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Pgm market report

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Johnson Matthey
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Definitions

Europe	EU+ (includes 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 control of the pgm throughout). Outside the autocatalyst, jewellery and electronics markets, **open-loop recycling** is negligible. **Autocatalyst 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 lower demand. **Autocatalyst 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, and non-road mobile machinery. (Fuel cell vehicles are 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 2020

Pgm supply and demand fell in tandem in 2020, leaving platinum, palladium and rhodium in continued deficit.

Industrial pgm demand was supported by the construction of new petrochemical and glass fibre capacity in China.

Autocatalyst pgm demand fell by 13%, as the first pandemic wave triggered widespread car plant closures.

Chinese platinum jewellery demand slumped to a twenty-year low, due to Covid lockdowns and weak consumer demand.

Net platinum investment exceeded 1 million oz, but investors continued to liquidate palladium and rhodium ETFs.

Primary pgm supplies shrank by 16%, due to processing outages and Covid-related disruption in South Africa.

Palladium and rhodium prices reached all-time highs in 2020, as market liquidity was drained by successive deficits.

Pgm supply and demand fell in 2020, reflecting Covid-related impacts on the automotive, industrial and jewellery sectors, and disruption to both primary and secondary supplies. Combined autocatalyst demand for platinum, palladium and rhodium fell by 13%, as the first pandemic wave triggered temporary shutdowns at car plants, and consumers deferred new vehicle purchases. Weak consumer spending also hit platinum jewellery fabrication, but industrial pgm demand was more resilient, with heavy buying from industrial customers in China, where new plant construction by petrochemical and glass companies proceeded on schedule. World primary pgm supplies shrank by around 16%, due to outages at Anglo American Platinum's converter plant in addition to pandemic-related disruption, while secondary supplies fell by 12% on lower vehicle scrappage rates. Weak platinum prices helped stimulate exceptional demand for platinum bars and ETFs, but palladium and rhodium investors took profits as both metals recorded all-time highs. Overall, changes in supply and demand were of a similar magnitude, leaving all three metals in continued deficit.

References to 'pgm' in this chapter refer to platinum, palladium and rhodium. A discussion of demand for iridium and ruthenium in 2020–2021 is included separately, on page 29.

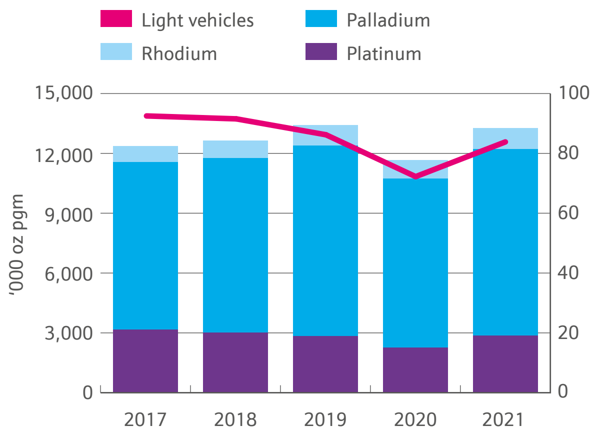


Figure 1 Autocatalyst pgm demand & light vehicle output

"Investment linked to China's Thirteenth Five-Year Plan helped support pgm purchasing by the glassmaking, petroleum refining and chemicals industries. Most projects planned for 2020 were implemented on schedule, despite the pandemic. There was also some advance purchasing of platinum for future projects, after prices fell to multi-year lows in March"

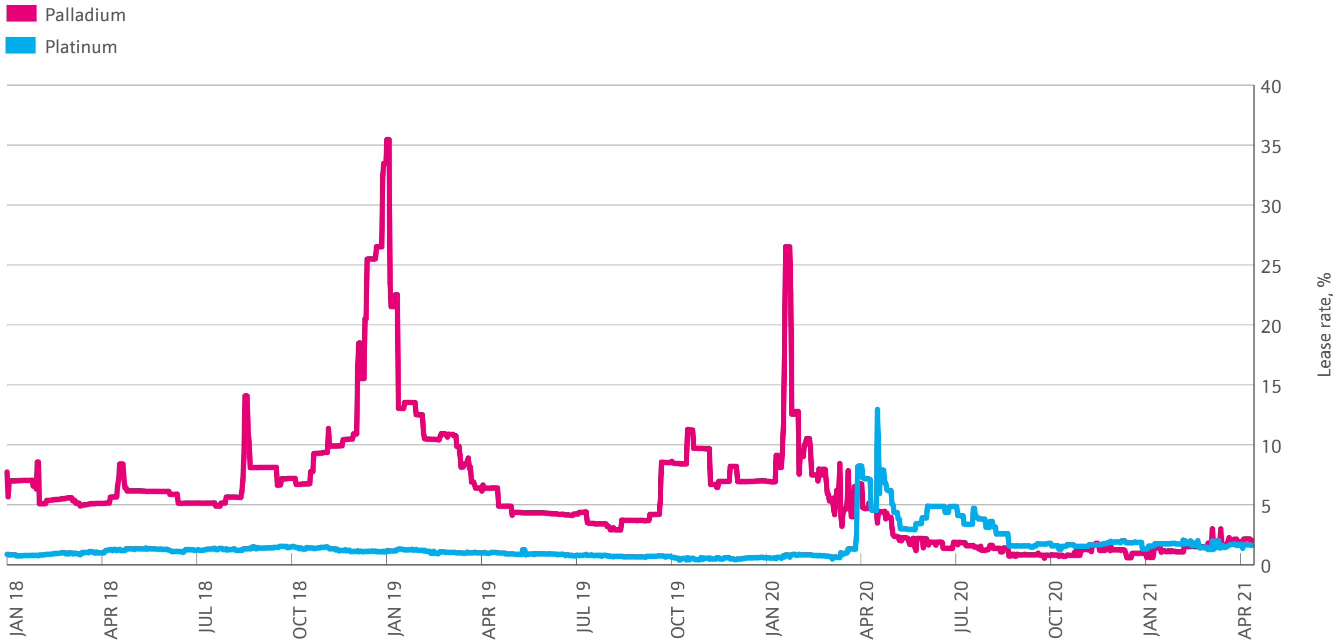


Figure 2 Platinum and palladium lease rates (3-month)

Market balances and liquidity

In the platinum market, investment demand has been a key driver of deficits over the past two years. Platinum ETF holdings rose by more than 1.5 million oz in 2019–2020, while Japanese retail investors purchased around 400,000 oz of metal in the form of physical investment bars. With gold and palladium trading at or near record prices, platinum was perceived as offering value for money to precious metal investors, especially in view of its potential for future use in gasoline autocatalysts and the hydrogen economy.

Despite this heavy investment demand, the platinum market remains theoretically well-supplied, following several years of surplus over the last decade. Nevertheless, the market recorded periods of exceptional tightness in 2020, with ingot shortages in platinum's traditional European trading hubs driving lease rates above 12% in April (Figure 2). This followed steep falls in the platinum price, which stimulated record monthly sales of platinum ingot on the Shanghai Gold Exchange (SGE) and of retail investment bars in Japan.

Platinum lease rates remained unusually elevated for much of the second and third quarters, as SGE purchasing and Japanese bar sales continued at high levels. For the full year, over 1.35 million oz of platinum ingot was purchased on the SGE, double the 2019 volume, and the highest since 2013 (the peak year for Chinese platinum jewellery demand, when jewellery fabricators consumed at least three times as much platinum as in 2020), (Figure 3). These exceptional 2020 SGE sales, in a pandemic-hit year, were primarily a result of extremely strong industrial demand, in particular in the petrochemical and glass sectors (see page 11).

In contrast to the platinum market, where recent deficits have primarily been a consequence of heavy investment buying, both palladium and rhodium are in significant structural deficit. This is a direct consequence of several years of strong growth in automotive consumption, at rates that greatly exceeded gains in primary and secondary supply. Between 2015 and 2019, the use of palladium and rhodium in autocatalysts expanded by over a quarter, while combined primary and secondary supplies rose by less than 10%. Although automotive demand for these metals fell in 2020, supply also contracted, leaving both markets in ongoing deficit.

"Japanese bar purchases surged as the retail platinum price plunged to a seventeen-year low"

Over the 2015–2020 period, we estimate that the cumulative palladium shortfall totalled over 3 million oz, even after allowing for the liquidation of ETF holdings, which returned 2.4 million oz of metal to the market over this period. Market stocks of metal held in the traditional trading hubs in the UK and Switzerland were significantly depleted, triggering periodic spikes in lease rates (Figure 2) and steady gains in the price (Figure 4). From around $500 at the start of 2016, palladium climbed through $1,000 in early 2018 and breached $2,000 in early 2020, on its way to all-time highs above $2,800 in February last year. The price fell briefly to lows of around $1,600 during Covid-related selling in March 2020, but recovered strongly to trade above $2,000 during the second half of the year.

The palladium market experienced unusual mismatches between the location and form of supply and demand during 2020, primarily due to market distortions arising from the pandemic. During the second quarter, as first European and then US automakers shuttered their plants due to Covid-19, there was a steep fall in demand for palladium sponge (the preferred form of most Western buyers), at a time when Chinese demand (primarily for ingot) was beginning to recover from earlier factory closures. Ingot moved to a large premium over sponge, and this eventually spurred market participants in the

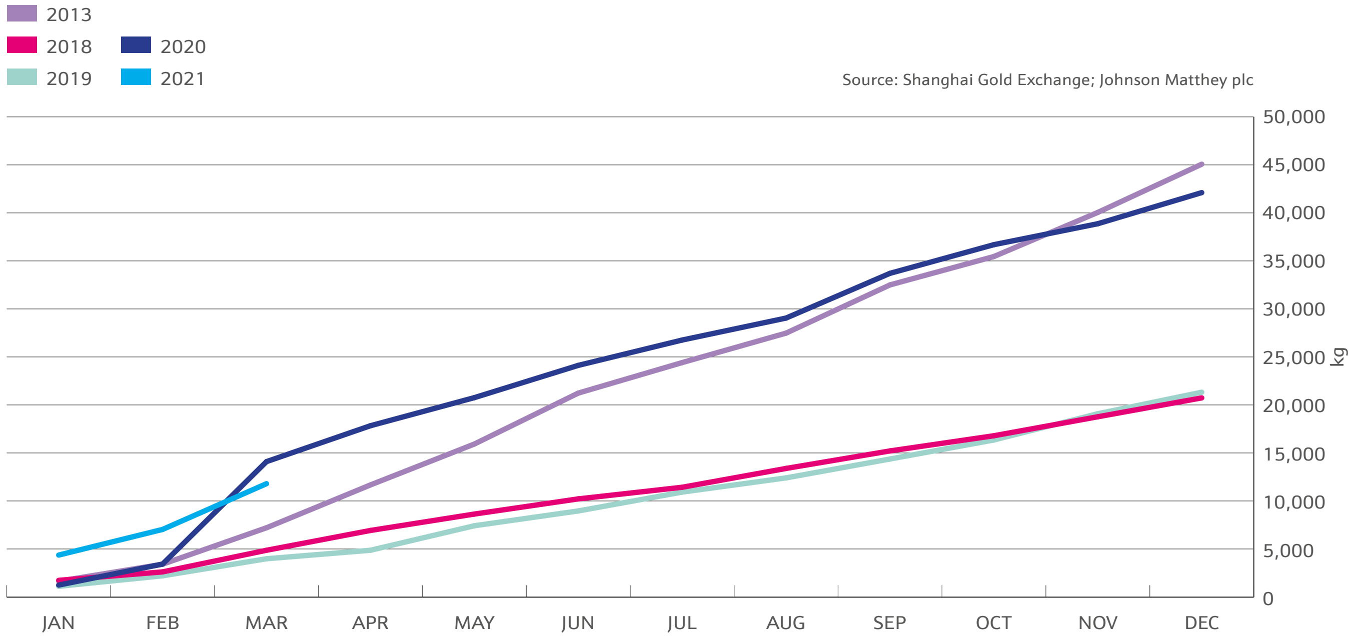


Figure 3 Cumulative SGE platinum sales

West to convert large quantities of sponge into bars. Some of this metal was purchased by customers in Asia, but some was delivered into traditional trading hubs in Europe. As a result, trade statistics suggest that inventories of palladium bars held in UK and Swiss vaults rose by around half a million ounces in 2020 – the first significant increase in at least a decade (Figure 5).

This increase in 'visible' market stocks primarily reflects changes in the form and location of metal inventories, rather than signalling a move out of deficit market conditions. It is likely that some of this metal came from the release of work-in-progress inventories at Western refineries, especially during the second quarter of 2020 when new intakes of pgm-bearing materials were sharply reduced.

Rhodium's move into market deficit is more recent: we estimate that the market accumulated a shortfall of around 130,000 oz in 2019–2020, following a period of surplus (Figure 6). However, this figure may understate the amount of liquidity drained from the market over this period. Our estimates of investment (in the case of rhodium, included in 'other' demand) account only for metal purchased in ETFs or in retail investment products such as small bars and coins. We do not make any allowance for speculative or investment purchases of pgm in other forms. It is also likely that some strategic stocks have been acquired by automakers and industrial purchasers. Our figures may therefore underestimate actual pgm purchasing in any individual year.

"As the pandemic progressed across Asia, Europe and North America, many large car factories closed temporarily"

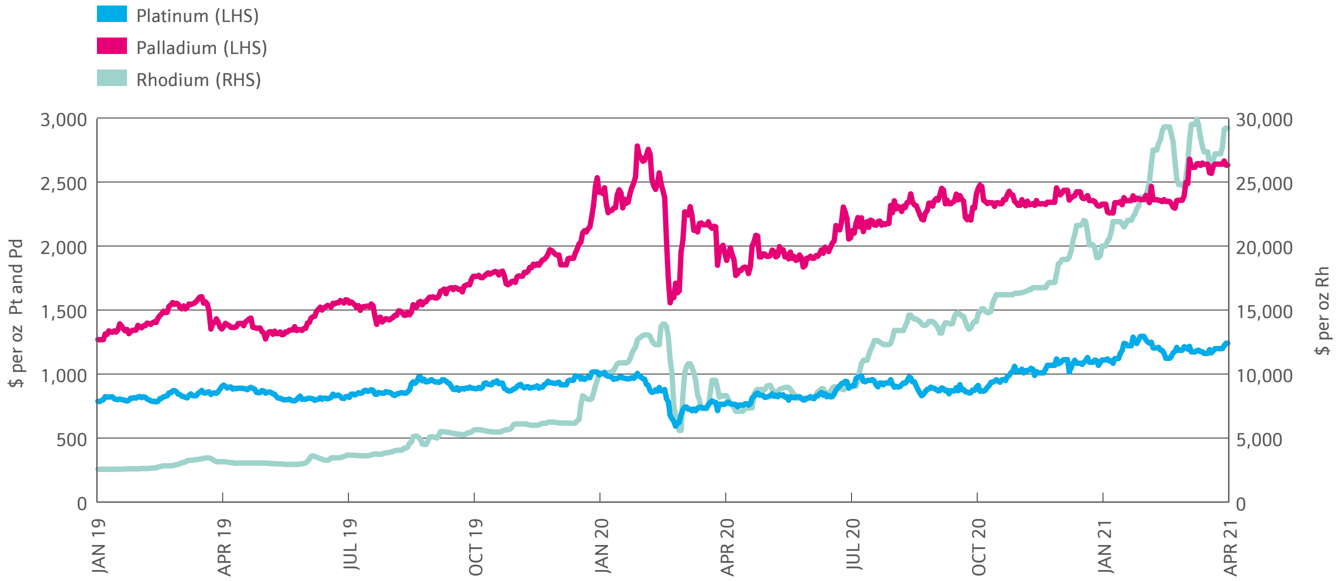


Figure 4 Platinum, palladium and rhodium prices

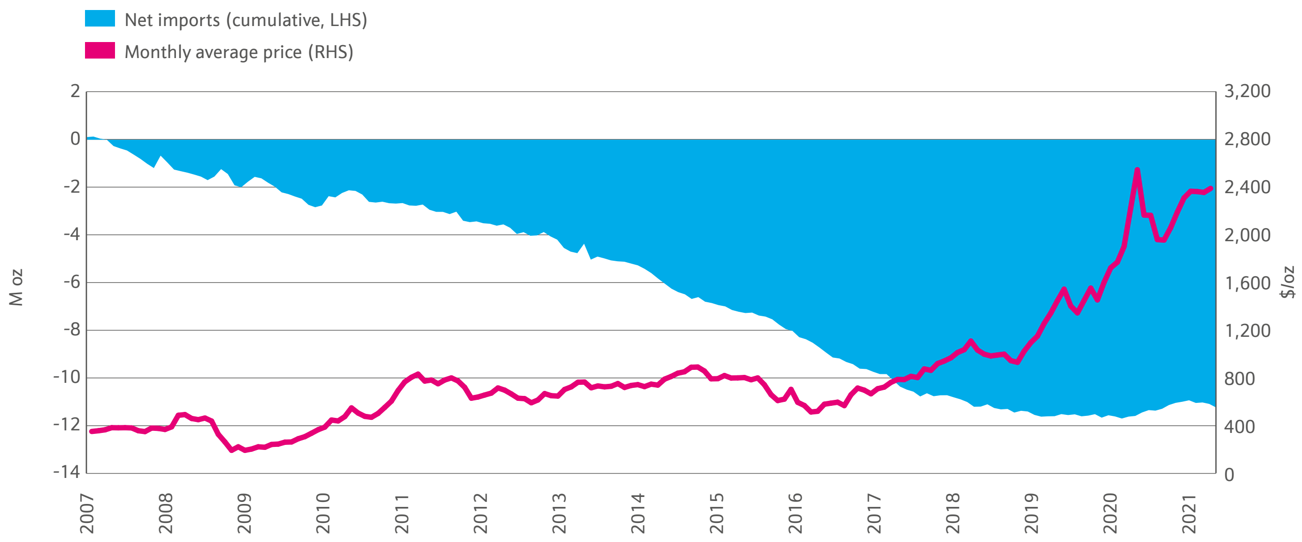


Figure 5 Cumulative net imports of palladium into the UK and Switzerland since 2007

Rhodium has been particularly affected by supply disruption over the past year. Mine supply is highly concentrated in South Africa, which accounts for over 80% of primary rhodium output; much of this metal comes from underground operations exploiting the rhodium-rich UG2 reef. Many of these mines use labour-intensive methods and were therefore especially vulnerable to Covid-related disruption.

Rhodium supply shortfalls were exacerbated by processing outages at the world's largest rhodium producer, Anglo American Platinum, which experienced a series of technical incidents at its Anglo Converter Plant (ACP) during 2020. This resulted in the accumulation of a significant backlog of semi-processed pgm that may take up to two years to treat. (For further information on primary supplies, see page 12).

This temporary supply disruption intensified the impact of underlying structural deficits, resulting in exceptionally high rhodium prices and extreme volatility. As auto industry requirements increased and market stocks were progressively depleted, rhodium climbed from below $3,000 in January 2019 to a (then record) high of $13,800 in March 2020, following Anglo's declaration of force majeure (Figure 4). Although rhodium lost nearly two-thirds of its value during pandemic-related sell-offs later that month, it subsequently embarked on another steep climb as demand from the auto industry began to recover, surging above $15,000 in November after Anglo announced a new ACP outage. Although the ACP resumed operations in early December (allowing refined rhodium output to return to more normal levels from early 2021), the rhodium price continued to surge higher. It reached $17,000 on 31st December and went on to record new all-time highs of nearly $30,000 in March 2021.

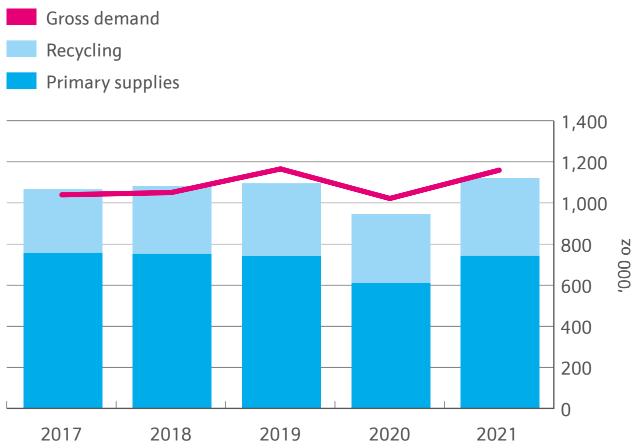


Figure 6 Rhodium supply and demand

Investment demand

In 2020, palladium and rhodium investors continued to take advantage of high prices to liquidate their ETF holdings. However, with only limited quantities of metal remaining, selling was relatively subdued. At the year-end, we estimate that ETFs contained around 527,000 oz of palladium (down from a peak of nearly 3 million oz in early 2015) and 16,000 oz of rhodium (versus a high of 130,000 oz in 2014).

In contrast, investment demand for platinum was strongly positive in 2020, helping to keep the market in deficit. Net investment in ETFs and other physical products such as platinum coins and bars amounted to over 1 million oz.

In Japan, purchases of physical investment bars in March 2020 set an all-time record for any single month, as the retail platinum price plunged through the key ¥3,000 level, briefly touching a seventeen-year low of just over ¥2,500 per gram. Although the price subsequently rose back towards ¥3,500, investors continued to accumulate metal during the second and third quarters, as a widening discount to gold reinforced investor perceptions that low platinum prices represented a buying opportunity (Figure 7). Towards the year-end, demand eased and even turned negative during December, as the platinum price moved above ¥3,800 per gram and some investors took profits. Nevertheless, we estimate that platinum investment in Japan totalled nearly 400,000 oz in 2020 – a four-year high. (Note: the prices quoted above are Japanese retail prices, i.e. net of sales tax, which is currently levied at a rate of 10%.)

Global ETF holdings of platinum were relatively stable in the first half of 2020. Rand weakness provided some profit-taking opportunities to South African investors, but this was broadly offset by renewed purchasing in Europe and North America. During the third quarter, there was a return to significant buying in all regions, with over half a million ounces being added to global ETF holdings. Investor interest in platinum slackened in November, when some profit-taking came into the market, but renewed buying at the year-end pushed holdings to a record 3.97 million oz. Some of this was probably 'safe haven' buying spilling over from gold, but platinum also benefited from improving sentiment based on the potential for increased use in gasoline autocatalysts in the near term, and fuel cells in the longer term.

Autocatalyst demand

Consumption of pgm in automotive applications contracted by 13% last year, as the pandemic cut short a decade-long rising trend in the use of palladium and rhodium in autocatalysts (Figure 1). Global light vehicle production fell by 16.5% to around 72 million units, but different market segments saw highly contrasting trends: output of battery electric vehicles enjoyed double-digit growth, while gasoline and diesel car volumes fell by an estimated 16% and 25%, respectively. In the heavy duty sector, most regions saw significant falls in truck output, but global volumes were supported by an exceptionally buoyant Chinese market.

> "The low point for global car production was in April, when light vehicle output outside China fell below one million units"

In the light duty sector, there was considerable variation in the size of the pandemic hit to regional automotive industries. Output of light duty vehicles in China fell by around 6% in 2020, to 21.4 million units. While first-quarter production volumes almost halved compared with the previous year, the industry subsequently staged a strong rebound, assisted by national and regional incentives such as vehicle replacement subsidies, scrappage schemes, and the relaxation of licence plate quotas. Output in the June, September and December quarters was up 7–9% compared with previous-year levels.

While the impact of Covid-19 in China was largely confined to a single quarter, other regions saw a steeper downturn and a slower recovery. As the pandemic progressed across Asia, Europe and North America, many large car factories closed for a period of several weeks during March and April. The low point for global production was reached in April, when light vehicle output in all regions outside China fell below one million units. During this month, only around 100,000 vehicles were produced in Europe, under 10,000 in North America, and none at all in India.

Most countries lost between one-half and two-thirds of their normal vehicle output during the second quarter, and many did not see any significant 'catch-up' during the remainder of 2020. For the full year, light vehicle production fell by around 16% in Japan, and over 20% in North America, Europe, and the Rest of World region.

From the pgm demand perspective, these exceptionally large falls in output were mitigated to some extent by further increases in average pgm loadings on gasoline autocatalysts, limiting the decline in combined palladium and rhodium demand to around 11%. Platinum benefited from a slight increase in global average diesel loadings, along with some very limited additional use in three-way catalysts for gasoline vehicles. Nevertheless, overall platinum demand in autocatalysts fell by 20%, with production of light and heavy duty diesel vehicles in key regional markets severely impacted by the pandemic.

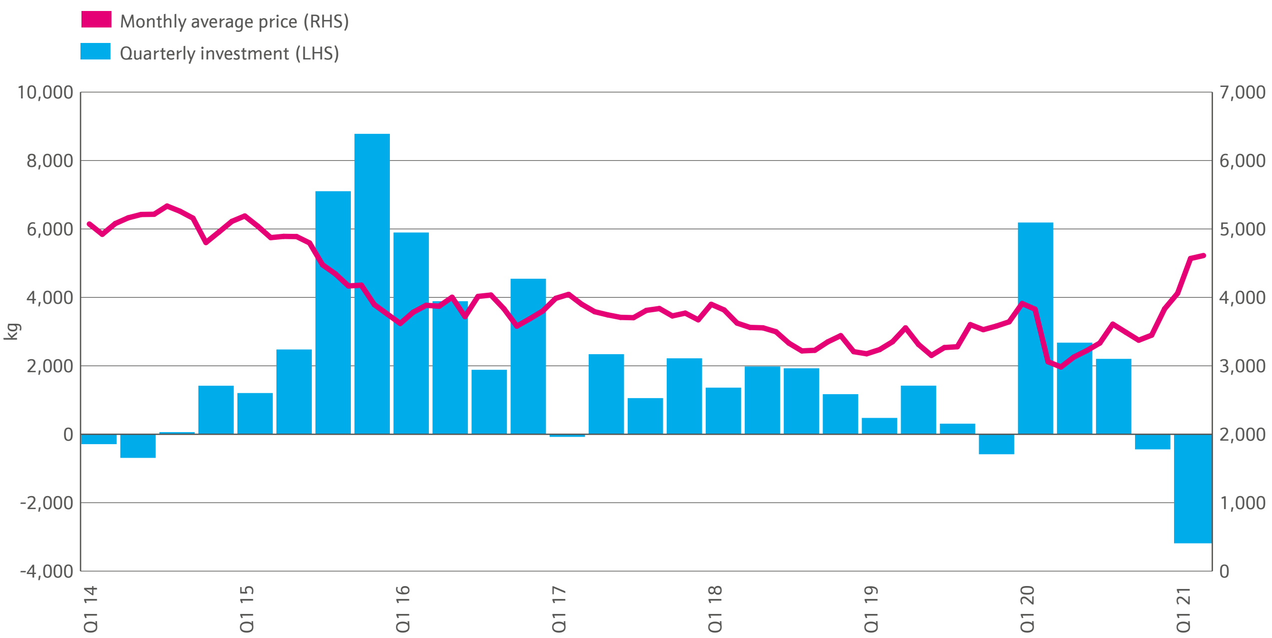


Figure 7 Japanese platinum bar investment

In China, the rollout of China 6 models helped lift the average pgm content of a gasoline catalyst system modestly in 2020, in the wake of a much larger increase the previous year. This was despite significant efforts to reduce the cost of aftertreatment systems, with pgm thrifting programmes intensifying in response to record palladium and rhodium prices. These thrifting efforts were facilitated by government initiatives, especially the introduction of a new, simplified vehicle conformity certification process in March 2020, which has enabled companies to accelerate changes to their catalyst fitment programmes.

As well as aggressively pursuing thrifting opportunities, some car companies in China began to implement substitution programmes, with the aim of replacing some of the palladium in their three-way catalysts with platinum. During 2020, platinum-containing catalysts were fitted to a small number of gasoline models, mainly in the underfloor position where loadings are relatively low. However, the impact on overall platinum and palladium demand was negligible.

Thrifting and substitution also began to receive greater attention in other regions, as car companies prioritised cost-cutting in response to weak sales and high pgm prices. However, changes to catalyst systems typically take longer to implement outside China. Indeed, with legislation still tightening in many major markets, there were further increases in the average palladium and rhodium content of gasoline catalysts in all regions in 2020 (in contrast, average platinum loadings remained broadly stable, with substitution programmes yet to have a significant impact).

In Europe, all light vehicle models sold last year were subject to RDE testing, to evaluate tailpipe emissions of NOx and particulates under real-world driving conditions. RDE legislation continues to tighten, with new passenger car models launched in 2020 required to comply with full Euro 6d legislation, which reduces NOx 'conformity factors' by around one-third compared to the previous 6d-TEMP standards.

The introduction of RDE and the subsequent tightening of conformity factors has dramatically increased the technical difficulty of meeting emissions standards, driving up the pgm content of catalysts. This has had a positive impact on use of all the autocatalyst pgm, but the impact has been greatest on rhodium, because RDE legislation focuses specifically on NOx emissions.

In India, the average pgm content of a gasoline car rose by around 6% in 2020, following the implementation of Bharat VI (BSVI) legislation in April 2020. This market has moved in a single step from Euro 4 type standards to the equivalent of Euro 6, although without RDE for the time being. Emissions legislation is also tightening gradually in North America, with Tier 3 federal legislation requiring a higher percentage of new vehicles to meet the very stringent SULEV standards each year between 2017 and 2025. The average pgm content of a gasoline vehicle rose by over a quarter between 2016 and 2020, and an upward trend in total loadings is expected to continue until at least 2025.

The light duty diesel sector also saw some gains in average pgm loadings in 2020, although this was largely offset by falls in vehicle output, as the Covid pandemic intensified pre-existing weakness in the key European diesel car market. Heavy-duty truck producers also slashed production volumes in all major markets except China. As a result, platinum auto demand contracted by 20% to 2.29 million oz, the lowest level since the Global Financial Crisis.

> "All European cars were subject to RDE testing, which regulates NOx and particulate emissions under real-world conditions"

In Europe, by far the largest regional user of platinum in autocatalysts, demand dropped 22% to a twenty-year low of under 1 million oz. The diesel vehicle segment was more heavily impacted by Covid-related losses than gasoline or battery electric: European diesel car production plunged by over a quarter to 5.35 million vehicles, the lowest full-year total recorded in this region since 2000. As a result, diesel represented a share of

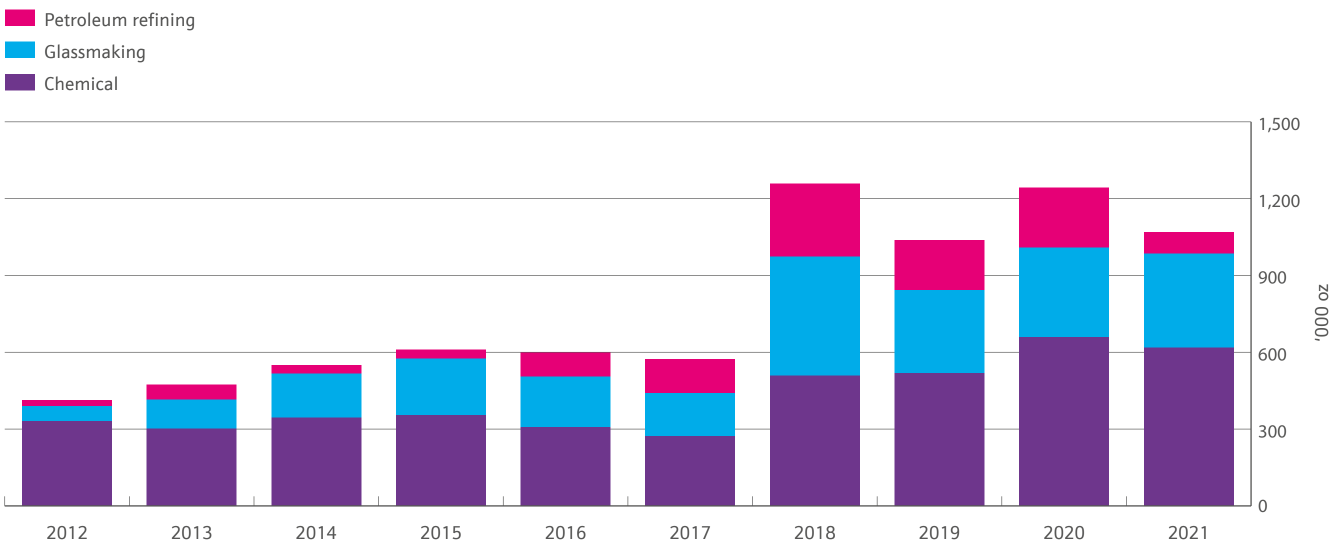


Figure 8 Chinese demand in chemicals, glassmaking and petroleum refining

just 35% of this market; as recently as five years ago diesel cars accounted for half of all European light vehicle production.

India (previously the world's second largest light duty diesel market) saw diesel car output slump by around 50% in 2020. While part of this decline was attributable to Covid, the diesel segment fared far worse than the light duty gasoline sector. Diesel volumes were hit by changes to automakers' vehicle production mix ahead of the introduction of BSVI legislation in April 2020. The new regulations require the addition of complex and expensive NOx control technology to diesel aftertreatment systems, and this has made diesel uneconomic in smaller vehicle segments.

Platinum use on heavy duty vehicles also declined steeply. Most regions saw a sharp contraction in truck output, particularly in the heaviest truck segments, where catalyst loadings are highest. For example, output of heavy duty diesel trucks with a gross vehicle weight of over 15 tonnes fell by nearly 30% in Europe and 40% in North America.

China bucked this trend, with a remarkable 22% increase in heavy duty volumes: all heavy vehicle categories except buses recorded strong double-digit gains. In the heaviest vehicle category, output leapt by 37%, adding over 400,000 units, as businesses purchased trucks ahead of the implementation of China VI emissions legislation in 2021. Most diesel trucks sold in China before this year were not equipped with pgm-containing aftertreatment systems, so last year's extraordinary production gains had only a limited impact on platinum demand.

Industrial demand

Despite steep falls in GDP in many regions, industrial demand for pgm outperformed expectations in 2020. Purchasing by the Chinese chemicals, glassmaking and petroleum refining industries remained elevated compared to historical levels (Figure 8), due to ongoing investment linked to the Thirteenth Five-Year Plan (2016–2020), while worldwide electronics demand benefited from pandemic-linked societal and cultural changes. Applications that saw significantly weaker demand were those more directly exposed to Covid-related retail closures, especially jewellery, and those related to air and road transport, such as aero-engine turbine blades and automotive spark plugs.

> "Exceptional prices stimulated a reduction in the rhodium content of platinum alloys used in glassmaking"

A key pillar of China's Thirteenth Five-Year Plan was to increase self-sufficiency in petrochemicals. Over the past three to four years this has been highly supportive of pgm catalyst demand both in petroleum refining and for the production of bulk chemicals such as paraxylene, propylene and hydrogen peroxide. Because capital investment in these sectors has been driven by state objectives, most projects planned for 2020 were implemented on schedule and saw little or no impact from the pandemic. The purchase of pgm for large petrochemical complexes typically takes place a few months ahead of plant commissioning, but during 2020 there was some advance purchasing of platinum for future projects after prices fell to multi-year lows in March.

The Chinese fibreglass industry also saw some pre-buying of platinum for future projects, in addition to metal required for new plants brought on-stream during 2020. However, rhodium demand fell sharply, as manufacturers reduced the rhodium content of platinum alloys used in glassmaking equipment. This alloy switching behaviour is commonly seen in the fibreglass industry during periods of high rhodium prices, but the exceptional price trends of the past eighteen months have led some manufacturers to reduce the rhodium content of their alloys to lower levels than was previously considered economically and technically viable.

The pandemic has been the catalyst for some wide-reaching changes in work and social behaviour that have been positive for the electronics industry generally. A dramatic increase in remote working and increased consumption of home entertainment has boosted demand for devices such as laptop computers and games consoles. This in turn has been broadly positive for pgm demand in electronic plating applications and components such as hard disks and chip resistors.

However, other pgm applications saw a much larger impact from Covid. Sectors linked to transport were among the most severely affected. Use of pgm in components such as spark plugs, automotive oxygen sensors and NOx sensors saw double-digit declines, broadly following trends in vehicle production, while platinum consumption in aero-engine turbine blades fell by around 50%, as Airbus and Boeing slashed aircraft production and engine refurbishment activity dropped sharply. Much of the platinum demand in aviation applications arises from periodic engine maintenance, during which turbine blades may be removed and either replaced or recoated. With passenger kilometres estimated to have fallen by around two-thirds in 2020, fewer aircraft underwent maintenance, while more were retired, leading to increased recovery of platinum from turbine blades.

Consumption of pgm in the dental sector was also hard-hit. Dental procedures can be dangerous for the practitioner, because of the risk of virus transmission via both droplets and aerosols. Many procedures were deferred during the active waves of the pandemic, and some of the lost demand will be foregone permanently.

Jewellery demand

Gross consumption of platinum in jewellery fell by 17% in 2020, as fabrication demand in the large Chinese market fell below one million ounces for the first time since 2005 (Figure 9). Chinese demand was exceptionally weak during the first half of the year, due to extended store closures, low footfall following the reopening of retail outlets during February and March, and consumers' reluctance to spend on luxury goods during the initial post-lockdown period. However, platinum jewellery fabrication

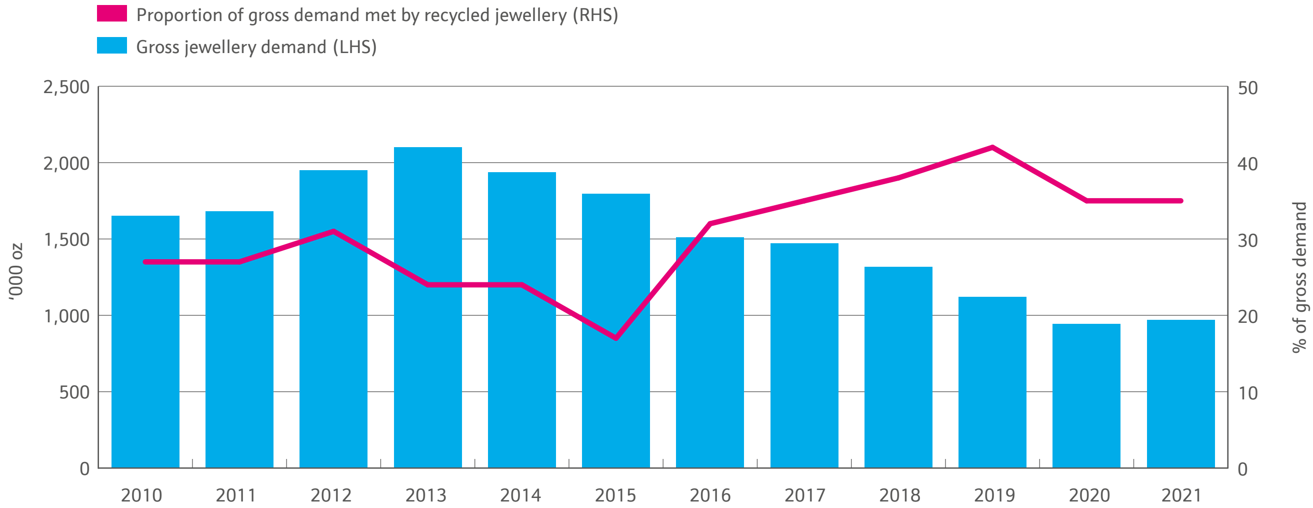


Figure 9 Chinese platinum jewellery demand & recycling

surged in the third quarter, largely as a result of record gold prices, which made karat gold jewellery significantly harder to sell and more expensive to stock. This in turn encouraged Chinese retailers to rotate their stock, and to devote more counter space to platinum.

Momentum was lost during the fourth quarter, as greater visibility of platinum jewellery on shop counters failed to translate into significantly higher sales. With the gold price slipping lower, and platinum moving above $1,000, the financial incentive to increase platinum jewellery stocks also began to wane.

Other regional jewellery markets are much less price-sensitive, and demand trends were primarily driven by Covid-related changes in consumer spending and behaviour. During the early stages of the pandemic, US platinum jewellery demand was severely hit by lockdowns and a collapse in consumer confidence. However, from mid-year, there was a remarkable recovery in consumer spending on durable goods: this reflected not only government policies such as stimulus cheques, but also changes in consumption patterns, as individuals diverted spending away from travel and other services towards consumer goods. Platinum jewellery was a beneficiary of this trend, with the result that US fabrication demand fell by only 2% in 2020. In contrast, Japanese demand fell by nearly 20%: sales of fashion jewellery were hit by retail store closures and restricted opening hours, while some couples postponed weddings due to the pandemic, leading to a decline in demand for bridal jewellery.

Primary supplies

Combined global primary pgm supplies fell by around 16% in 2020, in the wake of severe pandemic-related disruption to mining in South Africa, and prolonged outages at Anglo American Platinum's converter plant (ACP). Platinum and rhodium production bore the brunt of the decline, because their production is highly concentrated in South Africa; supplies of these metals fell by 18%. In contrast, palladium supplies fell by only 13%, reflecting the wider geographical distribution of palladium mining, and a lesser degree of Covid disruption at mines in Russia and North America.

Underground mines in South Africa were closed due to Covid lockdown regulations between 26th March and 16th April, when they were permitted to restart at 50% of usual levels. From June, full production was authorised, but in practice most mines took several months to return to normal operating conditions. The implementation of physical distancing and infection control measures created some capacity constraints, while delays in the return of migrant workers caused labour shortages.

The reopening process was particularly complex for deeper shafts where the platinum reefs are extracted using conventional labour-intensive methods, because physical distancing measures are particularly challenging to implement in this setting. Nevertheless, by the end of the third quarter, many shallower mines were operating near-normally, and most deeper operations had recovered to at least 90% of usual production levels.

"In the third quarter, exceptional gold prices encouraged Chinese retailers to devote more counter space to platinum"

The impact on annual production varied significantly between mines, largely as a function of their depth and mining method. Mined pgm output at Anglo American Platinum's open-cast Mogalakwena mine fell by 3% compared with 2019, while mechanised mines on the eastern Bushveld typically lost less than 10% of annual production. However, some older mines on the western Bushveld experienced more prolonged disruption, with annual pgm volumes falling by over 20%. Overall, we estimate that underlying pgm output (defined as production of pgm in concentrate from mining and tailings reprocessing operations in South Africa) fell by around 11%.

Refined pgm output took a much larger hit, falling by over 20%, as the impact of Covid disruption was exacerbated by interruptions at processing plants. In March 2020, Anglo American Platinum declared force majeure to customers and third-party concentrate suppliers, after technical problems at both ACP units left it with no operational converting capacity. The primary Phase A converter unit was taken off-line for ten months for a complete rebuild, while temporary repairs were undertaken at the back-up Phase B converter, enabling it to resume operations after a two-month shutdown. However, the plant continued to experience disruption due to ongoing repairs and, in early November, it was closed again for safety reasons.

Anglo was subsequently able to recommission the rebuilt Phase A unit ahead of schedule in early December, but the group nevertheless ended 2020 with excess pipeline inventory containing over 1 million oz of pgm. This backlog is expected to be processed during 2021 and 2022.

Elsewhere, mining operations were less severely impacted by the pandemic, partly due to less harsh government-imposed lockdowns, and partly due to the less labour-intensive nature of their mining operations. Zimbabwe's platinum mines are mechanised and received government dispensation to operate during the country's lockdown period, with the result that annual pgm supplies were broadly stable. In Russia, Norilsk Nickel reported no pandemic-related interruptions at its mining operations; full-year refined pgm output exceeded earlier guidance, although it was down slightly on the previous year. It should be noted that our estimate of Russian palladium supplies accounts for a modest increase in refined inventory at Norilsk, consisting of around 186,000 oz of palladium refined but not sold in 2020.

Covid disruption had only a limited impact on North American pgm supplies. Most mines operated continuously, although the Lac des Iles palladium mine (Impala Canada) and the Raglan nickel operation (Glencore) closed for several weeks during the first epidemic wave. Sibanye-Stillwater's mines in Montana, USA, remained open, but deferred some expansion activities and also reported some loss of productivity. Vale and Glencore saw only limited direct Covid impact on their Sudbury nickel mines, which produce platinum as by-products. However, Glencore reported lower pgm output as a result of a fall in grades at its Sudbury operations, while extended maintenance programmes at Vale's Sudbury mines and surface plants led to a dip in ore and metal production during the second half.

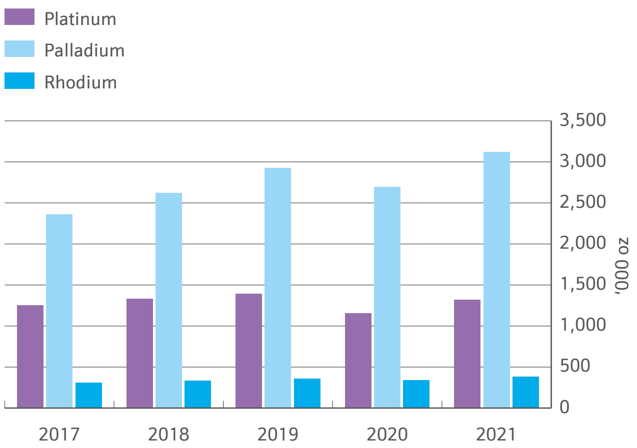


Figure 10 Autocatalyst recovery by metal

Secondary supplies

Despite record palladium and rhodium prices, recovery of pgm from secondary materials (primarily autocatalyst scrap) declined sharply in 2020 (Figure 10). New vehicle registrations are an important factor determining the availability of autocatalyst scrap, so a 14% fall in global light vehicle sales had a negative impact on recycling volumes. Lockdowns and travel restrictions affected driving activity, reducing wear-and-tear and accidental damage, with the result that fewer vehicles needed replacing in 2020, especially in the fleet and car rental sector. Moreover, a combination of economic uncertainty and rising lead-times for the delivery of new vehicles encouraged individuals and companies to extend leases on existing vehicles, or to buy second-hand instead. This in turn reduced the pool of used cars, driving prices up significantly in some regions, and encouraging owners to postpone deregistering vehicles that might normally have been scrapped.

In addition to falling numbers of scrapped vehicles, there was also significant disruption to the collection of autocatalyst scrap. During Covid-related lockdowns, some scrapyards were closed, while collectors experienced difficulties with transporting scrap material, particularly where this involved crossing international borders (catalyst scrap is often shipped to refineries in different countries or even continents). Cross-border collection of scrap was particularly problematic in Europe during the first pandemic wave.

Nevertheless, palladium and rhodium recoveries from auto scrap saw only a single-digit decline. During 2019 and early 2020, a combination of strong autocatalyst recycling volumes and capacity constraints in the secondary refining sector led to a build-up in inventories of pgm-bearing scrap and semi-processed materials. The Covid crisis triggered an abrupt fall in scrap intakes, which in turn freed up refining capacity and allowed backlogs to be processed. Extremely high metal prices also incentivised market participants to move scrap through the recycling network as promptly as possible.

In contrast, platinum recoveries fell by 17%, partly due to regional variations in the Covid impact on scrap collection networks, and partly due to specific technical challenges associated with treating some types of diesel catalyst. The European market, the largest source of platinum-rich diesel catalyst scrap, endured longer lockdown periods and greater restrictions on travel than the other major scrap market, the USA. We also believe that some lower tier collectors prioritised the recovery of higher-value and easier-to-treat palladium-rhodium catalysts. In comparison to gasoline scrap, spent diesel catalyst is less attractive to collectors and refiners because it has a lower pgm value and the silicon carbide content of diesel particulate filters makes this material harder to treat. Most refineries have only a limited capacity for feed containing silicon carbide, which must be blended in small quantities with other materials to reduce the carbon content to an acceptable level.

Platinum outlook

Supply and demand in 2021

With investment demand forecast to drop sharply, the platinum market is expected to move back into surplus.

South African supplies will be augmented by refining of a backlog of pgm from 2020 processing outages.

Growth in autocatalyst recoveries will be constrained by a shortage of processing capacity for diesel particulate filter scrap.

Autocatalyst demand will be boosted by stricter emissions limits for Chinese trucks and greater use in gasoline catalysts.

Chinese capacity additions will again support industrial demand, with sales to glassmakers at record levels.

Jewellery fabrication will rise modestly, as higher platinum prices hinder recovery in the Chinese jewellery market.

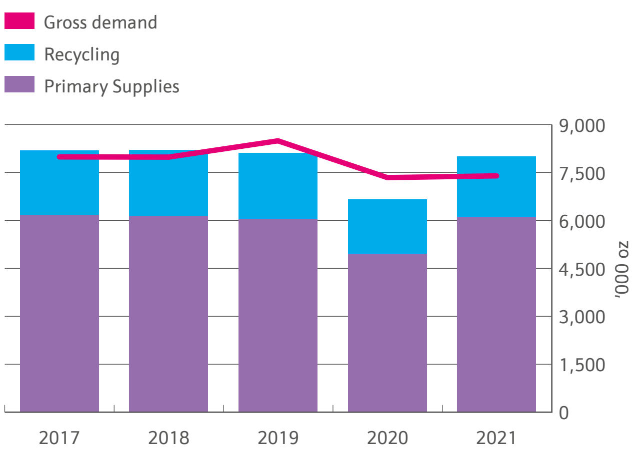


Figure 11 Platinum supply and demand

Assuming the record investment levels of the past two years are not repeated, the platinum market is forecast to move back into surplus in 2021, even though automotive and industrial consumption will recover to near pre-Covid levels. Autocatalyst demand will benefit from tightening emissions legislation on heavy duty trucks in China, and rising use of platinum in gasoline catalysts. Infrastructure investment in China will continue to support platinum use in industrial applications, with demand from the glassmaking sector at all-time highs. However, investment purchasing is forecast to contract sharply, with some investors taking advantage of higher prices to realise profits. Improved platinum prices and a narrower discount to gold may also hamper recovery of the Chinese jewellery market. Supplies will return to 2019 levels: South African output will be augmented by the refining of excess work-in-progress at Anglo American Platinum, more than offsetting lower Russian supplies due to flooding at two Norilsk Nickel mines. Recycling should also rise strongly, but platinum recoveries will remain constrained by a shortage of capacity for processing diesel catalyst scrap.

Market balance & investment demand

Since 2015, declines in Chinese jewellery fabrication and diesel autocatalyst consumption have left the platinum market increasingly dependent upon physical investment to balance the market. During years of strong investment demand, market deficits have been recorded (2016, and 2019–2020); however, when investment purchasing falters (as occurred in 2017–2018), the market swings back into surplus (Figure 11).

"Japanese investors took profits during the first quarter, as the retail platinum price soared to a peak of nearly ¥5,000 per gram"

During 2019–2020, over 2.1 million oz of physical platinum investment products were purchased by investors, mainly in the form of ETFs and platinum bars purchased 'over the counter' by retail investors in Japan. This sustained surge of investment appears to have been driven by a number of distinct factors. Platinum probably benefited from an overspill of 'safe haven' buying in gold, as investors reacted to economic threats such as the US-China trade war in 2019 and the Covid pandemic in 2020. Supply risks also played a role, with wage negotiations and electricity outages menacing South African supply in 2019, and pandemic disruption and processing outages

Supply '000 oz	2019	2020	2021
South Africa	4,344	3,222	4,475
Russia	721	699	610
Others	958	1,023	1,011
Total primary supply	**6,023**	**4,944**	**6,096**

Demand '000 oz	2019	2020	2021
Autocatalyst	2,863	2,290	2,910
Jewellery	2,066	1,707	1,797
Industrial	2,422	2,311	2,366
Investment	1,131	1,022	311
Total gross demand	**8,482**	**7,330**	**7,384**
Recycling	-2,094	-1,717	-1,903
Total net demand	**6,388**	**5,613**	**5,481**
Movements in stocks	-365	-669	615

Table 1 Platinum supply and demand

causing large production losses in 2020. At the same time, low prices reinforced perceptions that platinum offered 'value for money' compared to gold and palladium, 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.

By the beginning of 2021, ETF holdings had attained a record level of nearly 4 million oz, while Japanese buyers had accumulated a net 1.9 million oz of platinum bars since 2015. With the platinum price ascending to a six-year high of just over $1,300 in mid-February 2021, and then trading either side of $1,200 (a level last seen in early 2015), investors took advantage of opportunities to take profits during the first quarter. This was particularly true in the highly price-sensitive Japanese market,

"Platinum loadings on gasoline autocatalysts will rise, as automakers reduce costs by substituting some palladium with platinum"

where the retail platinum price soared to a peak of nearly ¥5,000 per gram, representing a doubling in value in less than a year. There was also some profit-taking by South African ETF investors during the first quarter; investment in European and North American funds remained in positive territory, but has been more muted than in the second half of last year (Figure 12).

Our forecast assumes that positive investor sentiment will continue to support ETF investment during 2021, albeit at lower levels than in the past two years. Japanese investor behaviour is more difficult to anticipate, as it remains particularly dependent upon short-term movements in yen-denominated metal prices. Indeed, overall selling (or buying) volumes are often more closely linked to the magnitude of price movements than to the absolute price level. For example, January and February saw heavy selling of platinum bars as the price moved through the psychologically important ¥4,000 and ¥4,500 per gram levels (Figure 7). Liquidation was much more subdued in March, even though the price averaged over ¥4,600 per gram during that month.

Jewellery demand

There were some glimpses of improvement in the Chinese platinum jewellery market in the second half of 2020, as high gold prices encouraged retailers to devote more counter space to platinum jewellery. Chinese jewellery fabrication also increased during the first quarter of this year, but this was primarily due to exceptional Covid-related weakness in early 2020, and does not necessarily reflect an increase in underlying consumer demand.

Indeed, the consumer response to increased retail stocking of platinum jewellery appears to have been somewhat

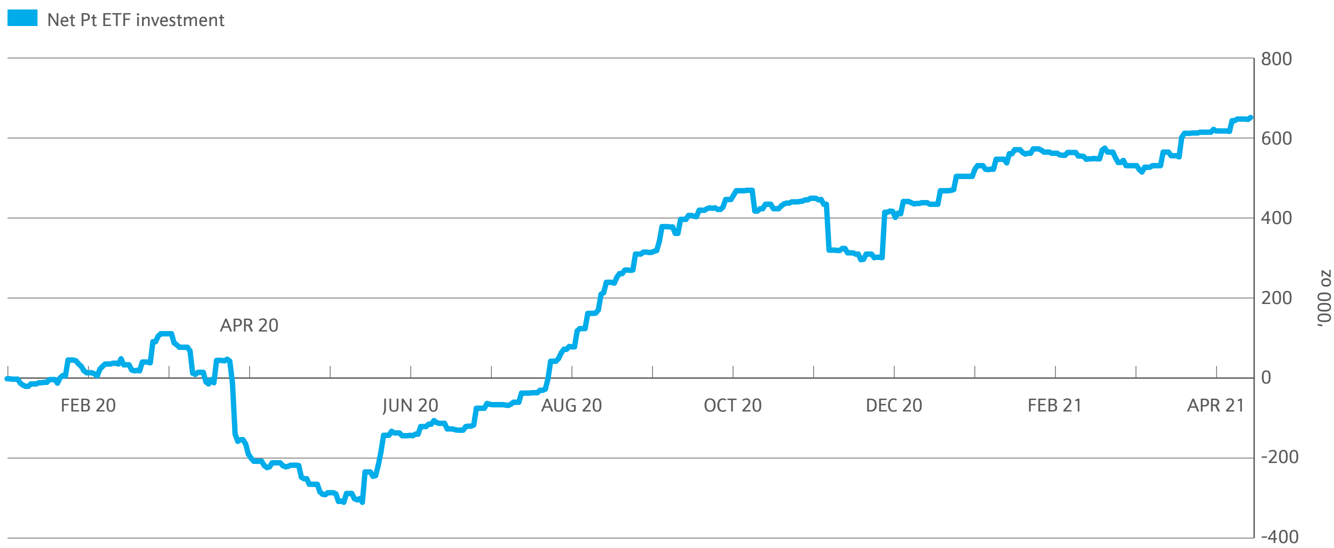


Figure 12 Net change in platinum ETF investment, January 2020 to April 2021

Demand '000 oz	2019	2020	Gross 2021	2019	2020	Recycling 2021	2019	2020	Net 2021
Europe	190	152	170	-5	-5	-5	185	147	165
Japan	294	238	265	-175	-143	-151	119	95	114
North America	211	206	213	-13	-10	-6	198	196	207
China	1,119	945	970	-465	-362	-372	654	583	598
Rest of World	252	166	179	-5	-3	-4	247	163	175
Total	**2,066**	**1,707**	**1,797**	**-663**	**-523**	**-538**	**1,403**	**1,184**	**1,259**

Table 2 Platinum demand: Jewellery

disappointing. Retail sales of platinum continue to be hampered by a more limited range of designs compared to karat gold, while higher prices more recently also appear to be deterring some consumers (in China, plain platinum jewellery is priced by weight). At the same time, recent falls in the gold price have made gold jewellery more competitive, with '5G gold' (a specially hardened 24 karat gold product) proving particularly popular.

From the retailers' perspective, karat gold has recovered its appeal following a narrowing in platinum's discount to gold. During 2020, a steep rise in the gold price greatly increased the cost of holding gold jewellery inventory while also contributing to lower turnover; this encouraged retailers to devote more counter space to platinum. However, at 2021 metal prices (and even after allowing for differing precious metal content and metal densities), the intrinsic metal value of a karat gold piece of jewellery is significantly lower than that of an equivalent sized platinum piece. This has enabled retailers to earn greater margins on karat gold jewellery without making it more expensive for the consumer.

Our forecast allows for a modest post-pandemic improvement in Chinese platinum jewellery demand in 2021 (Figure 9). However, to date the recovery appears to be largely a function of very weak demand in the post-Chinese New Year period of 2020, when jewellery stores were closed for up to two months. Retail stocks of platinum jewellery are currently at higher levels than they have been for some time, so distributors will be looking for evidence of sustained consumer buying before restocking. If this retail demand fails to materialise, we could see a reversal of recent inventory builds, and a further decline in Chinese platinum jewellery fabrication this year.

Autocatalyst demand

Demand for platinum in autocatalysts is forecast to bounce back strongly in 2021, with consumption this year matching or slightly exceeding the 2019 level, and platinum taking an increased share of total autocatalyst pgm demand (Figure 13). This is despite continued weakness in the European light duty diesel sector, where diesel market share is expected to shrink to 33%, down from a peak of around 50% only six years ago. Globally, platinum use on diesel cars will rise in line with production volumes (forecast to increase by around 14% in 2021, following a 25% decline last year) but will remain at least 10% below pre-pandemic levels (Figures 14 and 15).

While the light duty diesel sector will remain the largest single source of automotive platinum demand in 2021, other market segments will show much faster growth. Demand for platinum in gasoline vehicles is forecast to climb steeply this year, albeit from a low base, as automakers seek to reduce aftertreatment

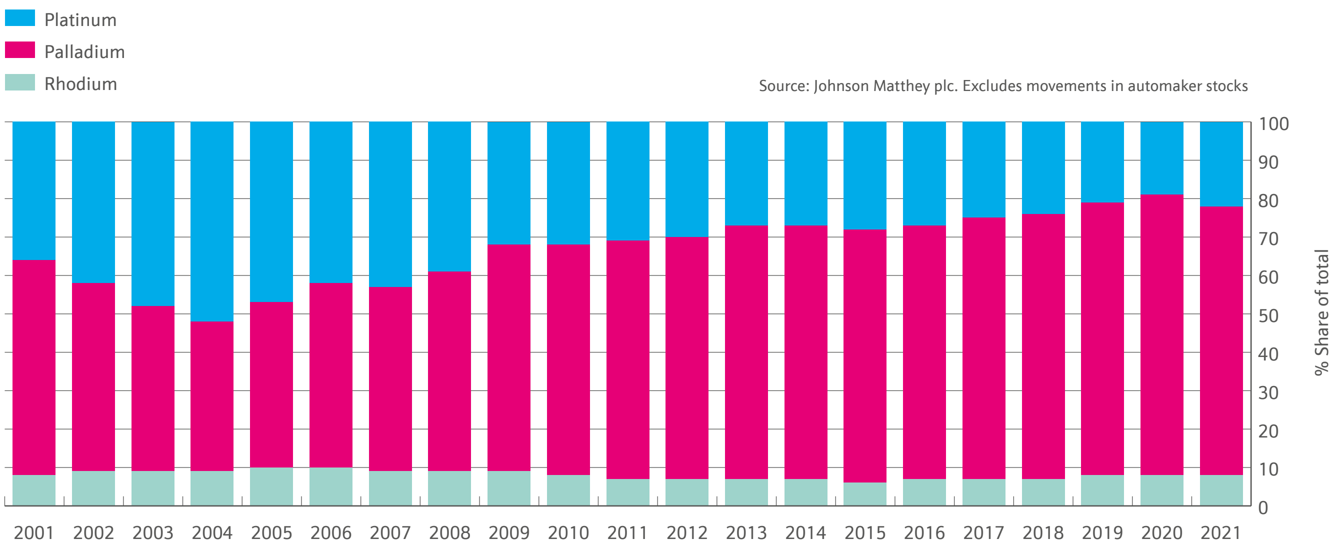


Figure 13 Share of autocatalyst pgm demand by metal

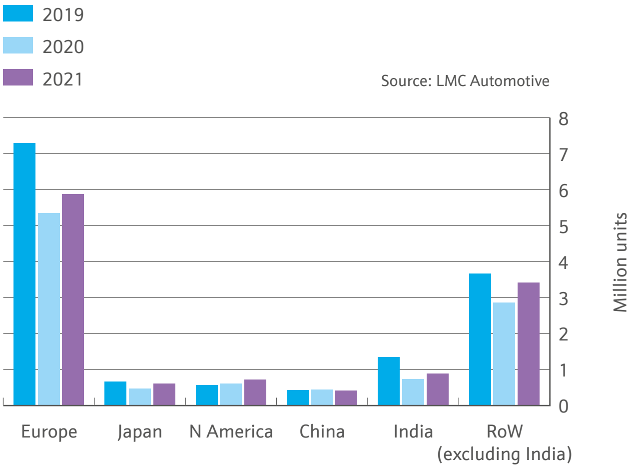


Figure 14 Light duty diesel vehicle production by region

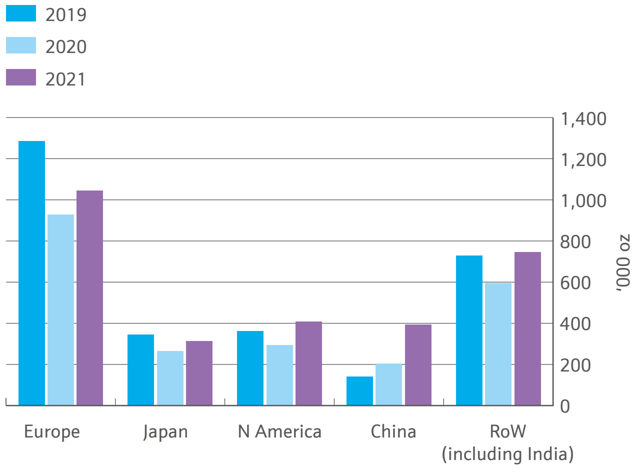


Figure 15 Autocatalyst demand for platinum (gross)

system costs by substituting some palladium with platinum. Prior to this year, adoption of platinum-containing catalysts was limited to a small number of models and was primarily confined to the cooler 'underfloor' position, where pgm loadings are comparatively light. During 2021, we expect to see much wider use of platinum in underfloor catalysts, and some adoption of platinum-containing formulations in the hotter 'closed-coupled' location, where catalyst bricks have much higher loadings. This will contribute to a material increase in the global average platinum loading per gasoline vehicle.

"China VI standards will be enforced nationwide by July 2021, requiring heavy diesel trucks to meet stricter emissions limits"

Chinese domestic automakers are at the forefront of this trend. These companies are highly sensitive to pgm prices, and also appear to be more agile than international car brands when it comes to implementing new technology. Recent changes to Chinese conformity procedures have facilitated the substitution process, by permitting new catalyst formulations to be certified more rapidly. As a result, we expect domestic Chinese automakers to make additional use of platinum in underfloor catalysts this year, and to adopt platinum-containing bricks in the close-coupled position on a limited number of models.

Gross demand '000 oz	2019	2020	2021
Europe	1,287	930	1,046
Japan	344	265	313
North America	361	293	408
China	141	205	395
Rest of World	730	597	748
Total	**2,863**	**2,290**	**2,910**

Table 3 Platinum demand: Autocatalyst

Joint-venture car companies (partnerships between Chinese manufacturers and international brands) appear to be taking a more measured approach to the use of platinum in gasoline catalysts, with some prioritising thrifting over changes in catalyst formulation. At these automakers, catalyst choice may be driven by global strategy considerations, with technology decisions often taken overseas. This has led to a slower uptake of platinum technology, and joint-venture car companies are expected to use only limited quantities of platinum on gasoline vehicles this year.

In other regions, individual automakers appear to be adopting very varied strategies, with some companies aggressively pursuing substitution (although the certification and roll-out of new catalyst formulations remains slower than in China), while others are more cautious about adopting platinum technology and prefer to focus on thrifting the overall pgm content of their catalysts. To date, substitution appears to have progressed more rapidly in North America than in Europe, perhaps because the larger average vehicle size in the USA provides a greater economic incentive.

Technical considerations are also playing a role in determining the speed and extent of platinum adoption. During catalyst development and qualification, accelerated-ageing protocols are used to simulate how the catalyst will perform over the lifetime of the vehicle. These tests differ both by region and to some extent between automakers. In China and the USA, ageing protocols tend to be relatively benign for catalyst durability and stability, with lower testing speeds limiting the peak temperatures to which the catalyst is exposed. This facilitates the use of platinum.

In contrast, ageing protocols used by European automakers are harsher, to reflect higher real-world driving speeds in this region. Because the catalyst is exposed to high temperatures for a longer period, substitution with platinum is more challenging. In addition, European automakers remain cautious about making significant changes to catalyst formulations, given the ongoing complexities of meeting real driving emissions (RDE) and in-service conformity requirements. Although there will be some limited additional use of platinum-containing three-way catalysts in Europe during 2021, this has not yet had a material impact on demand in this region.

While the gasoline car sector will see the largest percentage increase in platinum consumption this year, the largest gains in absolute terms will come from the heavy duty sector. Most of this growth will be in China, where the nationwide phase-in of China VI heavy duty standards will be complete by July 2021. This will require all heavy diesel trucks to meet much stricter emissions standards. (Trucks fuelled by gasoline and compressed natural gas were already covered by China VI limits before this year, but account for only a relatively small share of the market.)

Meeting China VI limits requires a complete overhaul of heavy duty diesel aftertreatment systems: whereas earlier legislation could usually be met using selective catalytic reduction (SCR) technology (often without any pgm catalyst bricks at all), the new standards require much greater use of diesel oxidation catalysts (DOC) and diesel particulate filters (DPFs). As a result, pgm loadings on Chinese diesel trucks will more than treble this year, with platinum accounting for most of this increase.

Industrial demand

Industrial demand for platinum should remain robust in 2021, with major applications in the chemicals, glassmaking and electronics sectors continuing to enjoy strong demand (Figure 16). Indeed, sales of platinum to the glass industry could set an all-time record, on the back of a fresh wave of Chinese capacity expansions.

Chinese demand for glass fibre has rebounded strongly following pandemic-related disruption in early 2020, supported by a recovery in the automotive sector (which uses large quantities of fibreglass in reinforced plastic components, important for vehicle light-weighting), along with rising need for glass-fibre-reinforced materials in the wind power, telecommunications and construction sectors. At the same time, some glass fibre manufacturers are reducing the rhodium content of the platinum alloys used in glass fibre 'bushings' (equipment used to extrude glass fibre). Each ounce of rhodium that is removed is replaced by approximately 1.7 oz of platinum, assuming the bushing design remains the same (in practice, changes in alloy composition may also necessitate the redesign of the bushings).

We also expect further investment in large integrated petrochemical complexes in China, stimulating purchases of platinum catalyst for new paraxylene capacity. However, demand for platinum in petroleum refining catalysts is forecast to fall, because much of the metal required for this year's expansions was bought in 2020 during periods of low price. Outside China, weak demand for transport fuels during the pandemic has had a negative impact on refinery capacity utilisation, and could ultimately lead to further refinery closures.

Demand '000 oz	2019	2020	2021
Chemical	666	640	634
Electronics	232	241	280
Glass	441	451	514
Medical & biomedical	240	218	230
Petroleum	255	299	170
Other	588	462	538
Total	**2,422**	**2,311**	**2,366**

Table 4 Platinum demand: Industrial

"Platinum demand in glassmaking could set an all-time record, with a fresh wave of Chinese capacity expansions"

Platinum demand from the electronics sector is forecast to see double-digit growth in 2021. The hard disk sector remains robust, reflecting continued capacity expansion in the data storage industry (see page 11), which is in turn boosting platinum use in disk coatings. Our estimates for the electronics sector also include demand for platinum in fuel cell applications; this is predicted to expand by over 40% in 2021.

The road vehicle sector will be the largest contributor to this year's growth in fuel cell demand (Figure 17), with Toyota alone expected to produce around 30,000 fuel cell electric vehicles (FCEVs). Looking further ahead, heavy duty vehicles are expected to become an increasingly important driver of growth in fuel cell demand. Significant electrification of the heavy duty fleet will be required to meet CO_2 targets and clean vehicle mandates that have already been legislated in regional and national markets such as California and the European Union. Due to their weight and limited range, batteries are less suitable for long-distance freight haulage and long-haul bus transport, and fuel cells are likely to be preferred for vehicles operating in these segments.

"A new Chinese government rewards scheme is specifically intended to create a domestic fuel cell vehicle industry"

The Chinese market will be a key driver of near-term fuel cell demand, with a new government rewards scheme announced in September 2020 that is specifically intended to create a domestic fuel cell vehicle industry. (In contrast, the development of fuel cell vehicles in other markets is being driven by wider CO_2 targets or zero-emission vehicle mandates, which primarily benefit battery electric vehicles in the first instance). This programme will run until 2025 and is intended to encourage local production of fuel cell components, such as electrodes and fuel cell stacks, in order to establish a domestic supply chain. Cities will receive awards if they meet targets on vehicle deployments and performance; heavier vehicles with larger fuel cell stacks will attract higher levels of support.

Although fuel cell passenger vehicles are included in the new scheme, the rewards policy prioritises fuel cell buses and

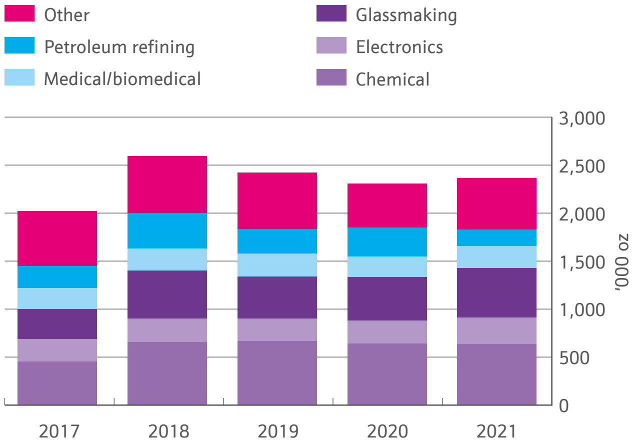


Figure 16 Industrial demand for platinum

commercial vehicles, offering up to 546,000 CNY (around $80,000) for the deployment of heavy duty vehicles (the amount awarded per vehicle decreases in each year of the scheme, so there is an element of front-loading). At the same time, targets for hydrogen stations have also been increased to 1,000 stations by 2025 (up from 500 previously) and 5,000 stations by 2035 (up from 1,000). Local governments have already responded to the new national policy by announcing a number of new initiatives for specific regions and cities, such as Guangdong and Shandong provinces, and Shanghai city. We expect this to support further strong growth in the Chinese fuel cell industry over the next few years.

See page 32 for a special feature focusing on the future development of the hydrogen market and the role of pgm technologies.

Primary & secondary supplies

Primary supplies of platinum should rebound strongly in 2021, reflecting a recovery from Covid disruption in South Africa, and the release of pgm from work-in-progress inventory that accumulated following outages at Anglo American Platinum's converter plant (ACP) during 2020.

Underlying output from South African ores should rise by over 10% in 2021, with most mines now operating close to pre-Covid levels. Although there have been some further shaft closures over the last eighteen months, there are several projects currently in the ramp-up stage, including Northam's Booysendal complex, Royal Bafokeng Platinum's Styldrift mine, and Impala Platinum's 16 and 20 shafts. Rising output from these operations will broadly offset the impact of recent shaft closures, leaving mine production close to 2019 levels.

Our forecast of South African platinum supplies allows for Anglo to refine several hundred thousand ounces of pgm from the ACP backlog (see page 12 and 13). The rebuilt ACP Phase A unit was commissioned in early December 2020, allowing the company to begin drawing-down its excess work-in-progress, a process which it expects to extend into 2022.

> "Platinum supplies from South Africa will rise strongly, as excess work-in-progress is processed, and mines operate close to pre-Covid levels"

After allowing for the refining and sale of pipeline metal from Anglo, we expect platinum supplies from South Africa to rise by over a third in 2021. This assumes that none of the producers experiences any major processing or geological incidents, and that electricity shortages and labour disruption have no significant impact on output. During the first quarter, there was sporadic 'load shedding' (electricity supply reduction) by South Africa's national electricity company, Eskom, but this did not have a major impact on mining activities. However, electricity provision remains a risk factor for supplies going forward.

The first quarter of 2021 saw South African producers announce a number of replacement and expansion projects, in response to exceptionally high pgm basket prices, strong cashflows, and improved prospects for future platinum demand. In February,

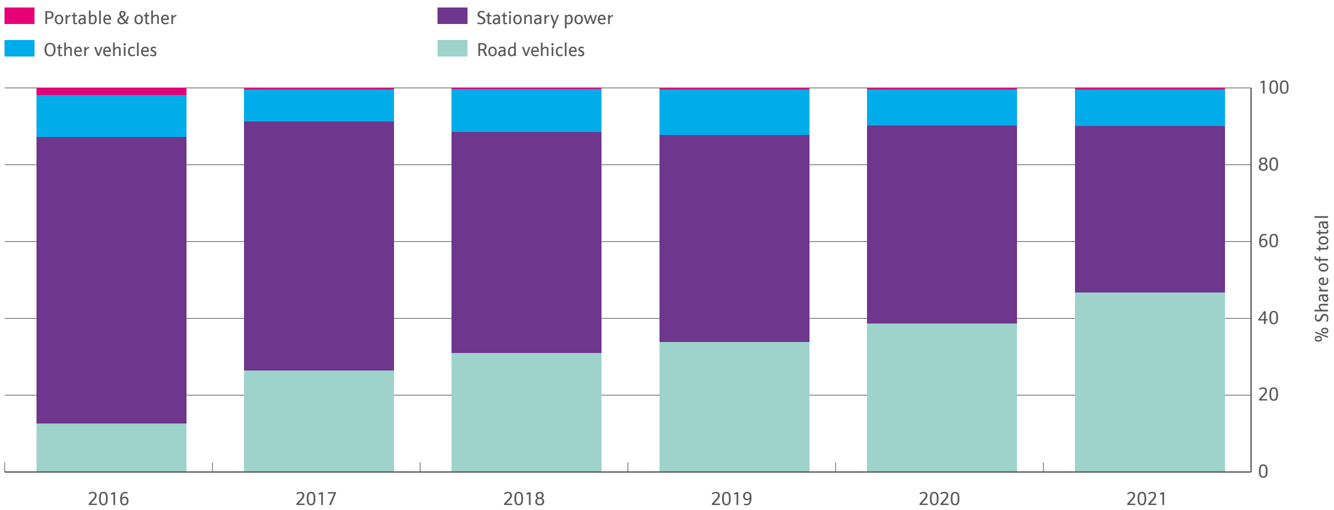


Figure 17 Platinum in fuel cells: demand by end-use

Sibanye Stillwater confirmed that it would proceed with the redevelopment of the K4 shaft at its Marikana operation, a project that was partly developed under the mine's previous owner (Lonmin) before being mothballed due to low prices. Sibanye expects steady-state production from K4 to be around 250,000 oz of pgm per annum, although this will be partly offset by declining output at other shafts on the Marikana complex.

Impala Platinum has also announced two major expansions. At its Zimbabwe operation, Zimplats, the development and ramp-up of the Mupani and Bimha mines will be accelerated, and concentrator capacity will be upgraded, lifting platinum output above 300,000 oz per annum. In South Africa, the Two Rivers joint venture (with African Rainbow Minerals) is to be expanded by extracting Merensky Reef in addition to UG2.

At Anglo American Platinum, the life of the Mototolo mine will be extended via a new decline to access the neighbouring Der Brochen ore body, while debottlenecking will be undertaken at the concentrator. Anglo is also expected to take a decision on an expansion at its Mogalakwena mine in early 2022.

Higher platinum supplies from southern Africa in 2021 will be partly offset by reduced shipments from Russia, following the temporary closure of two mines at Norilsk Nickel's Talnakh mining complex due to flooding, and the collapse of part of the Norilsk concentrator plant. We estimate that these incidents will reduce 2021 output by around half a million ounces of pgm (see page 21 for further details). With lower shipments from Norilsk Nickel, and very little remaining alluvial production in Russia, our forecast shows platinum supplies from Russia falling to the lowest level for two decades.

The recovery of platinum from spent autocatalyst should rise this year (Figure 10), but is unlikely to match the 2019 level. Last year, weak new car sales and strong demand for used vehicles led to a steep fall in the deregistration of older vehicles and a corresponding fall in catalyst scrap volumes. At the same time, the collection and processing of scrap was disrupted by Covid lockdowns, especially in Europe. These pandemic-related impacts have largely been reversed, and record quantities of scrap are now entering the recycling network.

However, platinum recoveries continue to be depressed by capacity constraints on the treatment of diesel particulate filter scrap. This material has a high silicon carbide content and must be blended with other materials before smelting, to reduce the carbon content to an acceptable level. With smelters setting increasingly strict limits on the carbon content of their scrap intakes, it has become more difficult for collectors to find an outlet for their platinum-rich diesel scrap.

This situation has been exacerbated by a shortage of secondary pgm refining capacity, with some smelters forced to limit intakes because downstream refineries are full. While palladium and rhodium prices remain at exceptionally high levels, we expect participants in the recycling chain to prioritise gasoline scrap, which has a higher value and is easier to process.

Palladium outlook

Supply and demand in 2021

Palladium demand will rise strongly, with a post-Covid rebound in vehicle production, and record use in the chemicals sector.

Palladium use in gasoline catalysts will see double-digit growth, despite some substitution by platinum.

Industrial demand will rise by 8%, with exceptionally strong investment by Chinese hydrogen peroxide producers.

Strong growth in South African supplies will be partly offset by lower Russian output, following flooding at two Norilsk Nickel mines.

Overall, palladium demand will rise faster than supply, and the market deficit will widen to over 800,000 oz.

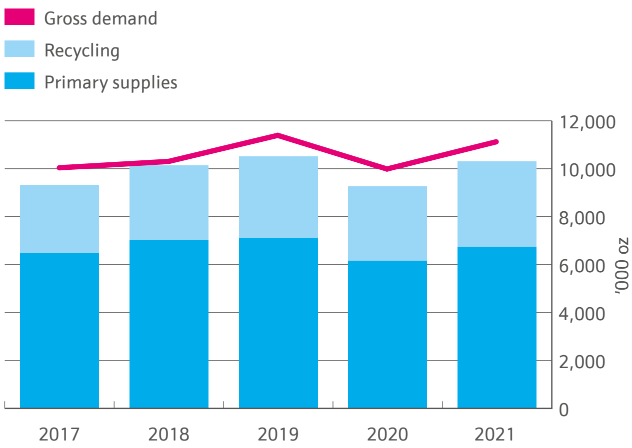


Figure 18 Palladium supply and demand

Gross demand for palladium will stage a strong recovery in 2021, reflecting a post-Covid rebound in vehicle production, higher loadings on European and US gasoline vehicles, and record consumption in the chemicals sector. Combined primary and secondary supplies will also rise, but will fall short of pre-Covid levels, despite record recoveries of palladium from automotive scrap, and sharply higher output in South Africa. These gains will be partly offset by lower Russian supplies, following flooding of underground workings at two Norilsk Nickel mines. With demand rising faster than supply, the market deficit is forecast to widen to over 800,000 oz. During the first quarter of 2021, palladium prices remained close to record levels, and industrial and automotive users are responding by intensifying their efforts to thrift palladium.

Prices & market balance

The palladium market will remain in structural deficit in 2021, with industrial and autocatalyst demand greatly exceeding combined primary and secondary supplies (Figure 18). While availability has improved over the last year, following a severe liquidity squeeze in early 2020 that pushed lease rates above 25% (Figure 2), market stocks continue to be drawn down. During the first four months of 2021, palladium sponge once again moved to a large premium over ingot, signalling a shortage of metal in the form usually required by Western industrial and automotive consumers. Market participants have responded by converting stocks of ingot into sponge in order to satisfy consumer demand.

Strong demand and ongoing supply concerns continued to support palladium close to all-time highs during early 2021. The price traded in a $2,300–2,400 range for much of January and February, before spiking above $2,600 in March (Figure 4) following news that Norilsk Nickel expected to lose significant quantities of production due to an accident at a processing plant and the temporary closure of two large mines.

Primary supplies

During February and March, groundwater ingress at Norilsk Nickel's Oktyabrsky mine led to flooding in the lower sections of this operation, as well as in the neighbouring Taimyrsky mine. Water inflow was stemmed by late March, allowing mining at Oktyabrsky to return to normal volumes by the end of April. However, the deeper Taimyrsky operation remained suspended at the time of writing. Large amounts of floodwater will need to be pumped out of the workings before the condition of underground infrastructure can be assessed and mining can restart, with a return to full production currently scheduled for June.

Supply '000 oz	2019	2020	2021
South Africa	2,588	1,977	2,655
Russia	2,987	2,636	2,560
Others	1,529	1,547	1,534
Total primary supply	**7,104**	**6,160**	**6,749**

Demand '000 oz	2019	2020	2021
Autocatalyst	9,667	8,551	9,447
Jewellery	129	87	103
Industrial	1,709	1,559	1,690
Investment	-87	-190	-93
Total gross demand	**11,418**	**10,007**	**11,147**
Recycling	-3,407	-3,119	-3,569
Total net demand	**8,011**	**6,888**	**7,578**
Movements in stocks	-907	-728	-829

Table 5 Palladium supply and demand

An accident at the Norilsk concentrator (one of two concentrator plants at the Polar mine site) will also have an impact on pgm production this year. Following the collapse of a building, the disseminated ore circuit was suspended and has yet to resume. However, the processing of copper-rich ores (which have a higher pgm content) was only briefly disrupted.

Together, we estimate that these incidents will reduce 2021 pgm output by around half a million ounces. However, we expect Norilsk Nickel to mitigate the impact on shipments by selling some palladium from stocks (metal refined in 2020 but held back from sale last year during Covid-related lulls in demand). Our forecast therefore allows for Russian supplies to fall by just 3%, to 2.56 million oz.

"Groundwater ingress led to the temporary suspension of mining at two Norilsk Nickel operations"

We also expect Norilsk Nickel to sell metal from its Global Palladium Fund, which was set up in 2016 with the aim of guaranteeing security of supply to its customers and reducing market volatility. This fund purchases metal from a number of sources, including the company's own production, as well as from other market participants, including the Russian Central Bank. The Central Bank holds stocks of palladium originally purchased from Gokhran (Russia's state repository of precious metals) and which have already been counted as supply in our data series. Any such sales by the Global Palladium Fund would therefore represent a drawdown of market stocks, rather than new primary supply.

"Auto recycling has recovered strongly from Covid disruption, but secondary refineries are now close to capacity ceilings"

South African palladium supplies are forecast to rise by 34% this year, as the mining industry recovers from Covid-related disruption, and Anglo American Platinum refines a backlog of semi-processed pgm that accumulated during converter outages in 2020. Most mines will produce as much as they did two years ago, and a small number will raise production as part of expansion programmes (for example, at Northam's Booysendal and Royal Bafokeng Platinum's Styldrift). However, underlying mine output (i.e. before adjusting for pipeline and refined stock movements) is likely to remain below the 2019 level, due to a small number of shaft and mine closures in the intervening period. These include the closure of the Nkomati Nickel operation that is now scheduled to take place this year. This open-cast nickel mine has produced over 100,000 oz of palladium by-product annually in recent years.

Secondary supplies

The recovery of palladium from secondary materials (primarily spent autocatalyst, with some metal from electronic scrap) is forecast to rise by 14% to a record 3.57 million oz in 2021. Auto recycling volumes have recovered strongly from Covid-related disruption to collection, transport and processing activities that occurred during the first half of 2020 (Figure 10). Since then, a rebound in new registrations has seen more end-of-life vehicles entering scrap yards, while the palladium content of spent catalyst material continues to rise.

Price continues to incentivise market participants to move pgm-containing materials through the recycling and processing network as quickly as possible. However, refining capacity constraints are beginning to create some bottlenecks. Most secondary pgm refineries in Europe and North America and Asia are operating close to their capacity ceilings, and have only limited ability to take on additional volumes. This in turn is leading some scrap collectors to turn away business: at current pgm prices, market participants are reluctant to purchase scrap unless they are certain that the contained pgm can be refined and sold promptly.

To date, capacity shortages have primarily impacted the recovery of lower-value materials which are more technically difficult to treat (especially diesel particulate filter scrap). However, going forward, a lack of refinery capacity could become an impediment to growth in palladium recoveries. Our forecast allows for palladium autocatalyst recycling to reach an all-time high of 3.1 million oz in 2021, but there is some downside risk to this figure, should refineries experience any downtime.

Autocatalyst demand

Autocatalyst consumption of palladium is forecast to recover strongly in 2021, despite thrifting and substitution programmes

Gross demand '000 oz	2019	2020	2021
Europe	2,057	1,769	2,074
Japan	906	778	833
North America	2,081	1,709	2,110
China	2,708	2,683	2,384
Rest of World	1,915	1,612	2,046
Total	**9,667**	**8,551**	**9,447**

Table 6 Palladium demand: Autocatalyst

at some automakers. Over 85% of automotive palladium demand occurs in light duty gasoline applications, where palladium-rhodium three-way catalysts have been the dominant emissions control technology for the past two decades.

Over the past five years, tightening legislation in Europe, North America and China has seen global average palladium loadings rise by more than a quarter, driving demand strongly higher at a time when world gasoline car output has been falling. Light duty gasoline volumes reached an all-time high of around 75 million vehicles in 2017; production in 2021 will be around 10% below this peak (Figure 19), yet palladium demand in gasoline vehicles is forecast to be at least 10% higher than five years ago.

This drop in global output (which pre-dates Covid) was primarily due to some cooling-off in the Chinese market, following a period of unprecedented expansion between 2008 and 2017. Looking forward, it is unclear when, or even whether, the 2017 peak in world gasoline car output will be surpassed. This year, vehicle output has been constrained by semiconductor shortages, which have resulted in temporary disruption at many automotive plants in most regions. At the same time, internal combustion engine (ICE) vehicles have begun to lose significant market share to battery electric vehicles (BEV), production of which rose by over 25% in 2020 and is forecast to increase by at least two-thirds this year. BEV share of the light duty market is likely to reach 6% in Europe in 2021, and could exceed 8% in China.

Most automotive market forecasters expect growth in the BEV segment to accelerate over the next few years, potentially leading to a flat or even descending profile for ICE vehicle production in some regions, especially Europe and North America. This means that future growth in overall pgm demand will rely primarily on regional legislative programmes (and their impact on loadings) rather than on increases in ICE vehicle output.

Palladium loadings on gasoline vehicles are still rising in most regions, in line with the progressive implementation of the current cycle of emissions legislation in many major markets. US Federal Tier 3 legislation is being phased-in between 2018 and 2025, requiring an increasing proportion of vehicles to meet very strict SULEV standards. There has been some uptake of platinum-containing catalysts on gasoline cars in this region, but the impact on palladium loadings has been offset by increases in the total pgm content per vehicle.

In Europe, all new passenger cars registered in 2021 will be required to meet the full Euro 6d standards, under which the 'conformity factors' (CF: the allowance by which real driving emissions may exceed laboratory test limits) applied during RDE testing are reduced from 2.1 (under Euro 6d-temp) to 1.43. This will lead to further growth in average pgm loadings on gasoline cars, although platinum will account for most of that gain.

"Vehicle output has been constrained by semiconductor shortages, while ICE vehicles are losing market share to BEVs"

High palladium and rhodium prices have fuelled active thrifting programmes at virtually all global automakers (whether or not they are also pursuing substitution) and these are starting to bear fruit. Although there is still some scope for near-term growth in pgm loadings in several major markets (notably, the USA, Mexico and India), palladium's share of the pgm mix is expected to fall as platinum-containing formulations find wider acceptance. In Europe, there are signs that gasoline loadings may begin to trend downwards next year, but this thrifting may be reversed in future when conformity factors move towards 1, and in particular for the next stage of EU legislation (Euro 7, currently expected to be implemented during the 2025–2027 timeframe).

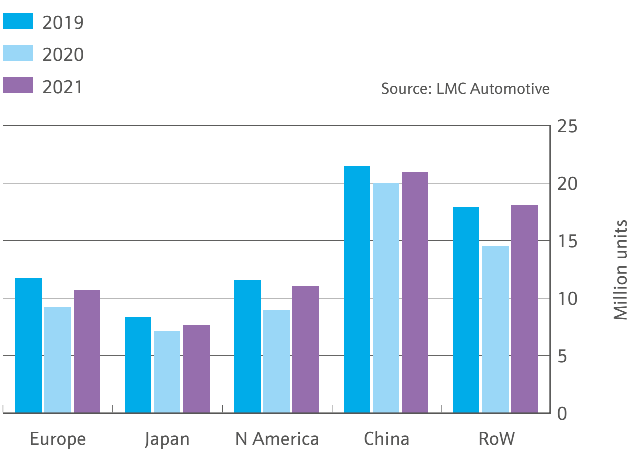


Figure 19 Light duty gasoline vehicle production by region

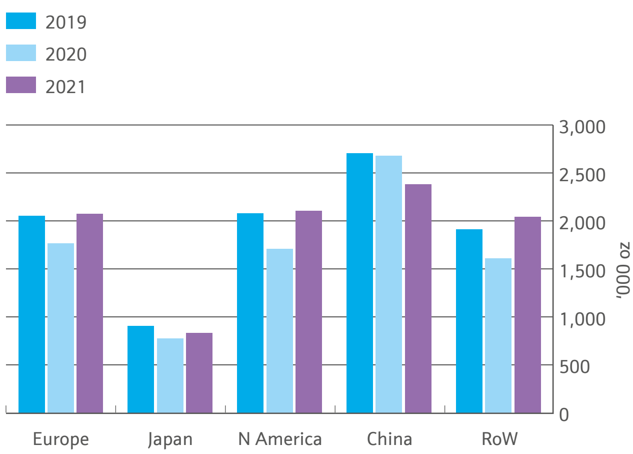


Figure 20 Autocatalyst demand for palladium (gross)

"High palladium and rhodium prices have fuelled active thrifting programmes at virtually all global automakers"

In China, the first phase of China 6 legislation has been fully enforced since January 2021; with the industry's focus now firmly on thrifting, we believe that pgm loadings have already peaked in the current legislative cycle. Two years ago, when China 6 vehicles were first widely launched, almost all automakers opted to equip their cars with catalysts capable of meeting China 6b legislation (rather than the less stringent 6a limits). With some cities and provinces imposing China 6b standards ahead of the nationwide implementation schedule, it made sense to streamline catalyst fitment and to market vehicles meeting the stricter standards nationally. At the time, pgm loadings were a secondary consideration.

Since then, steep rises in palladium and rhodium prices have incited sustained efforts to reduce the pgm content of Chinese gasoline vehicles, especially at domestic car companies, which typically have less advanced engine technology than joint ventures involving international OEMs. These domestic manufacturers have focused on improving engine performance to cut engine-out emissions, allowing the pgm content of their catalysts to be thrifted, sometimes quite significantly. At the same time, they have begun to make widespread use of platinum-containing catalysts in the 'underfloor' position. We expect these thrifting and substitution activities to lead to a decline of at least 10% in the average palladium content of a Chinese gasoline car in 2021. It should be noted, however, that despite very aggressive thrifting in this market, average pgm loadings will remain above the levels seen prior to 2019.

Emissions limits in China are set to tighten again in July 2023, when China 6b limits will be enforced nationwide. As noted above, most gasoline vehicles sold in this region are equipped with catalysts that meet China 6b standards, at least under laboratory conditions. However, China also plans to implement Real Driving Emissions (RDE) testing at the 6b stage, and this will probably create renewed upward pressure on loadings. The conformity factors have not yet been confirmed, but automakers appear to be working towards a CF of 1.5 for both NOx and PN, similar to the CF of 1.5 for PN and 1.43 for NOx enforced under Euro 6d.

Industrial demand

The last decade has seen exceptionally strong investment in the Chinese chemicals industry, associated with modernisation of the country's industrial infrastructure and a need to increase domestic production of 'building-block' chemicals essential for downstream chemical processes. In the last five years, this trend has intensified, in line with the emphasis on self-sufficiency in the Thirteenth Five-Year Plan (2016–2020). This has encouraged technology choices that facilitate increased utilisation of China's domestic natural resources (primarily coal), thereby reducing reliance on oil and gas imports.

Demand '000 oz	2019	2020	2021
Chemical	505	579	646
Dental	313	225	244
Electronics	714	626	656
Other	177	129	144
Total	**1,709**	**1,559**	**1,690**

Table 7 Palladium demand: Industrial

This has generally been positive for pgm demand, with Chinese producers often adopting specific pgm-catalysed routes that are not in widespread use elsewhere. For example, palladium catalysts are widely used in China to produce mono-ethylene glycol (MEG) from domestically produced coal (elsewhere, MEG is conventionally produced using an ethylene oxide production route that utilises crude oil and natural gas, and does not require a pgm catalyst).

In 2021, chemical industry demand for palladium should again be robust – indeed, there is potential for purchasing by chemical manufacturers to reach a new all-time high. We expect continued strong demand for palladium catalysts used in bulk chemical processes such as MEG and purified terephthalic acid (pTA), while the hydrogen peroxide industry is expected to add unusually large amounts of capacity this year. Much of this will be to feed new propylene oxide plants using the HPPO ('hydrogen peroxide to propylene oxide') process, which requires very large hydrogen peroxide feedstock volumes.

"Construction of new hydrogen peroxide plants in China will require large amounts of palladium catalyst"

One rapidly growing application for propylene oxide is in chemicals for the synthesis of polyurethane, an insulation material widely used in cold chain supply. The Covid pandemic has stimulated growth in home deliveries of fresh, chilled food, while cold chain capabilities are also critically important

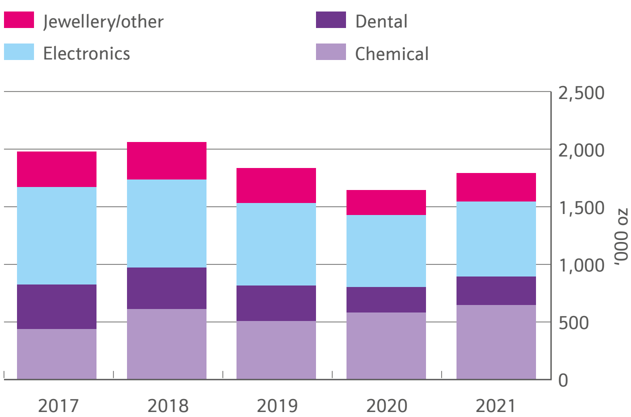


Figure 21 Industrial demand for palladium

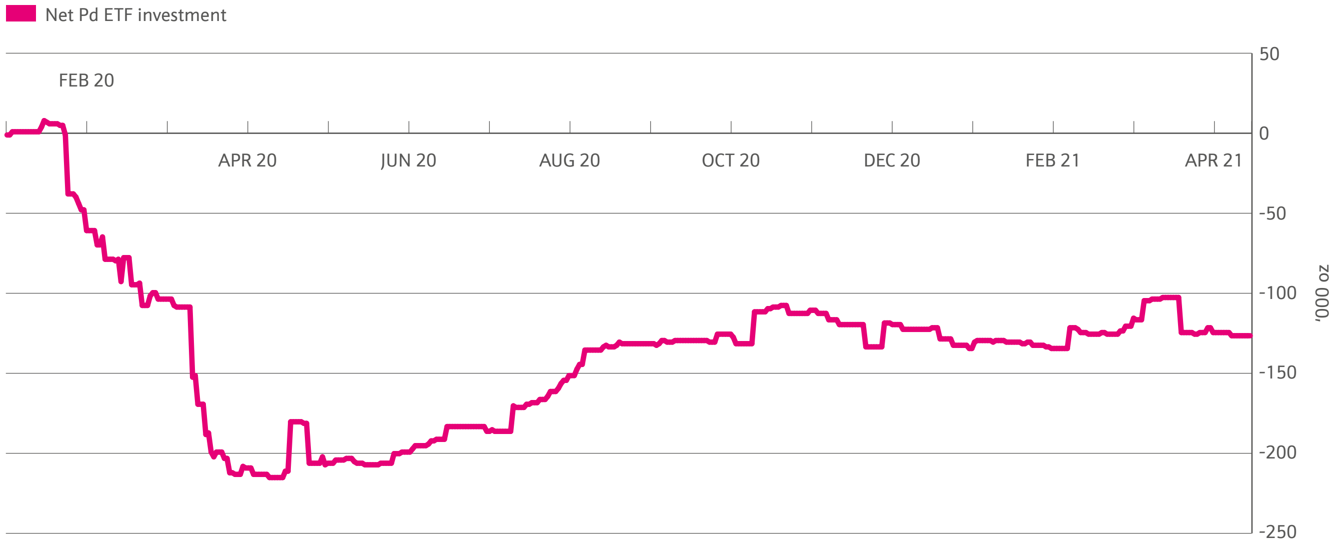


Figure 22 Net change in palladium ETF investment, January 2020 to April 2021

for vaccine distribution. The delivery of pharmaceutical products such as vaccines requires strict temperature control and significant volumes of insulating materials.

Palladium's other industrial applications will also see some gains this year, but will not recover to pre-Covid levels (Figure 21). Many of these applications have seen a long downward trend in palladium use over the last two decades, and recent record prices have only intensified thrifting and substitution efforts. For example, in the electronics sector, palladium has widely been replaced by nickel in electronic pastes used in capacitors, with remaining palladium use now confined to legacy applications and some high-reliability military and medical components. Although market conditions have improved this year compared to 2019–2020 (when the sector was impacted first by US-China trade disputes and then by Covid), palladium use in electronics is still forecast to be around 8% below the 2019 level.

"Palladium ETF investment was positive in the first quarter, but high prices continue to provide profit-taking opportunities"

Investment demand

During the 2015–2020 period, sustained selling by investors resulted in the return of over 2.5 million oz of palladium to the market, helping to mitigate palladium deficits over this period. By the beginning of 2021, only just over half a million ounces of palladium remained in ETF vaults. Most remaining investors are 'in the money', but to date have opted not to take profits, either during the 2020 price spike, or more recently at near-record prices during March and April 2021. Indeed, there was a small overall increase in palladium ETF holdings during the first quarter of this year (Figure 22), perhaps in response to news of flooding at two Norilsk Nickel mines.

Nevertheless, our forecast is based on a continuation of recent trends in palladium ETFs, as ongoing high prices continue to provide investors with an opportunity to exit their holdings at a profit. We allow for only modest liquidation, but even if all remaining palladium ETF holdings were sold this year, it would be insufficient to fill the forecast market deficit.

Rhodium outlook

Supply and demand in 2021

Rising vehicle volumes and tightening emissions legislation will lift auto demand by 11% in 2021.

Industrial demand will recover strongly, after falling to 25-year lows in 2020, but will remain below normal levels.

The glass fibre industry will continue to thrift rhodium from alloys used in glassmaking equipment.

Combined primary and secondary supplies will rise 19%, on recovery from 2020 disruption in South Africa, and a buoyant auto scrap market.

A supply squeeze in early 2021 pushed rhodium to all-time highs, but liquidity should improve as supply normalises.

"The vast majority of rhodium demand derives from its use in three-way catalysts on light duty gasoline vehicles: it plays an essential role in enabling automakers to meet strict NOx emissions limits"

During early 2021, the rhodium price surged repeatedly to highs of around \$30,000, with weekly price swings exceeding \$3,000, as a severe supply squeeze created extreme volatility in the market. This was a consequence of disruptions to primary rhodium shipments in 2020, following outages at Anglo American Platinum's converter plant (ACP), along with a rebound in demand, in line with a recovery in world car production from Covid disruption. The ACP resumed production in December 2020 and will process a backlog of semi-processed pgm over the next eighteen months, augmenting primary rhodium supplies. This could help improve liquidity in coming months, although we expect the market to remain in overall deficit in 2021.

While recent price gyrations have been exacerbated by supply issues, the extraordinary rally in the rhodium price from a low point of \$625 in August 2016 has primarily been driven by growth in autocatalyst consumption, resulting in three consecutive years of market deficit. The vast majority of rhodium demand is derived from its use in three-way catalysts on light duty gasoline vehicles: it is by far the best catalyst for the reduction of NOx, and therefore plays an essential role in enabling automakers to meet emissions limits for this pollutant.

The rhodium market is small and illiquid and has a history of extreme price movements dating back to the early years of automotive emissions control (Figure 23). Price gains have typically been associated with periods of tightening emissions legislation and steeply rising automotive demand, but the highest peaks in the market have been linked to disruption to supplies from South Africa (where the vast majority of world rhodium production is concentrated).

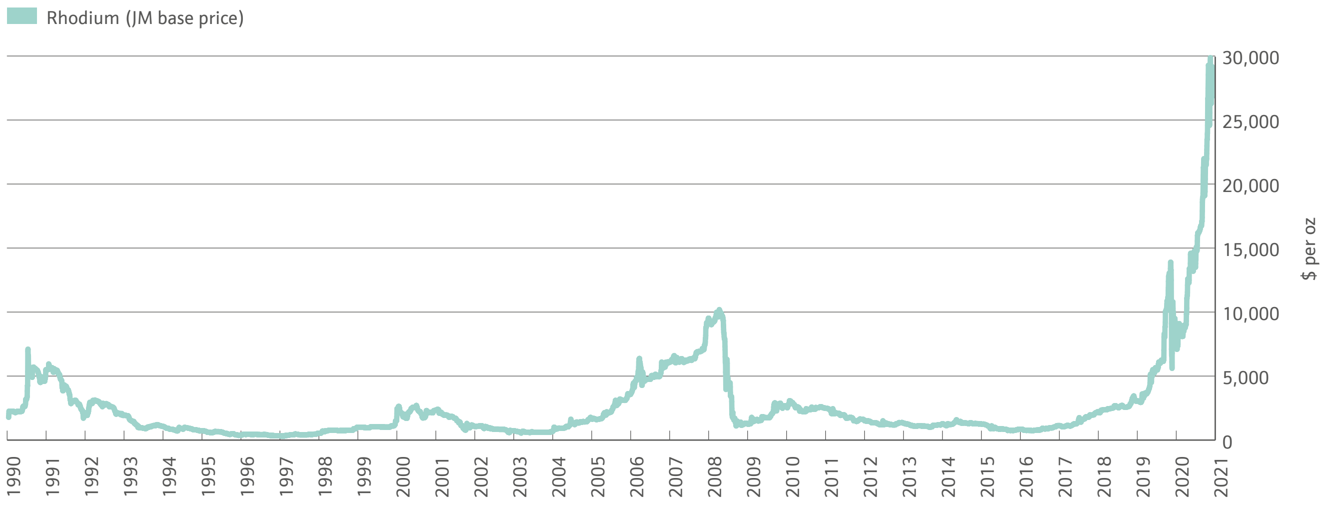


Figure 23 Rhodium prices 1990-2021

Supply '000 oz	2019	2020	2021
South Africa	607	481	624
Russia	68	58	55
Others	68	70	69
Total primary supply	**743**	**609**	**748**

Demand '000 oz	2019	2020	2021
Autocatalyst	1,031	947	1,051
Other	132	72	106
Total gross demand	**1,163**	**1,019**	**1,157**
Recycling	-357	-338	-378
Total net demand	**806**	**681**	**779**
Movements in stocks	-63	-72	-31

Table 8 Rhodium supply and demand

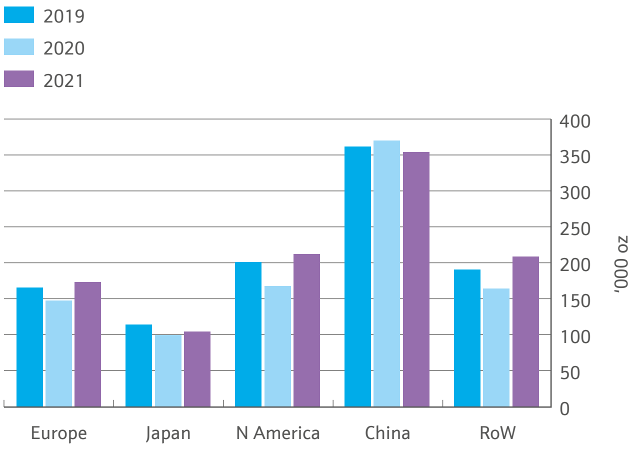


Figure 24 Autocatalyst demand for rhodium (gross)

For example, the 2008 price surge followed electricity outages that temporarily halted mining in South Africa, while recent all-time highs have occurred in the wake of processing plant outages and Covid-related mining interruptions.

Most rhodium consumers (with the exception of the glass industry; see below) have little or no short-term ability to flex their rhodium usage, but the extreme price levels attained during the price peaks in 1990, 2008 and 2020–2021 have all resulted in an acceleration of technical development with the objective of reducing rhodium use. In the automotive industry, this has contributed to distinct cycles of rising rhodium loadings during periods of tightening legislation, followed by aggressive thrifting programmes in response to high prices.

The 2017–2021 period has seen significant changes in emissions legislation in several major markets, including the implementation of the first phase of China 6 legislation, the gradual roll-out of Tier 3 Federal US regulations, and the introduction and then tightening of Real Driving Emissions (RDE) standards in the EU (under Euro 6d-TEMP and Euro 6d legislation). By last year, global average rhodium loadings were more than 45% higher than 2016 levels.

"With the exception of the glass industry, rhodium users have little short-term ability to flex their rhodium usage"

In Europe, the introduction of RDE and the subsequent tightening of conformity factors has dramatically increased the technical difficulty of meeting emissions standards. This has had a positive impact on use of all the autocatalyst pgm, but the impact has been greatest on rhodium, because RDE legislation focuses specifically on NOx emissions. By September 2020 all new vehicles were subject to RDE testing, but there will nevertheless be some further loadings increases in 2021, as conformity factors

Regulation	Vehicle types	Date	NOx CF	PN CF
Euro 6d-TEMP	PCs new vehicle types	1st September 2017	2.1	1.5
	PCs all new vehicles	1st September 2018		1.5
		1st September 2019	2.1	
	LCVs new vehicle types	1st September 2018	2.1	1.5
	LCVs all new vehicles	1st September 2019		1.5
	LCVs all new vehicles	1st September 2020	2.1	
Euro 6d	PCs new vehicle types	1st January 2020	1.43	1.5
	PCs all new vehicles	1st January 2021	1.43	1.5
	LCVs new vehicle types	1st January 2021	1.43	1.5
	LCVs all new vehicles	1st January 2022	1.43	1.5

PCs - passenger cars LCVs - light commercial vehicles CF - RDE conformity factor

Table 9 Euro 6d dates

(CFs) tighten under full Euro 6d legislation (which applied to new car models from January 2020 and has been enforced on all new passenger cars from January this year – Table 9).

European automakers are now responding to high prices by seeking to thrift rhodium, but this is not expected to have any significant impact in 2021. Beyond this year, we expect to see some downward pressure on loadings – although the window of opportunity for thrifting may be rather short, with CFs expected to tighten again in the near future. These factors allow for potential measurement error during RDE testing; this error is declining as portable emissions monitoring equipment improves, and the European Commission has said that it intends to reduce CFs to 1 (from 1.43 for NOx at present) by 2023.

"In Europe, the introduction of Real Driving Emissions testing has dramatically increased the technical difficulty of meeting emissions standards"

In contrast, we expect Chinese automakers to achieve material levels of rhodium thrifting this year and next, ahead of the introduction of RDE testing in 2023. Thrifting is likely to be especially significant at domestically owned car producers. Since China 6 vehicles were first introduced in 2019, these companies have upgraded their engine technology to reduce engine-out emissions, and this has facilitated significant reductions in loadings.

Because China accounts for over 30% of global light duty gasoline production, lower loadings in this region are having an appreciable negative impact on the global average rhodium content per vehicle. However, this will be outweighed by a predicted 14% rebound in world gasoline car output, which in turn will lift rhodium consumption in autocatalysts by 11% in 2021 (Figure 24). Unlike palladium demand – which will remain below its 2019 peak – we expect autocatalyst consumption of rhodium to set a new all-time high this year.

Industrial and other consumption of rhodium fell to a 25-year low of 72,000 oz in 2020, as high prices slashed demand in glassmaking and triggered further liquidation of ETF holdings. We expect some recovery in 2021, in line with ongoing investment in the chemicals and glass industries in China, but demand will nevertheless remain well below the levels seen over the last decade, due to thrifting by fibreglass companies and some limited further disinvestment. At the time of writing, around 14,000 oz of rhodium remained in ETFs.

The glass sector is the only significant consumer of rhodium that can respond to price on relatively short timescales, by reducing the rhodium content of alloys used in glassmaking equipment (see page 18). This alloy-switching process is expected to continue during 2021, curbing new demand for rhodium, although we expect heavy investment in new glass fibre production capacity in China to necessitate some fresh purchasing of metal (Figure 25).

Demand for rhodium catalysts from the chemicals industry is forecast to remain robust, reflecting ongoing investment in oxo alcohols capacity in China. However, it is difficult to anticipate the timing of rhodium catalyst purchasing; this usually occurs several months ahead of plant completion, but at current price levels companies may choose to defer their purchases as long as possible. There are also some early signs of potential future thrifting in this sector, with companies looking at ways to reduce the amount of rhodium used in their processes.

Combined primary and secondary supplies are forecast to rebound by 19% this year, outpacing the recovery in demand. South African mine production of rhodium will recover following Covid-related disruption in 2020, and will be augmented by the release of pgm from in-process inventories that accumulated during the ACP outage in 2020. This will more than offset a modest fall in Russian rhodium output due to flooding at two Norilsk Nickel mines. Recoveries of rhodium from spent autocatalyst are forecast to rise by around 12%, reflecting buoyant conditions in the automotive scrap sector, with secondary refineries operating close to their capacity ceilings (Figure 10). As supply normalises, we could see some improvement in market liquidity, although we still expect rhodium to remain in deficit this year.

"We expect Chinese automakers to achieve material levels of rhodium thrifting this year"

Demand '000 oz	2019	2020	2021
Chemical	59	55	72
Electronics	6	7	7
Glass	46	5	19
Other	21	5	8
Total	**132**	**72**	**106**

Table 10 Rhodium demand: Industrial

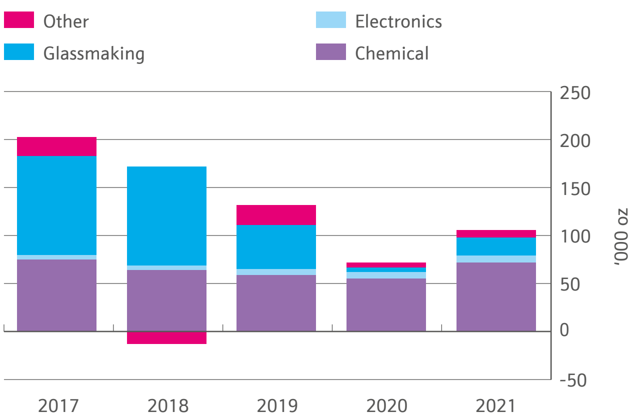


Figure 25 Industrial demand for rhodium

Ruthenium and iridium

Summary of demand in 2020 and outlook for 2021

Industrial consumption of iridium contracted by 8% in 2020, with firm chemicals demand partly offsetting lower use in spark plugs.

Ruthenium demand fell by 9% last year, in line with lower capacity additions in the caprolactam industry.

In 2021, iridium will see growth in all major applications, lifting demand by 13%.

Ruthenium demand will recover more modestly this year, with consumption in chemical catalysts below recent highs.

With supply impacted by processing outages in South Africa, iridium soared to a record high of $6,300 in April 2021.

Ruthenium also made strong price gains, recording a thirteen-year year high of $440.

Demand for ruthenium and iridium declined moderately in 2020 due to Covid-related impacts, including a dip in ruthenium chemicals demand due to delays in new plant construction, and a sharp fall in iridium use in spark plugs for gasoline vehicles. Consumption of both metals is forecast to recover in 2021, with the electrochemical and electronics sectors seeing robust demand. Prices of both metals climbed steeply in early 2021, reflecting higher industrial purchasing, disruptions to South African supply following processing outages, and rising investor awareness of the potential for pgm use in hydrogen applications.

Iridium

Iridium has been a particular focus of investor interest, due to its potential for future use in the production of 'green' hydrogen (see our special feature on hydrogen on page 32). It is possible that speculative buying has contributed to the remarkable price trends of recent months, during which the iridium price has more than trebled.

Iridium is an exceptionally small and illiquid market, but unlike rhodium and ruthenium it has no recent history of extreme price movements. The price traded below $1,000 during the 2014–2017 period, reflecting periodic selling of producer inventories that left the market well-supplied. Since then, a series of deficits has gradually consumed available above-ground stocks, leading to upward pressure on the price.

These price gains were slow and moderate during the 2017–2019 period, but accelerated abruptly in late 2020, as outages

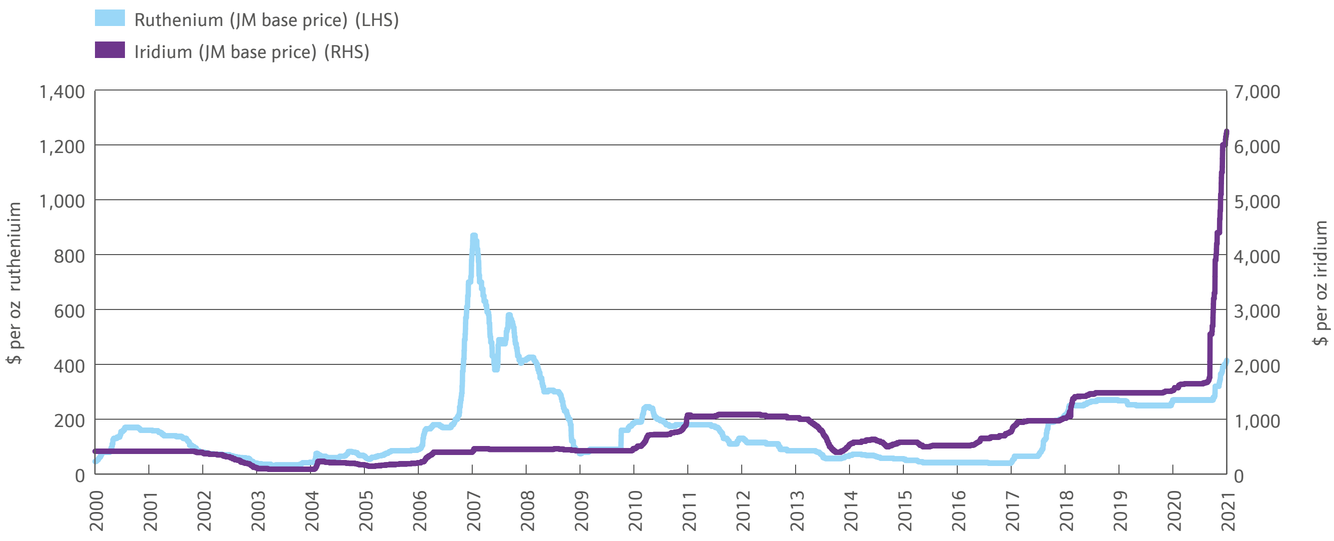


Figure 26 Ruthenium and iridium prices 2000-2021

at Anglo American Platinum's converter plant (ACP) coincided with a post-Covid recovery in demand. The price gained nearly $1,000 in the month of December 2020 alone, reaching $2,600 at the year-end. In early 2021, the rally continued to gain pace: iridium reached $4,000 in January, paused for breath briefly during February, then surged to $6,000 during March. At the time of writing, the price had stabilised at around $6,300 – by far the highest price ever seen for this metal (Figure 26).

We believe that these unusual price movements primarily reflect a temporary lack of liquidity in the iridium market following the ACP outages. The processing pipeline for the minor pgm is unusually long: several months may elapse between mining the metals, and final refining. Availability should improve this year and next, as Anglo American Platinum treats a large backlog of semi-processed pgm.

Industrial purchasing patterns may also have played a role in the rally, even though our headline figures do not show a dramatic increase in demand this year. We expect iridium consumption to rise by 13% to 267,000 oz in 2021, within the historical range of demand for this metal; assuming supply rebounds as anticipated, the market will not be in a large fundamental deficit this year. However, on a shorter timescale, there has clearly been a significant mismatch between supply and demand. As prices rose, we believe that some consumers purchased iridium ahead of their actual requirements, in order to secure metal for future needs. In addition, our figures do not necessarily capture short-term fluctuations in work-in-progress at fabricators. For example, electronics companies periodically need to replace iridium crucibles used in single crystal manufacture (see below); there may be timing differences between the purchase of replacement crucibles, and the recovery of the metal from the spent crucibles they replace. These temporary variations in work-in-progress are common in pgm-using industries, but are of particular significance for the iridium market, because it is so small and thinly traded.

Iridium demand from the chemicals sector was robust in 2020, despite Covid disruption, and is expected to be stable this year. This reflects steady 'top-up' demand to cover in-process losses from existing plants, in addition to purchasing of iridium for new acetic acid capacity. Acetic acid production generally involves either an iridium-ruthenium catalyst or a rhodium catalyst; although both ruthenium and iridium prices are currently high,

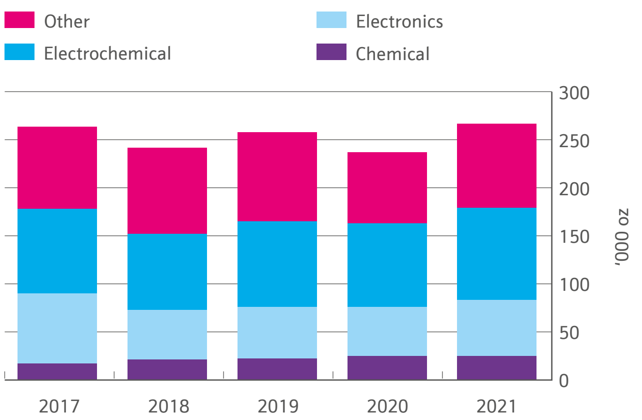


Figure 27 Industrial demand for iridium

Demand '000 oz	2019	2020	2021
Chemical	22	25	25
Electronics	54	51	58
Electrochemical	89	87	96
Other	93	74	88
Total	**258**	**237**	**267**

Table 11 Iridium demand

the cost of metal for the initial catalyst charge is significantly lower than for an equivalent rhodium-based process.

Demand for iridium from the electrochemical sector retreated slightly during the height of the Covid crisis, primarily due to lower consumption in ballast water treatment. In 2020, deliveries of new ships plummeted to a fifteen-year low, while pandemic-related measures also led to a fall in ship repair and maintenance activities during the first half of the year. Demand for iridium in this application is forecast to rise in 2021, as increasing numbers of ships are retrofitted with ballast water systems to meet the international rules agreed under the Ballast Water Management Convention. Electrochemical systems compete with alternative water treatment technology including ultraviolet treatment and chemical methods.

"Iridium has been a particular focus of investor interest, due to its potential for future use in the production of 'green' hydrogen"

In contrast, the use of iridium (and ruthenium) in chlor-alkali plants remained stable in 2020, reflecting firm underlying demand for caustic soda (a basic material used in a wide range of industries), and some improvement in the chlorine market during the pandemic. Not only is chlorine widely used in disinfectants, it is also an important feedstock for PVC, used in a wide range of applications in construction, agriculture and medical products. The latter category includes personal protective equipment such as goggles, face shields, protective clothing and gloves; these normally account for only a small proportion of PVC consumption, but their use increased dramatically during the pandemic. This contributed to high capacity utilisation in the chlorine industry, which has been in oversupply in recent years.

Iridium demand from the electronics sector fell slightly in 2020, but should recover strongly in 2021. Its principal use is in crucibles for the production of single crystals ('crystal-pulling', using the Czochralski process). Because iridium is rare, costly and difficult to work with, its use in crucibles is confined to very high temperature applications, for crystals that must be pulled above 1,600°C. These include sapphire, for light emitting diodes, and lithium tantalate, used in SAW filters for mobile phones and other wireless telecommunications equipment.

As in many industrial applications, demand for crucibles occurs mainly when new production capacity is installed, with on-going 'top-up' demand limited to small amounts of metal to offset losses that occur during the crucible's working life and subsequent recycling. Global capacity for lithium tantalate production has been broadly stable over the past three years, but this year is expected to see additional purchasing of iridium by crystal manufacturers, reflecting increased demand for SAW filters during the roll-out of 5G telecommunications technology.

Demand for iridium in spark plugs fell steeply in 2020, reflecting global cuts in output of gasoline vehicles, but should recover in line with car production volumes this year. Premium spark plugs with precious metal electrodes are widely used as original equipment on modern vehicles, because of their longer life compared to traditional base metal plugs. Many different pgm alloys are used for the electrodes, typically involving platinum and often iridium, for optimal reliability, durability and performance.

Ruthenium

Like iridium, ruthenium prices also rose strongly in early 2021. The price was stable at $270 during the second half of last year, but began to move sharply higher from late January 2021, climbing to a thirteen-year high of $430 in late April.

The last time ruthenium traded above $400 was in 2007, on its descent from all-time highs above $800 that were triggered by the roll-out of new hard disk technology, known as perpendicular magnetic recording (PMR). PMR technology – which is still used for almost all hard drives today – requires disks to be coated with thin layers of platinum and ruthenium, using a 'sputtering' (physical vapour deposition) process that ties up significant quantities of pgm in work-in-progress (in 'sputtering targets' installed in production equipment and in spent targets that must be refined before the metal can be reused).

As PMR technology matured, improvements in process yields and refining efficiencies resulted in a gradual release of work-in-progress from this industry, even though underlying consumption of ruthenium on hard disks continued to grow. Combined with some selling of producer stocks, this has helped keep the ruthenium market reasonably well-supplied and prices relatively low for the past five years, despite unusually strong demand from the Chinese chemicals industry over this period.

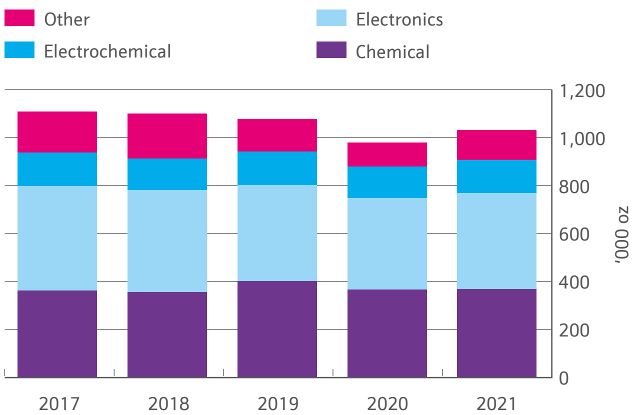


Figure 28 Industrial demand for ruthenium

Demand '000 oz	2019	2020	2021
Chemical	401	366	368
Electronics	401	381	400
Electrochemical	139	132	139
Other	137	101	124
Total	**1,078**	**980**	**1,031**

Table 12 Ruthenium demand

Much of this demand has come from the caprolactam and adipic acid industry, which in China typically uses the ruthenium-catalysed cyclohexene route, which is more energy efficient and less polluting than competing processes. Since 2011, the addition of significant new capacity for these chemicals has generated large quantities of ruthenium demand. New plant construction peaked in 2019 and the pace of capacity additions has since fallen, leading to lower ruthenium requirements.

Last year saw some delays in the purchasing of ruthenium catalysts for catalytic wet air oxidation (CWAO), with demand deferred into 2021. This process is used to treat effluent streams from petrochemical and pharmaceutical plants with high concentrations of aromatics and other organic chemicals. Ruthenium catalysts have been widely adopted for this application, because they provide excellent reactivity and are more environmentally friendly compared to base-metal alternatives.

Consumption of ruthenium in electronics, primarily in chip resistors and hard disks, was impacted by Covid-related plant closures in early 2020, but underlying demand trends remain robust. Sales of electronic devices have been supported by Covid-related increases in home-working, distance learning and virtual entertainment, while the roll-out of 5G and increased sales of battery electric vehicles have generated additional demand for electronic components. Miniaturisation continues to have some impact on ruthenium demand in resistors, but this is being offset by overall growth in chip volumes.

In the hard disk sector, drives using next-generation magnetic recording technology are beginning to be commercialised, and this could ultimately be negative for ruthenium demand, but the short-term impact is expected to be very small. Unlike in 2006–2007, when PMR technology swept to almost complete dominance in both consumer and business data storage applications over a period of less than two years, we do not expect any dramatic short-term changes in technology market shares. New technologies such as heat-assisted magnetic recording (HAMR) and microwave-assisted magnetic recording (MAMR) are significantly more expensive than current hard drive products, and will initially be used only in high-end applications in data centres.

Special feature

Green hydrogen for a net zero future

What role for pgm?

The 'hydrogen economy' – the use of hydrogen within a clean energy system – has become widely accepted as a credible proposition in the last year or two and there has been significant progress towards its realisation. Although still in its infancy, it is starting to shift sentiment towards the pgm, particularly platinum and iridium. So, why hydrogen, and why now? And what could it mean for pgm demand?

Why hydrogen?

The 2015 Paris Climate Agreement, a treaty that is binding under international law, requires rapid action: its goals dictate that global greenhouse gas emissions from human activities must peak within the next few years and fall to reach net zero soon after 2050[1]. This is starting to spur concrete regulatory action, helped no doubt by the fact that public sentiment in the 2020s is sufficiently in favour of climate action to facilitate a shift in the political calculus. Even so, the zeal with which some of these regulatory commitments are being made is perhaps surprising, given the societal and technical complexities involved. Beyond the political optics, this is explained by the growing recognition that the costs of climate chaos will far outweigh the costs of climate action, combined with a desire to grasp the opportunity presented by developing exportable clean energy technology and creating green jobs.

It is in this context that net-zero commitments have been announced by many regions and countries, including the European Union, the UK, China, and more recently the Biden administration in the USA. In turn this has led to the development of interim climate action plans, such as the 2030 Climate Target Plan proposed by the European Commission, and various forthcoming bans on vehicles with internal combustion engines. While the latter have been much discussed in the media, the demands of net zero apply to all sectors and industries, with equally dramatic ramifications.

Of relevance here is the fact that national net-zero commitments are usually accompanied by the formulation of national hydrogen strategies. According to the Hydrogen Council, over 30 such strategies have been created, including the EU Hydrogen Strategy, and a further six are at the draft stage.

This is not a coincidence: once policymakers commit to net zero and seriously engage with the implications, support for hydrogen as an energy vector tends to follow. This partly arises from the paucity of alternative energy carriers to replace the fossil hydrocarbons our global economy is reliant on[2]:

- **Bio-hydrocarbons** still contain carbon, but this carbon forms part of the natural global carbon cycle and hence will not disturb the climate equilibrium.
- **Electricity** generated by either renewable or nuclear energy.
- **Hydrogen**, or molecules synthesised using it, such as ammonia.

Bioenergy use is tightly constrained by the availability of sustainable biomass, which is not likely to be enough to supply more than a minor portion of global energy demand. But renewable electricity has already allowed significant decarbonisation of electricity grids, so why can't electricity cater to all our remaining decarbonisation needs? There is a two-part answer to this:

- Firstly, only about one-fifth of global energy consumption is in the form of electricity currently, the remainder being largely served by coal, oil and natural gas. Decarbonising the majority of our energy consumption through the direct use of electricity alone would require multiples of our current electrical grid, generation capacity and ancillary services, even with significant energy efficiency improvements.
- Secondly, practical constraints mean that some sectors will be impossible to fully electrify: specifically, heavy industry and heavy-duty transportation (road and rail haulage, shipping and aviation) – collectively known as the 'hard-to-abate' sectors.

Although efficiency improvements will help, deep decarbonisation of these hard-to-abate sectors must be accomplished by displacing fossil fuels with a combination of the three alternatives: electricity, bioenergy, and hydrogen. A substantial degree of electrification will happen where this is workable, while bioenergy will be used to the extent possible (probably limited to aviation and shipping). However, hydrogen will be required in some form to serve the remaining demand.

The hydrogen spectrum

Different hydrogen production methods are denoted in a shorthand using colours relating to their carbon intensity:

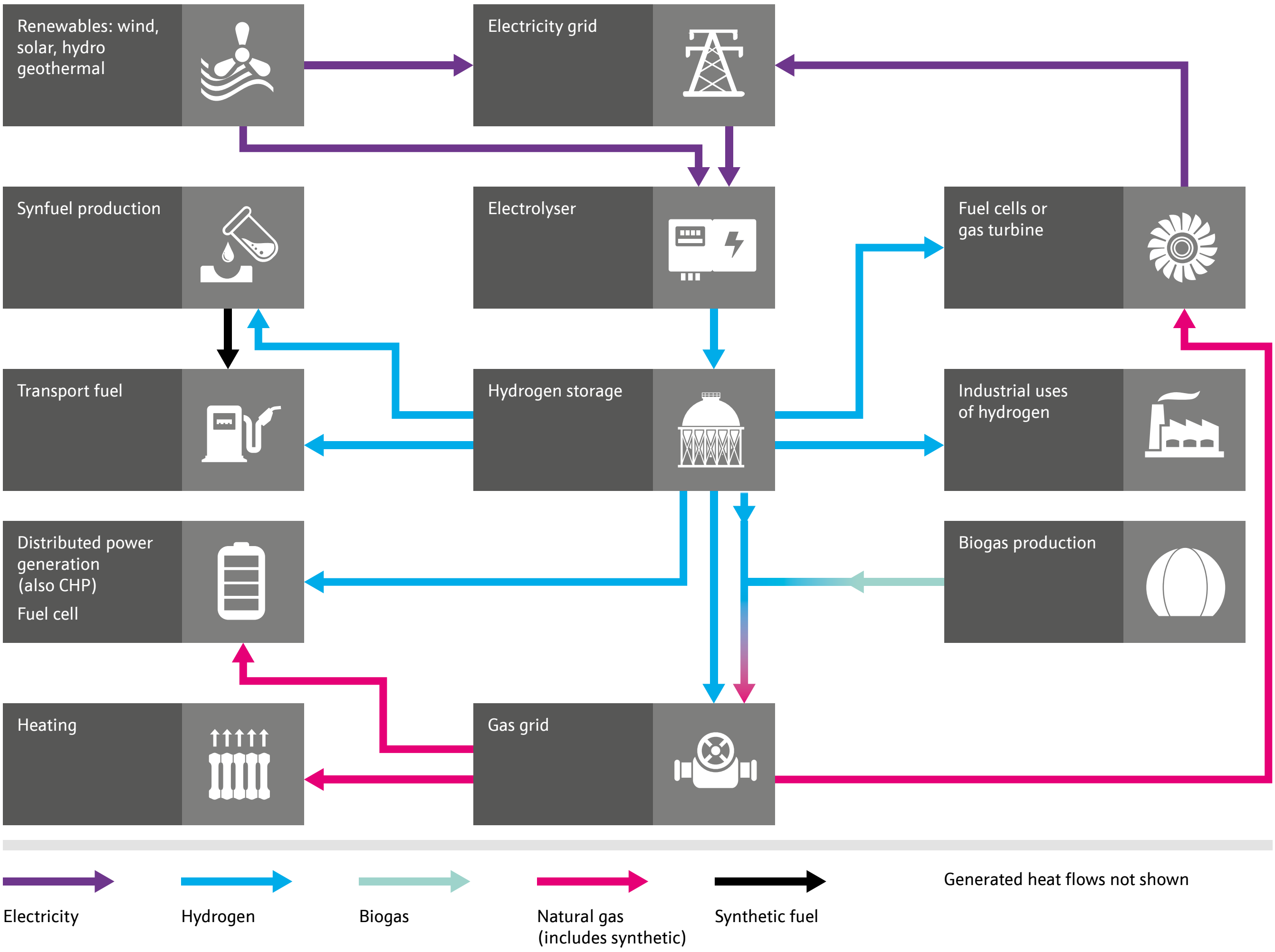


Figure 29 Sector coupling using green hydrogen

Brown or **black** hydrogen is produced by gasification of coal, either brown (lignite) or black (bituminous) coal.

Grey hydrogen is produced from natural gas through steam methane reforming and is by far the most common form in use today.

Blue hydrogen is also produced from natural gas, but most of the CO_2 emissions generated in the process are captured and stored. An alternative to steam methane reforming, known as autothermal reforming, facilitates a CO_2 capture percentage in excess of 95%[3].

Turquoise hydrogen is produced from natural gas by methane pyrolysis, generating solid carbon as a by-product rather than CO_2. This is currently in the experimental phase.

Green hydrogen is produced by the electrolysis of water and generates only oxygen as a by-product. Strictly it is only 'green' if the electricity driving this process is renewable. (If the electricity is nuclear power, the hydrogen is referred to as '**pink**' hydrogen.)

Hydrogen can also be produced directly from solar energy by photosynthetic organisms, but this is still in research and must be greatly improved for commercial viability. Such hydrogen has yet to be assigned a colour, but because of the use of sunlight it will perhaps be referred to as **yellow** hydrogen.

Clean hydrogen production

If hydrogen is to serve net-zero aims, it must be produced in a way that emits as little CO_2 as possible. Blue and green hydrogen are expected to be the dominant forms of hydrogen employed in decarbonisation efforts to 2050, with the proportions of each varying by region, depending on local resources and incentive structures. The scale of the global clean energy requirement means substantial quantities of both will be needed.

Blue hydrogen allows valorisation of fossil fuel reserves and infrastructure that would otherwise be stranded assets in a net-zero future. Carbon capture and storage (CCS) has proven to be viable and is being pursued in major projects around the world[4]. The use of blue hydrogen is pragmatic: its major advantage is that it directs some of the four-fifths of energy demand that is not presently electrified away from future dependence on renewable power generation and onto an alternative, accessible resource. Since it can already be implemented at large scale, it will be an important part of the energy transition, helping to seed and decarbonise hydrogen infrastructure ahead of more widespread use of green hydrogen.

Green hydrogen is appealing because it eliminates carbon emissions at source, does away with the need for CCS, and increases energy security for nations that are net importers of fossil energy. But to be green, hydrogen must use renewable electricity as a feedstock, thereby contributing to a vast requirement for renewable electricity generation in a net-zero world. That said, thanks to a number of synergies, a renewable energy system incorporating green hydrogen is more effective for decarbonisation overall, discussed further below.

Green hydrogen and renewable electricity

The difficulty in relying on renewable electricity, specifically wind and solar power, is that it is variable, intermittent and cannot be dispatched on demand. A perfectly integrated electricity grid covering a large enough geographical area and with sufficient transmission capacity should be able to smooth all mismatches in local supply and demand by transferring electricity from the point of generation to the location of need. But in the real world, renewable grids will require an energy storage mechanism to take up surplus electricity when and where it is generated, and to release it on-demand when and where there is a supply deficit.

Green hydrogen functions as exactly this: a means of storing green electrons. Moreover, it offers three key advantages as a storage technology:

- It is an alternative energy carrier that can be moved through gas or, if converted, through liquids infrastructure, removing strain from the electricity grid;
- It lends itself to large-scale, long-term storage, meaning it can address seasonal variation in renewable electricity supply and demand;
- It allows renewable electricity to be 'injected' into applications that cannot be otherwise electrified, and is thus an alternative means of sector coupling: linking up electricity, heating, transportation, and industry, to enable greater flexibility and efficacy in the overall system (Figure 29).

Electricity can be distributed to grid-connected electrolysers that operate as needed to provide demand-side management of supply-demand imbalances and generate hydrogen. Electrolysers can also be connected directly to wind or solar farms to generate hydrogen at source (cutting electricity losses through transmission and providing supply-side management). From either point, the hydrogen can be used in a variety of ways (which applies to blue hydrogen too, minus the link to renewable power).

For example, hydrogen can be stored in different forms[5] in dedicated above-ground storage, or in large quantities in underground storage (by injection into salt caverns for instance). From there, it can fuel on-demand electricity or combined heat and power (CHP) generation; be used as a vehicle fuel; be supplied to industry as a feedstock or for high-temperature heating duties; or be chemically combined with nitrogen to generate ammonia or with carbon dioxide to produce synthetic hydrocarbon fuels (both known as 'e-fuels' when the hydrogen is electrolytically generated). The CO_2 for synthetic hydrocarbons can be sourced from direct air capture (currently being piloted at the Haru Oni project in Patagonia, for example) or from gasified waste or biomass. Hydrogen can similarly be used to renewably upgrade the CO_2 generated when biogas is produced, maximising the value of this resource.

Hydrogen can also be injected into the gas grid to directly decarbonise heating, which is of particular interest in the northern hemisphere where domestic and commercial central heating is a substantial contributor to carbon emissions. Gas has been combusted for many years to generate electricity and heat, but electrolysis and hydrogen for the first time provide a link between the electricity and gas grids in the opposite direction.

The sector-coupling described above is why green hydrogen production is a key component of 'power-to-X', where X may be gas or liquids (synthetic fuel and/or chemicals).

What about energy efficiency?

There is a loss incurred whenever energy is converted, which is the case in converting electricity to hydrogen and *vice versa*. So why is this not a deterrent to the use of green hydrogen?

Our use of fossil fuels has shaped the way that we think about energy efficiency, because efficiency of consumption is an important metric when using finite and polluting energy sources. But renewable energy is by definition not finite and is also not polluting, so the measure of efficiency that matters is not how much of the resource is consumed, but how effectively the *installed generating base* is being used (i.e. the wind turbines and solar panels that are harnessing the sunlight and wind).

It is obviously still better to use a kilowatt-hour of generated electricity directly wherever possible. However, as discussed above, energy storage will be critical for effective use of renewable power because of supply and demand mismatches. Green hydrogen offers a carbon-free way to store wind and solar power in large quantities and for long periods, diverts demand from the electricity grid, and offers a means of injecting renewable energy into hard-to-abate sectors. It thereby helps to maximise the benefit of the installed renewable power base.

The use of 'curtailed wind' illustrates this explicitly. Wind farms are assigned a 'capacity factor' reflecting the amount of power they are credited with supplying to the grid, relative to the installed nameplate capacity. This is typically well below 100% for wind power, because the wind only blows some of the time and with variable force. But it can be further reduced if the wind farm at times produces power that the grid can't accept, either because there is no immediate demand for it or because transmission capacity is insufficient: the wind farm is not credited for producing this power and it is lost. Coupling an electrolyser to the wind farm to use the curtailed wind power to produce green hydrogen would increase the amount of wind power used, despite significant energy loss during the conversion.

The efficiency argument is also used in comparing battery electric vehicles (BEVs) to fuel cell electric vehicles (FCEVs). Electricity stored in a battery is converted directly to motive power through the electric drivetrain, whereas energy stored in a hydrogen tank must first be converted to electricity in a fuel cell, incurring a conversion loss. This would matter in application if the energy loss limits the range of the vehicle. In fact, due to the superior energy density of hydrogen compared to energy storage in a battery, the opposite is true: hydrogen-fuelled vehicles can

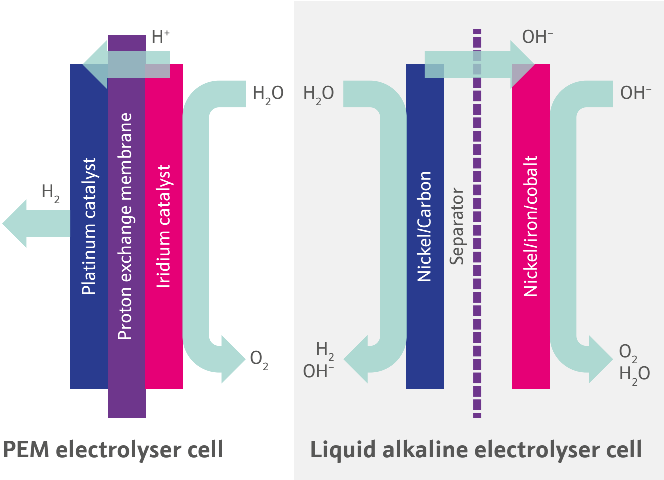


Figure 30 Schematic of PEM and alkaline electrolyser cells

achieve much longer ranges than pure battery-electric vehicles for the same weight of energy storage carried on the vehicle. The facility this offers, particularly for larger, heavier vehicles, justifies the consumption of some renewable electricity to make hydrogen to fuel a portion of the future net-zero vehicle fleet[6].

Electrolysis technology

The electrolysis of water to produce hydrogen is not new: an industrial electrolysis plant was first commissioned in Norway in the late 1920s to supply hydrogen for fertiliser production, benefiting from the abundance of hydropower available in that country. However, electrolysis has to date found only niche application at industrial scale because grey hydrogen is currently cheaper to make.

Three technologies are commercially available today: liquid alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid-oxide electrolysis. (A fourth technology – anion exchange membrane (AEM) electrolysis – is in development but is an early-stage technology that cannot yet compete at scale with the more established technologies.) Ceramic-based solid-oxide technology is at a relatively early stage of commercial readiness and its characteristic high operating temperature means it has a somewhat different application profile from PEM and alkaline electrolysis, and so will not be further considered here. Alkaline electrolysis is a mature technology that has been used in industrial settings for many decades, notably in Norway, and is now being adapted for clean energy applications. PEM electrolysis has only been used at small scale in the past, but it is rapidly gaining commercial maturity at scale as it is increasingly applied in clean energy projects.

In an alkaline electrolysis cell, the reaction occurs between two electrodes in a liquid electrolyte (usually a solution of potassium hydroxide in water). When a voltage is applied across the two electrodes, water molecules at the cathode gain electrons to make hydroxide (OH^-) ions and hydrogen. The OH^- ions move through the electrolyte to the anode, where they give up electrons to form water and oxygen. The reactions are catalysed by base metals, typically nickel, cobalt and/or iron.

In a PEM electrolysis cell, the electrolyte is an ionically conductive solid polymer membrane onto which the electrocatalysts are deposited, forming a catalyst-coated membrane (CCM) similar to that in a PEM fuel cell.

When a voltage is applied to the PEM electrolyser cell, water molecules are split at the anode to make hydrogen ions (i.e. protons) and oxygen. The hydrogen ions move through the polymer to the cathode, where they pick up electrons and combine to form hydrogen gas. Electrolysis is thus the reverse of the reaction that occurs in a fuel cell, in which hydrogen and oxygen are combined to produce water and an electric current. As in a PEM fuel cell, the anode and cathode reactions are pgm-catalysed, which we will revisit later in this article.

The CCM plus the gas diffusion layers (GDLs, which allow the gases to move away from the electrode surfaces) form the membrane electrode assembly (MEA) that is sandwiched between two bipolar plates. The bipolar plates transport water and gases to/from the cell, conduct electricity, and allow coolant circulation. As with fuel cells, electrolysers consist of several individual cells combined in series to form a stack.

Why use PEM electrolysis?

PEM electrolyser capital cost is currently higher than that of liquid alkaline systems due to the lower maturity level of the technology, but it is falling rapidly with optimisation and scale-up. The technology is benefiting from tremendous interest and investment[7] because it possesses fundamental characteristics that facilitate its use in clean energy applications.

Firstly, it offers the potential to reach high current densities (current density is loosely equivalent to the amount of electricity 'converted' to gas per square metre of cell area). This means that PEM systems can be relatively compact compared to liquid alkaline electrolysers. A compact footprint is advantageous in space-limited applications, such as forecourt electrolysers[8], but the major benefit is that it allows for more significant economies of scale when scaling up to multi-megawatt systems. PEM thus has the potential to have the lowest capital cost per megawatt in future bulk energy applications, which will operate at multi-megawatt or even multi-gigawatt scale.

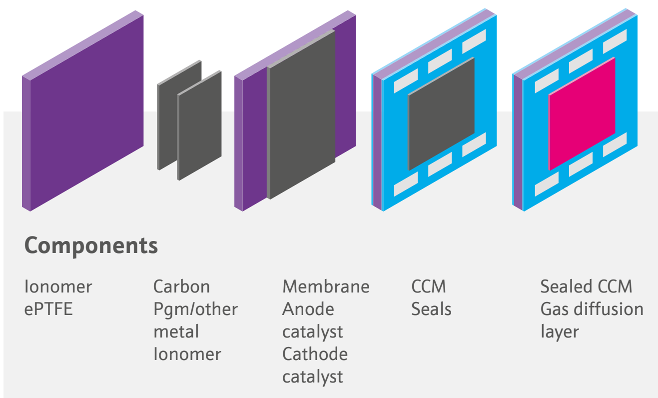


Figure 31 PEM electrolyser cell components

Electricity from renewable power is inherently variable, and hence should ideally be paired with electrolysis technology that is highly responsive to changes in load and can operate efficiently at low part-loads (<20%), thus maximising the use of available power. PEM technology performs highly effectively in variable operation, with rapid response times, an operation range of 0–100%, and the ability to operate safely in overload for periods if needed. Liquid alkaline electrolysers also have good load-following capabilities, which are often satisfactory for the application, but the technology is fundamentally less flexible than PEM.

PEM offers further advantages: due to the physical separation of the membrane, hydrogen can be produced under pressure on one side of the cell, while the oxygen side remains at atmospheric pressure, which is safer. PEM systems in use today typically offer direct hydrogen production at 30 to 50 bar (although electrochemical compression to much higher pressures in PEM systems has been demonstrated). Since many applications require compressed hydrogen, starting with a higher pressure reduces the energy needed for subsequent, expensive mechanical compression to the desired pressure. Hydrogen is also generated on the 'dry' side of the cell (rather than on the 'wet' side, as in alkaline electrolysis) and thus does not need to be dried before use.

PGM in PEM electrolysis

Electrolysis involves two 'half-reactions': an oxygen evolution reaction (OER) at the anode, and a hydrogen evolution reaction (HER) at the cathode. Although both occur without a catalyst, they proceed too slowly to be viable in real-world applications, so electrocatalysts are used to increase the kinetics of the OER and HER, thereby greatly improving energy efficiency.

A PEM cell is an acidic environment under a strongly oxidising voltage, a harsh environment for materials. The only effective catalysts for the anode OER under these conditions identified so far are noble metals, specifically iridium black or iridium oxide (IrOx) or ruthenium oxide (RuOx). Of the two, iridium is the most stable in the high-voltage conditions and commercial PEM electrolysers today rely on iridium. Ruthenium is inherently more active, but its relative instability must be addressed through advanced materials technology to prevent loss of electrolyser performance. The HER on the cathode is catalysed by platinum, but this is a less difficult reaction so loadings are lower than those of iridium (or iridium plus ruthenium) on the anode side.

The performance of pgm in PEM electrolysis under real-world operating conditions is highly unlikely to be equalled by alternative materials. From a cost perspective, if the elimination of pgm results in any reduction of durability (compromising lifetime and reliability), or reduces the efficiency of the electrolysis process and therefore raises operating costs, it is unlikely to make economic sense even if it reduces the upfront capital investment.

Beyond cost, the issue of availability must be addressed. Both iridium and ruthenium are supplied almost entirely as minor by-products of platinum mining and are unlikely to ever be extracted in their own right. At the loadings in use on electrolysers today, the availability of iridium imposes a constraint on the amount of PEM capacity that can be produced annually to meet all of the electrolyser capacity required through to 2030.

But nobody expects widespread uptake of PEM electrolysis at today's loadings. Over the past few years, electrolyser and hydrogen producers have been focused on demonstration of the technology; reduction of pgm use has been a secondary concern. However, just as FCEVs offered for sale today contain platinum at fractions of the amounts used on the demonstration vehicles of ten years ago, electrolysers are following the same course. With the proof-of-concept in the bag, focus has now turned to optimising the technology for commercial deployment and minimising pgm loadings. PGM loading per megawatt is expected to decline to a small fraction of present loadings over the next ten to twenty years.

This must be coupled with effective re-use of metal, and it will be imperative for iridium users to focus on the sustainability of their metal use. Although there are specific challenges to address, end-of-life PEM fuel cell CCMs are already being recycled in appreciable quantities today, with almost complete recovery of the pgm, and PEM electrolyser CCMs are expected to be no different.

Outlook for green hydrogen

Forecasting the future of this market is necessarily imprecise at present, given that the ink is hardly dry on the national hydrogen strategies published so far and many others are still being drafted. There is a wide range of potential outcomes, but all point to strong growth in demand for clean hydrogen and for PEM electrolysis technology within that.

One possible scenario is shown in Figure 32 from the Hydrogen Council. Total hydrogen production in 2020 was around 10 EJ, virtually all of which was derived conventionally from fossil fuels and used as industrial feedstock (in fertiliser production and for hydroprocessing in petroleum refineries, for instance). In this scenario, total hydrogen production grows strongly in the period to 2040 with increasing use in clean energy applications, and sees a sharp uptick by 2050 as net zero becomes more pressing. Hydrogen production reaches 78 EJ in 2050[9].

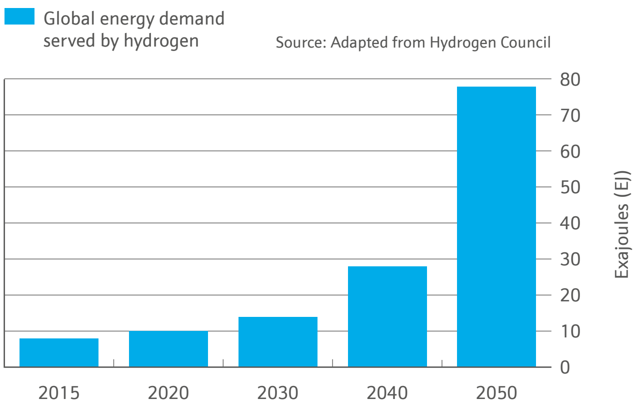


Figure 32 Scenario for growing hydrogen demand in a clean energy future

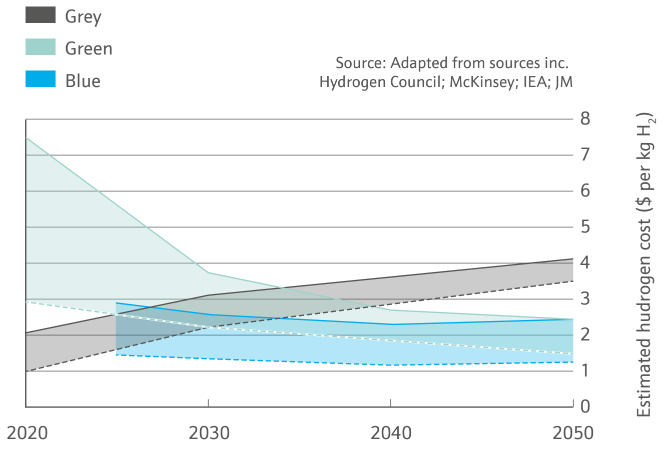


Figure 33 Hydrogen cost projection

The uptake of clean hydrogen over grey hydrogen is expected to be market-driven, as realistic carbon pricing drives up the cost of grey hydrogen and blue and green hydrogen become more cost-effective (see potential trajectories in Figure 33). Blue hydrogen is based on fairly well-established technology already employed at scale so is unlikely to see significant cost reduction, but there will be some benefit from more efficient production methods and a reduction in the cost of CCS (any non-captured CO_2 will be subject to carbon pricing). The cost of electricity is a major determinant of green hydrogen cost, but the costs of renewable electricity are already falling and will fall further (and, as discussed above, green hydrogen can make use of electricity that would otherwise be wasted and is accordingly likely to be very low cost). Added to that, electrolyser capital cost will come down with technology optimisation and economies of scale, bringing the total cost of hydrogen produced by electrolysis down dramatically.

Implications for the pgm industry

Although pgm loadings will diminish to maximise efficient use of metal, the anticipated growth in demand for PEM electrolysis capacity to produce green hydrogen presents significant demand potential in the longer term. Together with the use of platinum in automotive fuel cells, this places pgm at the heart of the hydrogen economy. There is therefore no doubt that the pgm will play a strong contributory role in the energy transition through 2050.

Sustainability in pgm demand must of course be matched by sustainability in pgm supply and use, encompassing both the decarbonisation of extraction and refining, and ensuring that any metal consumed can be effectively recycled for reuse. Both pgm users and pgm suppliers are increasingly focused on these metrics, which themselves have profound implications for the industry in the coming years.

To date, the conversation on the energy transition has focused on batteries and renewable electricity, and on base metals. But the pgm are now gaining ground in this conversation and taking their place alongside lithium, cobalt and copper as 'green energy metals' of the future.

[1]'Net' rather than 'absolute' zero recognises that some particularly challenging sectors will not be able to fully decarbonise and the use of carbon sinks – such as increased tree cover – will be employed to offset these residual emissions.

[2]Energy must be harnessed in the form of a carrier (or vector). The list of primary energy sources is as follows: the sun (from which wind power and bioenergy also derive, and from which fossil energy derived), nuclear energy, geothermal energy, and gravitational energy (which gives rise to tidal power). The latter two are relatively minor sources. Hydropower arises from a combination of solar and gravitational energy.

[3]The Johnson Matthey LCH™ process is an example of an advanced reforming technology using a gas heated reformer and autothermal reformer.

[4]See the Northern Lights project, for example.

[5]Compressed gas, cryogenic liquid, metal-hydride solid storage, or hydrogenated liquid organic compound (LOHC).

[6]For more information on fuel cell vehicles, see the Special Feature in our May 2018 report

[7]Major developers include Siemens, ITM Power, NEL Hydrogen (through its acquisition of Proton OnSite), Cummins (through its acquisition of Hydrogenics), and Plug Power (through its acquisition of Giner ELX).

[8]An example is the Honda Smart Hydrogen Station (SHS).

[9]1 EJ is about 278 TWh. A terawatt hour is one billion kilowatt hours (kWh). Global electricity generation in 2019 totalled 27,000 TWh or just over 97 EJ.

Platinum supply and demand

Troy ounces

Supply '000 oz[1]	2016	2017	2018	2019	2020	2021
South Africa	4,392	4,450	4,467	4,344	3,222	4,475
Russia[2]	714	720	687	721	699	610
North America	370	368	346	351	339	347
Zimbabwe[3]	489	466	474	451	482	497
Others[3]	162	157	152	156	202	167
Total supply	**6,127**	**6,161**	**6,126**	**6,023**	**4,944**	**6,096**

Demand '000 oz[4]	2016	2017	2018	2019	2020	2021
Autocatalyst[4]	3,339	3,211	3,053	2,863	2,290	2,910
Chemical	477	453	657	666	640	634
Electronics[4]	232	232	241	232	241	280
Glass	247	314	501	441	451	514
Investment	620	361	67	1,131	1,022	311
Jewellery[4]	2,413	2,385	2,258	2,066	1,707	1,797
Medical and biomedical[5]	218	220	232	240	218	230
Petroleum	186	227	372	255	299	170
Other	535	575	591	588	462	538
Total gross demand	**8,267**	**7,978**	**7,972**	**8,482**	**7,330**	**7,384**

Recycling '000 oz[6]	2016	2017	2018	2019	2020	2021
Autocatalyst	-1,132	-1,249	-1,329	-1,391	-1,156	-1,318
Electronics	-32	-35	-38	-40	-38	-47
Jewellery	-738	-746	-699	-663	-523	-538
Total recycling	**-1,902**	**-2,030**	**-2,066**	**-2,094**	**-1,717**	**-1,903**

Total net demand[7]	**6,365**	**5,948**	**5,906**	**6,388**	**5,613**	**5,481**
Movement in stocks[8]	-238	213	220	-365	-669	615

Platinum gross demand by region

Troy ounces

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
Europe	Autocatalyst	1,786	1,708	1,452	1,287	930	1,046
	Chemical	122	117	122	124	118	139
	Electronics	13	10	12	13	14	17
	Glass	11	11	11	13	12	15
	Investment	109	36	-102	566	308	181
	Jewellery	177	176	191	190	152	170
	Medical and biomedical	71	70	63	64	56	59
	Petroleum	3	7	29	15	9	6
	Other	154	172	174	180	141	160
	Total	**2,446**	**2,307**	**1,952**	**2,452**	**1,740**	**1,793**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
Japan	Autocatalyst	360	358	365	344	265	313
	Chemical	42	37	40	42	40	40
	Electronics	32	31	31	31	31	35
	Glass	2	25	7	27	16	5
	Investment	543	171	220	32	392	-44
	Jewellery	310	303	293	294	238	265
	Medical and biomedical	15	15	14	15	13	14
	Petroleum	3	2	2	2	2	2
	Other	77	79	79	79	69	77
	Total	**1,384**	**1,021**	**1,051**	**866**	**1,066**	**707**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
North America	Autocatalyst	360	314	354	361	293	408
	Chemical	103	112	108	109	104	111
	Electronics	26	33	37	30	29	40
	Glass	29	45	18	21	29	36
	Investment	109	127	66	156	602	222
	Jewellery	221	225	224	211	206	213

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
North America	Medical and biomedical	87	88	95	99	91	95
	Petroleum	35	18	15	17	0	12
	Other	146	147	156	155	101	118
	Total	**1,116**	**1,109**	**1,073**	**1,159**	**1,455**	**1,255**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
China	Autocatalyst	151	157	145	141	205	395
	Chemical	122	74	207	264	289	249
	Electronics	42	44	51	49	52	61
	Glass	135	111	388	294	336	358
	Investment	0	0	0	0	0	0
	Jewellery	1,510	1,470	1,316	1,119	945	970
	Medical and biomedical	19	20	29	30	29	31
	Petroleum	76	120	254	161	208	64
	Other	72	83	87	82	70	83
	Total	**2,127**	**2,079**	**2,477**	**2,140**	**2,134**	**2,211**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
Rest of World	Autocatalyst	682	674	737	730	597	748
	Chemical	88	113	180	127	89	95
	Electronics	119	114	110	109	115	127
	Glass	70	122	77	86	58	100
	Investment	-141	27	-117	377	-280	-48
	Jewellery	195	211	234	252	166	179
	Medical and biomedical	26	27	31	32	29	31
	Petroleum	69	80	72	60	80	86
	Other	86	94	95	92	81	100
	Total	**1,194**	**1,462**	**1,419**	**1,865**	**935**	**1,418**
	Grand total	**8,267**	**7,978**	**7,972**	**8,482**	**7,330**	**7,384**

Platinum supply and demand

Tonnes

Supply tonnes[1]	2016	2017	2018	2019	2020	2021
South Africa	136.6	138.4	138.9	135.1	100.2	139.2
Russia[2]	22.2	22.4	21.4	22.4	21.8	19.0
North America	11.5	11.4	10.8	10.9	10.5	10.8
Zimbabwe[3]	15.2	14.5	14.7	14.0	15.0	15.5
Others[3]	5.1	4.9	4.7	4.9	6.3	5.2
Total supply	**190.6**	**191.6**	**190.5**	**187.3**	**153.8**	**189.7**

Demand tonnes[4]	2016	2017	2018	2019	2020	2021
Autocatalyst[4]	103.9	99.9	95.0	89.0	71.2	90.5
Chemical	14.8	14.0	20.4	20.8	19.9	19.7
Electronics[4]	7.2	7.2	7.5	7.2	7.5	8.7
Glass	7.7	9.8	15.6	13.7	14.1	16.0
Investment	19.3	11.2	2.1	35.1	31.8	9.6
Jewellery[4]	75.1	74.2	70.2	64.2	53.1	55.9
Medical and biomedical[5]	6.8	6.8	7.2	7.5	6.7	7.2
Petroleum	5.8	7.1	11.6	8.0	9.4	5.4
Other	16.6	17.9	18.4	18.3	14.3	16.8
Total gross demand	**257.2**	**248.1**	**248.0**	**263.8**	**228.0**	**229.8**

Recycling tonnes[6]	2016	2017	2018	2019	2020	2021
Autocatalyst	-35.2	-38.8	-41.4	-43.2	-35.9	-41.0
Electronics	-1.0	-1.1	-1.2	-1.3	-1.2	-1.5
Jewellery	-23.0	-23.2	-21.7	-20.6	-16.3	-16.7
Total recycling	**-59.2**	**-63.1**	**-64.3**	**-65.1**	**-53.4**	**-59.2**

Total net demand[7]	**198.0**	**185.0**	**183.7**	**198.7**	**174.6**	**170.6**
Movement in stocks[8]	-7.4	6.6	6.8	-11.4	-20.8	19.1

Platinum gross demand by region

Tonnes

Gross demand tonnes		2016	2017	2018	2019	2020	2021
Europe	Autocatalyst	55.6	53.1	45.2	40.0	28.9	32.5
	Chemical	3.8	3.6	3.8	3.9	3.7	4.3
	Electronics	0.4	0.3	0.4	0.4	0.4	0.5
	Glass	0.3	0.3	0.3	0.4	0.4	0.5
	Investment	3.4	1.1	-3.2	17.6	9.6	5.6
	Jewellery	5.5	5.5	5.9	5.9	4.7	5.3
	Medical and biomedical	2.2	2.2	2.0	2.0	1.7	1.8
	Petroleum	0.1	0.2	0.9	0.5	0.3	0.2
	Other	4.8	5.3	5.4	5.6	4.4	5.0
	Total	**76.1**	**71.6**	**60.7**	**76.3**	**54.1**	**55.7**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
Japan	Autocatalyst	11.2	11.1	11.4	10.7	8.2	9.7
	Chemical	1.3	1.1	1.2	1.3	1.2	1.2
	Electronics	1.0	1.0	1.0	1.0	1.0	1.1
	Glass	0.1	0.8	0.2	0.8	0.5	0.2
	Investment	16.9	5.3	6.8	1.0	12.2	-1.4
	Jewellery	9.6	9.4	9.1	9.1	7.4	8.2
	Medical and biomedical	0.5	0.5	0.4	0.5	0.4	0.4
	Petroleum	0.1	0.1	0.1	0.1	0.1	0.1
	Other	2.4	2.5	2.5	2.5	2.1	2.4
	Total	**43.1**	**31.8**	**32.7**	**27.0**	**33.1**	**21.9**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
North America	Autocatalyst	11.2	9.8	11.0	11.2	9.1	12.7
	Chemical	3.2	3.5	3.4	3.4	3.2	3.5
	Electronics	0.8	1.0	1.1	0.9	0.9	1.2
	Glass	0.9	1.4	0.6	0.7	0.9	1.1
	Investment	3.4	4.0	2.1	4.8	18.7	6.9
	Jewellery	6.9	7.0	7.0	6.6	6.4	6.6

Gross demand tonnes		2016	2017	2018	2019	2020	2021
North America	Medical and biomedical	2.7	2.7	2.9	3.1	2.8	3.0
	Petroleum	1.1	0.6	0.5	0.5	0.0	0.4
	Other	4.5	4.6	4.8	4.8	3.1	3.7
	Total	**34.7**	**34.6**	**33.4**	**36.0**	**45.1**	**39.1**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
China	Autocatalyst	4.7	4.9	4.5	4.4	6.4	12.3
	Chemical	3.8	2.3	6.4	8.2	9.0	7.7
	Electronics	1.3	1.4	1.6	1.5	1.6	1.9
	Glass	4.2	3.5	12.1	9.1	10.5	11.1
	Investment	0.0	0.0	0.0	0.0	0.0	0.0
	Jewellery	47.0	45.7	40.9	34.8	29.4	30.2
	Medical and biomedical	0.6	0.6	0.9	0.9	0.9	1.0
	Petroleum	2.4	3.7	7.9	5.0	6.5	2.0
	Other	2.2	2.6	2.7	2.5	2.2	2.6
	Total	**66.2**	**64.7**	**77.0**	**66.4**	**66.5**	**68.8**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
Rest of World	Autocatalyst	21.2	21.0	22.9	22.7	18.6	23.3
	Chemical	2.7	3.5	5.6	4.0	2.8	3.0
	Electronics	3.7	3.5	3.4	3.4	3.6	4.0
	Glass	2.2	3.8	2.4	2.7	1.8	3.1
	Investment	-4.4	0.8	-3.6	11.7	-8.7	-1.5
	Jewellery	6.1	6.6	7.3	7.8	5.2	5.6
	Medical and biomedical	0.8	0.8	1.0	1.0	0.9	1.0
	Petroleum	2.1	2.5	2.2	1.9	2.5	2.7
	Other	2.7	2.9	3.0	2.9	2.5	3.1
	Total	**37.1**	**45.4**	**44.2**	**58.1**	**29.2**	**44.3**
	Grand total	**257.2**	**248.1**	**248.0**	**263.8**	**228.0**	**229.8**

Palladium supply and demand

Troy ounces

Supply '000 oz[1]	2016	2017	2018	2019	2020	2021
South Africa	2,570	2,547	2,543	2,588	1,977	2,655
Russia[2]	2,781	2,452	2,976	2,987	2,636	2,560
North America	917	956	978	1,010	956	976
Zimbabwe[3]	396	386	393	379	410	412
Others[3]	129	131	135	140	181	146
Total supply	**6,793**	**6,472**	**7,025**	**7,104**	**6,160**	**6,749**

Demand '000 oz[4]	2016	2017	2018	2019	2020	2021
Autocatalyst[4]	8,042	8,464	8,836	9,667	8,551	9,447
Chemical	419	435	612	505	579	646
Dental	429	391	358	313	225	244
Electronics[4]	872	844	769	714	626	656
Investment	-646	-386	-574	-87	-190	-93
Jewellery[4]	189	167	148	129	87	103
Other	157	144	175	177	129	144
Total gross demand	**9,462**	**10,059**	**10,324**	**11,418**	**10,007**	**11,147**

Recycling '000 oz[6]	2016	2017	2018	2019	2020	2021
Autocatalyst	-1,986	-2,358	-2,621	-2,924	-2,696	-3,119
Electronics	-481	-479	-475	-471	-414	-440
Jewellery	-21	-21	-12	-12	-9	-10
Total recycling	**-2,488**	**-2,858**	**-3,108**	**-3,407**	**-3,119**	**-3,569**

Total net demand[7]	**6,974**	**7,201**	**7,216**	**8,011**	**6,888**	**7,578**
Movement in stocks[8]	-181	-729	-191	-907	-728	-829

Palladium gross demand by region

Troy ounces

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
Europe	Autocatalyst	1,637	1,703	1,902	2,057	1,769	2,074
	Chemical	74	75	71	67	73	117
	Dental	65	60	51	42	28	30
	Electronics	99	97	92	86	72	75
	Investment	-269	-287	-141	-56	-17	-68
	Jewellery	58	53	49	43	28	39
	Other	24	23	30	26	23	23
	Total	**1,688**	**1,724**	**2,054**	**2,265**	**1,976**	**2,290**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
Japan	Autocatalyst	786	828	875	906	778	833
	Chemical	15	17	17	17	16	17
	Dental	200	174	156	140	103	113
	Electronics	227	221	199	182	160	161
	Investment	-3	-3	-1	1	3	0
	Jewellery	64	57	52	45	31	34
	Other	9	9	9	9	7	7
	Total	**1,298**	**1,303**	**1,307**	**1,300**	**1,098**	**1,165**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
North America	Autocatalyst	1,992	2,022	2,097	2,081	1,709	2,110
	Chemical	73	75	76	84	37	73
	Dental	138	131	125	106	74	80
	Electronics	128	124	112	103	89	93
	Investment	-71	-19	-87	-5	-35	-20
	Jewellery	36	29	27	21	14	15
	Other	46	44	44	45	32	38
	Total	**2,342**	**2,406**	**2,394**	**2,435**	**1,920**	**2,389**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
China	Autocatalyst	2,038	2,179	2,080	2,708	2,683	2,384
	Chemical	162	174	272	230	345	330
	Dental	7	7	7	6	6	5
	Electronics	156	155	141	131	116	124
	Investment	0	0	0	0	0	0
	Jewellery	10	9	2	1	0	0
	Other	45	51	72	74	51	58
	Total	**2,418**	**2,575**	**2,574**	**3,150**	**3,201**	**2,901**

Gross demand '000 oz		2016	2017	2018	2019	2020	2021
Rest of World	Autocatalyst	1,589	1,732	1,882	1,915	1,612	2,046
	Chemical	95	94	176	107	108	109
	Dental	19	19	19	19	14	16
	Electronics	262	247	225	212	189	203
	Investment	-303	-77	-345	-27	-141	-5
	Jewellery	21	19	18	19	14	15
	Other	33	17	20	23	16	18
	Total	**1,716**	**2,051**	**1,995**	**2,268**	**1,812**	**2,402**
	Grand total	**9,462**	**10,059**	**10,324**	**11,418**	**10,007**	**11,147**

Palladium supply and demand

Tonnes

Supply tonnes[1]	2016	2017	2018	2019	2020	2021
South Africa	80.0	79.2	79.1	80.5	61.5	82.6
Russia[2]	86.5	76.3	92.6	92.9	82.0	79.6
North America	28.5	29.7	30.4	31.4	29.7	30.4
Zimbabwe[3]	12.3	12.0	12.2	11.8	12.8	12.8
Others[3]	4.0	4.1	4.2	4.4	5.6	4.5
Total supply	**211.3**	**201.3**	**218.5**	**221.0**	**191.6**	**209.9**

Demand tonnes[4]	2016	2017	2018	2019	2020	2021
Autocatalyst[4]	250.1	263.3	274.8	300.7	266.0	293.7
Chemical	13.1	13.4	19.1	15.7	18.0	20.1
Dental	13.3	12.2	11.1	9.8	7.0	7.6
Electronics[4]	27.2	26.3	23.9	22.3	19.5	20.4
Investment	-20.1	-12.0	-17.8	-2.7	-5.9	-2.9
Jewellery[4]	5.9	5.2	4.6	4.0	2.7	3.3
Other	4.8	4.5	5.4	5.5	4.0	4.5
Total gross demand	**294.3**	**312.9**	**321.1**	**355.3**	**311.3**	**346.7**

Recycling tonnes[6]	2016	2017	2018	2019	2020	2021
Autocatalyst	-61.7	-73.4	-81.5	-91.0	-83.9	-97.0
Electronics	-15.0	-14.9	-14.8	-14.7	-12.8	-13.7
Jewellery	-0.7	-0.6	-0.4	-0.4	-0.3	-0.3
Total recycling	**-77.4**	**-88.9**	**-96.7**	**-106.1**	**-97.0**	**-111.0**

Total net demand[7]	**216.9**	**224.0**	**224.4**	**249.2**	**214.3**	**235.7**
Movement in stocks[8]	-5.6	-22.7	-5.9	-28.2	-22.7	-25.8

Palladium gross demand by region

Tonnes

Gross demand tonnes		2016	2017	2018	2019	2020	2021
Europe	Autocatalyst	50.9	53.0	59.2	64.0	55.0	64.5
	Chemical	2.3	2.3	2.2	2.1	2.3	3.6
	Dental	2.0	1.9	1.6	1.3	0.9	0.9
	Electronics	3.1	3.0	2.8	2.7	2.2	2.3
	Investment	-8.4	-8.9	-4.4	-1.7	-0.5	-2.1
	Jewellery	1.8	1.6	1.5	1.3	0.9	1.2
	Other	0.7	0.7	0.9	0.8	0.7	0.7
	Total	**52.4**	**53.6**	**63.8**	**70.5**	**61.5**	**71.1**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
Japan	Autocatalyst	24.4	25.7	27.2	28.2	24.2	25.9
	Chemical	0.5	0.5	0.5	0.5	0.5	0.5
	Dental	6.2	5.4	4.8	4.4	3.2	3.5
	Electronics	7.1	6.9	6.2	5.7	5.0	5.0
	Investment	-0.1	-0.1	0.0	0.0	0.1	0.0
	Jewellery	2.0	1.8	1.6	1.4	1.0	1.1
	Other	0.3	0.3	0.3	0.3	0.2	0.2
	Total	**40.4**	**40.5**	**40.6**	**40.5**	**34.2**	**36.2**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
North America	Autocatalyst	62.0	62.9	65.2	64.7	53.2	65.6
	Chemical	2.3	2.3	2.4	2.6	1.1	2.3
	Dental	4.3	4.1	3.9	3.3	2.3	2.5
	Electronics	4.0	3.9	3.5	3.2	2.8	2.9
	Investment	-2.2	-0.6	-2.7	-0.2	-1.1	-0.6
	Jewellery	1.1	0.9	0.8	0.7	0.4	0.5
	Other	1.4	1.4	1.4	1.4	1.0	1.2
	Total	**72.9**	**74.9**	**74.5**	**75.7**	**59.7**	**74.4**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
China	Autocatalyst	63.4	67.8	64.7	84.2	83.5	74.1
	Chemical	5.0	5.4	8.5	7.2	10.7	10.3
	Dental	0.2	0.2	0.2	0.2	0.2	0.2
	Electronics	4.9	4.8	4.4	4.1	3.6	3.9
	Investment	0.0	0.0	0.0	0.0	0.0	0.0
	Jewellery	0.3	0.3	0.1	0.0	0.0	0.0
	Other	1.4	1.6	2.2	2.3	1.6	1.8
	Total	**75.2**	**80.1**	**80.1**	**98.0**	**99.6**	**90.3**

Gross demand tonnes		2016	2017	2018	2019	2020	2021
Rest of World	Autocatalyst	49.4	53.9	58.5	59.6	50.1	63.6
	Chemical	3.0	2.9	5.5	3.3	3.4	3.4
	Dental	0.6	0.6	0.6	0.6	0.4	0.5
	Electronics	8.1	7.7	7.0	6.6	5.9	6.3
	Investment	-9.4	-2.4	-10.7	-0.8	-4.4	-0.2
	Jewellery	0.7	0.6	0.6	0.6	0.4	0.5
	Other	1.0	0.5	0.6	0.7	0.5	0.6
	Total	**53.4**	**63.8**	**62.1**	**70.6**	**56.3**	**74.7**
	Grand total	**294.3**	**312.9**	**321.1**	**355.3**	**311.3**	**346.7**

Rhodium supply and demand

Troy ounces

Supply '000 oz[1]	2016	2017	2018	2019	2020	2021
South Africa	615	611	618	607	481	624
Russia[2]	85	78	69	68	58	55
North America	24	24	21	21	21	21
Zimbabwe[3]	44	42	43	40	43	42
Others[3]	5	5	5	7	6	6
Total supply	**773**	**760**	**756**	**743**	**609**	**748**

Demand '000 oz[4]	2016	2017	2018	2019	2020	2021
Autocatalyst[4]	806	834	889	1,031	947	1,051
Chemical	64	75	64	59	55	72
Electronics	4	5	5	6	7	7
Glass	85	103	103	46	5	19
Other	41	20	-13	21	5	8
Total gross demand	**1,000**	**1,037**	**1,048**	**1,163**	**1,019**	**1,157**

Recycling '000 oz[6]	2016	2017	2018	2019	2020	2021
Autocatalyst	-276	-310	-331	-357	-338	-378
Total recycling	**-276**	**-310**	**-331**	**-357**	**-338**	**-378**

Total net demand[7]	**724**	**727**	**717**	**806**	**681**	**779**
Movement in stocks[8]	49	33	39	-63	-72	-31

Rhodium supply and demand

Tonnes

Supply tonnes[1]	2016	2017	2018	2019	2020	2021
South Africa	19.1	19.0	19.2	18.9	14.9	19.4
Russia[2]	2.6	2.4	2.1	2.1	1.8	1.7
North America	0.7	0.7	0.7	0.7	0.7	0.7
Zimbabwe[3]	1.4	1.3	1.3	1.2	1.3	1.3
Others[3]	0.2	0.2	0.2	0.2	0.2	0.2
Total supply	**24.0**	**23.6**	**23.5**	**23.1**	**18.9**	**23.3**

Demand tonnes[4]	2016	2017	2018	2019	2020	2021
Autocatalyst[4]	25.1	25.9	27.7	32.0	29.4	32.7
Chemical	2.0	2.4	2.0	1.9	1.7	2.3
Electronics	0.1	0.2	0.2	0.2	0.2	0.2
Glass	2.6	3.1	3.2	1.5	0.2	0.6
Other	1.3	0.6	-0.4	0.6	0.2	0.3
Total gross demand	**31.1**	**32.2**	**32.7**	**36.2**	**31.7**	**36.1**

Recycling tonnes[6]	2016	2017	2018	2019	2020	2021
Autocatalyst	-8.6	-9.6	-10.3	-11.1	-10.5	-11.8
Total recycling	**-8.6**	**-9.6**	**-10.3**	**-11.1**	**-10.5**	**-11.8**

Total net demand[7]	**22.5**	**22.6**	**22.4**	**25.1**	**21.2**	**24.3**
Movement in stocks[8]	1.5	1.0	1.1	-2.0	-2.3	-1.0

Ruthenium demand

Troy ounces

Demand '000 oz[4]	2016	2017	2018	2019	2020	2021
Chemical	364	361	356	401	366	368
Electronics	436	437	424	401	381	400
Electrochemical	146	139	133	139	132	139
Other	155	173	187	137	101	124
Total gross demand	**1,101**	**1,110**	**1,100**	**1,078**	**980**	**1,031**

Ruthenium demand

Tonnes

Demand tonnes[4]	2016	2017	2018	2019	2020	2021
Chemical	11.3	11.2	11.1	12.5	11.4	11.4
Electronics	13.6	13.6	13.2	12.5	11.8	12.4
Electrochemical	4.6	4.3	4.1	4.3	4.1	4.3
Other	4.8	5.4	5.8	4.3	3.2	3.9
Total gross demand	**34.3**	**34.5**	**34.2**	**33.6**	**30.5**	**32.0**

Iridium demand

Troy ounces

Demand '000 oz[4]	2016	2017	2018	2019	2020	2021
Chemical	23	17	21	22	25	25
Electronics	100	73	52	54	51	58
Electrochemical	57	88	79	89	87	96
Other	83	86	90	93	74	88
Total gross demand	**263**	**264**	**242**	**258**	**237**	**267**

Iridium demand

Tonnes

Demand tonnes[4]	2016	2017	2018	2019	2020	2021
Chemical	0.7	0.5	0.6	0.7	0.8	0.8
Electronics	3.1	2.3	1.6	1.7	1.6	1.8
Electrochemical	1.8	2.7	2.4	2.8	2.7	3.0
Other	2.6	2.7	2.8	2.9	2.3	2.7
Total gross demand	**8.2**	**8.2**	**7.4**	**8.1**	**7.4**	**8.3**

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 **Medical and 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 (i.e. where the original purchaser does not retain control of the metal throughout). For instance, autocatalyst 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.

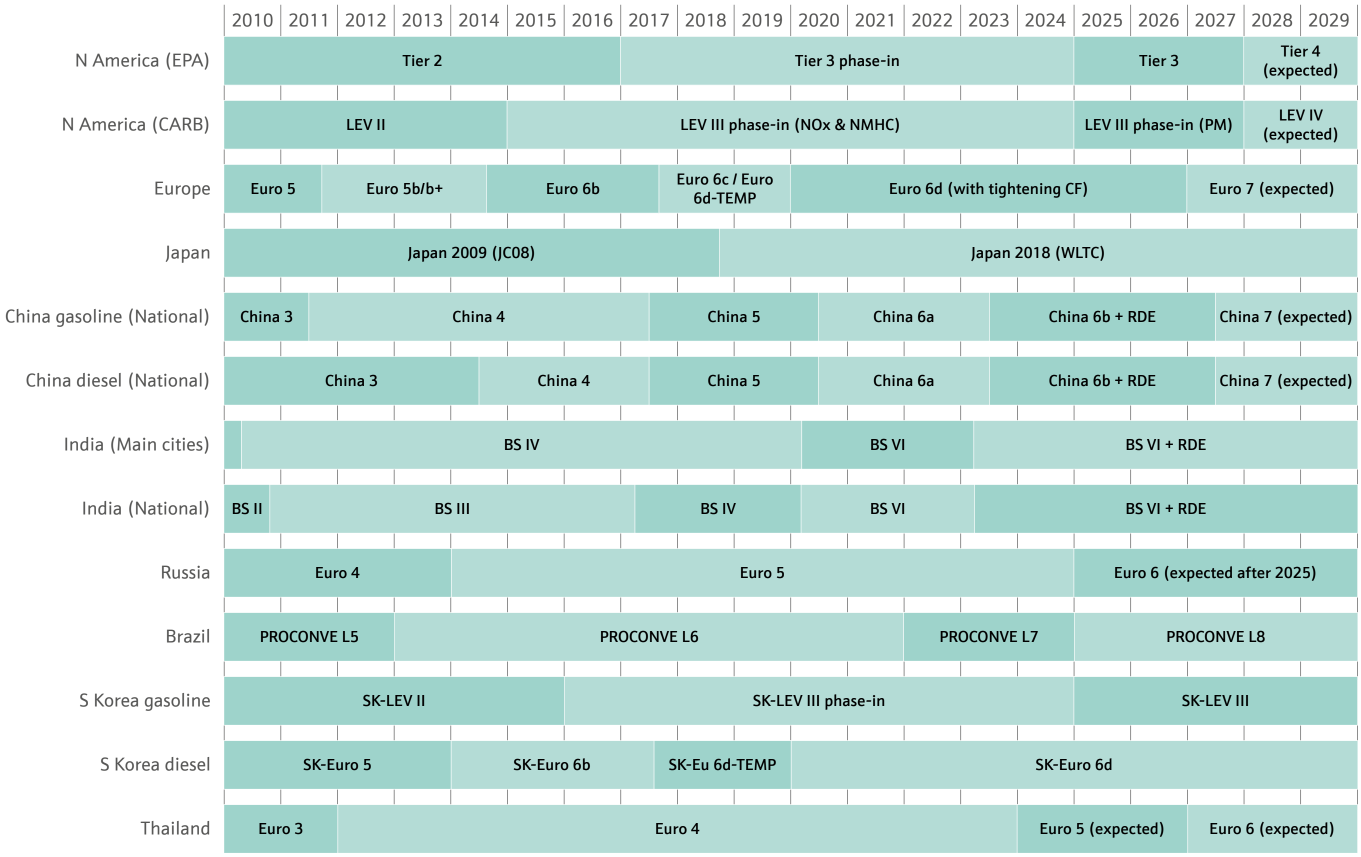
[8]**Movements in stocks** in any given year reflect changes in stocks held by fabricators, dealers, banks and depositories but excluding stocks held by primary refiners and final consumers. A positive figure (sometimes referred to as a 'surplus') reflects an increase in market stocks. A negative value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

Glossary

AEM	Anion exchange membrane
ASC	Ammonia slip catalyst
BEV	Battery electric vehicle
CCM	Catalyst-coated membrane
CCS	Carbon capture and storage
CF	Conformity factor
CO	Carbon monoxide
CO_2	Carbon dioxide
CWAO	Catalytic wet air oxidation
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
EC	European Commission
ELV	End-of-life vehicle
ETF	Exchange traded fund
FCEV	Fuel cell electric vehicle
GDI	Gasoline direct injection
GDL	Gas diffusion layers
GPF	Gasoline particulate filter
HAMR	Heat-assisted magnetic recording
HC	Hydrocarbon
HDD	Heavy duty diesel
HER	Hydrogen evolution reaction
ISC	In-service conformity
LAB	Linear alkyl benzene
LDG	Light duty gasoline
LDD	Light duty diesel
LOHC	Liquid organic hydrogen carrier
LEV	Low emission vehicle
MAMR	Microwave-assisted magnetic recording
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
OER	Oxygen evolution reaction
PDH	Propane dehydrogenation
PEM	Proton exchange membrane
PHEV	Plug-in hybrid vehicle
PM	Particulate matter or soot
PMR	Perpendicular magnetic recording
PN	Particle number
PTA	Purified terephthalic acid
PVC	Polyvinyl chloride
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
4E grade	Combined content of four elements: platinum, palladium, rhodium and gold

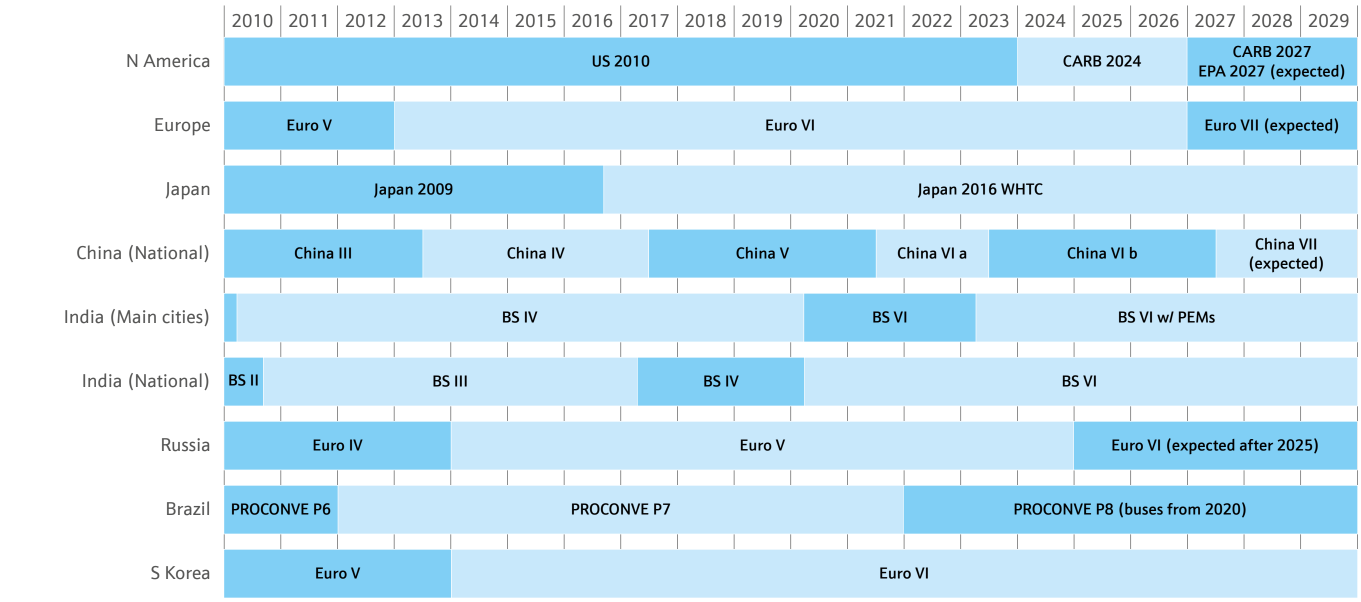
Emissions legislation

Light duty



Dates shown are for New Vehicle Type Approvals for passenger cars

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 is being 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 on-board 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 phase-in of CFs takes 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 is being reduced to 1.43, applying to new type approvals for passenger cars from January 2020, and to all vehicles from January 2022.

The European Commission (EC) intends to review the CFs over time as the measurement accuracy of PEMS equipment improves, with the intention of lowering them to 1.0 by 2023, allowing for no measurement error in the tests.

These transitions inevitably lead to changes in catalyst system designs and loadings.