, adjusted for typical refining recoveries.

[4]**Gross demand** figures for any given application represent the sum of manufacturer demand for new metal in that application and any changes in unrefined metal stocks in that sector. Increases in unrefined stocks lead to additional demand, reductions in stock lead to a lower demand figure.

[5]Our **Dental & biomedical** category represents combined metal demand in the medical, biomedical and dental sectors; however, pharmaceutical metal use is included under Chemical demand.

[6]**Recycling** figures represent estimates of the quantity of metal recovered from open-loop recycling (see definitions on page 4). For instance, automotive recycling represents the weight of metal recovered from end-of-life vehicles and aftermarket scrap in an individual region. These figures do not include warranty or production scrap. Where no recycling figures are given, open-loop recycling is negligible.

[7]**Net demand** figures are equivalent to the sum of gross demand in an application less any metal recovery from open-loop scrap in that application, whether the recycled metal is reused in that industry or sold into another application. Where no recycling figure is given for an application, gross and net demand are identical.

[8]**Movements in stocks** in any given year reflect changes in stocks held by fabricators, dealers, banks and depositories but excluding stocks held by primary refiners and final consumers. A positive figure (sometimes referred to as a 'surplus') reflects an increase in market stocks. A negative value (or 'deficit') indicates a decrease in market stocks.

Platinum supply and demand

Troy ounces

Supply '000 oz[1]	2017	2018	2019	2020	2021	2022
South Africa	4,450	4,467	4,344	3,222	4,611	4,204
Russia[2]	720	687	721	699	638	-
North America	368	346	360	331	276	320
Zimbabwe[3]	466	474	451	482	465	498
Others[3]	157	152	154	202	207	200
Total supply	**6,161**	**6,126**	**6,030**	**4,936**	**6,197**	**-**

Demand '000 oz[4]	2017	2018	2019	2020	2021	2022
Automotive[4]	3,061	2,815	2,598	2,045	2,353	2,820
Chemical	453	654	665	616	638	662
Dental & biomedical[5]	238	241	254	233	251	256
Electrical & electronics[4]	224	228	214	221	266	289
Glass	314	501	441	476	913	475
Investment	361	67	1,131	1,022	-28	-92
Jewellery[4]	2,385	2,258	2,073	1,656	1,478	1,447
Petroleum	228	379	258	335	236	231
Pollution control	184	196	192	176	199	224
Other	530	531	542	417	446	490
Total gross demand	**7,978**	**7,870**	**8,368**	**7,197**	**6,752**	**6,802**

Recycling '000 oz[6]	2017	2018	2019	2020	2021	2022
Automotive	-1,249	-1,332	-1,389	-1,154	-1,235	-1,219
Electrical & electronics	-35	-38	-40	-38	-44	-51
Jewellery	-746	-699	-663	-510	-380	-358
Total recycling	**-2,030**	**-2,069**	**-2,092**	**-1,702**	**-1,659**	**-1,628**

Total net demand[7]	**5,948**	**5,801**	**6,276**	**5,495**	**5,093**	**5,174**
Movement in stocks[8]	213	325	-246	-559	1,104	-

Platinum gross demand by region

Troy ounces

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
Europe	Automotive	1,675	1,377	1,194	856	715	820
	Chemical	117	122	122	116	126	141
	Dental & biomedical	70	63	63	60	65	66
	Electrical & electronics	10	12	12	13	14	15
	Glass	11	11	13	14	18	15
	Investment	36	-102	566	308	126	-141
	Jewellery	176	191	195	150	173	179
	Petroleum	7	29	16	9	2	-2
	Pollution control	41	41	41	44	50	55
	Other	164	171	171	128	134	150
	Total	**2,307**	**1,915**	**2,393**	**1,698**	**1,423**	**1,298**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
Japan	Automotive	314	291	264	208	232	261
	Chemical	37	40	42	40	41	39
	Dental & biomedical	15	14	14	14	15	15
	Electrical & electronics	25	24	23	22	24	25
	Glass	25	7	27	17	14	11
	Investment	171	220	32	392	-21	-40
	Jewellery	303	293	296	237	250	259
	Petroleum	2	2	2	2	1	1
	Pollution control	57	59	62	52	61	66
	Other	68	55	68	56	59	59
	Total	**1,017**	**1,005**	**830**	**1,040**	**676**	**696**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
North America	Automotive	250	287	290	216	324	444
	Chemical	112	105	100	95	115	111
	Dental & biomedical	88	94	98	79	86	88

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
North America	Electrical & electronics	33	38	28	24	32	33
	Glass	45	18	21	34	58	26
	Investment	127	66	156	602	115	109
	Jewellery	225	224	211	210	224	231
	Petroleum	18	15	17	14	47	30
	Pollution control	52	57	53	44	38	39
	Other	143	152	150	95	104	124
	Total	**1,093**	**1,056**	**1,124**	**1,413**	**1,143**	**1,235**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
China	Automotive	160	165	165	231	390	528
	Chemical	74	207	274	275	260	250
	Dental & biomedical	38	39	47	32	34	35
	Electrical & electronics	42	45	43	44	49	51
	Glass	111	388	294	353	747	330
	Investment	0	0	0	0	13	13
	Jewellery	1,470	1,316	1,119	945	705	635
	Petroleum	120	261	163	236	94	128
	Pollution control	16	20	19	18	25	40
	Other	67	69	66	61	62	63
	Total	**2,098**	**2,510**	**2,190**	**2,195**	**2,379**	**2,073**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
Rest of World	Automotive	662	695	685	534	692	767
	Chemical	113	180	127	90	96	121
	Dental & biomedical	27	31	32	48	51	52
	Electrical & electronics	114	109	108	118	147	165
	Glass	122	77	86	58	76	93
	Investment	27	-117	377	-280	-261	-33
	Jewellery	211	234	252	114	126	143
	Petroleum	81	72	60	74	92	74
	Pollution control	18	19	17	18	25	24
	Other	88	84	87	77	87	94
	Total	**1,463**	**1,384**	**1,831**	**851**	**1,131**	**1,500**
	Grand total	**7,978**	**7,870**	**8,368**	**7,197**	**6,752**	**6,802**

Platinum supply and demand

Tonnes

Supply tonnes[1]	2017	2018	2019	2020	2021	2022
South Africa	138.4	138.9	135.1	100.2	143.4	130.8
Russia[2]	22.4	21.4	22.4	21.7	19.8	-
North America	11.4	10.8	11.2	10.3	8.6	9.9
Zimbabwe[3]	14.5	14.7	14.0	15.0	14.5	15.5
Others[3]	4.9	4.7	4.8	6.3	6.4	6.2
Total supply	**191.6**	**190.5**	**187.5**	**153.5**	**192.7**	**-**

Demand tonnes[4]	2017	2018	2019	2020	2021	2022
Automotive[4]	95.3	87.5	80.7	63.6	73.1	87.7
Chemical	14.1	20.3	20.7	19.2	19.9	20.6
Dental & biomedical[5]	7.4	7.5	7.9	7.2	7.9	8.0
Electrical & electronics[4]	6.9	7.1	6.7	6.9	8.2	9.0
Glass	9.8	15.6	13.7	14.8	28.4	14.8
Investment	11.2	2.1	35.2	31.8	-0.9	-2.8
Jewellery[4]	74.2	70.2	64.5	51.5	46.0	45.0
Petroleum	7.1	11.8	8.1	10.4	7.3	7.1
Pollution control	5.7	6.1	5.9	5.5	6.3	6.9
Other	16.4	16.5	16.9	13.0	13.8	15.3
Total gross demand	**248.1**	**244.7**	**260.3**	**223.9**	**210.0**	**211.6**

Recycling tonnes[6]	2017	2018	2019	2020	2021	2022
Automotive	-38.8	-41.5	-43.2	-35.9	-38.4	-37.9
Electrical & electronics	-1.1	-1.2	-1.3	-1.2	-1.4	-1.6
Jewellery	-23.2	-21.7	-20.6	-15.9	-11.8	-11.1
Total recycling	**-63.1**	**-64.4**	**-65.1**	**-53.0**	**-51.6**	**-50.6**

Total net demand[7]	**185.0**	**180.3**	**195.2**	**170.9**	**158.4**	**161.0**
Movement in stocks[8]	6.6	10.2	-7.7	-17.4	34.3	-

Platinum gross demand by region

Tonnes

Gross demand tonnes		2017	2018	2019	2020	2021	2022
Europe	Automotive	52.1	42.8	37.1	26.6	22.2	25.5
	Chemical	3.6	3.8	3.8	3.6	3.9	4.4
	Dental & biomedical	2.2	2.0	2.0	1.9	2.0	2.1
	Electrical & electronics	0.3	0.4	0.4	0.4	0.4	0.5
	Glass	0.3	0.3	0.4	0.4	0.6	0.5
	Investment	1.1	-3.2	17.6	9.6	3.9	-4.4
	Jewellery	5.5	5.9	6.1	4.7	5.4	5.6
	Petroleum	0.2	0.9	0.5	0.3	0.1	-0.1
	Pollution control	1.3	1.3	1.3	1.4	1.6	1.7
	Other	5.1	5.3	5.3	4.0	4.2	4.7
	Total	**71.7**	**59.5**	**74.5**	**52.9**	**44.3**	**40.5**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
Japan	Automotive	9.8	9.1	8.2	6.5	7.2	8.1
	Chemical	1.2	1.2	1.3	1.2	1.3	1.2
	Dental & biomedical	0.5	0.4	0.4	0.4	0.5	0.5
	Electrical & electronics	0.8	0.7	0.7	0.7	0.7	0.8
	Glass	0.8	0.2	0.8	0.5	0.4	0.3
	Investment	5.3	6.8	1.0	12.2	-0.7	-1.2
	Jewellery	9.4	9.1	9.2	7.4	7.8	8.1
	Petroleum	0.1	0.1	0.1	0.1	0.0	0.0
	Pollution control	1.8	1.8	1.9	1.6	1.9	2.1
	Other	2.1	1.7	2.1	1.7	1.8	1.8
	Total	**31.8**	**31.1**	**25.7**	**32.3**	**20.9**	**21.7**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
North America	Automotive	7.8	8.9	9.0	6.7	10.1	13.8
	Chemical	3.5	3.3	3.1	3.0	3.6	3.4
	Dental & biomedical	2.7	2.9	3.0	2.4	2.7	2.7

Gross demand tonnes		2017	2018	2019	2020	2021	2022
North America	Electrical & electronics	1.0	1.2	0.9	0.7	1.0	1.0
	Glass	1.4	0.6	0.7	1.1	1.8	0.8
	Investment	4.0	2.1	4.9	18.7	3.6	3.4
	Jewellery	7.0	7.0	6.6	6.5	7.0	7.2
	Petroleum	0.6	0.5	0.5	0.4	1.4	0.9
	Pollution control	1.6	1.8	1.6	1.4	1.2	1.2
	Other	4.4	4.7	4.7	3.0	3.2	3.9
	Total	**34.0**	**33.0**	**35.0**	**43.9**	**35.6**	**38.3**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
China	Automotive	5.0	5.1	5.1	7.2	12.1	16.4
	Chemical	2.3	6.4	8.5	8.6	8.1	7.8
	Dental & biomedical	1.2	1.2	1.5	1.0	1.1	1.1
	Electrical & electronics	1.3	1.4	1.3	1.4	1.5	1.6
	Glass	3.5	12.1	9.1	11.0	23.2	10.3
	Investment	0.0	0.0	0.0	0.0	0.4	0.4
	Jewellery	45.7	40.9	34.8	29.4	21.9	19.7
	Petroleum	3.7	8.1	5.1	7.3	2.9	4.0
	Pollution control	0.5	0.6	0.6	0.5	0.8	1.2
	Other	2.1	2.2	2.1	1.9	1.9	2.0
	Total	**65.3**	**78.0**	**68.1**	**68.3**	**73.9**	**64.5**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
Rest of World	Automotive	20.6	21.6	21.3	16.6	21.5	23.9
	Chemical	3.5	5.6	4.0	2.8	3.0	3.8
	Dental & biomedical	0.8	1.0	1.0	1.5	1.6	1.6
	Electrical & electronics	3.5	3.4	3.4	3.7	4.6	5.1
	Glass	3.8	2.4	2.7	1.8	2.4	2.9
	Investment	0.8	-3.6	11.7	-8.7	-8.1	-1.0
	Jewellery	6.6	7.3	7.8	3.5	3.9	4.4
	Petroleum	2.5	2.2	1.9	2.3	2.9	2.3
	Pollution control	0.5	0.6	0.5	0.6	0.8	0.7
	Other	2.7	2.6	2.7	2.4	2.7	2.9
	Total	**45.3**	**43.1**	**57.0**	**26.5**	**35.3**	**46.6**
	Grand total	**248.1**	**244.7**	**260.3**	**223.9**	**210.0**	**211.6**

Palladium supply and demand

Troy ounces

Supply '000 oz[1]	2017	2018	2019	2020	2021	2022
South Africa	2,547	2,543	2,588	1,975	2,652	2,486
Russia[2]	2,452	2,976	2,987	2,636	2,689	-
North America	956	978	1,010	956	874	922
Zimbabwe[3]	386	393	379	410	392	412
Others[3]	131	135	140	185	187	187
Total supply	**6,472**	**7,025**	**7,104**	**6,162**	**6,794**	**-**

Demand '000 oz[4]	2017	2018	2019	2020	2021	2022
Automotive[4]	8,423	8,837	9,653	8,503	8,340	8,411
Chemical	435	605	511	524	589	614
Dental & biomedical	398	364	320	228	210	191
Electrical & electronics[4]	844	768	711	634	655	644
Investment	-386	-574	-87	-190	17	0
Jewellery[4]	167	148	128	85	91	93
Pollution control	78	87	88	76	96	109
Other	91	117	121	94	99	84
Total gross demand	**10,050**	**10,352**	**11,445**	**9,954**	**10,097**	**10,146**

Recycling '000 oz[6]	2017	2018	2019	2020	2021	2022
Automotive	-2,357	-2,624	-2,916	-2,686	-2,891	-2,734
Electrical & electronics	-479	-475	-477	-450	-463	-468
Jewellery	-21	-12	-12	-9	-9	-9
Total recycling	**-2,857**	**-3,111**	**-3,405**	**-3,145**	**-3,363**	**-3,211**

Total net demand[7]	**7,193**	**7,241**	**8,040**	**6,809**	**6,734**	**6,935**
Movement in stocks[8]	-721	-216	-936	-647	60	-

Palladium gross demand by region

Troy ounces

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
Europe	Automotive	1,690	1,917	2,092	1,786	1,849	1,971
	Chemical	75	65	71	53	74	116
	Dental & biomedical	61	52	43	29	32	31
	Electrical & electronics	96	91	85	73	75	74
	Investment	-287	-141	-56	-17	-17	3
	Jewellery	53	49	42	28	31	32
	Pollution control	21	22	26	27	29	31
	Other	12	18	12	10	12	12
	Total	**1,721**	**2,073**	**2,315**	**1,989**	**2,085**	**2,270**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
Japan	Automotive	818	880	917	777	740	768
	Chemical	17	17	17	16	17	16
	Dental & biomedical	174	156	140	102	90	81
	Electrical & electronics	220	198	180	162	161	155
	Investment	-3	-1	1	3	2	0
	Jewellery	57	52	45	31	33	33
	Pollution control	13	13	14	12	13	15
	Other	6	6	6	4	6	6
	Total	**1,302**	**1,321**	**1,320**	**1,107**	**1,062**	**1,074**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
North America	Automotive	2,009	2,069	2,059	1,701	1,723	1,880
	Chemical	75	76	84	35	73	73
	Dental & biomedical	137	130	112	77	70	63
	Electrical & electronics	126	113	103	91	94	91
	Investment	-19	-87	-5	-35	34	17
	Jewellery	29	27	21	13	13	14
	Pollution control	11	15	13	10	12	13
	Other	37	36	37	27	30	31
	Total	**2,405**	**2,379**	**2,424**	**1,919**	**2,049**	**2,182**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
China	Automotive	2,179	2,097	2,702	2,631	2,186	1,821
	Chemical	174	272	233	315	318	300
	Dental & biomedical	7	7	6	6	5	5
	Electrical & electronics	155	141	131	118	124	125
	Investment	0	0	0	0	0	0
	Jewellery	9	2	1	0	0	0
	Pollution control	31	34	31	23	35	42
	Other	20	38	43	38	34	18
	Total	**2,575**	**2,591**	**3,147**	**3,131**	**2,702**	**2,311**

Gross demand '000 oz		2017	2018	2019	2020	2021	2022
Rest of World	Automotive	1,727	1,874	1,883	1,608	1,842	1,971
	Chemical	94	175	106	105	107	109
	Dental & biomedical	19	19	19	14	13	11
	Electrical & electronics	247	225	212	190	201	199
	Investment	-77	-345	-27	-141	-2	-20
	Jewellery	19	18	19	13	14	14
	Pollution control	2	3	4	4	7	8
	Other	16	19	23	15	17	17
	Total	**2,047**	**1,988**	**2,239**	**1,808**	**2,199**	**2,309**
	Grand total	**10,050**	**10,352**	**11,445**	**9,954**	**10,097**	**10,146**

Palladium supply and demand

Tonnes

Supply tonnes[1]	2017	2018	2019	2020	2021	2022
South Africa	79.2	79.1	80.5	61.4	82.5	77.3
Russia[2]	76.3	92.6	92.9	82.0	83.6	-
North America	29.7	30.4	31.4	29.7	27.2	28.7
Zimbabwe[3]	12.0	12.2	11.8	12.8	12.2	12.8
Others[3]	4.1	4.2	4.4	5.8	5.8	5.8
Total supply	**201.3**	**218.5**	**221.0**	**191.7**	**211.3**	**-**

Demand tonnes[4]	2017	2018	2019	2020	2021	2022
Automotive[4]	262.0	274.8	300.2	264.5	259.4	261.6
Chemical	13.4	18.8	15.9	16.3	18.3	19.1
Dental & biomedical	12.4	11.2	10.0	7.1	6.6	6.0
Electrical & electronics[4]	26.2	23.9	22.1	19.7	20.3	20.0
Investment	-12.0	-17.8	-2.7	-5.9	0.6	0.0
Jewellery[4]	5.2	4.6	4.0	2.7	2.8	2.8
Pollution control	2.5	2.8	2.7	2.3	3.0	3.4
Other	2.9	3.7	3.8	2.9	3.1	2.7
Total gross demand	**312.6**	**322.0**	**356.0**	**309.6**	**314.1**	**315.6**

Recycling tonnes[6]	2017	2018	2019	2020	2021	2022
Automotive	-73.3	-81.6	-90.6	-83.6	-90.0	-85.0
Electrical & electronics	-15.0	-14.8	-14.9	-13.9	-14.3	-14.6
Jewellery	-0.6	-0.4	-0.4	-0.3	-0.3	-0.3
Total recycling	**-88.9**	**-96.8**	**-105.9**	**-97.8**	**-104.6**	**-99.9**

Total net demand[7]	**223.7**	**225.2**	**250.1**	**211.8**	**209.5**	**215.7**
Movement in stocks[8]	-22.4	-6.7	-29.1	-20.1	1.8	-

Palladium gross demand by region

Tonnes

Gross demand tonnes		2017	2018	2019	2020	2021	2022
Europe	Automotive	52.6	59.6	65.1	55.6	57.5	61.3
	Chemical	2.3	2.0	2.2	1.6	2.3	3.6
	Dental & biomedical	1.9	1.6	1.3	0.9	1.0	1.0
	Electrical & electronics	3.0	2.8	2.6	2.3	2.3	2.3
	Investment	-8.9	-4.4	-1.7	-0.5	-0.5	0.1
	Jewellery	1.6	1.5	1.3	0.9	1.0	1.0
	Pollution control	0.7	0.7	0.8	0.8	0.9	1.0
	Other	0.4	0.6	0.4	0.3	0.4	0.4
	Total	**53.6**	**64.4**	**72.0**	**61.9**	**64.9**	**70.7**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
Japan	Automotive	25.4	27.4	28.5	24.2	23.0	23.9
	Chemical	0.5	0.5	0.5	0.5	0.5	0.5
	Dental & biomedical	5.4	4.8	4.4	3.2	2.8	2.5
	Electrical & electronics	6.8	6.2	5.6	5.0	5.0	4.8
	Investment	-0.1	0.0	0.0	0.1	0.1	0.0
	Jewellery	1.8	1.6	1.4	1.0	1.0	1.0
	Pollution control	0.4	0.4	0.4	0.4	0.4	0.5
	Other	0.2	0.2	0.2	0.1	0.2	0.2
	Total	**40.4**	**41.1**	**41.0**	**34.5**	**33.0**	**33.4**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
North America	Automotive	62.5	64.3	64.0	52.9	53.6	58.5
	Chemical	2.3	2.4	2.6	1.1	2.3	2.3
	Dental & biomedical	4.3	4.0	3.5	2.4	2.2	2.0
	Electrical & electronics	3.9	3.5	3.2	2.8	2.9	2.8
	Investment	-0.6	-2.7	-0.2	-1.1	1.1	0.5
	Jewellery	0.9	0.8	0.7	0.4	0.4	0.4
	Pollution control	0.3	0.5	0.4	0.3	0.4	0.4
	Other	1.2	1.1	1.2	0.8	0.9	1.0
	Total	**74.8**	**73.9**	**75.4**	**59.6**	**63.8**	**67.9**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
China	Automotive	67.8	65.2	84.0	81.8	68.0	56.6
	Chemical	5.4	8.5	7.3	9.8	9.9	9.3
	Dental & biomedical	0.2	0.2	0.2	0.2	0.2	0.2
	Electrical & electronics	4.8	4.4	4.1	3.7	3.9	3.9
	Investment	0.0	0.0	0.0	0.0	0.0	0.0
	Jewellery	0.3	0.1	0.0	0.0	0.0	0.0
	Pollution control	1.0	1.1	1.0	0.7	1.1	1.3
	Other	0.6	1.2	1.3	1.2	1.1	0.6
	Total	**80.1**	**80.7**	**97.9**	**97.4**	**84.2**	**71.9**

Gross demand tonnes		2017	2018	2019	2020	2021	2022
Rest of World	Automotive	53.7	58.3	58.6	50.0	57.3	61.3
	Chemical	2.9	5.4	3.3	3.3	3.3	3.4
	Dental & biomedical	0.6	0.6	0.6	0.4	0.4	0.3
	Electrical & electronics	7.7	7.0	6.6	5.9	6.2	6.2
	Investment	-2.4	-10.7	-0.8	-4.4	-0.1	-0.6
	Jewellery	0.6	0.6	0.6	0.4	0.4	0.4
	Pollution control	0.1	0.1	0.1	0.1	0.2	0.2
	Other	0.5	0.6	0.7	0.5	0.5	0.5
	Total	**63.7**	**61.9**	**69.7**	**56.2**	**68.2**	**71.7**

	Grand total	**312.6**	**322.0**	**356.0**	**309.6**	**314.1**	**315.6**

Rhodium supply and demand

Troy ounces

Supply '000 oz[1]	2017	2018	2019	2020	2021	2022
South Africa	611	618	611	484	646	575
Russia[2]	78	69	68	58	53	-
North America	24	21	21	20	17	21
Zimbabwe[3]	42	43	40	43	42	42
Others[3]	5	5	7	6	6	6
Total supply	**760**	**756**	**747**	**611**	**764**	**-**

Demand '000 oz[4]	2017	2018	2019	2020	2021	2022
Automotive[4]	834	900	1,035	959	946	962
Chemical	75	63	58	57	52	65
Electrical & electronics	4	4	6	7	7	5
Glass	103	103	46	6	16	35
Other	20	-13	22	5	11	15
Total gross demand	**1,036**	**1,057**	**1,167**	**1,034**	**1,032**	**1,082**

Recycling '000 oz[6]	2017	2018	2019	2020	2021	2022
Automotive	-310	-331	-356	-338	-369	-351
Total recycling	**-310**	**-331**	**-356**	**-338**	**-369**	**-351**

Total net demand[7]	**726**	**726**	**811**	**696**	**663**	**731**
Movement in stocks[8]	34	30	-64	-85	101	-

Rhodium supply and demand

Tonnes

Supply tonnes[1]	2017	2018	2019	2020	2021	2022
South Africa	19.0	19.2	19.0	15.1	20.1	17.9
Russia[2]	2.4	2.1	2.1	1.8	1.7	-
North America	0.7	0.7	0.7	0.6	0.5	0.6
Zimbabwe[3]	1.3	1.3	1.2	1.3	1.3	1.3
Others[3]	0.2	0.2	0.2	0.2	0.2	0.2
Total supply	**23.6**	**23.5**	**23.2**	**19.0**	**23.8**	**-**

Demand tonnes[4]	2017	2018	2019	2020	2021	2022
Automotive[4]	25.8	28.0	32.2	29.8	29.4	29.9
Chemical	2.4	2.0	1.8	1.8	1.7	2.0
Electrical & electronics	0.1	0.1	0.2	0.2	0.2	0.1
Glass	3.2	3.2	1.4	0.1	0.5	1.1
Other	0.6	-0.4	0.7	0.3	0.4	0.6
Total gross demand	**32.1**	**32.9**	**36.3**	**32.2**	**32.2**	**33.7**

Recycling tonnes[6]	2017	2018	2019	2020	2021	2022
Automotive	-9.6	-10.3	-11.1	-10.5	-11.5	-10.9
Total recycling	**-9.6**	**-10.3**	**-11.1**	**-10.5**	**-11.5**	**-10.9**

Total net demand[7]	**22.5**	**22.6**	**25.2**	**21.7**	**20.7**	**22.8**
Movement in stocks[8]	1.1	0.9	-2.0	-2.7	3.1	-

Ruthenium demand

Troy ounces

Demand '000 oz[4]	2017	2018	2019	2020	2021	2022
Chemical	361	356	401	385	329	455
Electrical & electronics	437	431	410	404	432	448
Electrochemical	147	139	144	136	131	134
Other	173	187	136	102	124	153
Total gross demand	**1,118**	**1,113**	**1,091**	**1,027**	**1,016**	**1,190**

Tonnes

Demand tonnes[4]	2017	2018	2019	2020	2021	2022
Chemical	11.2	11.1	12.5	12	10.2	14.1
Electrical & electronics	13.6	13.4	12.7	12.6	13.4	13.9
Electrochemical	4.6	4.3	4.5	4.2	4.1	4.2
Other	5.4	5.8	4.2	3.2	3.9	4.8
Total gross demand	**34.8**	**34.6**	**33.9**	**32**	**31.6**	**37**

Iridium demand

Troy ounces

Demand '000 oz[4]	2017	2018	2019	2020	2021	2022
Chemical	17	21	22	25	25	30
Electrical & electronics	69	46	48	59	53	61
Electrochemical	81	72	83	86	88	99
Other	86	104	92	65	65	65
Total gross demand	**253**	**243**	**245**	**235**	**231**	**255**

Tonnes

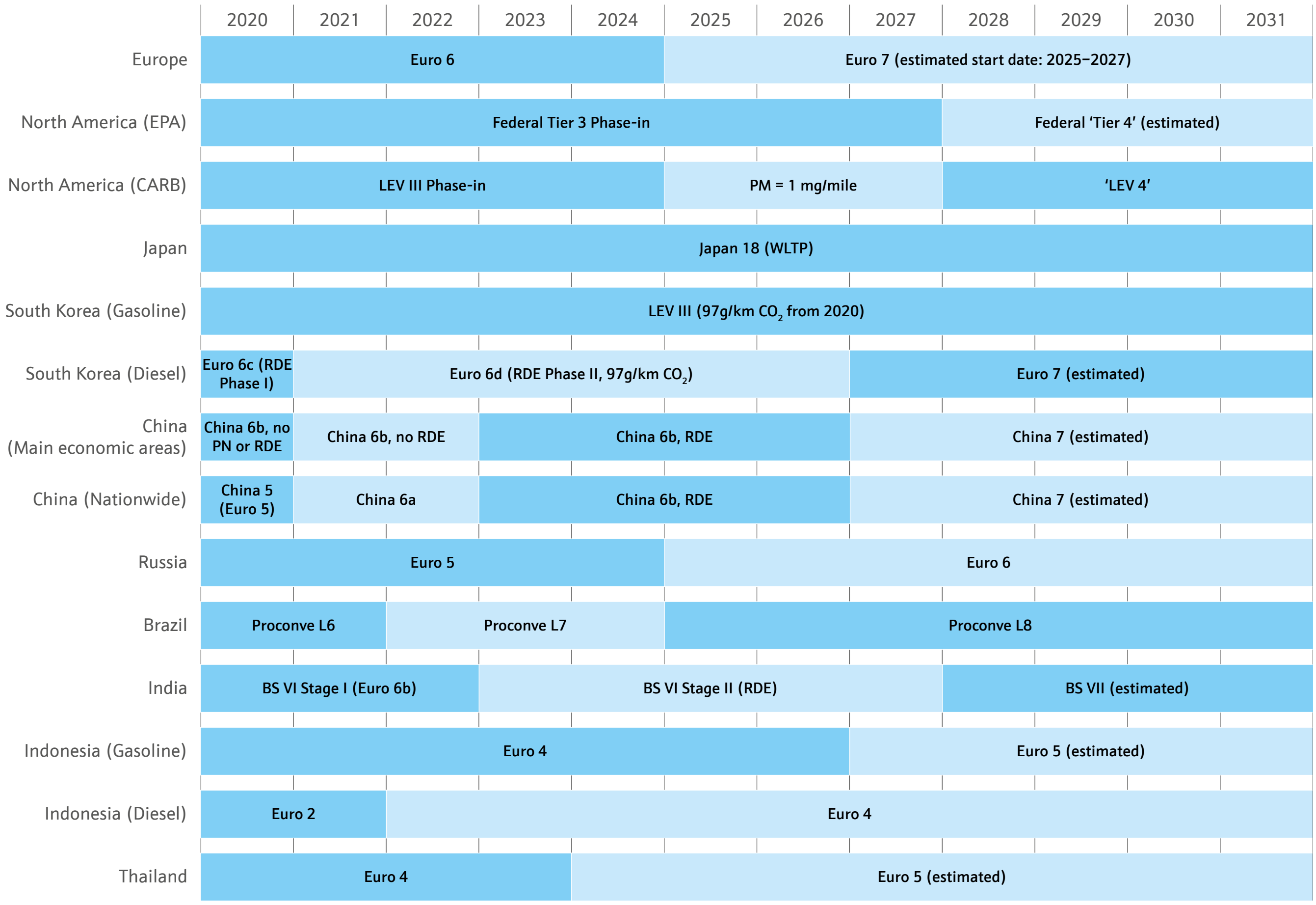
Demand tonnes[4]	2017	2018	2019	2020	2021	2022
Chemical	0.5	0.7	0.7	0.8	0.8	0.9
Electrical & electronics	2.1	1.4	1.5	1.8	1.7	1.9
Electrochemical	2.5	2.3	2.6	2.7	2.7	3.1
Other	2.7	3.2	2.8	2	2	2
Total gross demand	**7.8**	**7.6**	**7.6**	**7.3**	**7.2**	**7.9**

Glossary

ACP	Anglo American Platinum Converter Plant
BEV	Battery electric vehicle
CF	Conformity factor
CO	Carbon monoxide
CO_2	Carbon dioxide
CPL	Caprolactam
CTMEG	Coal-to-mono-ethylene glycol
CWAO	Catalytic wet air oxidation
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EC	European Commission
ELV	End-of-life vehicle
ETF	Exchange traded fund
FCEV	Fuel cell electric vehicle
GPF	Gasoline particulate filter
GVW	Gross vehicle weight
HDD	Heavy duty diesel
HPS	Hydrogen portfolio standard
ICE	Internal combustion engine
IMO	International Maritime Organisation
ISC	In-service conformity
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
MEG	Mono-ethylene glycol
MLCC	Multi-layer ceramic capacitor
NEDC	New European Driving Cycle
NEV	New energy vehicle (BEV, PHEV or FCEV)
NOx	Oxides of nitrogen
NRMM	Non-road mobile machinery
NYMEX	New York Mercantile Exchange
PDH	Propane dehydrogenation
PEM	Proton exchange membrane
PET	Polyethylene terephthalate
PGM	Platinum group metals
PHEV	Plug-in hybrid vehicle
PM	Particulate matter or soot
PMR	Perpendicular magnetic recording
PN	Particle number
PP	Polypropylene
PTA	Purified terephthalic acid
PX	Paraxylene
RDE	Real driving emissions
RoW	Rest of world region
SAW filter	Surface acoustic wave filter
SCR	Selective catalytic reduction
SCRF®	SCR integrated with a soot filter
SGE	Shanghai Gold Exchange
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
USCG	United States Coast Guard
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

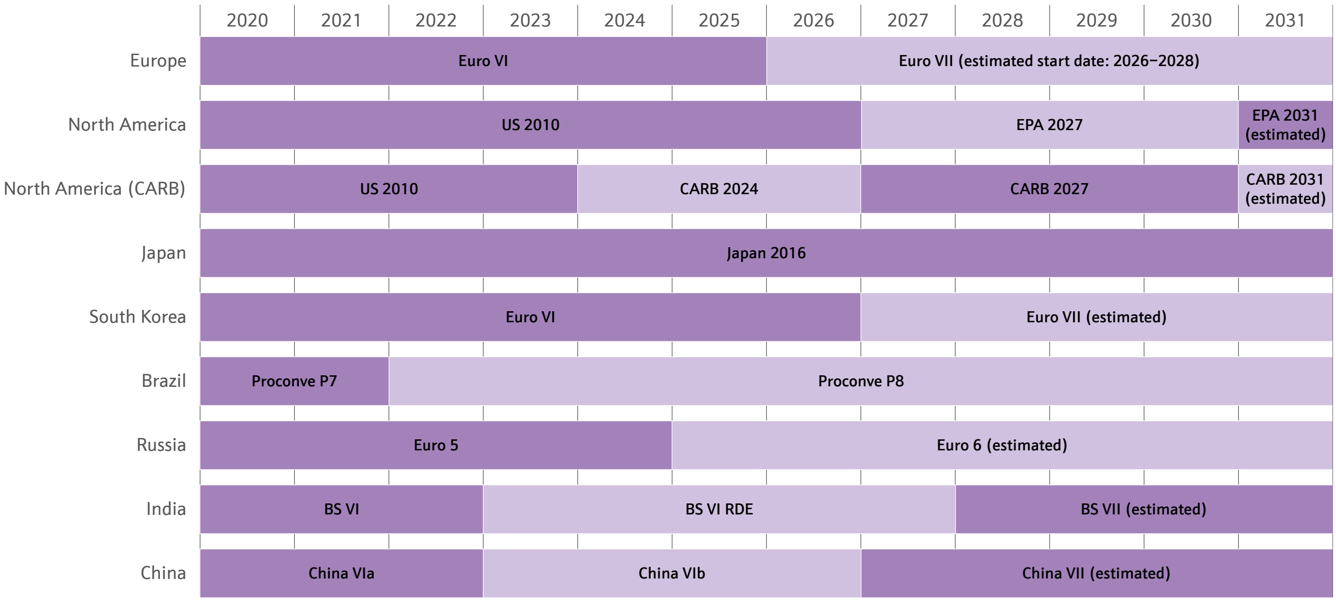
Emissions legislation

Light duty



Emissions legislation

Heavy duty



Euro 6 emissions legislation

Euro 6 is a generic standard that defines emissions limits for light vehicles to be phased in on various dates and according to various tests and procedures.

Euro 6a was a voluntary stage which allowed vehicles to be introduced with Euro 6 type approval earlier than required. It had minimal impact on PGM demand.

Euro 6b applied to new type approvals for passenger cars from September 2014, and to all vehicles sold in the European market from September 2016. From this point, vehicles had to meet Euro 6 emissions limits when tested over the New European Driving Cycle (NEDC). At Euro 6b there was no change to the emissions limits for gasoline vehicles from Euro 5 limits, other than the introduction of a particle number limit on these engines (although manufacturers could apply for a three-year exemption to meet a slightly higher limit). For diesel vehicles, allowable NOx emissions over the test cycle were reduced by 56% relative to Euro 5 legislation. This had significant implications for PGM loadings on diesel vehicles.

Euro 6c began to be phased in from September 2017 and applied to all vehicles from September 2019. In terms of emissions limits, there are no differences between 6b and 6c for diesel engines and the only difference for gasoline engines is that 6c brings particle number emissions down for all vehicles, fully in line with those from diesel vehicles. This has implications for gasoline particulate filter (GPF) fitment.

In parallel, a new laboratory test replaced the NEDC. The Worldwide Harmonised Light Vehicle Test Procedure (WLTP) applied to new type approvals from September 2017 and to all vehicles from September 2018.

Euro 6d has been phased in over several years, starting in September 2017. Euro 6d differs from 6b/6c in that it changes the way in which NOx emissions and particle number (PN) emissions are tested and measured, with the introduction of Real Driving Emissions (RDE) testing, alongside laboratory testing. During RDE testing, vehicles are driven on the road according to random acceleration and deceleration patterns, with emissions measured using onboard portable emissions monitoring systems (PEMS).

Conformity Factors (CFs) have been introduced, which govern the multiple by which the vehicles' NOx and PN emissions can exceed the emissions limits during RDE testing. The exceedance is intended to allow a margin for measurement error using PEMS. The European Commission (EC) intended to review the CFs over time as the measurement accuracy of PEMS equipment improves. The phase-in of CFs has so far taken place in two stages:

In the first stage (**Euro 6d-TEMP**), a NOx CF of 2.1 and a PN CF of 1.5 were introduced for new type approvals of passenger cars from September 2017, and for new type approvals of light commercial vehicles (LCVs) from September 2018. The CFs applied to all new passenger vehicles from September 2018 for PN and September 2019 for NOx, and a year later to all new LCVs.

In the second stage (**Euro 6d**), the NOx CF was reduced to 1.43, applying to new type approvals for passenger cars from January 2020, and to all vehicles from January 2022.

At the time of writing, the creation of a further stage of Euro 6 was under consideration, to be introduced as Euro 6e. The Joint Research Centre of the European Commission currently recommends reducing conformity factors to 1.1 for NOx and 1.34 for PN. A proposal for such amendments was presented in the Motor Vehicle Working Group (MVWG) on the 9th February 2022.