PLATINUM ESSENTIALS

Palladium: An introduction for platinum and palladium investors

The spectacular increase in the price of palladium since 2016, in particular during 2019, attracted widespread interest from investors, industrial users of palladium and market commentators. It also highlighted the importance of understanding the palladium market when considering an investment in palladium or platinum.

The palladium and platinum markets are interlinked with regard to supply as well as demand. They are co-products or by-products in the majority of their mining locations, and they are substitutes for each other in several industrial applications, most importantly in the most dominant use of palladium; in automotive catalysts.

Determining the value of palladium is a significant challenge. The typical approach to valuing a commodity is using a combination of several indicators including: the marginal cost of production; market balances; historic supply demand trends; visible and available inventories; value-in-use across different uses and the cost of the next best alternative product for those uses. Since almost all palladium production is as a co-product or by-product, the only such data that can be used as an indication of market value or price is the cost of the next best alternative product for a particular use. Palladium's primary use, over 80%, has been historically as a cost-effective alternative to platinum in automotive applications. The platinum price sets the long-term "value" of platinum's next best alternative product in automotive catalysis; palladium.

The current sharply contrasting prices and market balances between the palladium and platinum markets suggests demand rebalancing is inevitable.

Palladium is currently characterised by sustained growing demand exceeding inelastic supply, combined with depleting inventories, driving the price to new highs. The sustained market shortage of palladium is underlined by palladium futures' sustained backwardation since February 2017.

In this edition of ***Platinum Essentials***, we present a detailed analysis of the palladium market to provide a framework for platinum investors and others interested in the palladium market. The high price of palladium relative to platinum is positive for platinum demand as palladium substitution by platinum in automotive catalysis is the likely mechanism that will drive market rebalancing.

This publication does not include analysis of recent developments related to the Covid-19 virus impact on global markets including platinum and palladium.

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What is palladium?

Palladium is a soft silver-white metal discovered in 1803, well after the discovery of similar looking platinum in 1735, but one year before the discovery of sister metal rhodium. Prior to the 1803 discovery, palladium was generally viewed as a platinum-mercury based alloy rather than a distinct metal.

Palladium, much like platinum, is very resistant to oxidation and corrosion and has excellent catalytic properties. In addition, it is soft and ductile when annealed (the process of heating and then slowly cooling a metal to make it malleable). Cold working palladium, as well as alloying with other metals, greatly increases the strength and hardness of the metal.

Palladium metal is produced in several forms to suit its use, with ingots or bars and sponge the most common.

Figure 1: Palladium bar

Source: Valcambi
Uses: storage and investment

Figure 2: Palladium sponge

Source: Heraeus
Uses: industrial including autocatalysts

Palladium sponge is the form of palladium most produced. It is a high purity, coarse powdered or granular form of palladium metal with high porosity. Palladium sponge is the form used for manufacture of many Platinum Group Metal (PGM) based chemicals and catalysts. Producers of palladium have historically met the needs of automotive customers who use palladium sponge for catalyst coating. Consequently, the ratio of palladium being produced as sponge over time is over 80%.

Palladium good delivery bars, usually of 99.95% purity, are the form of palladium that underlies palladium trading on the London Platinum and Palladium Market (LPPM). They also underlie the NYMEX futures market; this is the form used for storage and physical investment purposes. Bars can be converted to sponge (and vice versa) at a cost, typically around $5/oz dependent on the nature of the refinery and the opportunity cost of refining capacity at the time. Whatever the prevailing metal price, owners of one form will often swap what they own for another form at a charge approximating the conversion cost. This conversion cost or charge is often referred to as a sponge-ingot premium.

Palladium is the least dense of the six PGMs, at 12 g/cm^3, compared to 12.1 g/cm^3 for ruthenium, 12.4 g/cm^3 for rhodium, 21.5 g/ cm^3 for platinum, 22.6 g/cm^3 for osmium, and 22.7 g/cm^3 for iridium. It also has the lowest melting point of the PGMs, at 1,555 ºC, compared to 1,768 ºC for platinum, 1,964 ºC for rhodium, 2,334 ºC for ruthenium, 2,443 ºC for Iridium and 3,033 ºC for osmium.

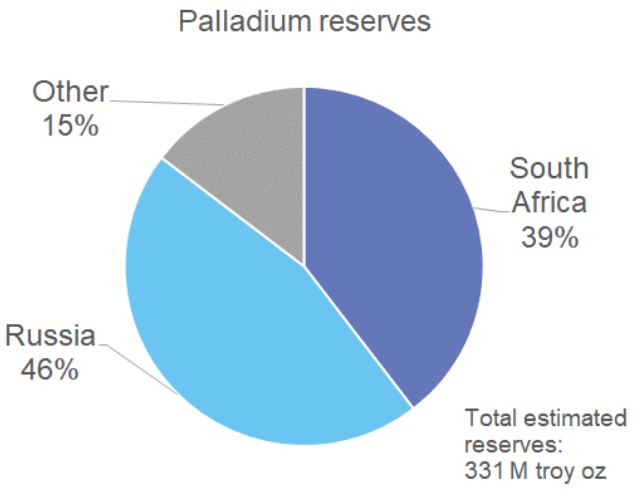
Palladium is the forty-sixth element of the periodic table, and one of the rarest metals on earth. At the end of 2018, known global palladium reserves totalled around 331 moz (c.10,300 tonnes) according to data compiled from company reports, reserve and resource statements, NI 43-101 technical reports and feasibility studies. In contrast, known platinum reserves, compiled on the same basis, were estimated to be around 248 moz (c.7,720 tonnes). This greater preponderance of palladium resource in comparison to platinum largely reflects the higher portion of palladium versus platinum in the large nickel-copper ore bodies in Canada and Russia.

What is the nature of palladium supply?

Where is palladium found?

Palladium is almost exclusively found in ore bodies together with other metals; primarily with base metals such as nickel and copper, and platinum. Southern African deposits have ore that contains all six Platinum Group Metals (PGMs) including platinum, palladium, rhodium, iridium, ruthenium and osmium. Historically, the value of the palladium content in the ore bodies responsible for over 90% of palladium's annual global mine supply has been much lower than the primary metal being mined. Consequently, palladium is produced as a by-product or co-product to these other precious or base metals which, over time, dominate mine economics. This means that less than 10% of global palladium mine production has been driven by the palladium price.

Figure 3: Palladium reserves by country



Source: Company Reports, reserve and resource statements, NI 43-101 technical reports and feasibility studies

The two largest deposits of palladium are contained in the Norilsk–Talnakh nickel-copper deposits in Siberia, and the Bushveld Igneous Complex PGM deposit in South Africa. These two locations account for 46% and 39% respectively of known palladium containing deposits. The balance is largely found in the Great Dyke deposit in Zimbabwe, and in North America in the Sudbury Basin and Lac des Îles nickel-copper deposits in Ontario, and the Stillwater palladium-platinum deposit in Montana.

Russia's Norilsk–Talnakh nickel-copper deposits

Exploitation of PGM-containing copper-nickel deposits first began in 1935 on the Taimyr Peninsula in northern Siberia. The first to be exploited was the Norilsk deposit, initially via horizontal underground mining (known as 'adit' mining) and from the 1940s by two open pit mines, Ugol Creek (now closed), and Medvezhy Ruchey (still operating). In the early 1950s the Zapolyarny underground mine began exploiting the same Norilsk deposit.

In 1960, high grade copper-nickel deposits were discovered at Talnakh, 27 kilometres north of the town of Norilsk. Five mines were subsequently developed, namely the Mayak mine (400 m depth) which began operations in 1965, the Komsomolsky mine in around 1970, and the Oktyabrsky mine in 1975, and the Taimyrsky mine in the 1980s. Lastly, at depths of up to 2,000 metres, the Skalisty mine, which is the deepest of these mines, opened in the late 1990s.

All ore produced at these mines, owned and run by Nornickel Limited, is processed at the Talnakh and Norilsk Concentrators. The Talnakh

Concentrator processes high grade and cupriferous (copper yielding) ores into nickel-pyrrhotite, copper concentrates and metal bearing products. The Norilsk Concentrator processes cupriferous and all disseminated ores into nickel and copper concentrates.

Figure 4: Norilsk –Talnakh nickel-copper operations

Source: Nornickel

Thickened concentrates are transported via a pipeline from the Talnakh and Norilsk Concentrators to the Nadezhda Metallurgical Plant and Copper Plant for smelting. PGM bearing slime/sludge is largely refined at the Krasnoyarsk metallurgical complex, JSC Krastsvetmet (not shown but c.1,600 km South-East of the town of Norilsk).

Norilsk sludge was first refined into platinum and palladium at the Krasnoyarsk metallurgical complex in 1943, with the first casting of palladium ingots occurring 1947. Sponge production capacity was installed towards the end of the 1970s after the introduction in the US of catalytic converters on passenger cars.

South Africa's Bushveld Igneous Complex (Bushveld)

The two types of Bushveld PGM ore bodies, in the western and eastern parts ("limbs") of the Bushveld, are the Merensky and Upper Group2 (UG2) ore bodies. Merensky, which historically provided the majority of PGMs, was shallower, higher grade, and higher revenue compared to UG2 ore. However, with increasing depletion of Merensky ore, more UG2 ore was mined. Platreef ore is found in the northern limb of the Bushveld. It is much shallower than Merensky and UG2 and is mined from several open pit operations. It has a higher palladium and base metal content with different mine economics.

Figure 5: PGM ore types in the Bushveld and characteristics

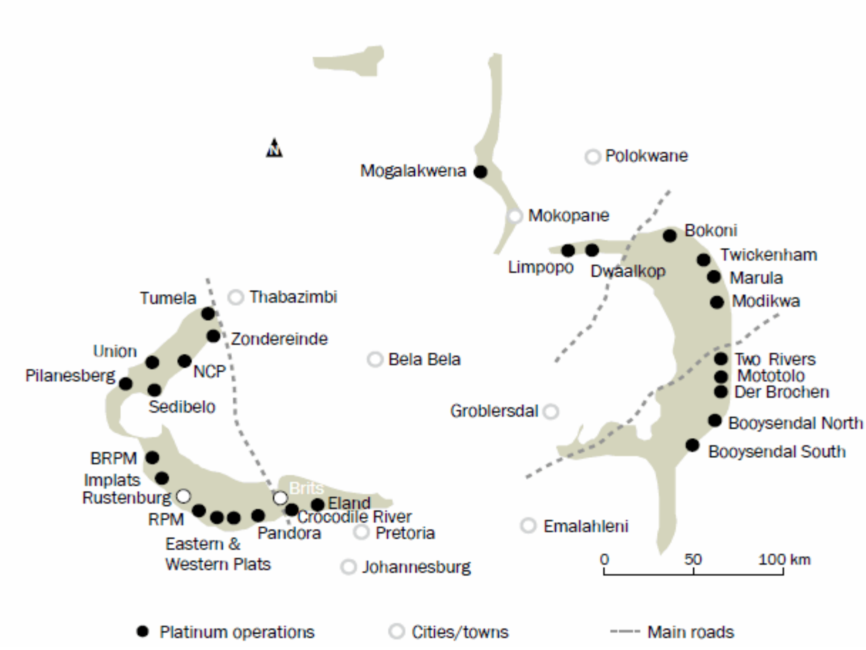
Ore type	Merensky	UG2	Platreef
Location in the Bushveld	Western limb and Eastern limb	Western limb and Eastern limb	Northern limb
Depth (m)	Up to 1.5km deep	Up to 1.7km deep	Currently mined upto 250m deep
PGM - 4E	Platinum (62%), Palladium (29%), Rhodium (4%), Gold (5%)	Platinum (53%), Palladium (36%), Rhodium (10%), Gold (1%)	Platinum (43%), Palladium (36%), Rhodium (10%), Gold (1%)
Grades (grams 4E PGMs / tonne)	c.4-6	c.3-5	c.2-5
Base metal contribution	high (0.2% nickel, 0.1% copper	low (0.1% nickel, 0.01% copper)	higher (0.25% nickel, 0.15% copper)
Processing temperature	high	very high (due to high chrome content)	high

Source: Company Reports, WPI Research

The different ore types in the Bushveld have different geological characteristics (i.e. depth of deposit, concentration of PGMs) and different ratios of metals (i.e. ratio of platinum to palladium, rhodium, and gold; and concentration of base metals such as chrome, nickel and copper).

In the western and eastern parts of the Bushveld, PGM ore is traditionally extracted from underground mines (usually between 700 metres and 1,700 metres deep).In the northern part of the Bushveld, the PGM ore (Platreef) is close enough to the surface for some mining to be open pit.

Figure 6: Bushveld pgm operations

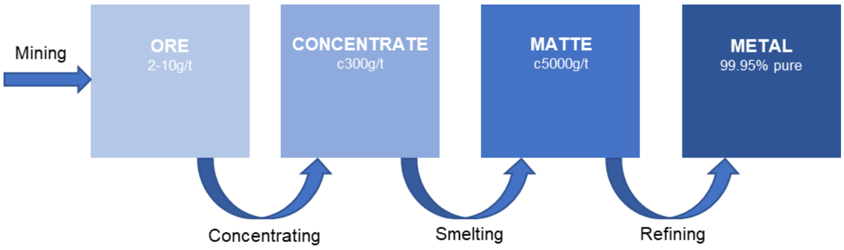


Source: Chamber of Mines (South Africa)

How is palladium mined and refined?

Palladium is extracted, processed and purified through a complex series of physical and chemical processes, namely mining, concentrating, smelting and refining. For PGM orebodies the production process requires the extraction of several metals including palladium as shown and described below.

Figure 7: Overview of PGM production



Source: WPIC Research, concentrations shown are typical for Southern African production

Mining

Mining of PGM ores is mostly conducted via underground mines with less than 20% from open pit mines. In Russia, the depth of the underground mines typically ranges between 400 metres and 2,000 metres, while in South Africa the range is between 700 metres and 1,700 metres. The underground mining method entails vertical or inclined shafts being drilled into or adjacent to the ore body (a process that, for vertical shafts, can take up to ten years), from which horizontal and / or diagonal paths are drilled to gain access to the ore body. At the ore face, horizontal channels are drilled, explosives are placed into the holes and blasted to liberate the ore.

The ore is transported to the surface through a network of underground ore handling machinery.

In open pit mines, the ore is accessed directly from the surface rather than through a shaft. Unlike underground mining, drilling and blasting in an open pit mine is mechanised. Trucks and shovels can be used to move large volumes of ore; which can make open pit mining quicker, cheaper and safer than underground mining.

Concentrating

The mined ore is crushed and milled to liberate the minerals which contain PGMs. Thereafter, the material undergoes a chemical process known as froth flotation. This uses a combination of reagents and the addition of air to create bubbles which the PGM-containing particles attach to. This is done to ensure that the optimal grade and recovery is achieved. In this process, the concentration is increased from 2-6g of 4E (platinum, palladium, rhodium and gold) per tonne of ore, to around 300g of 4E per tonne in concentrate.

Smelting

The concentrate is then dried and processed through a smelter. The concentrate is heated in a furnace to temperatures which can exceed 1,500°C. PGM smelting temperatures are high due to the presence of chrome in the ore. Within the furnace, the matte rises to the surface and the waste product discarded. During this process, the concentration is increased from 300g 4E per tonne to 5000g 4E per tonne.

Refining

The matte is processed through a base metals refinery to extract copper, nickel and other base metals. It is then routed to a precious metals' refinery for extraction and purification of the PGMs. Gold, palladium and platinum are generally the first to be extracted, followed by iridium and rhodium. Precipitation, solvent extraction and ion-exchange technologies are used across producers in the refining process. Refined metals have a purity of over 99.95% and are usually in the form of sponge or granules (for industrial applications) or ingot (for storage / investment).

Palladium supply trends

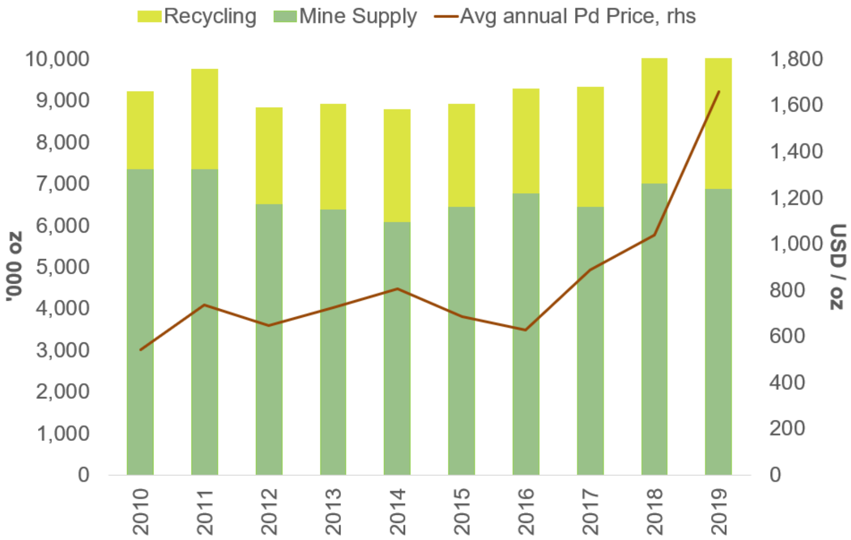
In the decade from 2010, total annual palladium supply, comprising of mined supply, direct sales from Russian Government stock and recycled supply, grew by 12.0%, from 9.2 moz to 10.3 moz in 2019. This represents an average annual growth rate of 2.0% per annum over the decade. Over the same period, the average annual palladium price rose by 206% from $542/oz to $1,657/oz. It is incorrect to conclude that palladium mine supply has grown in response to an increase in the palladium price. This is because palladium is a by-product or co-product to other metals that govern long-term mine economics and volumes, and consequent palladium supply.

Palladium mine supply trends

Palladium supply from mining has declined over the last decade. In 2010, total mined palladium supply was 7.35 moz. By 2019 this had reduced to 6.89 moz, a decline of 6.3% over the decade or an annual rate of decline of 0.1% per annum over the period. This was despite the rise of the palladium price in 2014 and the significant rises in 2017 and 2018/2019, highlighting the by-product nature of palladium mine supply.

Direct sales from Russian Government stocks (in effect delayed mine supply) also reduced over the last decade. Annual state stock sales peaked at 1.49 moz in 2007 then declined to only 100 koz in 2013. Despite the rise in the average annual palladium price in 2014 and the significant rises in 2017, 2018 and 2019 there have been no further similar direct stockpile sales reported.

Figure 8: Total palladium supply vs. price 2010 - 2019



Source: Johnson Matthey, Bloomberg, WPIC Research

For most commodities, such a strong and sustained price rally over a period of 10 years would incentivise investment, exploration and development of new mine capacity. Palladium's dominant by-product nature has prevented this. This absence of supply response to price suggests that palladium should perhaps not be categorised as a commodity, despite global markets treating it as one. Indeed, it is this lack of price driven supply response that heightens concerns over the future availability of palladium and increases the likelihood for substitution of palladium by platinum.

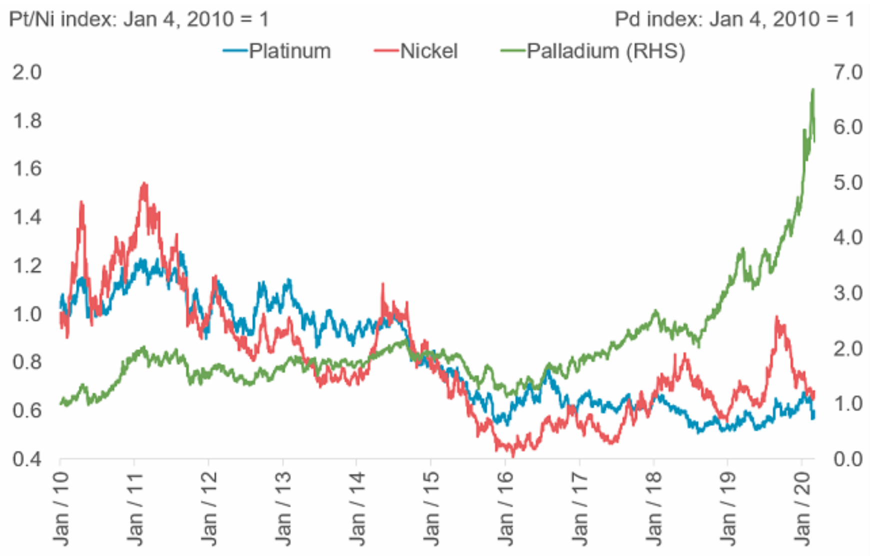
Nornickel, the company that mines the Norilsk and Talnakh deposits has announced that it will be developing supply growth opportunities in the medium to long-term as part of a strategy to maintain a balanced palladium market. Most notable is the company's South Cluster project, where development was approved in March 2019, but will not reach full production until 2027. This project aims to develop the northern part of the Norilsk deposit, and produce 625 koz per annum (19.4 tonnes) of PGMs plus copper and nickel at full capacity. Nornickel also announced it will potentially enter into off-take agreements with Russian Platinum for material from Russian Platinum's Maslovskoe and Chernogoskoe deposits. Production from these two deposits is only likely to start in 2025 at the earliest.

Other factors influencing palladium mine supply

1. Other commodity prices

The by-product nature of palladium mine supply means palladium prices have traditionally only been a minor factor driving mine investment and thus mine supply. With over 90% of palladium mine supply being a by-product to either platinum mining in Southern Africa or nickel-copper mining in Russia and Canada, mine capacity investment decisions that result in a change in palladium supply are dominated by the prevailing platinum and nickel prices as well as their outlook.

Figure 9: Platinum and Nickel prices are almost unchanged from 2009



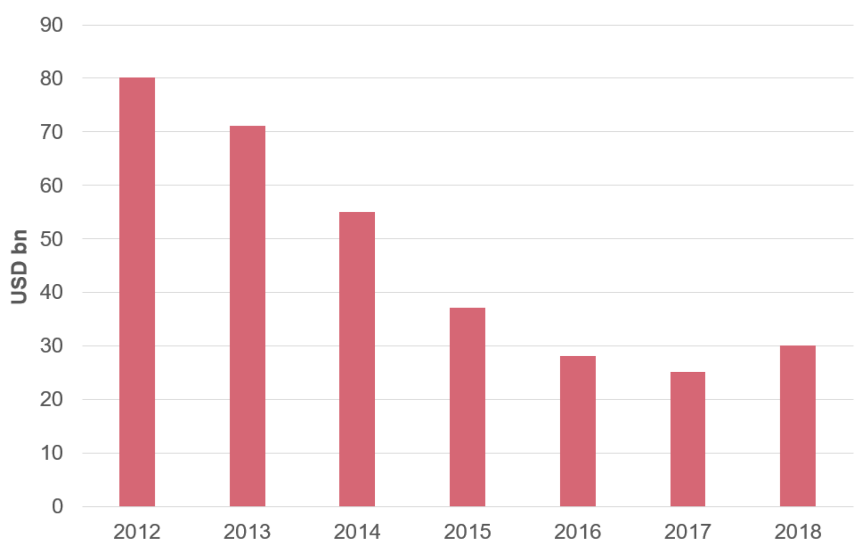
Source: Bloomberg, WPIC Research

In direct contrast to palladium prices, platinum and nickel prices fell over the decade from 2010. Platinum fell by 36% and Nickel by 26% between January 2010 and December 2019. Platinum mine supply, and consequently palladium mine supply, from Southern Africa has fallen steadily since 2006 mainly due to labour costs, some 60% of costs, rising at above inflation levels each year for over 17 years. This is related to the complex socio-political developments in South Africa.

In Russia, the Norilsk-Talnakh deposits have some of the highest nickel grades in the world. Consequently, their output is typically maintained at full capacity with little need to reduce high-cost production due to weak nickel prices as a low grade mine might.

In both Russia and Southern Africa, production growth is unlikely in the short and medium term due to the long lead times for underground mine development and processing capacity for higher production levels. While the prices of Nickel and platinum rose in 2019 this is unlikely to change production levels in the next few years.

Figure 10: Global mine capex trends – investment levels remain well below 2012 peak



Source: Deloitte

Total annual global mining capital investment last peaked in 2012, at close to $80 bn at the same time as peak prices of industrial metals. Annual capital investment fell to $25 bn by 2017, with a modest year-on-year recovery in 2018. Research by PwC, shows that PGM mining capital investment peaked in 2008, also the year in which platinum peaked at $2,250/oz. The PGM mining sector has had a longer period of declining capital investment than the global mining sector. Sustained high platinum prices will typically be required to reverse this trend.

The reason for the lack of palladium supply response to price is further illustrated by palladium's share of miners' revenue over the last decade. In 2010, palladium sales accounted for 9% of Nornickel's total sales revenue while nickel sales, the primary metal, contributed 52%. Unusually in the company's over 80-year history in 2019, high palladium prices increased the palladium contribution to 39% of revenue, with nickel's share reducing to 26%. Over this same period, Nornickel's palladium production (as opposed to sales) rose modestly from 2.86 moz to 2.92 moz in 2019.

The relative portion of revenue per metal has also changed for South African PGM mining companies. In 2010, PGM miners earned c.60% of revenue from platinum sales, and c.10% from palladium. By 2019, this revenue split had shifted to c.30% for platinum and c.40% for palladium. South African mine supply of palladium increased from 2.64 moz in 2010 to 2.65 moz in 2019. This increase was mainly due to changes in ore type that resulted in a higher average palladium content despite platinum production declining by 4.7% over the same period.

2. Geological constraints

In most of the poly-metallic mines in Russia, Canada and Southern Africa, the concentration of PGMs in a single mine tends to be relatively uniform. Consequently, PGM miners cannot generally reformulate the mine plan to focus on areas of higher metal concentration, known as high grading, nor can they extract higher volumes of one particular metal within the ore body. High grading is possible in many other metals dependent on the ore body (e.g. copper in Chile in 2006/07); and while a common approach to material downturn in prices, this is not possible for PGM miners.

3. Operational constraints

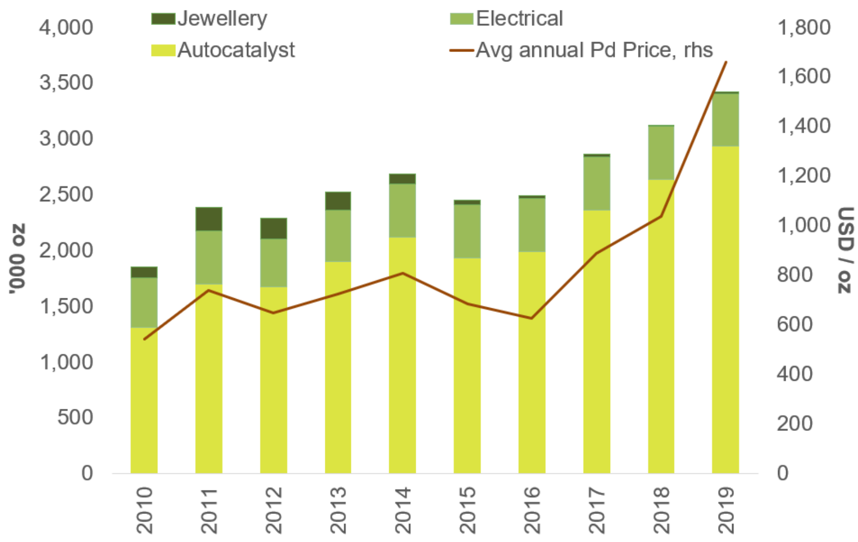
Where palladium is mined as a by-product (over 90%) the mines have been established to meet the capacity needs of the primary metals. The underground mines in Russia, Canada, and most of Southern Africa have very limited flexibility to adjust output to a change in palladium demand.

Palladium recycled supply trends

The primary source of recycled palladium arises from recycled automotive emissions control catalysts when vehicles reach the end of their lives. Most palladium is used in gasoline cars and in 2019 almost 9.7 moz of palladium was used in the manufacture of cars. Recycled palladium from jewellery has become almost insignificant as the palladium jewellery market failed to become established and then declined.

Autocatalyst recycling follows the end-of-life vehicle scrappage profiles in various regions and palladium supply from this source, or secondary palladium supplies, reflects the loadings per used catalyst. This loading reflects the amount of metal necessary, at the time the vehicle was produced, to achieve the emissions level per region over time. It is this loading that governs secondary palladium volumes and consequently the supply is relatively price inelastic. As the catalyst recycle business grew following the introduction of catalysts in the 1970's, recycling became a mature business with largely fixed, yet low, margins. This is because the price paid for scrap catalysts is based on the metal content at market prices.

Figure 11: Recycled palladium supply by source 2010 – 2019



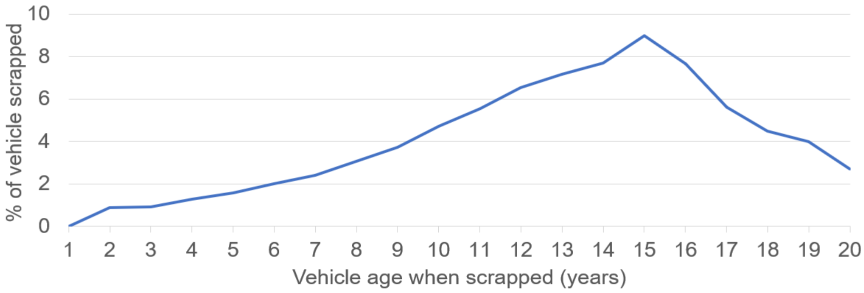
Source: Johnson Matthey, Bloomberg, WPIC Research

This also means that even at very low PGM prices these end-of-life catalysts will always be processed and explains further the inelastic nature of this supply. Consequently, almost all catalysts are removed and recycled. Recycling of palladium from auto catalysts has been suggested as a source of supply to offset the ongoing deficits in the palladium market. In 2019, recycled material from autocatalysis, jewellery and electronic sectors accounted for 34% (2.9 moz) of total palladium supply. This rose from 230 koz (3% of supply) in 2000 when early catalysts were being recycled, but is only 37% up from 2016 volumes, despite a price rally of over 400%

Despite the rising palladium price trend over the last decade, supply from the recycling of auto catalysts has largely followed expected growth based on historic vehicle loadings and scrappage profiles, rather than being price driven.

Palladium usage in auto catalysts began to grow strongly in the mid-1990s, driven largely by the significant price differential between platinum and palladium. Indeed, for much of the early to mid-1990s platinum prices were typically over 3 times higher than palladium. In major auto markets such as the US and Europe, light vehicles have an average life span of around 14 years, with typically 50% of vehicles scrapped after between 9 and 16 years of usage. This results in recycled palladium supply from scrap auto catalysts growing at a far slower rate than the past increase of palladium loadings per car. Meeting tighter emissions limits was the dominant reason for increased PGM usage rather than the number of cars produced (see Figure 16 on page 15). The supply from recycling reflects this increase in loading but the rate of growth is diluted by the very flat scrappage profile. This explains why recycled auto catalyst palladium supply has followed a relatively smooth growth path since the mid-2000s.

Figure 12: Annual US auto scrappage rates



Source: US Department of Transport

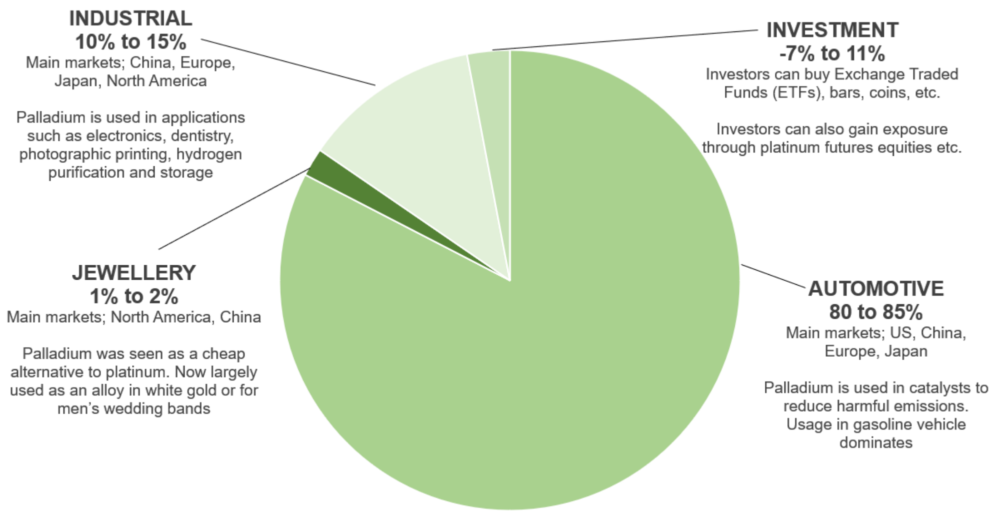
Recycled supply from other end-use sectors, such as jewellery and electronics, represent a relatively small proportion of overall recycled supply. In 2018, jewellery scrap accounted for only 13 koz of recycled palladium supply, down substantially compared to the peak in 2005 of 305 koz. This trend reflects the declining usage of palladium in jewellery in recent years as well as the inefficiency of palladium jewellery recycling as the segment never really matured. In contrast to jewellery, recycled supply from the electronics sector has been relatively stable at c.480 koz per annum over much of the last decade.

What is palladium used for?

Palladium's physical and catalytic properties result in it having a wide range of uses in industrial and consumer applications, and for investment The dominant use of palladium today is in catalytic converters used to control emissions from gasoline and diesel internal combustion engines in passenger and light-duty commercial vehicles. In 2019 84%, or 9,677 koz, of palladium was used in automotive emissions control. Palladium is also used in jewellery, dentistry, watch making, blood sugar test strips, spark plugs, surgical instruments, hydrogen storage, and electrical contacts. In total, these non-automotive uses represent a very small proportion of palladiums total annual consumption. In comparison, platinum has a more balanced end-use exposure, and in 2019 the split in the 4 main segments of demand were: automotive 36%, jewellery 26%, industrial 23% and investment demand 15%. Platinum's wider and more diverse end-uses protects its demand against sudden or unexpected changes in automotive demand far more than is the case for palladium.

The four main demand segments of palladium are shown below with 5-year ranges (2015 to 2019) shown. Negative investment demand is due to net sales from physically backed Exchange Traded Funds (ETFs) over the period.

Figure 13: Palladium end-uses



Source: Johnson Mathey, WPIC Research

Note: Investment demand is negative during periods of dis-investment

Automotive demand

By far, the largest use of palladium is in automotive applications, specifically catalytic converters which accounted for 85% of demand in 2019. Palladium is an excellent catalyst and is instrumental in reducing the emissions of the three main emissions from internal combustion engines: unburned hydrocarbons (HC); carbon monoxide (CO) and oxides of nitrogen. Emissions continue to be subject to increasingly strict regulations in most countries around the World.

Palladium automotive demand is determined by the four main drivers detailed below. The same factors drive automotive demand for platinum, palladium and rhodium (collectively PGMs); and these trends are examined below. Because automotive demand is the dominant use of palladium, its expected future use in automotive applications dominates its future demand profile.

1) **Vehicle numbers** – The more vehicles on the road, the more autocatalysts are needed which increases the total PGMs required or demand. Vehicle production and sales are driven by economic growth, and consumer trends. Shared vehicle use for example (Uber, Lyft) could reduce vehicle ownership in developed markets. The opposite is true in growing markets as vehicle ownership per capita grows.

2) **Vehicle sizes** - Large vehicles typically have large or more powerful combustion engines and require higher amounts of PGMs per vehicle to achieve the regulated emissions levels. Historically, this relationship was broadly linear; i.e. a 1.5 litre vehicle needed about half as much PGM content as a 3 litre one did. So, a consumer trend for larger vehicles had a positive impact on PGM demand (and vice versa). This remains largely true although higher performance vehicles of similar engine size can have far higher loadings and fear of missing regulatory compliance has resulted in over engineering. This is where more metal is used to ensure emissions regulation compliance under all conditions and mainly due to fears after the dieselgate scandal in 2015 (cheating in the US) and introduction of more stringent on-road test that replaced in-laboratory ones.

3) **Powertrain trends** - Different powertrains (e.g. diesel, gasoline hybrid, battery electric and fuel cell electric) have significantly different loadings of palladium, platinum and rhodium. Only Battery Electric Vehicles do not contain any PGMs. Historically, gasoline vehicles have the highest palladium loadings of internal combustion engine vehicles. A higher share of gasoline vehicles on the road would increase palladium demand (and vice versa).

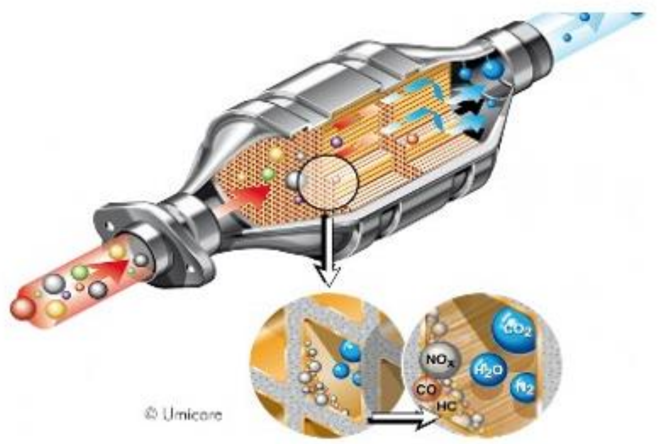
Figure 14: Vehicle powertrain breakdown

	Acronym	Description	PGM content
Diesel conventional		Conventional vehicle with a diesel engine	5 - 10g of total PGM content; high platinum, low palladium
Gasoline conventional		Conventional vehicle with a gasoline engine	2 - 5g of total PGM content; typically in a ratio of 1:8:2 of platinum to palladium to rhodium
Diesel mild hybrid	48V	Conventional diesel car with a small 48 volt battery and electric motor to help with fuel efficiency. Cannot run on battery power alone	Likely to contain similar PGM loadings to a conventional diesel vehicle - same combustion engine size
Gasoline mild hybrid	48V	Conventional gasoline car with a small 48 volt battery and electric motor to help with fuel efficiency. Cannot run on battery power alone	Likely to contain similar PGM loadings to a conventional gasoline vehicle - same combustion engine size
Diesel hybrid	HEV	Contains both a diesel combustion engine and a battery, can run on either battery or combustion engine or both in parallel, but smaller battery than a PHEV, so the battery-only range is shorter	Likely contains similar PGM loadings to a conventional diesel vehicle. Smaller combustion engine, variable technology
Gasoline hybrid	HEV	Contains both a gasoline combustion engine and a battery, can run on either battery or combustion engine or both in parallel, but smaller battery than a PHEV, so the battery-only range is shorter	Likely contains similar PGM loadings to a conventional gasoline vehicle. Smaller combustion engine but runs intermittently (at lower average temperature, so higher PGMs relative to combustion engine size)
Diesel plug-in hybrid	PHEV	Like a HEV (can run on battery, diesel combustion engine or both), can run solely on battery power for at least 10 miles, battery can be plugged in to be recharged	Likely contains similar PGM loadings to a conventional diesel vehicle. Smaller combustion engine, variable technology
Gasoline plug-in hybrid	PHEV	Like a HEV (can run on battery, gasoline combustion engine or both), can run solely on battery power for at least 10 miles, battery can be plugged in to be recharged	Likely contains similar PGM loadings to a conventional gasoline vehicle. Smaller combustion engine but runs intermittently (at lower average temperature, so higher PGMs relative to combustion engine size)
Battery Electric Vehicle	BEV	Contains a battery (minimum 30 minute recharge time) which stores electricity. Always runs on battery power alone	Contains no PGMs
Fuel Cell Electric Vehicle	FCEV	Contains a fuel cell which uses hydrogen to generate electricity which is the only powertrain for the vehicle (5 mins to refuel H_2)	Currently contain 30-80g of platinum per vehicle; DoE target of 12.5g of platinum

Source: WPIC Research

4) **Technology changes** – The dominant driver of increased palladium automotive use has been to meet tightening emissions legislation. Countries and regions have applied progressively more stringent emission limits on HC, CO, CO_2, NOx, NH_3 and particulates emitted from vehicles. Regulation is currently most stringent in developed countries with developing countries following a similar trend. All else being equal, to achieve lower emissions from a (non-battery) vehicle a higher volume of PGM content is needed. Technological improvements can go some way to offset this; autocatalyst manufacturers have significantly improved the efficiency of catalysts in meeting emissions regulations and this has allowed them to 'thrift' PGM usage per catalyst. This has been achieved by, for example, advances in wash-coat formulations, and the tailoring of catalysts to individual vehicle models, as well as the impact of reduced sulphur content in fuels.

Figure 15: A typical autocatalyst

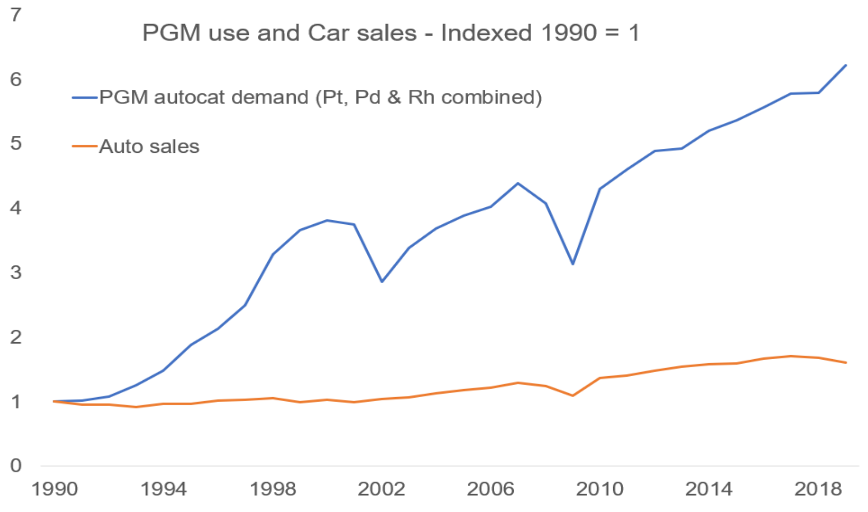


Source: Umicore

Automotive demand trends

Historically, tightening emissions legislation more than actual changes in volumes of auto sales has driven palladium and PGM automotive demand growth. Between 1990 and 2019 annual car sales rose from c.54 m to c.92 m but PGM use in autocatalysis rose from 2.2 moz per annum to 13.8 moz per annum.

Figure 16: Total PGM autocatalyst demand growth is well above global auto sales growth over 28 years (6.2 times v 1.6 times)

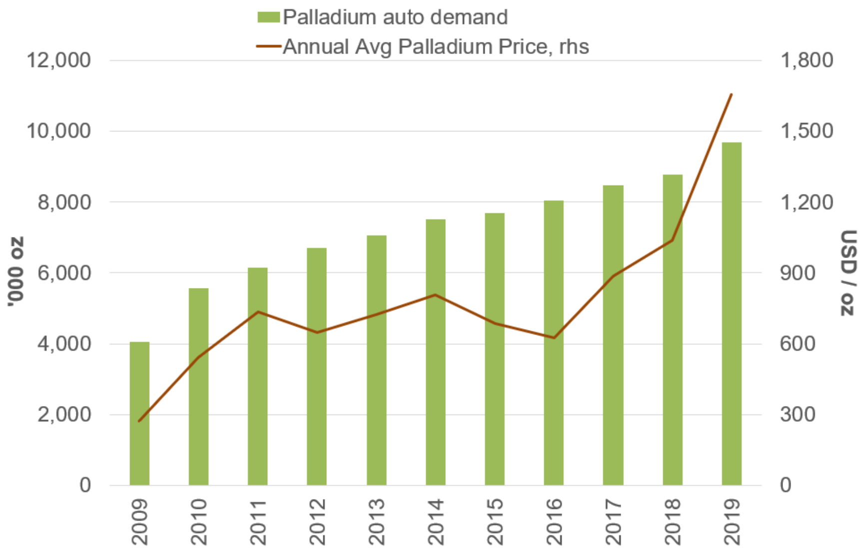


Source: OICA, LMC Automotive, Johnson Matthey. Indexed chart with 1990 = 1

All major auto markets have introduced tighter vehicle emissions limits over time and significantly tighter light duty vehicle emissions legislation in recent years. The introduction that has had the biggest impact on palladium is the China 6 standards which started being implemented in major cities in China from mid-2019.

Annual growth in gross palladium demand for use in automotive catalysts has averaged 300 koz per year between 1990 and 2019, rising from 315 koz to 9.7 moz. Much of this increase has occurred in the last decade, with average annual growth of c.410 koz between 2010 and 2019. In 2019 alone, demand rose by 10% (895 koz) despite a c.4% fall in global light vehicle sales, with the initial voluntary implementation of China 6 standards during 2019 having a significant demand impact.

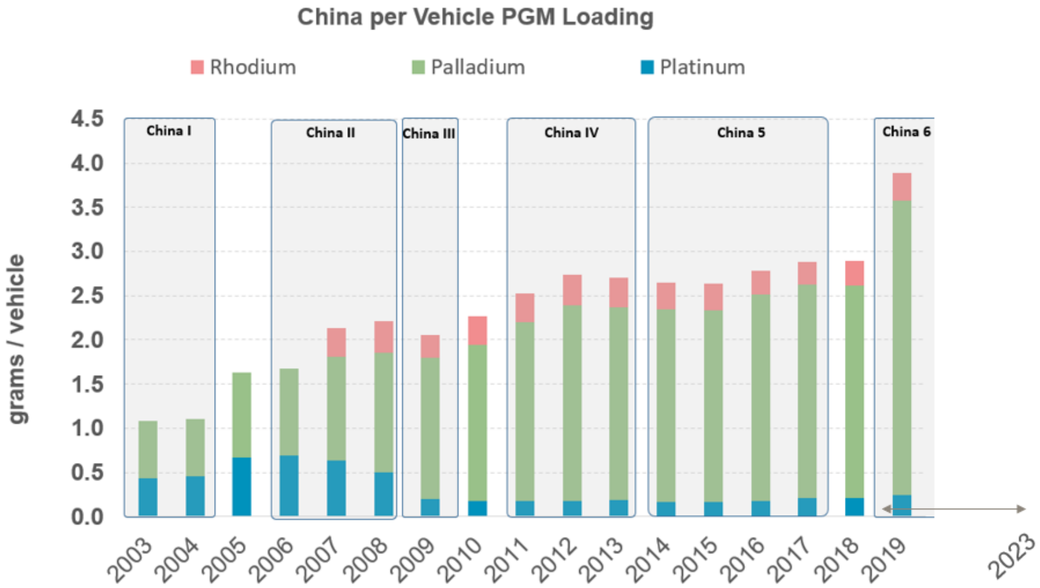
Figure 17: Auto catalyst demand for palladium 2009 – 2019



Source: Johnson Matthey, Bloomberg, WPIC Research

China has a history of voluntary early introduction of tighter emissions standards as shown below. The impact of China 6 emissions limits, now tighter than limits in the US and EU, are show by the step change in 2019.

Figure 18: China 6 implementation: step change in loadings



Source: Johnson Matthey, WPIC Research

Figure 19: Key light duty auto emissions legislation recently implemented

Region/Country	Emission	Measurement	Event	Consequences
EU	NOx	Per car	60mg / km /(gasoline) car - moving from laboratory to on-road testing 2017 / 2019	RDE on-road emissions testing: Higher loadings (+175 koz pd in 2019)
	CO_2	Fleet	95g / km / car fleet average 2020 / 2021	Annual fine of between €14.7 bn & €34 bn. Incentive to lower CO_2 via Hybrid and BEV
China	NOx, CO, HC	Per car	China 6 2020/2021 Early addoption in some cites in 2019	+ 40% Pd loadings +50% - 100 % Rh loadings Driving higher Pd and Rh prices. Incentive for substitution
North America	NOx, CO, HC	Fleet	Tier 3 / LEV III	Steady increase in palladium loadings

Source: WPIC Research

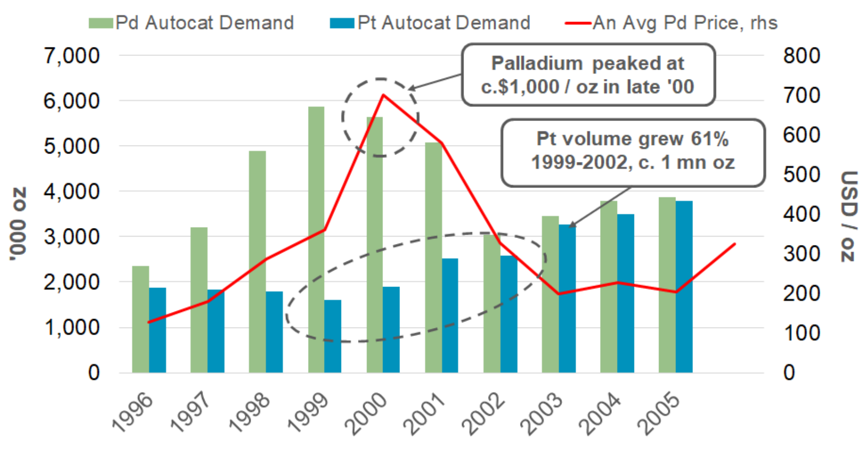
The combination of rapid auto sector driven palladium demand growth, combined with limited supply growth outlined above, suggests a re-balancing between platinum and palladium markets is highly likely.

Substitution of platinum for palladium in autocatalysts

Substitution of platinum for palladium in response to price misalignment is not a new phenomenon. The US first introduced emissions standards in 1974 which required the use of auto catalysts. This led to the use of both platinum and palladium in internal combustion engine vehicle emissions control. By the late 1990s, palladium demand consistently outstripped supply. The annual shortfall was supplied from Russian state stocks. These stocks had built up as palladium was seen as having little value or application during the early years of production from the Russian Nickel-copper mines. Much of this stock had built up almost accidentally and had been transferred to state stocks. In 2000, an administrative failure in Russia coincided with a processing failure in South Africa that resulted in palladium increasing from around $200/oz to over $1,000/oz within a few months.

The consequence of this short-term price spike to levels well above the price of platinum was substitution of palladium by platinum with a significant demand increase for less expensive platinum. As illustrated in the figure below, gross palladium usage in auto catalysts contracted by 48% between 1999 and 2002. Palladium prices quickly reduced in line with reduced demand to $260/oz by January 2003. Platinum auto catalyst usage rose by 60% over this same period.

Figure 20: Palladium and Platinum auto demand vs Price, 1996 – 2005

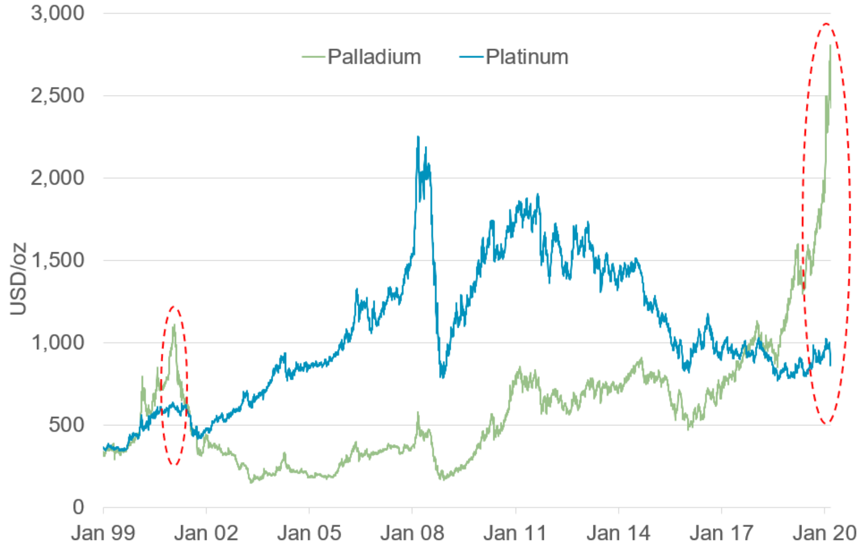


Source: Johnson Matthey, Bloomberg, WPIC Research

Until the early 2000s, twice as much palladium than platinum by mass was required to achieve similar levels of emissions reduction in gasoline engines. However, technological innovation, namely the improved stability of PGM molecules in the coating on catalysts and the significant reduction in sulphur content of gasoline, reduced this substitution ratio to the point where similar amounts of palladium or platinum can achieve the same level of emissions control. This 1:1 ratio was confirmed by Johnson Matthey in an academic paper publishing in 2013 (A Study of Platinum Group Metals in Three-Way Autocatalysts – Platinum Metals Rev., 2013).

Palladium is not solely used in gasoline autocatalysts. Around 700 koz of palladium per annum is used in diesel autocatalyst applications in key markets (Western Europe, North America and China). Platinum substituting palladium in diesel catalysis, the natural and long-standing home of platinum, has much lower emissions control risk than substitution in gasoline catalysis and should have a significantly shorter substitution implementation lead time. In May 2019, Johnson Matthey said it expected that platinum use in diesel autocatalysts to replace palladium could grow by tens of thousands of ounces in the short to medium term.

Figure 21: Palladium premium to platinum averaged $675/oz in 2019, and averaged $1,354/oz Jan-Feb 2020



Source: Bloomberg, WPIC Research

The economic theory of substitution suggests that manufacturers will substitute a cheaper input for a more expensive one, up to a point where it is no longer economically logical to do so. That point can be price/cost driven, as rising demand for the initially cheaper alternative drives up prices of that input or related to the impact of substitution on the performance of the output product. A substitute good is also a good with a positive cross elasticity of demand i.e., an increase in the price of one good will (all things being equal) increase demand for its substitute. Theoretically, if the prices of the goods differed, there would be reduced demand for the more expensive good.

In the case of the palladium price above the platinum price, theory suggests that where viable, more platinum should be used in automotive catalysts instead of palladium. The 1:1 substitution ratio further suggests that platinum and palladium can be viewed as almost perfect substitutes.

At the current palladium premium to platinum, and with a 1:1 substitution ratio between the two metals, there is a very strong economic argument for auto producers to substitute more platinum on future models. Palladium's current elevated price is an availability signal that also argues for PGM diversification to maintain supply chain security. Historically, sustained relative premiums (e.g., Pd over Pt) of at least 18 months or more were needed to see significant auto catalyst loadings change among the 3 PGMs (i.e., the ratios used of Pt, Pd and Rh). With no short to medium term palladium supply growth likely, the only adjustment can be via demand. The concerns of unavailability of palladium were known by OEMs and fabricators some years ago, which suggests substitution has happened on models recently launched or about to be launched. In principle, the substitutability of platinum and palladium suggests that their diverging prices should converge over the medium-term (3-5 years) as demand substitution adjusts the relative demand-supply balances.

The platinum versus palladium price chart (Figure 21) above shows palladium's overshoot in 2000 and currently as well as the change in price to reflect the change in substitution ratio from 2:1 to 1:1 between 2014 and 2017.

Nornickel has recently announced that it would sell palladium from its palladium fund to stabilise the market and prevent further rapid increases in the palladium price. The fund was established in 2016 with between 1 moz and 1.5 moz to be used as a tool to improve Nornickel's industrial customers' security of supply. This appears unusual for a mining company to want to reduce rather than increase the price of a metal it mines and sells, particularly a by-product. This is consistent with announcements that it will increase capacity to produce more palladium in response to price increases. One rationale that might support these actions is to avoid the substitution of palladium by platinum as this would potentially reduce future demand for palladium. The current size of the Nornickel fund is c.430 - 630 koz, a volume which is insignificant compared to the 2020 palladium deficit estimates of up to 1.9 moz.

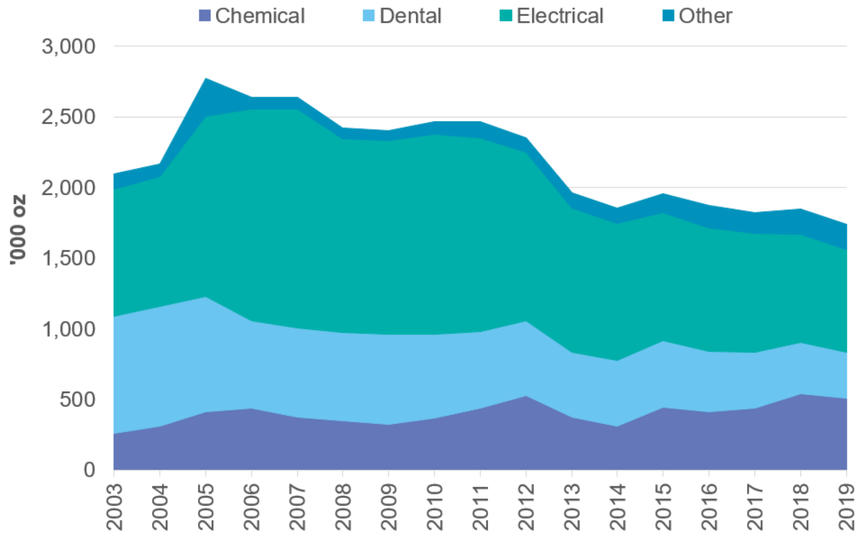
Industrial demand

Given its physical and catalytic properties, palladium has a broad variety of applications in the industrial sector (separate from automotive demand). In the 2000's industrial end-uses typically accounted for one-third of annual palladium demand. However, the rapid rise in autocatalyst demand for palladium together with its price related substitution to platinum, has resulted in palladium's industrial demand share falling to 16% in 2019. Over the last decade, industrial demand has declined from 2.4 moz in 2009, to 1.8 moz in 2019, largely as a result of substitution by nickel in electronics and gold in dentistry during the 2000 palladium price spike. The lost electronics demand never returned but use of palladium in dentistry returned as its price fell below that of gold. Total industrial end usage has been relatively stable in volume terms since 2014, at between 1.8 -1.9 moz in most subsequent years.

Non-automotive industrial demand is dominated by electronic, dental and chemical applications, but also has other uses including photographic printing, and even in the manufacture of high-end woodwind orchestral flutes.

Electronics - In the electronics industry, palladium is used for electrical contacts, in multi-layer ceramic capacitors (MLCCs) and for soldering materials. It is used in almost every type of electronic device. MLCCs store energy in electronic devices such as broadcasting equipment, mobile telephones, computers, electronic lighting and high voltage circuits. MLCCs represented the most important electronic use of palladium during the 1990's but the price spike in the run up to 2000 resulted in permanent loss of demand in this segment, as other metals (including base metals for electrode use) were substituted in to replace palladium. Indeed, electronics sector palladium usage peaked in 1997 at 2.55 moz, and declined to 795 koz by 2019.

Figure 22: Industrial demand for palladium (excluding-automotive)



Source: Johnson Matthey, WPIC Research

Dentistry - In dental amalgams small amounts of palladium were traditionally used to help fight against corrosion and increase the lustre of the filling, and also used in dental bridges and crowns. This is typically done at less than 0.5% palladium; with mercury, silver, tin and copper commonly making up the rest. Crowns now represent the most common application, where the palladium-based alloy is used as a base onto which a crown is bonded to build up an artificial tooth. Using palladium in dental alloys provides strength, stiffness and durability and malleability.

Over the last two decades, palladium usage in dentistry applications has been in sharp decline, due to competition from cosmetically more appealing alternatives particularly resin composites, ceramics and porcelains, combined with impact of rising palladium prices. Volumes of palladium used in dentistry peaked in 1997 at 1.35 moz, falling to 328 koz in 2019. The current high price of palladium is likely to see a further loss of demand from the dental sector.

Chemical applications – Palladium, when in sponge/powder form, and when heated, has the ability to absorb significant volumes of hydrogen. It is used to purify, and safely store, the highly volatile element hydrogen. This is useful for fuel cells; hydrogen is a highly efficient fuel source and finding ways to store large amounts safely could help power technologies of the future. Nanoparticles of palladium have been found to be even more efficient in absorbing hydrogen, and research is ongoing into how this can be used at scale.

Transverse flutes – Professional, concert-grade flutes, are often made of precious metals. Although sterling silver is a common material, palladium is sometimes used to produce the tubes inside these flutes.

Photographic printing – Similar to silver, palladium salts are often used as a light sensitive material used in printing. Palladium salts produce a unique tonal quality that was used extensively in the late 19th century, and today are used in artistic appreciation of the style.

Jewellery demand

Palladium has been used in jewellery since the 1930s, it is a relatively new metal in terms of discovery. It was initially used as an alternative alloy metal added to 'yellow' gold in the making of white gold. The addition of a small amount of white metal (like nickel or platinum) alloys turned gold white.

Lower priced palladium replaced platinum and high-quality white gold contains up to 13.5% palladium. Palladium only gained its own hallmark in July 2009, which also marked the start of the legal requirement, in 2010 in the West for any jewellery containing more than 1 gram of palladium metal to be hallmarked. The hallmark bears the head of Pallas Athena to distinguish it from platinum. In jewellery uses, Palladium has a similar appearance to platinum, with steely white colouring, but it is around 40% lighter (for the same volume) than Platinum due to its lower density.

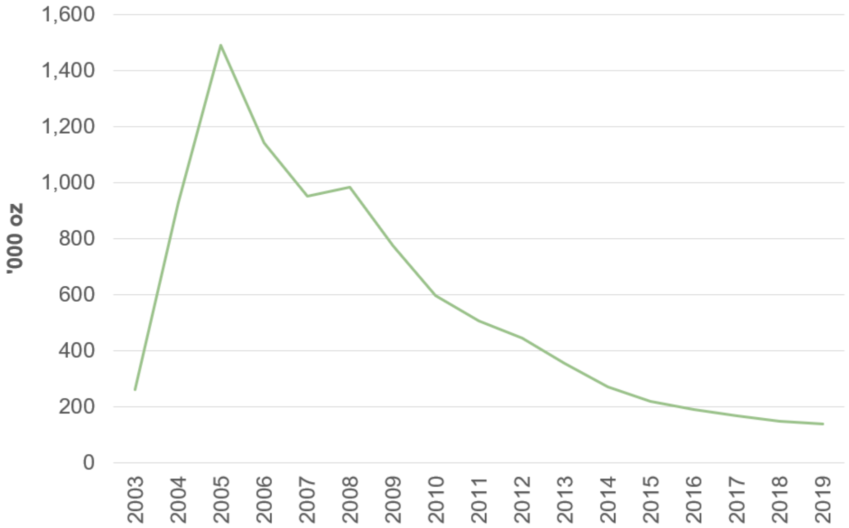
A major impediment to the use of palladium as a main jewellery metal has been that it has never received the same level of industry backing or promotion for jewellery usage as has been the case for gold and platinum. Despite promotional work by the Palladium Alliance International (PAI) from 2006, and the International Palladium Board from 2011, palladium did not and still does not receive the same perceived value recognition amongst the jewellery trade and consumers as gold and platinum. This lack of promotion and market recognition has been a key factor central to the fall off in palladium jewellery usage since the mid-2000s.

The form of palladium used for jewellery is usually at 95% fineness due to palladium's inherent softness. Like gold and platinum, palladium is typically alloyed with other metals such as silver, copper and zinc, to make it workable in jewellery. Palladium is still commonly used today as a constituent metal in the fabrication of white gold alloys for jewellery, while its use as a 'primary' jewellery metal like gold and platinum has become mainly limited to men's wedding bands. In addition, palladium's light weight and strength when alloyed still see it used in watch casings.

Jewellery demand trends

Palladium jewellery demand peaked in terms of volume in 2005 at 1.49 moz and accounted for 18% of total palladium consumption that year. Since 2005, the trend in palladium jewellery consumption has followed an unbroken downtrend, primarily due to the lack of promotional funding.

Figure 23: Palladium jewellery demand, 2003 – 2019



Source: Johnson Matthey, WPIC Research

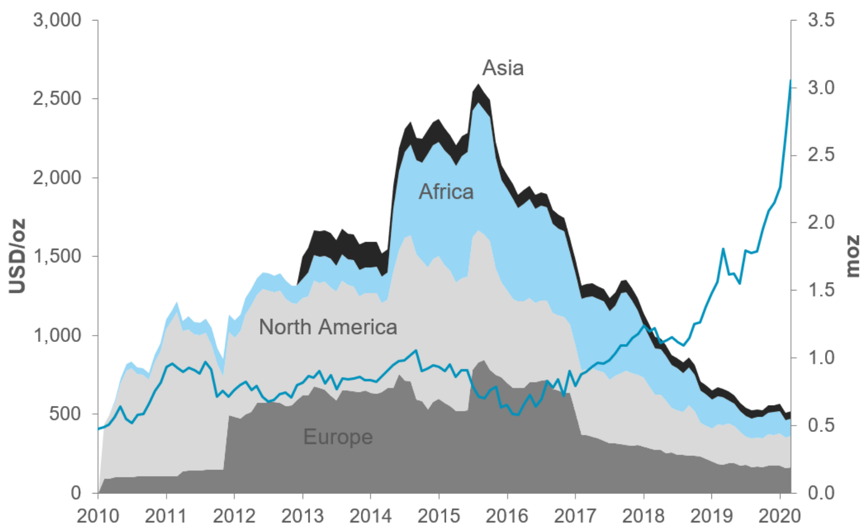
By 2019, palladium jewellery demand accounted for only 1.4% (156 koz) of palladium demand. Indeed, the sharp downturn occurred despite the formation of the Palladium Alliance International (PAI) in March 2006 which was tasked with establishing Palladium as a luxurious, precious and distinctive metal.

Investment demand

Physical palladium investment demand is included in many supply-demand analyses in the form of net purchases or sales of palladium bars and coins, and Exchange Traded Funds (ETFs). ETFs are a financial asset backed by physical palladium; i.e. a new share in a palladium ETF requires the issuer, assisted by the market maker, to buy palladium in the spot or over the counter (OTC) market to be delivered into a vault. Investors invest in palladium for varying reasons ranging from palladium's fundamentals or the macro fundamentals impacting palladium. This investment is complicated, but is more volatile, due to the high portion of palladium produced as a by-product and its consequent lack of supply response to price.

Palladium ETFs were first launched in 2007, with assets under management rising rapidly from early 2010 until July 2015, when volumes under management reached 3.03 moz. However, since this peak, volumes of palladium in ETFs have fallen by almost 80%, with c.660 koz held at the end of 2019. ETFs have divested 2.36 moz of palladium since the July 2015 peak, presumably due to profit-taking induced by the rapid more-than-doubling price. This trend and the resultant sale of metal helped counter sustained annual market deficits.

Figure 24: ETF holdings (moz, rhs) and price (USD / oz)



Source: Bloomberg, WPIC Research

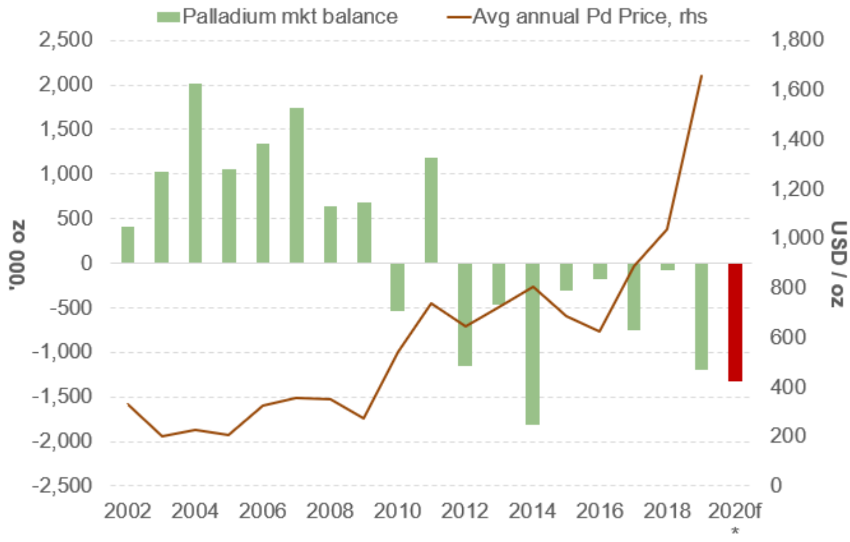
The exiting of palladium ETF positioning looks to be counter-intuitive from an investment point of view, as normally an investor would want to hold or increase a position where the underlying asset is rising in value. We believe this ETF disinvestment trend reflects the profit taking by investors who had typically doubled the value of their holding in a commodity that had very few features of all other commodities. The reason current ETF positioning has not increased with the rapid rise in the price of palladium is that it is difficult for investors to take positions in palladium with its price so far removed from the price of its 1:1 substitute metal, platinum.

Palladium vs. platinum market balances

Palladium

2019 represented the eighth consecutive year of a palladium market deficit. Cumulative deficits over this 8-year period amount to 5.7 moz, a result of the lack of mine supply growth, combined with surging auto sector demand. Consensus expectations point to a deeper deficit in 2020 than that in 2019, particularly with the continued implementation of China 6 emissions regulations across China, with 6a becoming nationally mandatory from July onwards. Many auto-manufacturers have implemented 6b immediately to reduce implementation costs of doing them separately.

Figure 25: Palladium market balance: 8 consecutive years of deficits up to 2019



*Source: Johnson Matthey, WPIC Research *Average of 2 producers and Johnson Matthey*

Annual palladium deficits have been met by metal supplied from visible and non-visible vaulted stocks. Significant stocks of palladium became visible during the 1990s and 2000s stemming from Russian government sales of metal inventory. Much of these metal sales from Russia accumulated in vaults in Switzerland and the UK. Johnson Matthey estimated that around 11.6 moz of palladium has been withdrawn from Swiss and UK vaults since 2007. However, it is believed that some of this metal was simply being moved to other storage locations rather than being sold into the market for consumption purposes.

In contrast to this reduction in above ground stocks, palladium ETF stocks rose rapidly from 2010 to their peak in July 2015. Indeed, total ETF volumes peaked at 3.03 moz, up by 3.02 moz from the start of 2010. The ETF increase would suggest a transfer of metal out of non-visible vaulted holdings. Since the 2015 peak, volumes held by ETFs have fallen by 2.36 moz and stood at c.660 koz at the end of 2019. We estimate the ETF divestment covered around 60% of the market deficits experienced since 2014.

Another important source of metal that met successive deficits has been the Nornickel Global Palladium Fund. The fund was first mooted in 2014, to be used as a tool to improve Nornickel's industrial customers' security of supply and was launched in 2016 with between 1 moz and 1.5 moz. Volumes were accumulated from the company's own production and acquired from unpublished stocks. Volumes have subsequently been drawn to ease market tightness. Levels were down to 550 koz by end of 2017/early 2018, according to Nornickel CFO Sergey Malyshev, and were reduced further to c.130 koz by the end of 2018. The company announced its plans to purchase between 300-500 koz of during 2019 to replenish the fund. In early 2020, Norilsk guaranteed to sell 3 tonnes (97 koz) of palladium ingots during 2020 from the fund in order to ease current short-term market tightness. This suggests there will be modest volumes backing the Global Palladium Fund by the end of this year, of between 330 – 530 koz, in the absence of further purchases of non-visible vault stocks. It appears that purchases of palladium by Nornickel for their fund are competing with all other demand for palladium. This maybe counter-productive.

Figure 26: Palladium supply and demand table (koz)

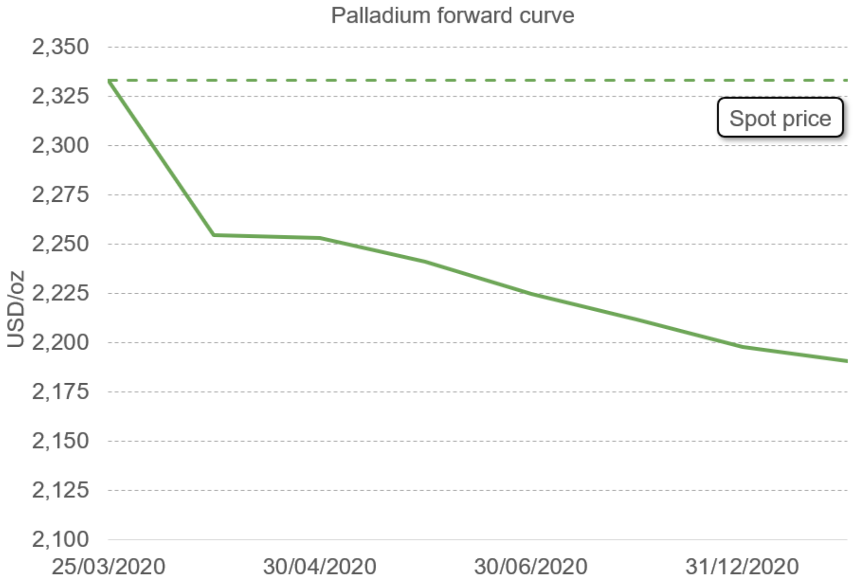
	2015	2016	2017	2018	2019
SUPPLY					
South Africa	2,683	2,570	2,547	2,543	2,648
Russia	2,434	2,781	2,452	2,976	2,802
North America	872	911	935	959	943
Zimbabwe	320	396	386	393	378
Other	144	129	131	135	123
Total Mining Supply	**6,453**	**6,787**	**6,451**	**7,006**	**6,894**
Recycling					
Autocatalyst	1,930	1,986	2,361	2,634	2,932
Electrical	475	481	479	475	471
Jewellery	46	21	21	12	13
Total Recycling	**2,451**	**2,488**	**2,861**	**3,121**	**3,416**
Total Supply	**8,904**	**9,275**	**9,312**	**10,127**	**10,310**
DEMAND					
Autocatalyst	**7,693**	**8,041**	**8,462**	**8,782**	**9,677**
Jewellery	**220**	**189**	**167**	**148**	**140**
Industrial	**1,954**	**1,871**	**1,820**	**1,848**	**1,742**
Chemical	449	413	442	545	511
Dental	468	429	391	358	323
Electrical	903	872	843	768	728
Other	134	157	144	177	180
Investment	**-659**	**-646**	**-386**	**-574**	**-57**
Total Demand	**9,208**	**9,455**	**10,063**	**10,204**	**11,502**
Balance	**-304**	**-180**	**-751**	**-77**	**-1,192**

Source: Johnson Matthey, WPIC Research

The extent of tightness in availability of palladium units, whether sponge or ingot, is clearly shown by the palladium forward price structure. Currently, the palladium forward curve is fully backwardated, a situation where prices further into the future are lower than the nearby prices, as shown below.

Palladium’s fully backwardated curve structure has now been in place for over 35 months, with the market moving from a contango structure (where prices further into the future are above the nearby prices) to full backwardation between February and April 2017. A backwardated market structure stretching over a 35-month period is not a normal occurrence in any metals market, precious or industrial. In a normally functioning and ‘fundamentally’ balanced market, the forward curve would be upward sloping, a contango structure, with the slope effectively reflecting the cost of financing and storage. Backwardation usually reflects unavailability of the underlying commodity until the market balances. The sustained state emphasises that both ingots and sponge are not available.

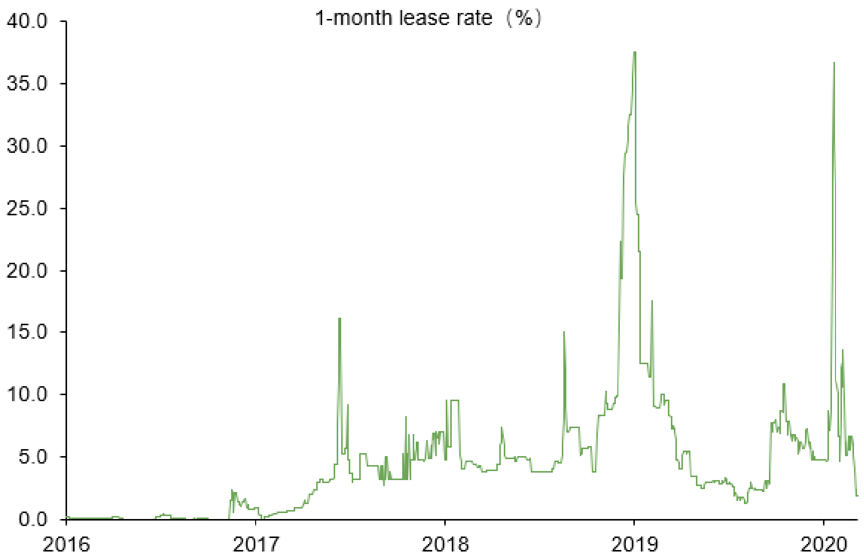
Figure 27: NYMEX palladium forward curve – March 2020



Source: Bloomberg, WPIC Research

A further indication of the lack of availability of palladium is the recent trend in palladium lease rates. Palladium consumers can often cover immediate metal needs in what is known as the lease, or lending, market. Here, holders of metal put their stocks to work for a profit. A lease rate is simply the going market 'price' for borrowing or lending the metal. 1-month rates charged to lease palladium spiked in January 2019 and in January 2020, reaching 37%, compared to an average over the last 8 years of 2.4%. Such spikes emphasise the lack of physical metal availability to the market.

Figure 28: Palladium lease rates spiked in January 2020 on limited metal availability



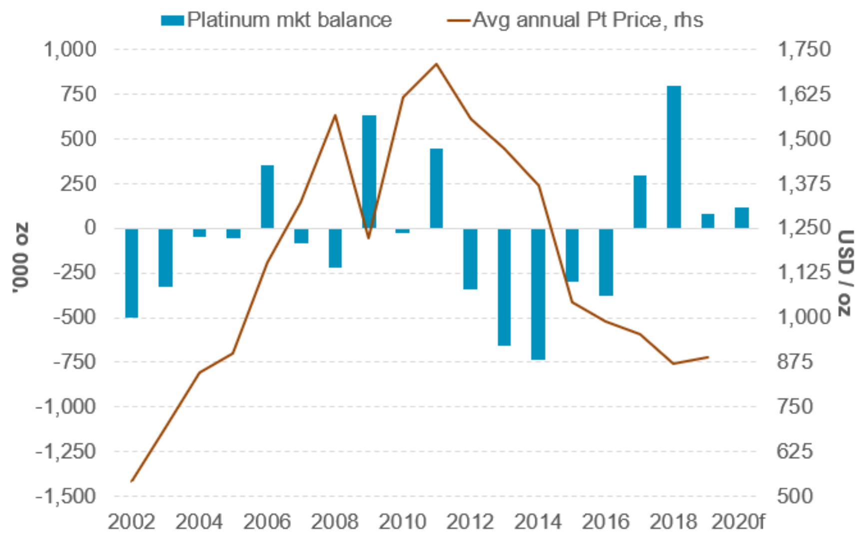
Source: Bloomberg, WPIC Research

Palladium's deficit seems likely to continue, sustaining the impetus for platinum substitution. PGM mine production is slow to change with supply growth unlikely to resolve the supply deficit. Because the driver of palladium deficits is increased loadings, slowing cars sales will not ameliorate the deficits. The palladium price premium looks likely to remain elevated, despite growing substitution by platinum in auto catalysts.

Platinum

The platinum market was in a small surplus in 2019, at 65 koz, driven by 985 koz of metal being purchased in the spot or OTC market to physically back the increased holdings of platinum ETFs mainly by institutional investors. However, this relative balance occurred after 2 years of more sizable surpluses in 2017 and 2018. In contrast to palladium, platinum is expected to remain in a small surplus in 2020, largely as a result of reduced expectations for investor demand. The key difference between the platinum and palladium markets today is platinum's balanced position and low price, relative to itself, gold and palladium, and palladiums sustained consecutive deficits and record high price.

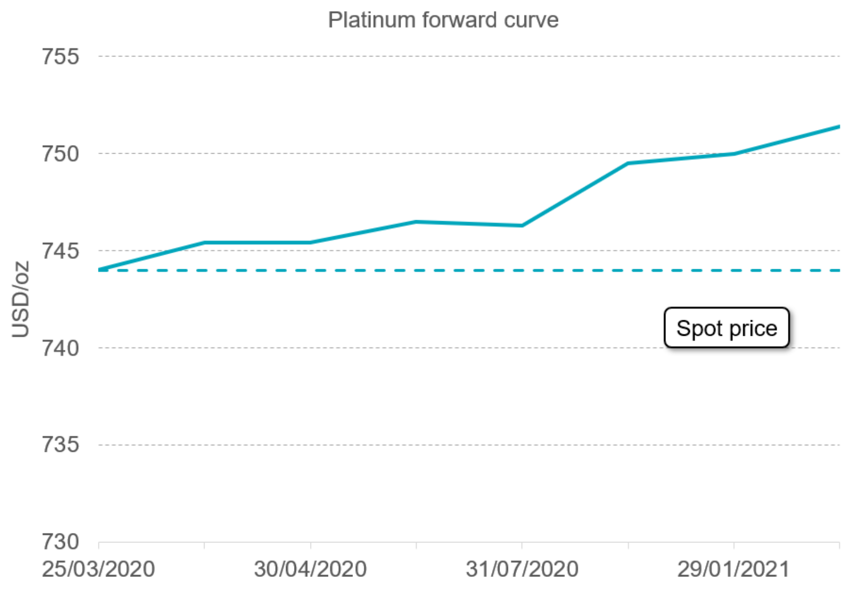
Figure 29: Platinum market balance, a small surplus in 2019 after 2 years of large surpluses



Source: SFA, WPIC Research

In contrast to the palladium forward curve, the platinum curve is largely in contango, apart from very nearby dated contracts. This price structure largely reflects a typical metal market with no lack of availability and the forward price largely reflecting the finance cost of holding the asset.

Figure 30: NYMEX platinum forward curve – March 2020



Source: Bloomberg, WPIC Research

Is palladium a precious or an industrial metal?

Precious metals are defined scientifically as rare, naturally occurring metallic chemical elements that hold a high economic value. They are typically less reactive and have a higher melting point than other metals, making them highly durable, ductile, and able to have a high lustre. More commonly, the notion of what qualifies a metal as “precious” is any expensive metal that may be sold as jewellery or used to make coins.

From a jewellery perspective, Palladium is not widely used, accounting for less than 2% of palladium’s end-use annually over the last 4 years. This compares poorly with gold, where jewellery typically accounts for around 50% of end-use demand, or platinum with jewellery usage of typically 30-35% of demand annually.

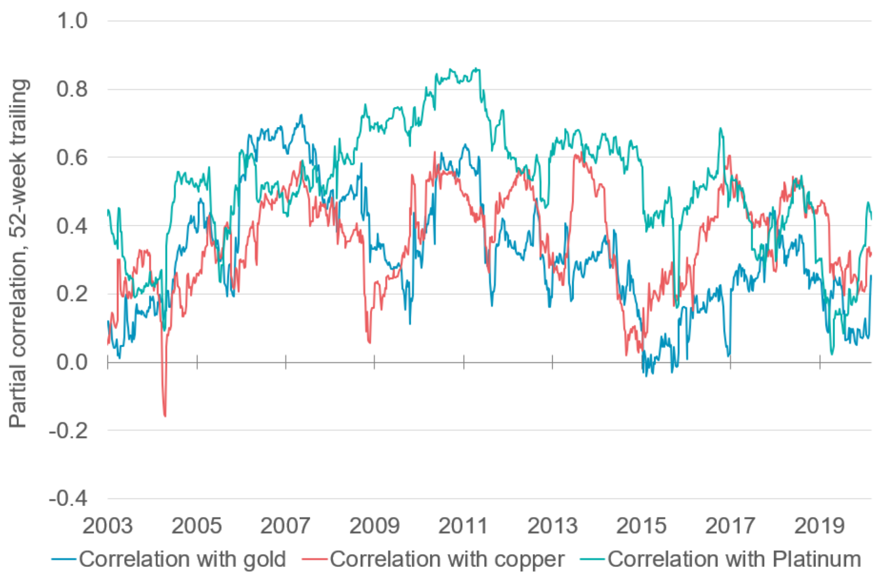
Despite the strong increase in the price of palladium since 2015, investors have generally been reducing palladium holdings over the last 4 years. Investors have been a source of palladium supply, divesting a net 2.575 moz of metal between 2015 and end-2019. This trend suggests palladium is not seen as a long-term store of value by investors. In contrast, gold investment buying (excluding Central Bank buying) consistently accounts for around 30% of annualised demand, while over the last decade investors have accounted for on average 6% of annual platinum demand.

End-use of palladium is significantly skewed to Industrial sectors, which have accounted for over 90% of annual palladium consumption in recent years. This is a significantly higher share than any other precious metal. In comparison, for gold, industrial end uses account for 7-8% of annual demand, while for palladium’s sister metal platinum, the share (including automotive use) is around 60% of annual demand.

Analysis of palladium’s price correlations with other precious and industrial metals suggests palladium behaves neither as an industrial nor a precious metal but is most closely correlated to platinum. Statistically, a coefficient of below 0.30 suggests negligible correlation, 0.50 to 0.70 represents a moderate positive correlation, and above 0.70 a highly positive correlation.

Looking at trailing 52-week correlations on a rolling basis, palladium has a low correlation to gold, at 0.32 since 2003. In the period since the Global Financial Crisis (GFC) in 2008/09, palladium’s correlation with gold has been even lower, at 0.27; negligible.

Figure 31: Palladium price correlations with gold, copper and platinum



Source: Bloomberg, WPIC Research

Against an industrial metal such as copper, palladium has a slightly higher correlation coefficient than gold, of 0.36 since 2003, and 0.38 post the GFC; both not significant. This suggests palladium does not behave as an industrial metal.

The highest historic price correlation for palladium is with sister metal platinum. Palladium's correlation coefficient with platinum has averaged 0.52 since 2003, and 0.55 since the GFC, peaking at 0.86 in September 2010.

The correlation coefficient between palladium and platinum has recently been volatile, averaging 0.40 since 2016, less than 0.20 in 2019, but reaching 0.50 by the end of the year. These changes coincided with the fall in the diesel share of Western Europe auto sales from over 50% to around 31%. This fall was precipitated by 2015's Dieselgate emissions scandal causing lost diesel sales that were largely replaced by sales of higher CO_2 emitting gasoline cars. The changes in correlation also coincided with the introduction of tighter emissions controls globally, notably China 6 standards, in a highly gasoline centric market, from mid-2019 that led to significantly higher palladium loadings and increased buying of palladium.

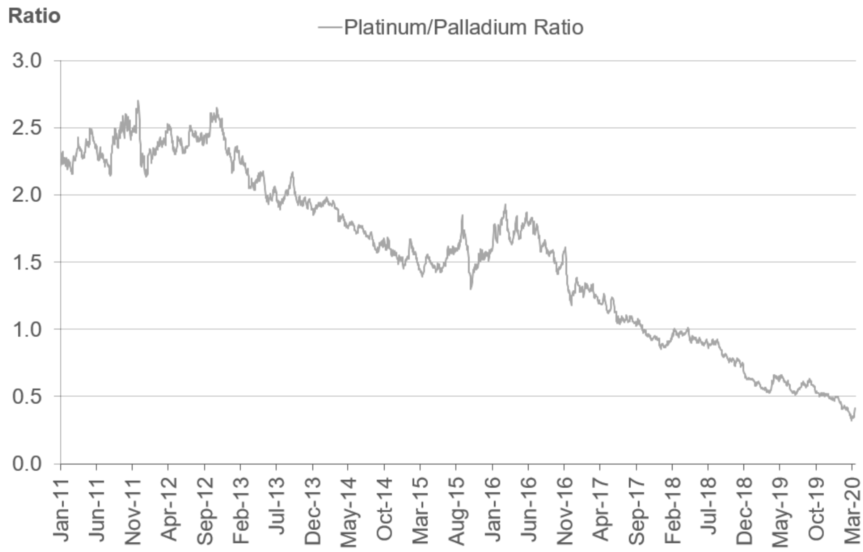
Given the close relationship between platinum and palladium in terms of their mutual substitutability in automotive emissions controls, it should not be a surprise that over the medium and long-term palladium has a higher price correlation to platinum than other precious and industrial metals.

What is the value of palladium?

The spectacular increase in the price of palladium since 2016, in particular during 2019 and into 2020, attracted widespread interest from investors, industrial users of palladium and market commentators. It also highlighted the importance of understanding the palladium market when considering an investment in platinum.

Determining in isolation the value of palladium is a significant challenge. The typical approach to valuing a commodity is using the marginal cost of production, market balances, historic supply demand trends, visible and available inventories, value-in-use and the cost of the next best alternative metal for those uses. Because almost all palladium production is as a co-product or by-product the only such data available is the value of the next best alternative metal for a particular use. Palladium's primary use has been as a cost-effective alternative to platinum in automotive applications.

Figure 32: Platinum / Palladium ratio



Source: Bloomberg, WPIC Research

When palladium was first used to replace platinum in autocatalysts in the late 1980s, the substitution ratio between palladium and platinum in auto-catalyst uses was 2:1; where 2g of palladium were required to replace 1g of platinum and achieve similar emissions control. This 2:1 level remained a financial market perception long after engineering advances had resulted in this ratio becoming 1:1. For much of the period between 2011 and 2016, the 2:1 ratio was trusted by metal traders and it resulted in platinum maintaining a level around twice the value of palladium, as shown in the above price ratio chart.

From mid-2016 onwards, prices began to converge, reaching parity in 2017, as it became more widely accepted in financial markets that palladium and platinum could be substituted at a 1:1 ratio. It took a surprisingly long time for financial markets to recognise the 1:1 ratio confirmed in the 2013 Johnson Matthey study. While palladium prices have significantly overshot parity with platinum since mid-2018, driven by extreme physical market tightness, over the longer term, all things being equal, palladium prices should closely match the price of platinum given their interchangeability in use.

How can I invest in palladium?

Financial exposure to palladium can be obtained through physical palladium like bars and coins, physically backed financial assets like ETFs, financial assets that are linked to palladium's price movements or derivatives, and assets that are affected by palladium's price movements (amongst other drivers), most notably mining equities and platinum.

Below we outline some palladium investments. The total return for an investor is also impacted by the total cost of ownership and disposal, which may include tax implications, which are not detailed below. An example is coins which have a higher premium than other investment products but may for example in the UK not be liable for capital gains tax. We refer investors to the disclaimer at the end of this document.

Figure 33: A range of palladium ETF investments (volumes and values as of 28 February 2020)

ETP holdings (koz)

Region	Fund	Country	Inception	Ticker	Management fee (%)	Current Oz	Value (USD mn)	% of total
Asia	Japan Physical Palladium ETF	JP	02/07/2010	1543 JP EQUITY	0.59	5,356	13	1%
	ETFS Metal Securities Australia Ltd - ETFS Physical Palladium	AU	19/12/2008	ETPMPD AU EQUITY	0.49	3,430	9	1%
	Total Asia					**8,787**	**22**	**1%**
Europe	Swisscanto ETF Precious Metal Physical Palladium	CH	06/01/2010	JBPAEA SW EQUITY	0.50	18,673	47	3%
	WisdomTree Physical Palladium	GB	24/04/2007	PHPD LN EQUITY	0.49	82,299	206	14%
	Xtrackers Physical Palladium ETC	GB	22/07/2010	XPAL LN EQUITY	0.45	3,584	9	1%
	Xtrackers Physical Palladium EUR Hedged ETC	DE	26/07/2010	XAD4 GY EQUITY	0.75	10,773	27	2%
	iShares Physical Palladium ETC	GB	11/04/2011	IPDM LN EQUITY	0.00	4,611	12	1%
	Invesco Physical Palladium ETC	GB	14/04/2011	SPAL LN Equity	0.39	1,921	5	0%
	ZKB Palladium ETF	CH	10/05/2007	ZPAL SW EQUITY	0.50	84,258	211	14%
	Total Europe					**206,119**	**516**	**34%**
North America	Aberdeen Standard Physical Palladium Shares ETF	US	08/01/2010	PALL US Equity	0.60	166,954	418	28%
	Sprott Physical Platinum & Palladium Trust	US	19/12/2012	SPPP US EQUITY	0.50	46,093	115	8%
	Aberdeen Standard Physical Precious Metals Basket Shares ETF	US	22/10/2010	GLTR US Equity	0.60	38,981	98	6%
	Total North America					**252,028**	**631**	**42%**
South Africa	NewPalladium ETF	ZA	27/03/2014	NGPLD SJ EQUITY	0.40	28,316	71	5%
	1nvest Palladium ETF	ZA	24/03/2014	ETFPLD SJ EQUITY	0.35	109,739	275	18%
	Total South Africa					**138,055**	**345**	**23%**
						604,988	**1,514**	

Source: Bloomberg, Respective ETP providers, WPIC research

Physical investments

Physical palladium investments exist across a spectrum from bullion products to collectible products, with the latter garnering higher premiums. Bars and coins are examples of physical investments. The positives are that the investor gains direct price exposure and has physical possession of the asset. The negatives are palladium bars are often liable for sales taxes (unlike gold coins). Coins and bars also often garner storage and insurance fees. Palladium coins and small bars are harder to produce than gold and silver, given palladium's more complex casting requirements relative to gold and an established infrastructure that is optimised for gold and silver, not palladium. This means that the premium (e.g. price paid in excess of the value of the metal) is likely to be higher than that paid e.g. on gold coins and small bars. The premium can be significantly reduced on purchase of multiple coins/bars.

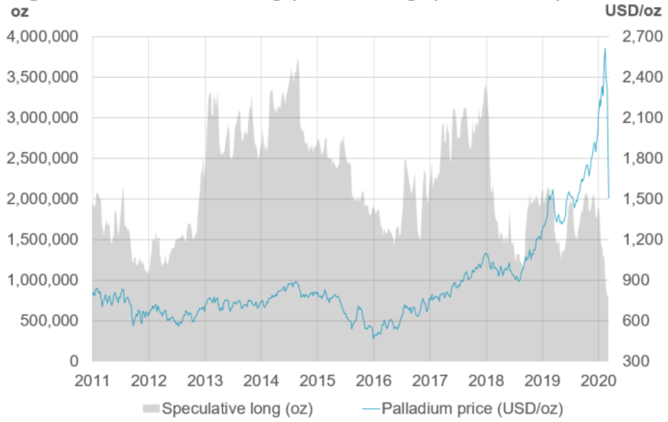
Physically backed investments

Palladium Exchange Traded Funds (ETFs) provide direct price exposure, and easy re-sale (given their exchange traded nature). There are also no insurance, storage costs and sales taxes on ETFs, although there are management fees typically between 0.35% and 0.75%. However, financial ownership of the ETF does not necessarily confer the right to take possession of the physical palladium.

Investments directly linked to the palladium price

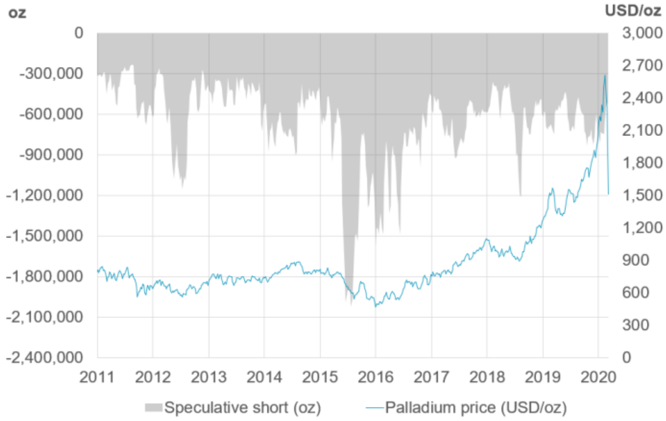
Investor exposure to palladium can also be achieved by buying a palladium futures position. Palladium futures are standardised, exchange traded contracts, in which the buyer agrees to take delivery from the seller, a specific quantity of platinum. Although the contract is theoretically for settlement of physical metal; in practice a very small amount of futures positions result in delivery of the underlying metal; instead traders are more likely to trade or cash settle their futures contracts before they mature. Palladium futures listed on the CME cover a period of 13 months, beginning with the current month, the next two calendar months and moving into the quarterly cycle of January, April, July and October. One NYMEX futures contract is for the purchase or delivery of 50 troy ounces which at $1,500/oz is a value of $75,000 and is typically used by large institutional investors and industrial users.

Figure 34: NYMEX long positioning, palladium price



Source: Bloomberg, WPIC Research

Figure 35: NYMEX short positioning, palladium price



Source: Bloomberg, WPIC Research

Futures have some peculiarities compared to other ways of investing. Firstly, only a fraction of the value of the investment is required when buying or selling, known as the initial margin. This fraction can be as low as 5%, which entails a leverage of 20 times the initial stake. Secondly, futures have a finite maturity, so to avoid owning the future past the maturity of the contract, an investor needs to roll into the next available contract (sell the old one and buy the new one).

In a normally functioning and 'fundamentally' balanced market, the palladium forward curve would usually be upward sloping (a contango structure where prices are higher further into the future), this implies rolling from a cheaper contract into a more expensive one to maintain the same exposure. Over time, this 'rolling' incurs a cost known as a 'negative roll yield'. In this circumstance, as for other precious metals, the negative roll yield can exert a considerable drag on returns. Currently, the palladium forward curve is backwardated, a situation where prices further into the future are lower than the nearby prices, effectively meaning a positive role yield for palladium.

Investments significantly affected by the palladium price

An example of investments effected by the palladium price are equities of mining companies, where c.30-40% of revenues are generated from palladium. However, there are other significant drivers of these mining equities, including the price of other elements of the mining basket price (e.g. platinum, gold, and nickel); the exchange rate in the mining region (e.g. RUB and ZAR); operational performance including costs and efficiency; and the associated social, regulatory and environmental risk of mining companies.

How does palladium influence an investment in platinum?

The palladium and platinum markets are interlinked with regard to supply as well as demand. They are co-products or by-products in the majority of their mining locations, and they are substitutes for each other in several industrial applications, most importantly in palladium's dominant use in automotive catalysts. In this context, the market balance and resulting price movements in one metal should logically have an impact on market balance and pricing of the other. The contrast in market balances for platinum versus palladium raises the issue of rebalancing. We saw this mechanism in the 1990s as cheaper palladium substituted for more expensive platinum and again in reverse in 1999-2002 as palladium was replaced by less expensive platinum. A similar mechanism was observed with rhodium in 2008 when it rose to $10,000/oz and was largely replaced by palladium.

The current sharply contrasting prices and market balances between these two fungible metals, suggests demand rebalancing is inevitable. Palladium is currently characterised by sustained growing demand exceeding inelastic supply, combined with depleting inventories, driving the price to new highs. The sustained market shortage of palladium is underlined by palladium futures' sustained backwardation since February 2017. The longer Palladium's deficit continues, and longer the price remains elevated, the greater is the impetus for platinum substitution. To put this simply, high palladium pricing should be positive for platinum demand and therefore platinum pricing as market rebalancing occurs via demand substitution, underscoring the positive investment case for platinum.

WPIC aims to increase investment in platinum

World Platinum Investment Council (WPIC) was established by the leading South African PGM miners in 2014 to increase investment ownership in platinum. This is done through both actionable insights and targeted development. We provide investors with the information to support informed decisions e.g. the *Platinum Quarterly* and monthly *Platinum Perspectives* and *Platinum Essentials*. We also analyse the platinum investment value chain by investor, product, channel and geography and work with partners to enhance market efficiency and increase the range of cost-effective products available to investors of all types.

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Glossary

3E – 3 Elements, total content of platinum, palladium and rhodium

4**E** – Total of platinum, palladium, rhodium and gold

5E – Total of platinum, palladium, rhodium, iridium and ruthenium

6E – Total of platinum, palladium, rhodium, gold, iridium and ruthenium

Alluvial – An ore deposit that is in a current or old riverbed

Bushveld Igneous Complex – a large layered, saucer shaped, body of metal containing rock, approximately 500km wide and with depths over 2,000m formed through the cooling and solidification of a volcanic lava intrusion, north west of Johannesburg in South Africa. It is rich in Platinum Group Metals

By-product – In mining, a metal that contributes much less in revenue than the primary metal produced at the mine. In mining also known as a co-product

Concentrate – The product of mineral processing that is a higher grade than the ore that contains valuable minerals recovered by froth flotation

Deposit – A collection of ore that is contained in an area

Grade – A measure of concentration indicating how much valuable metal is contained ore. In PGM mining, grade is often commonly referred to as grams of 4E (platinum, palladium, rhodium and gold) content per tonne of ore (g 4E/t)

IRR (Internal Rate of Return) – a financial measure of the return (or profitability) of an investment including a mine to extract a valuable material from an orebody. It is the discount rate on a project such the such that net present value (NPV) of a project is equal to zero. NPV is the present value of future (net) cash flows

koz – thousand troy ounces – equivalent to 31.103 kilograms

Matte – A layer of valuable minerals produced through smelting. In the case of platinum smelting it is enriched with platinum group metals

Merensky reef – Layer of the Bushveld Complex supplying PGMs, and yields significant quantities of copper, nickel, cobalt and gold as by-products. It is mined on both the eastern and western limbs of the Bushveld Complex

moz – million troy ounces – equivalent to 31.103 metric tonnes

Norilsk–Talnakh nickel-copper-palladium deposits – The world's largest known PGM-containing nickel-copper deposits are situated on the Taimyr Peninsula in northern Siberia, in the province of Krasnojarsk. The deposit was discovered in about 1860, but mining operations did not commence until 1935

Open pit – A type of mining operation whereby ore extraction is from the surface without the use of shafts

Ore – Raw material in the earth's crust that contains a valuable mineral or metal. With the exception of coal and steel raw materials, most ores are further processed to produce the material for sale or for trading

Platinum Guild International (PGI) – Platinum Guild International (PGI) is a marketing organisation created to develop the global platinum jewellery market as a demand source for platinum. Founded in 1975 and currently funded by leading South African platinum producers with co-funding of programmes from the jewellery industry. Since 2015 PGI is based in Hong Kong supporting the four main platinum jewellery markets of China, Japan USA and India

Platinum Group Metals (PGMs) – A group of metals commonly present with platinum in platinum bearing ore. Can refer to some or all of platinum, palladium, rhodium, iridium, ruthenium and osmium. Commonly, measures of PGMs exclude osmium, which is also a PGM, but is discovered in quantities too small to make a meaningful economic contribution, is usually not assayed and is highly toxic. Measures of PGMs also commonly include gold given its co-occurrence with PGMs

Platreef – Ore body of the Bushveld Complex on the northern limb. It is a different nature of rock due to magma in this region reacting with the lime rich floor rocks. It is the third largest PGM deposit, after Merensky and UG2 with different metal ratios and much higher base metal content

Powertrain – used to describe the type of components in a vehicle that generate the power that is delivered to the road surface. Usually used to refer to the engine or electric motor and the transmission and various combinations thereof

Prill split – ratio of Platinum Group Metals

Reef – A regularly shaped and lengthy occurrence of a mineral or metal in an ore body

Reserves – a measure of the volume of valuable material (e.g. platinum, gold, oil etc), that can be mined or extracted from an ore body, and provide an adequate commercial return to the operator, given a certain set of assumptions on technological capabilities, commodity prices, foreign exchange rates, and other variables. Commonly reported in annual reports of extractive companies (e.g. mining, oil). It includes losses that are expected to occur when the material is mined

Shaft – a narrow vertical or inclined hole or tunnel blasted or drilled into the earth to provide access for men, material or ventilating air to an ore body

Troy ounce – Traditional unit of weight used to measure precious metals, equivalent to 31.103 grams (compared to a normal ounce which is 28.349 grams)

UG2 reef – Upper Group 2, layer of the Bushveld Complex, usually 20-400m below the Merensky Reef with lower PGM grades but a richer chromite content

ZAR – South African Rand