Heraeus

Precious Metals

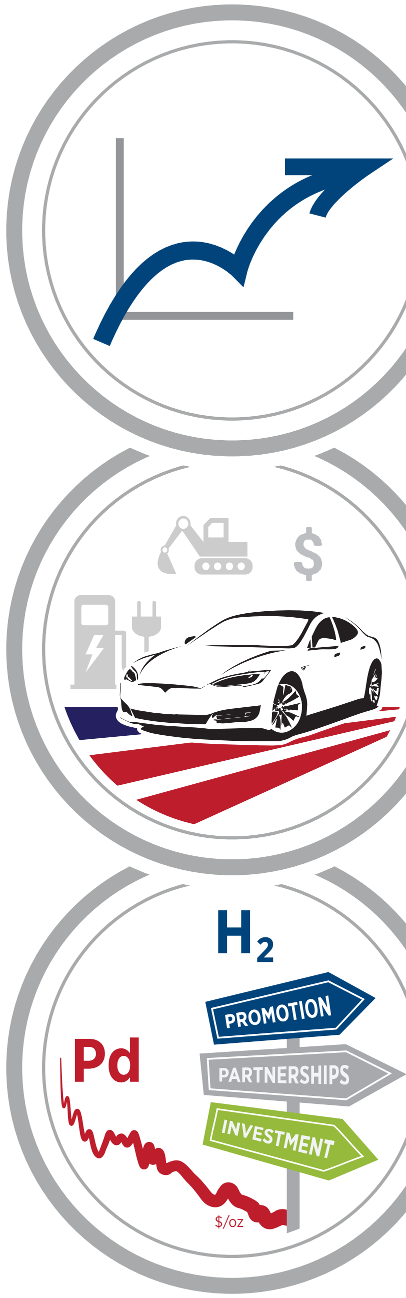
Palladium coatings provide effective exhaust gas cleaning in catalytic converters.

The Palladium Standard 2023

Setting the PGM agenda for the years ahead

Produced in collaboration with

SFA Oxford



THE PALLADIUM STANDARD

September 2023

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CONTENTS

TPS COLLECTION: AGENDA-SETTING COMMENTARY

The Palladium Standard was first published in September 2016, following the successful launch of The Platinum Standard in May 2014

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

If you are interested in reading the collection, you can now download the editions via our new website

FOREWORD:
PEAK PALLADIUM

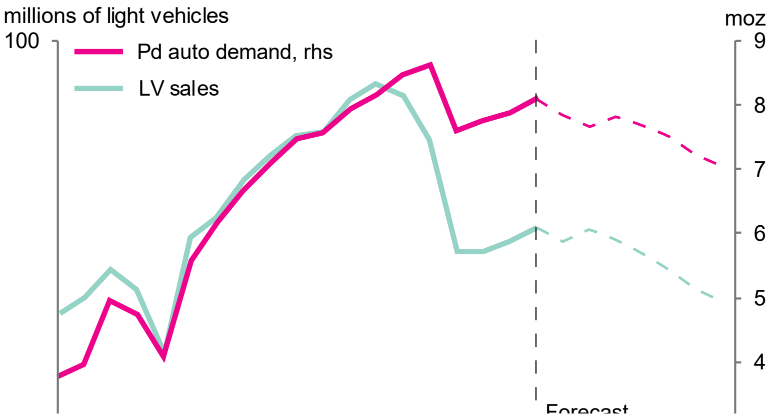
Foreword: Peak palladium

Is it all downhill from here?

The 2020s will see the beginning of a new palladium demand cycle

It looks as if the third decade of the twenty-first century is beginning to witness a new cycle in the long series of rises and falls in demand for palladium. King of the autocatalyst precious metals, palladium's use in vehicle emissions control far outstrips that of platinum and rhodium, and accounts for over 80% of palladium usage in all applications. Yet the peak of demand for palladium has almost certainly passed. The new energy paradigm, in its quest to achieve a net-zero world by 2050, will slash the use of traditional fossil fuels to power transport in all its forms, and demand for palladium will suffer as a result.

Global catalyst-containing light-vehicle sales vs. palladium demand



Source: SFA (Oxford), GlobalData

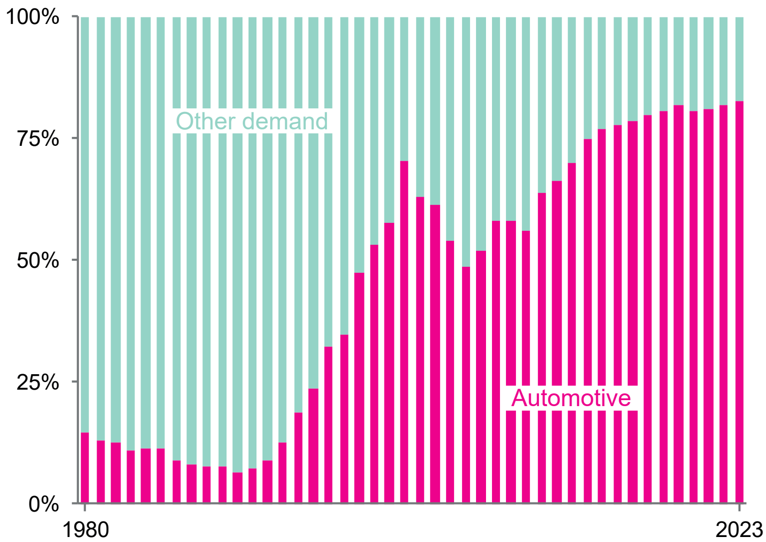
Calling the top

Palladium has been here before, and more than once. Demand over the years has been buffeted by technical change, substitution and volatile prices. Who remembers that the leading use of palladium until the 1970s was in the form of contacts installed in the relay switches of mechanical telephone exchanges? Wiped out by the advent of the digital age, electrical demand was restored and expanded by a new use for palladium in conductive tracks in electronic circuits and multi-layer ceramic capacitors.

Electrical applications were the kingpin of palladium demand, and were not overtaken in importance by autocatalysts until 1996. Then, as palladium catalysts became dominant in gasoline engine emissions control, its price volatility increased and drove the electronic component industry to make an irreversible switch to nickel. Palladium's price has lately also been responsible for reintroducing platinum into autocatalyst systems at the expense of palladium demand.

As every observer of PGM fundamentals understands, a conventional market response to declining demand — contracting supply — is more difficult to apply to palladium than to many other metals. The non-elasticity of supply inhibits it. More than 80% of palladium is mined as a by-product of nickel, copper or platinum. And secondary supply from spent catalytic converters, stimulated by circularity and material security concerns, will continue to pump recycled material into the market on a 15- to 20-year time lag.

Palladium demand by application



Source: SFA (Oxford)

For now, autocatalysts remain undeniably dominant in global palladium demand

This has negative implications for long-term palladium prices and producer revenues. The problem is further compounded this time around by the difficulty of identifying — at least at present — one single new giant application that can replace the inevitable loss of autocatalyst demand. The more likely case is that many smaller applications will be needed, challenging PGM stakeholders to explore more diverse sources of demand and work within a greater range of industrial sectors to build back palladium demand over the long term.

How far, how fast?

The forecast near-term decline in autocatalyst demand for palladium is not abrupt, but it is progressive — as much as a 20% decrease by 2030 from its peak in 2019. That is largely predicated on the increased penetration of electric vehicles in the new car fleet. It is now only a question of how far demand for palladium in catalytic converters will fall, and how long it will take, but the answers remain unclear. There are many reasons why the take-up of electric vehicles might not be as rapid, or as extensive, as official targets such as bans on sales of new ICE cars, subsidies and incentives and zero-emission driving zones would imply.

Western governments are busy legislating away the combustion engine market

In her article, ***The US auto market in the spotlight***, Kimberly Berman addresses these issues using the US experience as a template. The weight of American legislation is swinging behind the promotion of electric vehicle manufacture, and the rate of growth of sales is increasing at a pace suggesting that the majority of new cars sold nationwide will be electric by 2030. Yet there are anxieties beyond the established ones of driving range: weightier issues (which apply to most Western markets) include material security — the high exposure of the US to foreign sources of battery raw materials — and ready access to energy in the shape of a uniform and widespread public charging infrastructure.

No time to waste

Regulation, technological advances and public acceptance were the foundations of the development and global application of PGMs in the control of air pollution from the mid-1970s onwards. PGMs succeeded because of their unique catalytic properties. The same qualities imply that the metals can find application in the future green energy economy too: in, for example, the abatement of carbon emissions from chemicals manufacturing and in the energy transition away from fossil fuels. But not automatically, however, as cost, scarcity and the ever-present possibility of substitution will continue to influence how far PGMs can be utilised.

The energy transition is equally an opportunity for PGM market development

In our second article, ***The future of PGMs: Navigating a rapidly changing energy landscape***, Gyubin Hwang considers some of the ways in which the expected shifts in energy production and a sharper focus on energy efficiency and decarbonisation could provide new opportunities for palladium and other PGM demand. Since conventional vehicle and energy technologies are in decline, the old certainties for demand are dissolving; PGM stakeholders need to recognise the imperative to be proactive in discovering new avenues for palladium use. Gyubin highlights three strategies which the PGM industry should consider to ensure a place for palladium and other PGMs in a green energy economy, and provides case studies to illustrate the possibilities.

THE US AUTO MARKET IN THE SPOTLIGHT

The US auto market in the spotlight

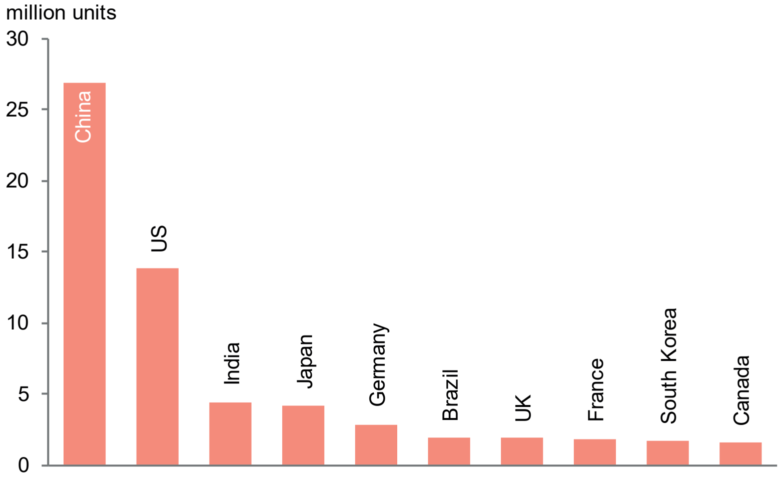
Kimberly Berman, Energy Transition Technology and Metals Specialist, SFA (Oxford)

Gasoline and diesel-only vehicles represent 80% of the US light-vehicle market

Surprisingly, the US represented only 13% of new battery electric vehicle (BEV) sales globally in H1'23, despite being the second-largest automobile producer and market in the world. Furthermore, given the cultural and symbolic significance of cars in American life, the need for two cars per household and that Tesla is a home-grown success story, EV adoption should have gained much more traction by now. By contrast, China and Europe made up over 75% of global new electric vehicle sales in the same period.

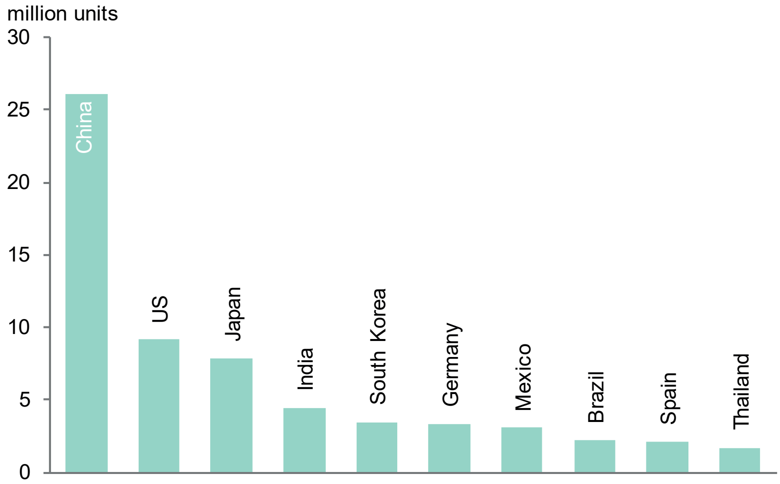
The US lags other advanced economies in the uptake of battery electric vehicles

Top car production markets



Source: carlogos.org

Top car sales markets

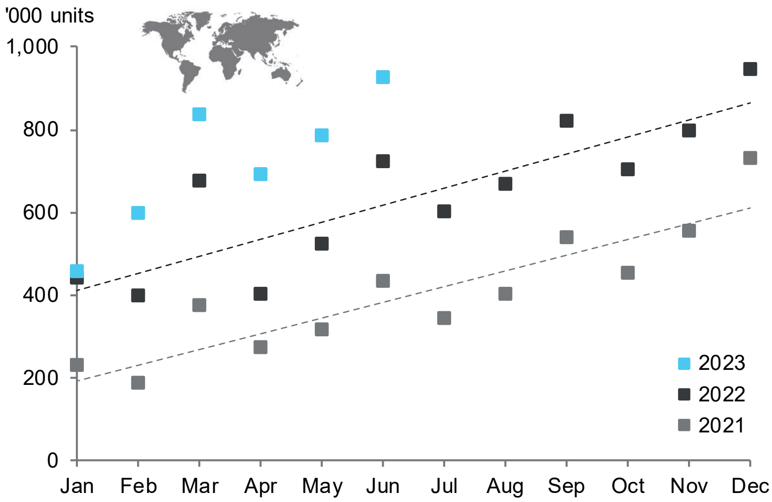


Source: worldpopulationreview.com

EV adoption is increasing but we see many headwinds that could impede growth

There has been substantial growth in new EV sales in the US over the past three years, albeit from a small base, due to favourable legislation and increased investment from both the public and private sectors. Although legislation such as the Inflation Reduction Act (IRA) has kick-started long-overdue industry development, this sales growth will continue its long-term trend, but we see many roadblocks such as the absence of domestic critical metals production, battery material processing and battery manufacturing excluding Tesla. This reality, along with the lower upfront costs and greater variety of ICE vehicles, curbs our optimism.

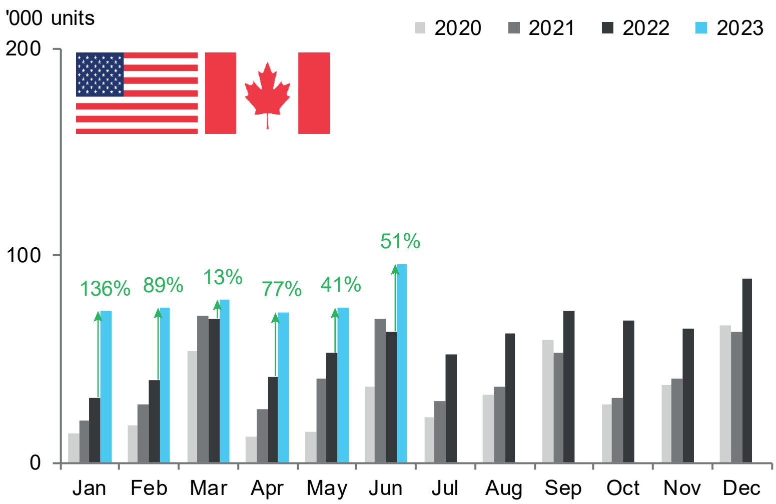
Global BEV sales trend



Source: SFA (Oxford), EV-Volumes

The largest EV markets continue to be China and Europe as global BEV sales rise

Growth of BEV sales in North American markets



Source: SFA (Oxford), EV-Volumes

North American BEV sales have increased 58% in 2023 year-to-date through to the end of May

A dire need for critical minerals development

The transition towards a low carbon energy future will result in a dramatic increase in the intensity of metals and minerals use, especially for those that are key for lithium-ion battery storage, and will expand the global metals and mining industry. However, mine production is largely outside of North America and battery supply chains are mired in geopolitics and ESG complications. Furthermore, battery metals such as lithium and cobalt are subject to high price volatility.

There is no energy transition without a significant increase in metals and minerals production

The Inflation Reduction Act (IRA) has sparked many plans to develop the domestic battery and EV industry. While the Bipartisan Infrastructure Investment and Jobs Act, passed in 2021, included $15 billion for EV industry development, it is the IRA that is causing the most excitement with its aim of investing $389 billion in energy and climate programmes over the next 10 years.

The IRA has also reinstated the $7,500 tax credit for Tesla and GM, both of which were excluded after reaching the 200,000-vehicle cap under the previous regime. However, in order to receive the full $7,500 tax credit amount, EVs need to be assembled in North America and battery packs must meet the following criteria:

Since last year, the IRA has broadened its vehicle inclusion for top brands Tesla and GM

1. At least 50% of materials sourced within North America.
2. 40% of the value of critical minerals used must be extracted, processed and/or recycled domestically, or from one of the countries with a free trade agreement in place.

If only one of these requirements is met, then the tax credit is halved to $3,750 and these percentages are going to increase by 10% per annum. According to a study by Trost and Dunn (2023),[1] the 80% target by 2027 will be difficult to achieve to say the least and recycling infrastructure will not be ready to meet mineral demand by that time. Although the material supply to produce lithium-iron-phosphate (LFP) is likely to be sufficient, the supply for nickel-cobalt-aluminium (NCA) is constrained and the supply for nickel-manganese-cobalt (NMC) is insufficient.

Critical raw material requirements in the Inflation Reduction Act

	2023	2024	2025	2026	2027	2028	2029
Materials sourced in North America	50%	60%	60%	70%	80%	90%	100%
Minimum percentage of critical minerals extracted, processed, and/or recycled in nations with a free trade agreement	40%	50%	60%	70%	80%	80%	80%

Source: bipartisanpolicy.org

Only 12 BEV types currently qualify for the full tax credit amount

On 17 April 2023, the US Treasury Department announced that only 12 vehicle types, including 6 EV models under GM's brands, Ford's F-150 Lightning and Lincoln Aviator, Chrysler's Pacifica PHEV, Tesla's Models 3 and Y, and VW's ID.4, qualify for the full EV credit amount. Domestically produced vehicles such as Ford's Mustang Mach-E sport utility and the standard range version of Tesla's Model 3 will see the tax credit halved, and many vehicles by VW, BMW, Nissan and Rivian are currently not eligible for the EV tax credit.

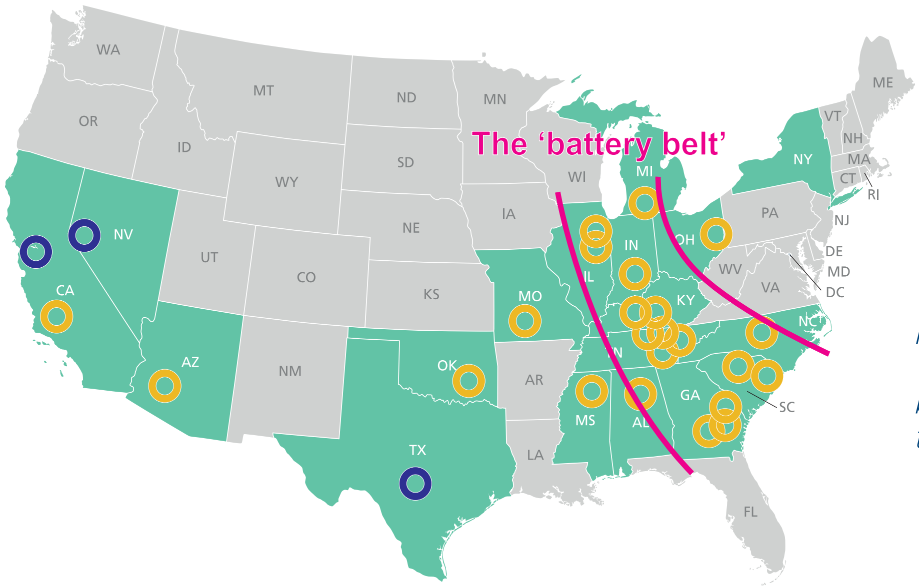
Mexico and Canada immediately benefited from the passing of the IRA, but most plans announced so far are about meeting the vehicle assembly criteria.

The US's NAFTA partners have been immediate beneficiaries of the IRA

Mexico:

- Tesla announced that all the necessary paperwork was cleared by the Mexican authorities to begin building Gigafactory Mexico that should be operational in 12-15 months.
- Chinese automaker Jetour announced plans to build a $3 billion EV plant in Mexico that will be operational by the end of 2024.
- VW, BMW and Stellantis have announced investments of $763 million, $800 million and $200 million, respectively, to expand current manufacturing facilities to include EV production.

Automotive companies' gigafactories in the US



Source: SFA (Oxford), company announcements. Blue circles represent Tesla facilities. Yellow circles represent other OEM and OEM-partnered facilities. Includes battery and EV factories.

Kentucky and Tennessee have become the buckle on the US 'battery belt'

Canada:

- GM re-tooled the CAMI plant in Ingersoll, Ontario, and opened Canada's first EV production plant in 2022.
- The federal government and the provincial government in Ontario have agreed to provide C$15 billion in incentives to support the $5 billion Stellantis-LG Energy Solution plant in Windsor, Ontario.
- VW is planning to invest $7 billion to establish the company's first overseas EV battery manufacturing plant in St. Thomas, Ontario, and the federal government has agreed to provide up to C$13 billion in subsidies in the form of manufacturing tax credits.
- Ford is planning to invest $1.35 billion to re-tool its Oakville plant to include EV production in 2024.
- Honda is investing $1.4 billion to re-tool its manufacturing plant in Alliston, Ontario, to produce its next-generation hybrid electric vehicles.

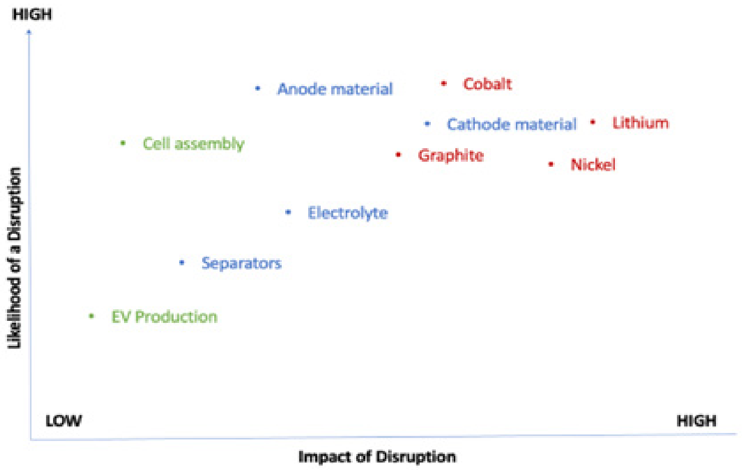
Canada is seeing the development of its own 'battery belt'

Many vehicles will not meet the critical metals component of the federal tax credit anytime soon

According to the US Geological Survey's (USGS) Mineral Commodity Summaries 2023 report, supply chain stability of critical metals has hit an all-time low. Producing EV battery packs that use NMC cathodes is currently difficult as the US is 100% dependent on imports of natural graphite and manganese, 75% dependent on imports of cobalt, and 56% dependent on imports of nickel. The only nickel mine in production, Lundin's Eagle mine in Michigan, will be decommissioned in 2027, but does not meet the requirements to receive IRA funding at present.

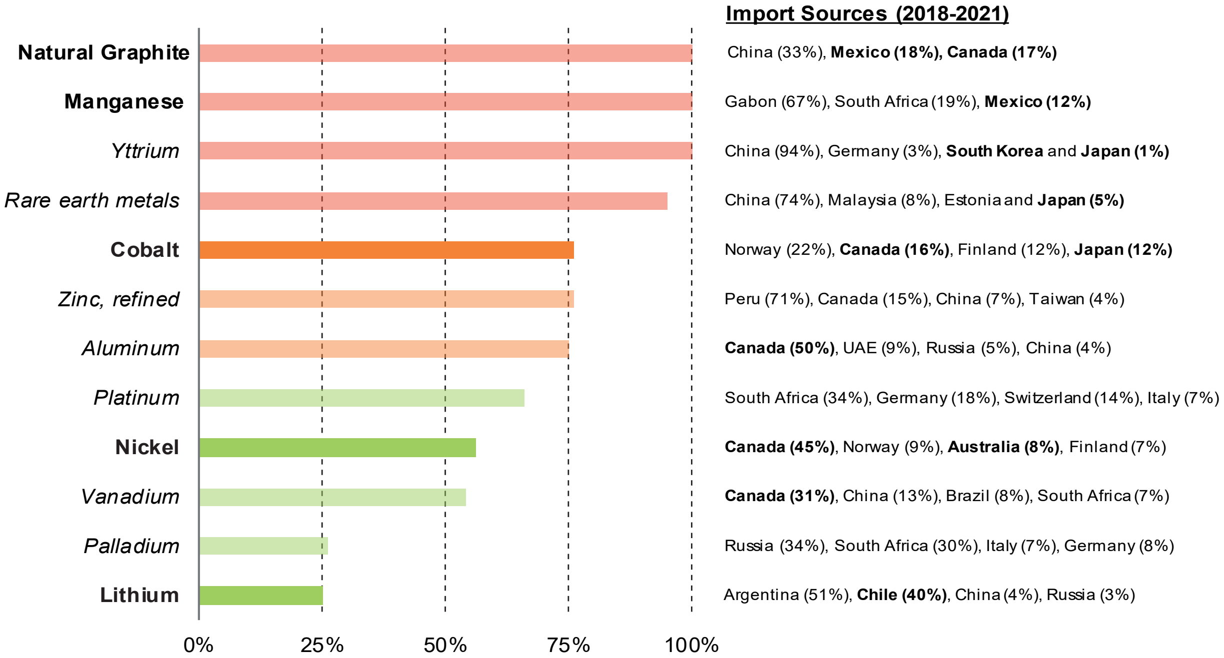
The raw materials requirements have spurred supply chain development, but qualification is still far off for most vehicles

Battery raw materials are the weakest link in the EV chain



Source: SFA (Oxford), Financial Times

US net import dependence of critical energy transition metals, 2022



Source: USGS. Note: Countries listed in bold have an FTA with the US.

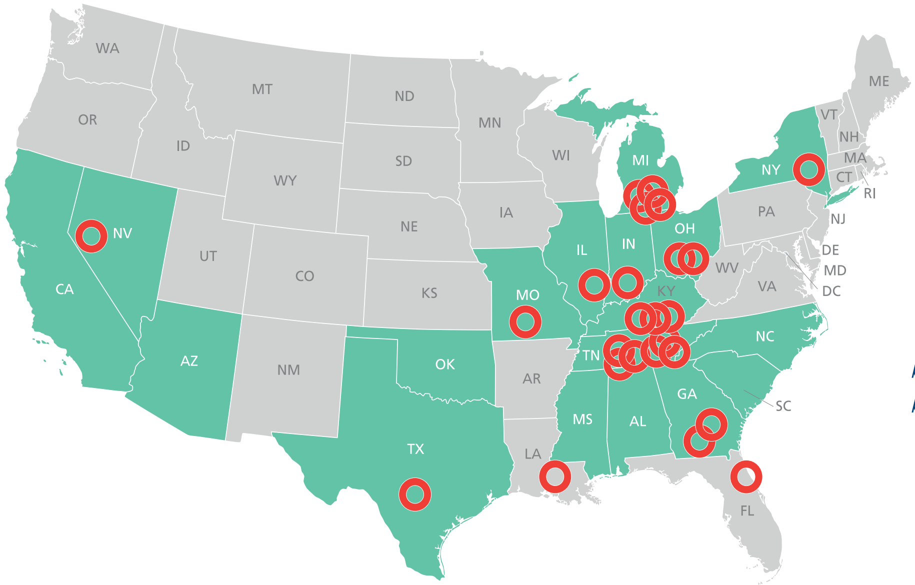
Of the 21 countries that have an FTA with the US, only Australia, Canada, Chile, South Korea and Morocco have the component manufacturing or critical metals necessary. The value of the critical metal content will increase incrementally per annum, eventually capping out at 100% for the battery component (in 2029) and 80% for the critical metal component (in 2027). However, countries that have an FTA are not representative of the EV battery supply chain and separate negotiations are ongoing with other countries that do not have an FTA with the US in place. Automakers are seeking to secure their own supply chain sources:

Morocco has seen several development deals this year for battery materials, motivated by the IRA

- The US and Japan signed the US-Japan Critical Minerals Agreement to strengthen supply chains and promote EV battery technologies.
- The EU adopted its negotiating directives for an agreement with the US. The EU exported €8.3 billion worth of critical materials globally last year and OEMs are investing heavily to build domestic vehicle assembly plants.
- The US signed a memorandum of understanding (MOU) with Zambia and the DRC “to facilitate the development of an integrated value chain” for the development of an integrated plan for EV production.
- VW and Mercedes-Benz have entered into separate agreements with the Canadian Government to supply battery raw materials to support their US facilities.
- GM entered into an agreement with Element 25 in Australia to supply manganese, in addition to its agreement with Vale to supply nickel sulphate from its proposed facility in Canada. GM also made a $650 million equity investment in Lithium Americas.

Some OEMs have been particularly active in securing future mineral supply

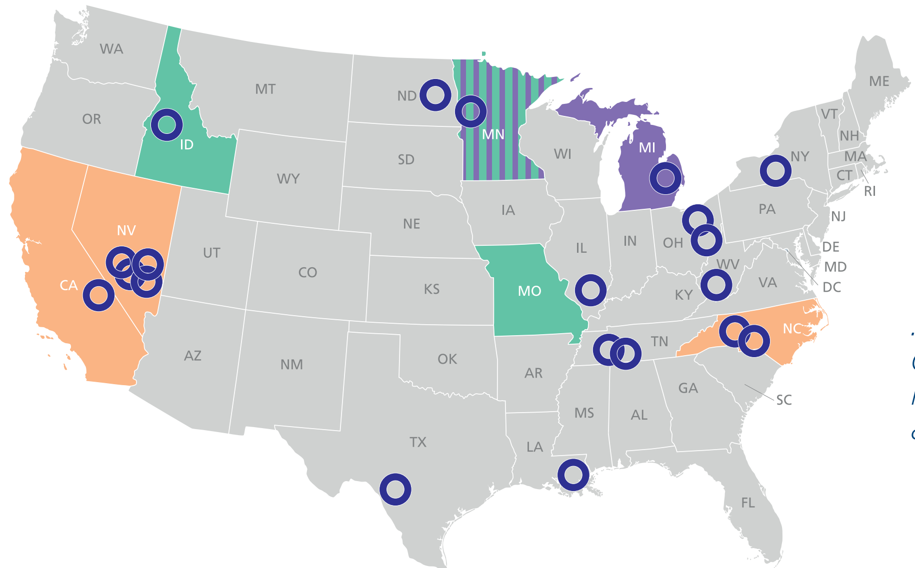
US midstream projects — cathode and recycling plants



Source: SFA (Oxford), company announcements. Note: The US DOE is responsible for allocating funds from the Bipartisan Infrastructure Law and the IRA. The funding is typically in the form of grants.

The midstream of the battery value chain has blossomed...

US upstream projects — mining and refining sites



- Ni-Cu-Co projects
- Cobalt deposits, not as Cu or Ni byproduct
- Only domestic primary nickel mine
- Lithium deposits estimated to be 4% of global resources

Source: SFA (Oxford), USGS, company announcements

...but discovery and development of Tier-1 mineral resources are lagging

Range anxiety, vehicle variety and charging network are key to this market

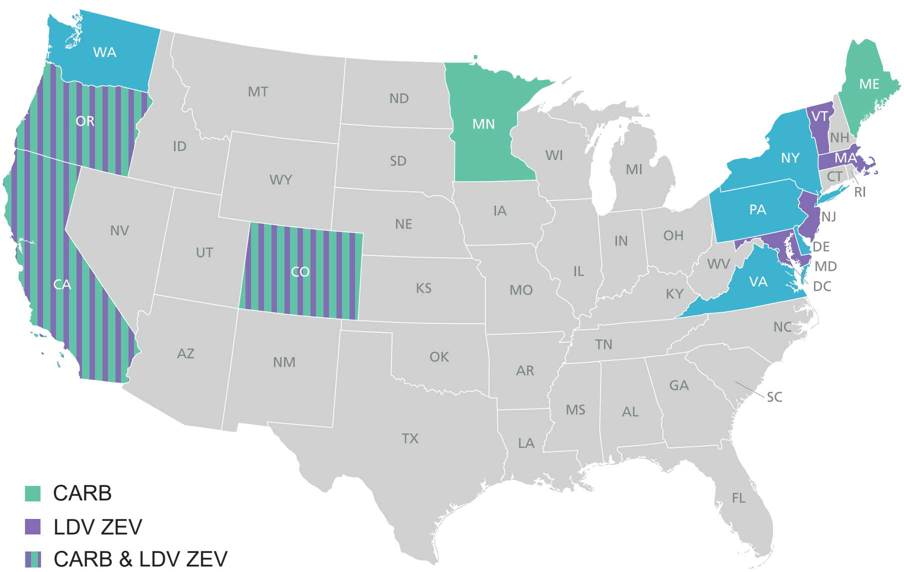
Currently, 53% of the US population live in car-centric suburban areas with low walkability scores and a lack of public transportation options, while another 31% live in rural areas. Furthermore, public transport in most American cities has lower ridership levels, longer waiting times and fewer service hours compared to other countries, largely due to a lack of funding. In general, the US has a long history of car-centric urban planning that favours using highways, straight roads, curved roads and cul-de-sacs, and logically this means that EV adoption should have accelerated at a much greater pace.

Overlapping federal and state regulations are part of the problem

More stringent emissions standards have been proposed by the Environmental Protection Agency (EPA) at the federal level for light-duty vehicles and Class 2b and 3 medium-duty vehicles that would be phased in starting in 2027 through to 2032. If approved, this could mean that OEMs would need to achieve fleet-wide CO_2 emissions reduction from 152 g/mile in 2026 to 73 g/mile by 2032, translating to 60% of new vehicles sold nationally being fully electric by 2030 compared to the original 50% goal set out in 2021 and streamlining emissions regulations across all states. Emissions standards used to vary across states and this impacted the availability of many EV models, as OEMs would only ship to states with more stringent measures that offered incentives over and above the federal tax credit.

The car is king where public transportation and walkability are poor

Various inter-state clean-air policies are in place



Source: SFA (Oxford), California Air Resources Board

'Flyover' states generally lack a comprehensive clean-air policy

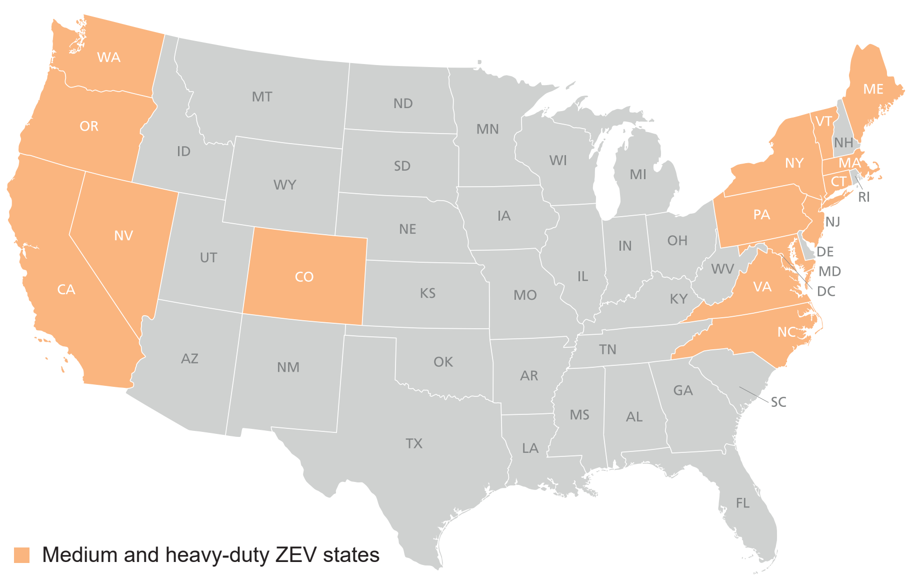
In the past, the emissions standards of the state of California were more stringent than the national EPA standards. Fifteen states, dubbed CARB states, opted to follow California's lead. However, in many respects, the EPA's Tier 3 standards that were phased in starting in 2017 through to 2025 mirrored California's LEV III standards initiated in 2025, and this meant that vehicle standards were more harmonised across all states.

In the US, the National Highway Traffic Safety Administration (NHTSA) sets and enforces the Corporate Average Fuel Economy (CAFE) standards, while the EPA calculates average fuel economy levels for manufacturers and sets greenhouse gas emissions standards. Therefore, the EPA's lag behind the CARB rules meant that OEMs could sell higher emitting vehicles in most states until 2017 without incurring fines. This changed with the new EPA Tier 3 rules and Stellantis was fined $235.5 million for 2018 and 2019 model years. Consequently, if these new proposed standards are approved, all automakers would have to increase their electrification efforts more aggressively than previously anticipated or risk hefty fines.

Proposed standards would require OEMs to pursue more aggressive electrification

In addition to the increasing emissions standards for passenger vehicles, medium- to heavy-duty vehicle standards are following suit. The Multi-State Zero Emission Vehicle (ZEV) Task Force laid out an action plan to reduce emissions from the medium- to heavy-duty trucking segments by accelerating electrification in 17 states that include many CARB states, but also Hawaii, Nevada and North Carolina. In addition, the EPA approved California's manufacturers plan in March that requires half of all heavy-duty trucks sold in the state to be electric by 2035, and it has since struck a deal with truck manufacturers on how this will be rolled out.

States with ZEV mandates for medium- and heavy-duty vehicles



Source: SFA (Oxford), Centre for Climate and Energy Solutions

Lack of a cohesive public fast charging network

The bottom line is that EVs are not being purchased for even that second ‘commuter’ car due to a variety of reasons such as higher upfront costs, a lack of public charging infrastructure, vehicle variety, and a lack of the qualitative incentives seen in Europe (high-occupancy vehicle (HOV) lane access, free parking, rebates, etc.).

Although EV prices have come down recently, their higher sticker prices compared to ICE vehicles are a deterrent, especially given the current inflationary environment. In addition, although there are electric SUVs and pick-up trucks available, costs and availability are a deterrent as well. Since there are mostly two-car households in the US, waiting lists and availability become an important part of the buying decisions. Lastly, buying an EV in many states is still difficult, except in coastal states or those that have incentives over and above the federal tax credit.

Cost is clearly still an issue for prospective BEV owners

Charging infrastructure may be improving, but it is still problematic for non-Tesla EV drivers. The Infrastructure Investment and Jobs Act that was passed in 2021 earmarked $7.5 billion for charging infrastructure and according to PwC, the number of charge points is expected to grow from 4 million today to 35 million by the end of the decade. However, while there are many public fast-charging ports located along the Pacific and Atlantic coasts and in the Eastern half of the country, they are limited in the middle part of the country.

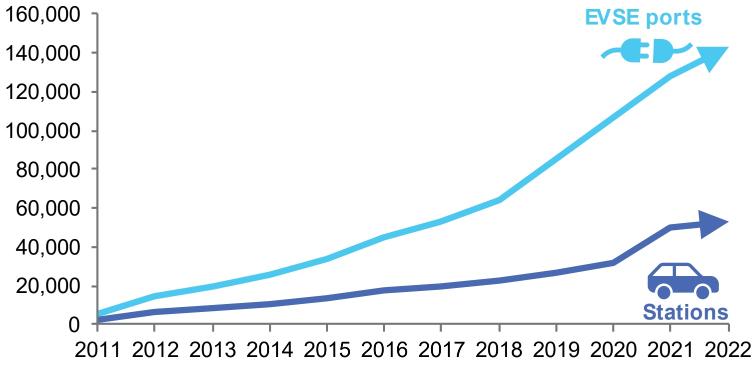
OEMs use different types of charging ports, apps and management systems. Non-Tesla drivers have reported very different experiences, and a recent report by J.D. Power and Associates[2] noted that 25% of EV drivers find the public charging experience unreliable. While Tesla drivers tend to be satisfied given Tesla’s common and predictable charging network, those same drivers tend to exhibit ‘charging anxiety’ when having to rely on third-party charging ports.

Those unable to use the Tesla network have reported frustration over reliability

Except for Tesla, OEMs have been held captive to third-party fast-charging systems until now. Tesla had the foresight to build its own charging network in the US for exclusive use of its vehicles and provided adapters for use with other charging ports. This, along with a more integrated charging management system, allowed for a more consistent charging experience in public spaces and during long-haul journeys. However, non-Tesla drivers had to use third-party chargers that could use either CHAdeMO or Combined Charging System (CCS) connectors that are installed and managed by numerous independent operators, each with their own style of apps to manage the charging process.

Automakers adopting Tesla’s charging standard will be a game changer and promote universality. Recently, many automakers have chosen to adopt Tesla’s charging port type, which is now called the North American Charging Standard (NACS).

The number of US public charge points have increased exponentially



Source: Alternative Fuels Data Center

Ford reached an agreement with Tesla to provide customer access to its supercharging network starting next year and GM is planning to incorporate the NACS connector in its EVs starting in 2025.

OEMs are planning a more cohesive charging strategy. BMW, GM, Honda, Hyundai, Kia, Mercedes-Benz and Stellantis have created a joint venture to make EV charging more convenient, accessible and reliable for their drivers. This joint venture appears to be following Tesla's original charging model as a new, high-powered charging network with at least 30,000 chargers with CCS or NACS ports.

Tesla paved the way for the North American Charging Standard, now other OEMs are onboard

A longer tail for US PGM autocatalyst demand?

Though we see electric vehicle adoption accelerating in the US between now and 2030, there are, and will be impediments to the pace of growth. As domestic raw material requirements rise year-by-year, fewer vehicles could qualify for full IRA tax credits. This is an issue unlikely to be resolved soon. The profound dependency on non-FTA nations for critical minerals puts the need for domestic supply firmly in the spotlight, particularly if the US is to meet fleet electrification targets. The relative lack of BEV models compared to the ICE market is stark, and the higher up-front cost of electric also likely dissuades some potential buyers. Charging network limitations, although being increasingly addressed, are set to add further to the huge challenge to attain a majority BEV US light-vehicle fleet – despite regulators' urgency to achieve this. There is therefore a reasonable likelihood that combustion engines will see a longer-than-expected tail, and hence, that PGM demand will be sustained for longer.

A range of structural impediments to BEV uptake could lend combustion engines a longer lease on life

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THE FUTURE OF PGMs: NAVIGATING A RAPIDLY CHANGING ENERGY LANDSCAPE

The future of PGMs: Navigating a rapidly changing energy landscape

Gyubin Hwang, Consultant, SFA (Oxford)

PGM industry stakeholders should take a broader perspective on opportunities from the green transition rather than focusing on hydrogen as the next one-trick pony.

As automotive demand plateaus, the platinum-group metal (PGM) industry faces an inflection point. But new opportunities await in hydrogen and adjacent spaces if strategic challenges can be addressed.

For decades, the fortunes of platinum, palladium and rhodium have risen and fallen with the automotive industry. Tailpipe emissions regulations drove the incorporation of PGMs into catalytic converters, securing demand. But with internal combustion engine (ICE, including hybrid) vehicle sales peaking in 2017 and electric vehicles gaining market share even in heavy-duty segments, this reliable source of demand will inevitably dry up. The industry must adapt or face decline.

ICE sales have already peaked, and the electrification of road transport is all but inevitable

Fortunately, PGMs possess unique catalytic properties that make them well-suited for enabling the transition to cleaner energy and a hydrogen economy. Realising this potential will require overcoming hurdles around cost, supply chain security and substitution risk. Successful navigation of this inflection point hinges on strategic changes to technology, partnerships, and business models.

PGMs can play an important role in the green economy but industry stakeholders need to carefully assess strategies

To better understand the future of PGMs, it is essential to reflect on the market forces that led to their adoption in emissions reduction systems in the automotive industry.

Environmental regulations: The introduction and enforcement of stricter environmental regulations played a significant role in the incorporation of PGMs into automotive emissions reduction systems. In the early 1970s, as the detrimental impact of vehicle emissions on air quality became more evident, governments around the world began implementing regulations to limit these emissions.

Technological advancements: Catalytic converter technologies were being developed by scientists at, among others, Engelhard Corporation and Johnson Matthey. Over time, advancements in catalyst technology enabled more efficient use of these metals even as emissions regulations became more stringent, allowing the PGM industry to scale up to meet global demand for cleaner, better vehicles.

Market demand: The growing public awareness of environmental issues, particularly around air quality, has led to increasing market demand for cleaner and more efficient vehicles. This has further incentivised automakers to invest in emissions reduction technologies, including PGM-based catalytic converters and more efficient engines.

These market forces have remained a constant in a changing world, ensuring that the latest and greatest technologies are more efficient and effective than the preceding generation. These trends will continue to drive new demand for PGMs in green energy economy sectors, but the high cost and scarcity of these metals could also spur efforts to find more sustainable and economical alternatives, underscoring the need for the PGM industry to continually innovate and adapt.

The technological market forces that drive PGM usage in the automotive sector continue to be relevant in the green transition

SFA's analysis of various industries and associated catalytic processes has highlighted three key strategies that could be employed to develop the PGM industry as a key partner to a green energy economy.

PGMs as key technology partners in the energy transition

- Promoting catalysts that are optimised for energy and chemical efficiency.
- Partnering with end-users to proactively shape technologies and policies
- Investing in recycling and recovery technologies

Promoting high-efficiency catalysis

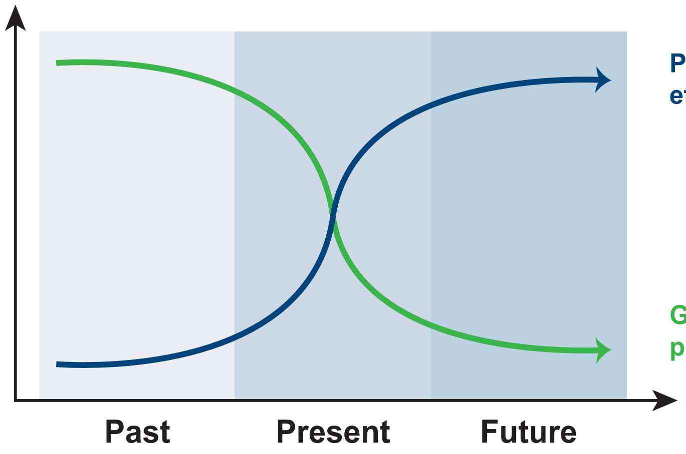
The global transition to a green, low-carbon future represents a pivotal moment for the chemicals industry. By supporting the development of industrial policies to drive the rapid uptake of green industrial chemistry, the PGM sector has the opportunity to play a key role in enhancing industrial efficiency via reduced energy consumption and lower life-cycle emissions.

PGM stakeholders should identify opportunities to establish greener, more efficient chemical value chains in line with environmental and geopolitical trends

Recent statistics show that over 75% of the global chemical industry's CO_2 emissions come from the production of the top 18 bulk chemicals. The three largest contributors are ammonia (22%), ethylene (20%) and methanol (13%). To reduce carbon emissions in chemical production, the focus should be on developing decarbonised synthetic pathways for these key chemicals that form feedstocks for many everyday materials.

Despite challenges ahead in the commercial adoption of PGMs in major industrial chemistry processes, it is clear that PGM catalysts' superior energetic properties can contribute to abating emissions from many essential industries.

We are near the tipping point in catalyst efficiency



Source: SFA (Oxford)

Case study

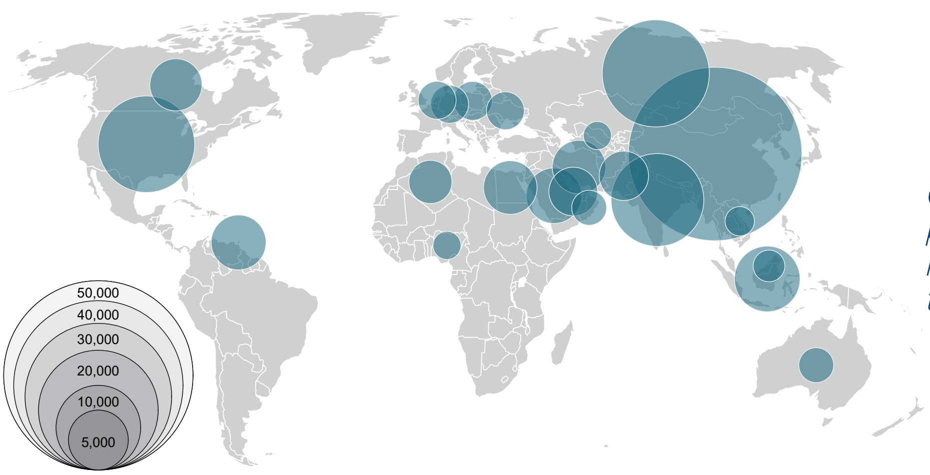
First commercialised over a century ago, the Haber-Bosch process produces about 200 million tonnes of ammonia per annum, primarily for fertiliser production. This massive scale makes it one of the world's most important industrial chemical processes.

However, the process is also highly energy-intensive. Conventional Haber-Bosch relies on fused-iron catalysts operating at extreme temperatures and pressures, accounting for ~2% of global energy use. The process would benefit enormously from efficiency improvements.[1]

New NH_3 synthesis catalysts, such as the ruthenium-based catalyst used in the KBR Advanced Ammonia Process (KAAP), thus seek to achieve high catalytic activity at milder temperatures and pressures, resulting in energy savings.[2]

The Haber-Bosch process transformed global food production with new synthetic fertilisers

Largest ammonia producers, ktpa



Source: SFA (Oxford), USGS

Global ammonia production capacity is more than 200 million tonnes per annum

However, SFA's techno-economic analysis of catalytic pathways shows that ruthenium catalysts are advantageous for small-scale production of NH_3 (<100 tpd), rather than for the >1,000 tpd plants in use now.

This means that in the near term, ruthenium-based NH_3 production is unlikely to gain significant market share despite its advantages. However, the twin trends of decarbonisation and localisation mean that efficient, modular and flexible manufacturing will play a major role in redefining the chemicals value chain.[3]

Despite the low market share currently held by ruthenium-based NH_3 production technologies, PGM industry stakeholders have the opportunity to push for the development of sustainable chemical facilities to accelerate commercial validation and market uptake.

By demonstrating the advantages of highly efficient PGM-based catalysts over conventional processes through robust techno-economic analyses, the sector has the opportunity to drive the transformation of the energy-chemicals nexus.

Partnering with end-users

Cross-sectoral participation as well as a greater understanding of policy drivers are also key factors to improve the market share of PGM-containing technologies in the hydrogen economy.

The future of PGM demand will be much more diverse than it is now. Stakeholders should identify areas of collaboration to support high-efficiency industrial transitions

PGM industry stakeholders often lack knowledge about emerging end-uses and therefore rely on traditional partnerships to secure demand for metal. These partners, such as automakers and catalyst manufacturers, are rapidly revising their strategies amidst increasing competition in the electric vehicle segment.

Against this backdrop, it is essential for the PGM industry to speak to industry certification agencies, start-ups and established operators alike to understand the key bottlenecks in scaling up the usage of high-efficiency catalysts in various sectors. Coupled with research partnerships, this could firmly establish the PGM sector as a key technological partner in the energy transition.

Case study

As industries across the world race to find cost-effective measures to reduce their carbon footprints, one sector that stands out as being particularly hard to decarbonise is passenger aviation. While there are efforts to develop hydrogen fuel cell- or battery-powered aircraft for short-range flights carrying fewer than a dozen people, long-haul passenger or freight aviation is a vastly different challenge in terms of both scale and difficulty.

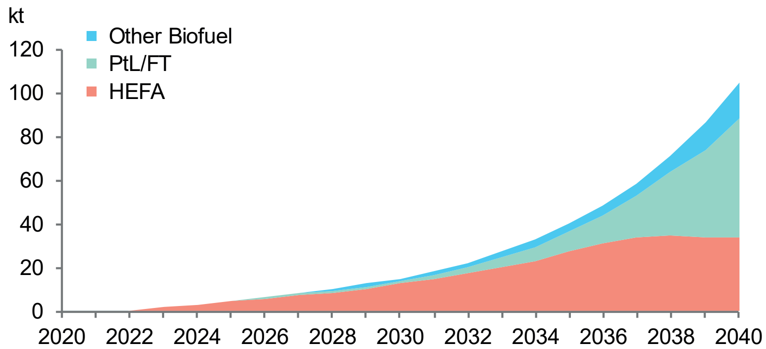
Fuel cell-powered aviation works for small aircraft but is difficult to implement for long-haul or freight...

A key pathway for decarbonisation is the use of sustainable aviation fuels (SAFs), which are drop-in substitutes that can be used in existing aviation infrastructure, including engines.

...that is where SAFs can advance decarbonisation, and add to PGM demand

SFA's analysis shows that the Fischer-Tropsch (FT) pathway will be the dominant technology to produce SAFs starting in the 2030s as feedstock availability for competing SAF pathways, particularly hydroprocessed esters and fatty acids (HEFA), begins to plateau. This process takes as inputs CO_2 or CO alongside H_2 and electricity, and produces useful long-chain hydrocarbons that can be used in existing combustion engines.

Sustainable aviation fuels production by pathway



Source: SFA (Oxford), IATA, Topsoe, IEA

Production pathways for SAFs are specified in the international standard ASTM D7566, which is the globally recognised fuel standard for the production and use of SAFs in existing aircraft engines.

This standard explicitly refers to Fe- and Co-based catalysis for SAF production via FT, which is likely to preclude the utilisation of other types of catalyst, including those that use PGMs. This poses a challenge to the uptake of Pt/Pd-based catalysts and promoters in this segment despite their superior selectivity towards high-value hydrocarbons — the approval processes for the relevant standards typically take 3-5 years in total and cost more than $5 million.

However, given that the fundamental chemical process is similar, there are likely to be opportunities to shorten this timeframe significantly and ensure that PGM catalysts are well-positioned to capitalise on a rapidly growing market.

Investing in recycling and recovery technologies

The importance of recycled metal will only increase

Despite the technological advantages conferred by some PGM technologies, many sub-sectors in the hydrogen industry are actively seeking technological pathways away from PGMs over concerns about ESG, supply security and costs. In fact, many technology researchers and start-ups are actively marketing “PGM-free” as a key selling point, highlighting the importance of using low-impact (and often cheaper) materials such as base metals.

Developing and improving technologies to efficiently collect and recover PGMs from spent catalysts from beyond the automotive sector will not only secure a more stable supply, but also serve to alleviate concerns about the future security and environmental impact of PGMs.

The transition to a circular economy is an inevitable trend, and the PGM industry needs to capitalise on this trend in order to be an essential partner to technology providers in the clean energy economy.

The future of the PGM industry is thus inextricably linked to the evolution of environmental regulations and technological advancements, two trends that are only accelerating.

As the world transitions towards cleaner energy sources and lower resource intensity, the PGM industry has the potential to make significant contributions in key areas of industrial economics even as the industry’s traditional dominant emission catalyst demand wanes.

However, the industry must keep in mind that future sources of demand for PGMs will have to come from more diverse areas. This means that business models must evolve to serve diverse customer segments beyond automotive incumbents, with a focus on addressing challenges around technological nascency, high cost, and supply chain concerns.

Above all, the PGM industry must remain flexible, adaptive and innovative in the face of a rapidly changing global energy landscape. Its future will be shaped not just by its ability to meet demand, but also by its ability to evolve alongside the global push towards a greener, more sustainable future.

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2. https://www.netl.doe.gov/research/carbon-management/energy-systems/gasification/gasifipedia/fertilizer-commercial-technologies

3. van Kranenburg, K., et al., *Small-Scale Flexible Plants*, TNO, https://www.nitechsolutions.co.uk/wp-content/uploads/2015/06/small-scale_flexible_plants-TNO-Achema2015.pdf

THE PGM MARKETS IN 2023

The PGM markets in 2023

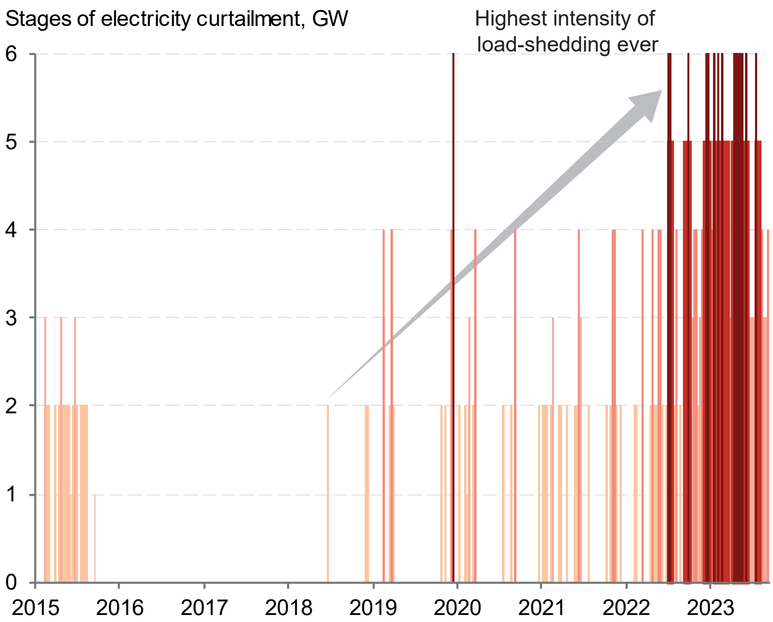
Dr. Ralph Grimble, SFA (Oxford)

The palladium market

The palladium market is forecast to have a significant deficit this year (>1 moz), owing to a combination of improved automotive demand and constrained primary and secondary supply. The semiconductor chip shortage has not been completely resolved but its impact is much reduced this year and light-vehicle production is expected to increase by over 5% to around 87 million units, which is better than predicted at the start of the year. This has helped to lift palladium demand despite the increasing use of tri-metal gasoline autocatalysts in which some platinum has replaced some palladium.

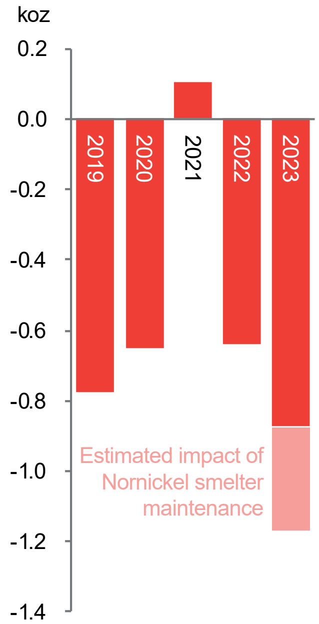
Prolonged load curtailment by Eskom earlier this year has hindered PGM processing in South Africa. Meanwhile, in Russia, Nornickel has scheduled the replacement of a smelter furnace to begin in September, and the lower end of the company's annual production guidance is almost 400 koz lower than last year's output. At the same time, the knock-on effects of the chip shortage on new car production have continued to be felt in the second-hand market with fewer vehicles being scrapped than would normally be the case, which has constrained PGM recycling.

South Africa load-shedding, all-time



Source: SFA (Oxford), EskomSePush. Note: Data to 31 August 2023.

Pd supply-demand balance



Source: SFA (Oxford)

Mine supply

Global palladium production is forecast to fall by 4% to 6.20 moz in 2023. Output in Russia is predicted to be almost 400 koz lower than last year owing to Nornickel replacing a furnace at the Nadezhda smelter. South African supply is expected to be modestly higher than last year but that includes the processing of some work-in-progress stock that had built up and was not processed in the first half of the year owing to Eskom's persistent load-shedding. Output in Zimbabwe is also forecast to increase as production at Zimplats' Mupani and Bimha mines continues to ramp up. A modest recovery is anticipated in North America as Stillwater mine moves on from the flooding incident last year, although an accident that damaged a shaft has hindered that progress.

Russian output impacted by smelter maintenance at Norilsk

Recycling

Secondary palladium supply is projected to slip by 3% to 2.46 moz, as a result of lower autocatalyst recycling which has been underperforming expectations, particularly in Western Europe and North America. This is related partly to the constrained new vehicle production over the last couple of years which has led to second-hand cars being kept on the road for longer, and partly to the decline in the palladium and rhodium prices which has resulted in some collectors holding on to material hoping for a rebound in the prices. The auto market in China has been relatively robust despite the weaker economic situation and so autocatalyst recycling is still expected to rise modestly there this year, partly offsetting the declines elsewhere.

Autocatalyst recycling will fall to lowest level in two years

Demand

Global palladium demand is forecast to expand by 2% to 9.83 moz this year. Light-vehicle production has been more robust than anticipated at the start of the year and this is helping to lift automotive demand despite ongoing gains in BEV market share and the wider use of platinum in gasoline three-way catalysts. This more than offsets a further modest decline in each of the industrial sectors' requirements.

Automotive demand

Automotive palladium demand is predicted to climb by 3% to 8.11 moz in 2023. The chip shortage has not been completely resolved but its impact is now much reduced and light-vehicle production is projected to be around 4.5 million units higher than last year. Light-vehicle sales in Western Europe, in particular, have been stronger than anticipated earlier this year despite the weak economic situation.

Light-vehicle production growth boosts automotive demand, year-on-year

Industrial demand

Industrial use of palladium is estimated to fall by 2% to 1.48 moz. Chemical, dental, electrical and other end-uses are all predicted to contract slightly this year. The electrical sector is still cutting its palladium use in multi-layer ceramic capacitors (MLCCs), and palladium's high price and the more cosmetically appealing alternative materials continue to squeeze palladium's dental usage.

Investment

Palladium ETF holdings have risen by 47 koz to 507 koz in late August. ETF holdings in the US, UK, Switzerland and South Africa all saw moderate increases. However, speculative futures positions on NYMEX have been net short for two years. The non-commercial traders' net short position was 936 koz in late August after having been over 1 moz earlier in the month, at which point the short positions were 1.44 moz while the long positions were 0.42 moz.

Short positions in palladium reached record levels earlier this year

The platinum market

The platinum market is forecast to have a moderate deficit of 310 koz (excluding investment) in 2023, as demand is expanding whereas primary and secondary supply have hit some snags. Automotive demand has surged as light-vehicle production recovers and platinum is more widely used in gasoline three-way catalysts. Industrial consumption remains robust and jewellery demand is expected to improve slightly after a dismal 2022.

Refined platinum supply is estimated to be little changed year-on-year at 5.52 moz. Platinum production in South Africa is predicted to climb by 3% to 4.18 moz. However, that is dependent on processing of the work-in-progress stock that has built up owing to a combination of smelter maintenance and load-shedding. Russian output is expected to be limited to 610 koz owing to the replacement of a furnace at the Nadezhda smelter. North American output is predicted to jump by 10% as the Stillwater mine recovers from the flooding incident in 2022, and production in Zimbabwe is also expected to trend higher.

North American production to rise 10% in 2023

Secondary platinum supply is forecast to be flat at 1.45 moz this year. Autocatalyst recycling is likely to dip owing to fewer old vehicles being scrapped, whereas jewellery recycling is projected to be somewhat higher as jewellery demand improves and activity picks up in China.

Platinum demand benefits from substitution for palladium in autocatalysts

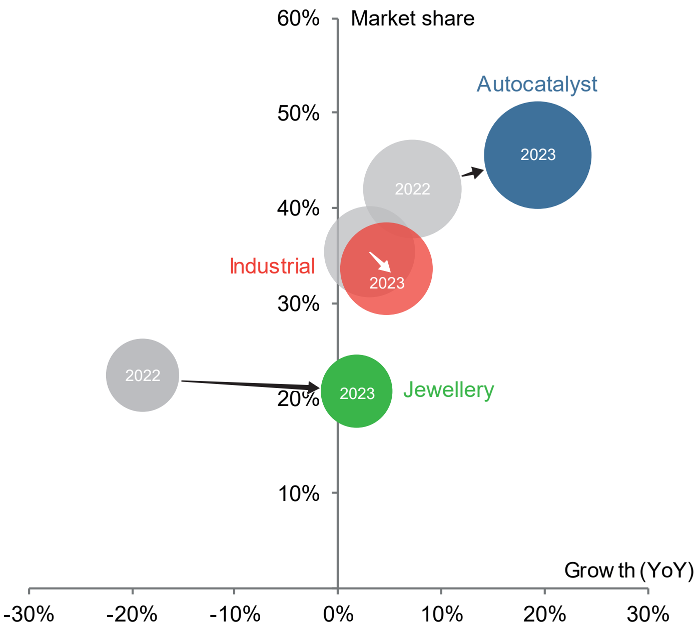
Automotive demand is estimated to jump by 18% to 3.28 moz in 2023. Light-vehicle production has continued to climb as the worst of the chip shortage is now in the rear-view mirror and the use of gasoline autocatalysts with platinum substituted in place of some palladium has become more widespread. These two factors have contributed the majority of the growth but the heavy-duty market in China is also adding some demand as it recovers after a poor 2022.

Global platinum jewellery demand is predicted to climb by 2% to 1.47 moz this year. After a very weak year last year, platinum jewellery consumption in China is projected to recover somewhat, although platinum faces greater competition from gold as the price performance of the two metals has diverged. The Indian economy is relatively robust which is supportive of further gains in platinum jewellery requirements. Demand in Japan is expected to edge up slightly. In contrast, jewellery demand in Europe and North America is forecast to drop owing to the weaker economic situation in those regions.

Industrial platinum consumption is projected to expand by 5% to 2.31 moz in 2023, mostly as a result of growth in the glass and chemical sectors. Chemical demand is predicted to be up this year, helped by a recovery in China after a difficult year in 2022 when Covid lockdowns negatively impacted the economy. The glass sector sees continued capacity expansions in China. Petroleum industry usage slips slightly as capacity increases are limited with OPEC+ cutting crude oil production.

Platinum demand expected to grow across all major sectors

Changes to platinum demand, 2022-2023



Source: SFA (Oxford). Note: size of bubbles represents demand in troy ounces.

The rhodium market

A second year of an under-supplied market

The rhodium market is predicted to have a deficit of 85 koz in 2023, although sales of stock by the glass industry have added liquidity to the market. Automotive demand is higher this year as light-vehicle production has continued to rise, while both primary and secondary supply have struggled amid power supply problems in South Africa and with fewer second-hand vehicles being scrapped.

Automotive rhodium demand is projected to grow by 4% to 990 koz. Light-vehicle production forecasts have been lifted as the chip shortage has eased and car sales have held up in Europe and North America despite rising inflation and higher interest rates pressuring consumers' disposable incomes.

Industrial rhodium requirements are estimated to fall by 15% to 85 koz owing to net supply from the glass sector more than outweighing higher chemical sector needs as demand rebounds in China. As the rhodium price rose it was thrifted out of glass manufacturing equipment and some fibreglass manufacturers have been returning that metal to the market, resulting in the sector becoming a net supplier of metal.

Supply forecast to fall from South African and Russian mines

Primary rhodium supply is forecast to drop by 4% to 705 koz. Production in South Africa is projected to fall by 2% to 595 koz, as declining yield from Kroondal mine outweighs modest gains at some other operations and some work-in-progress stock being processed. Russian rhodium output is anticipated to dip by 5 koz owing to a furnace being replaced at Nadezhda, while production in North America and Zimbabwe is expected to be little changed. Recycled rhodium is forecast to contract by 7% as the lack of new vehicles over the last two years has led to stronger demand for second-hand vehicles, with the result that fewer old vehicles are being scrapped.

The price outlook for the next six months

Palladium: $1,175/oz

Weak economic outlook

The fundamentals seem positive for the palladium price: automotive demand is rising as light-vehicle sales continue to grow, supply is constrained, and the market is in a large deficit. Unfortunately, that has not helped to support the price, which has continued to decline from its record high of $3,339/oz set in March last year. Strategic stocks that were built up as a result of the supply uncertainty after the Russian invasion of Ukraine and Eskom's problems in South Africa have been sold down as the situation has not been as bad as was feared, adding liquidity to the market and depressing the price.

The economic outlook is deteriorating, growth in China is not as strong as anticipated and the US and Eurozone are on the cusp of recessions, if not already in recession. Consumers' disposable income is being cut by inflation and tightening lending standards, and rising interest rates are making the financing of vehicle purchases more expensive. This does not bode well for automotive demand. Nornickel's work on a replacement smelter furnace could reduce liquidity for a while, but Nornickel has the palladium fund to provide metal to its customers during periods of lower refined output. The price is predicted to continue to move lower and average $1,175/oz over the next six months.

Platinum: $920/oz

Downside risk exists

The platinum market is forecast to be in deficit this year. Although platinum supply is less constrained than palladium or rhodium, demand is growing strongly. The Eskom load-shedding situation is not as dire as it was earlier in the year but there is still a risk that it could worsen and curb refined output. Automotive demand is being boosted by platinum's use in gasoline autocatalysts, and industrial demand is projected to show robust growth.

However, platinum demand is now more susceptible to falling auto production, which is a risk if the US and Eurozone enter recessions, and a weakening economic outlook in China adds downside risk to industrial demand. The platinum price has held up better than would be expected given the depreciation of the rand against the US dollar, but the risks appear to be to the downside and the price is forecast to average $920/oz over the next six months.

Rhodium: $3,950/oz

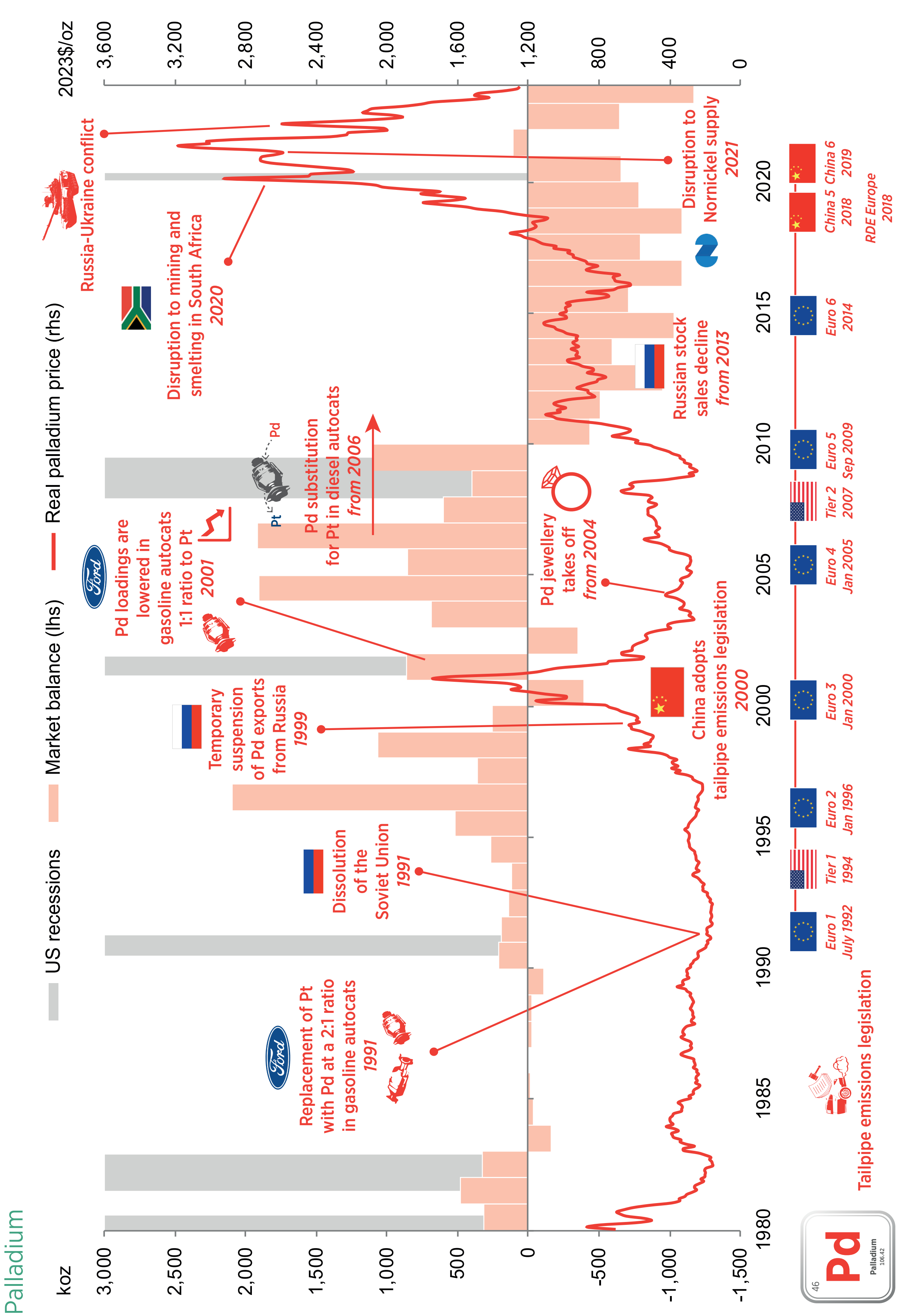
Prices remain soft

As for palladium, the improvement in light-vehicle production this year is lifting rhodium demand and with supply underperforming, the rhodium market is predicted to be in deficit. However, the price may have been pushed lower by sales of stock from the glass industry after thrifting of the rhodium content in manufacturing equipment.

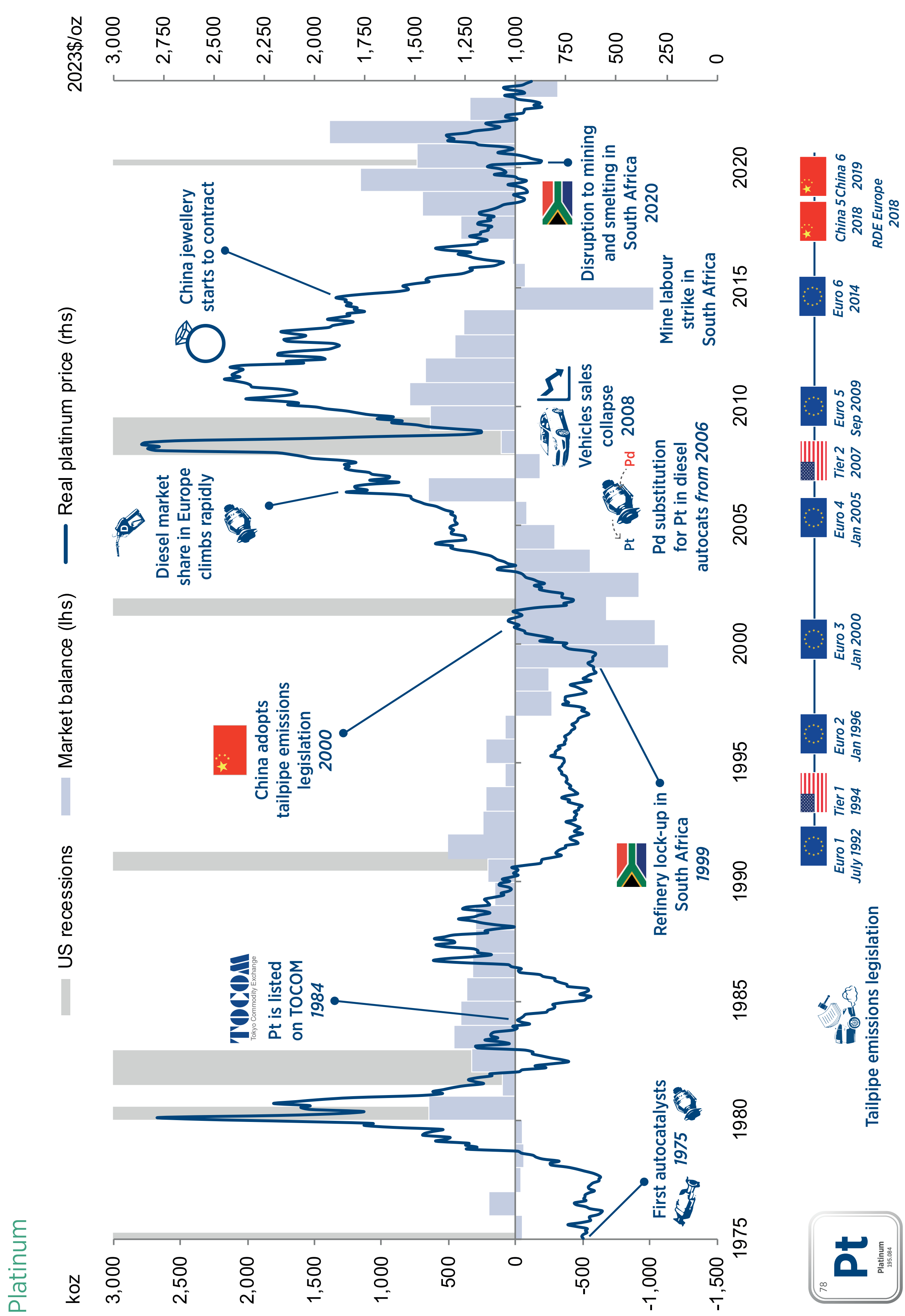
Rhodium has a 12-month lead on palladium in its price decline, having hit its record price in 2021. Price risk for rhodium is more nuanced because it has now fallen by ~87% from its peak, which is in the region of typical retracements after historical price spikes. That said, the price is still relatively high by historical standards and without the deficit the price might have fallen further already.

Further price volatility cannot be ruled out if auto demand holds up but, as demand risks appear to be to the downside as the economic outlook weakens, the price is forecast to average $3,950/oz over the next six months.

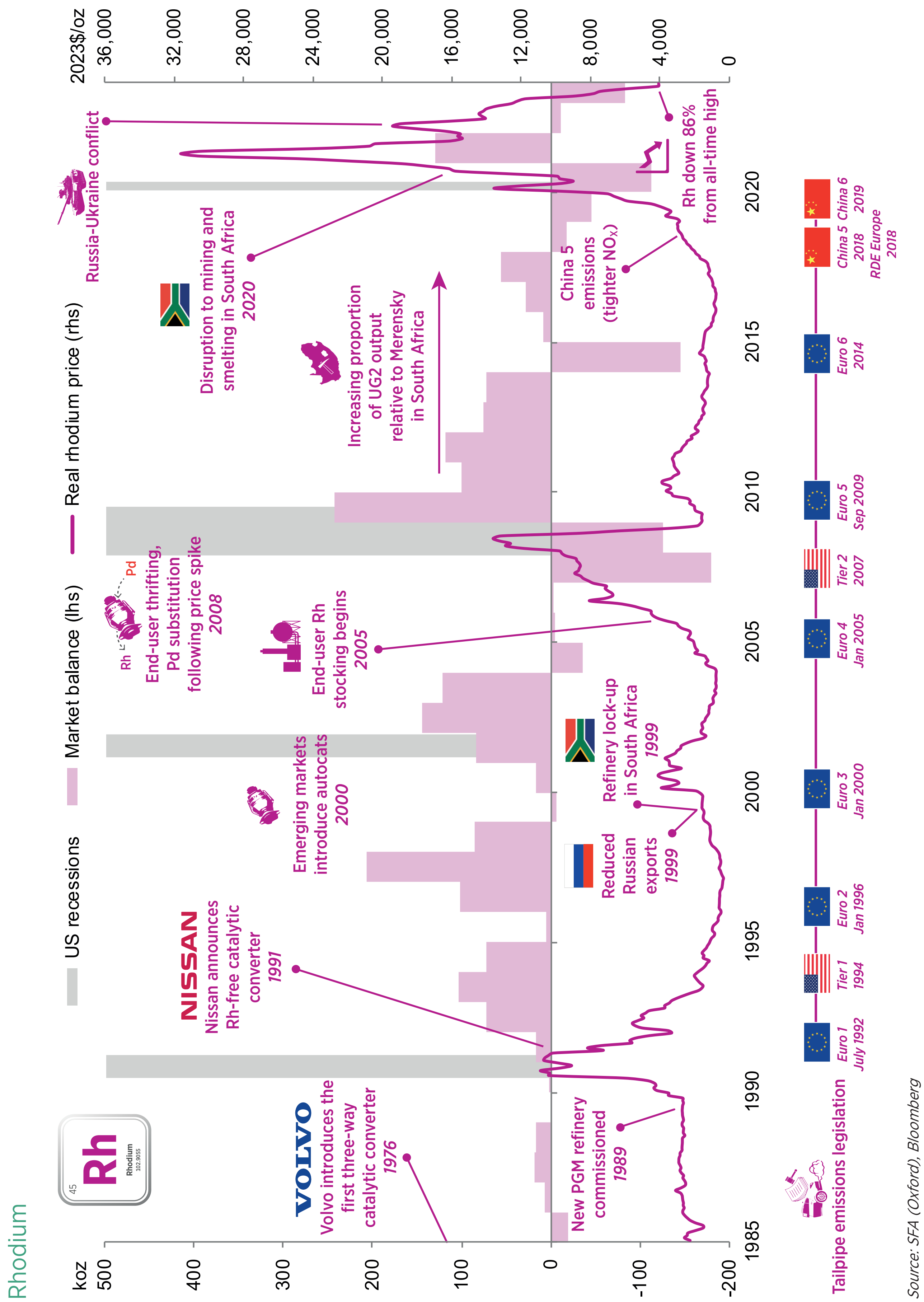
PGM PRICE HISTORY



Source: SFA (Oxford), Bloomberg



Source: SFA (Oxford), Bloomberg


Rhodium
US recessions
Market balance (lhs)
Real rhodium price (rhs)
koz
2023$/oz
Rh
Rhodium
VOLVO
Volvo introduces the first three-way catalytic converter 1976
New PGM refinery commissioned 1989
NISSAN
Nissan announces Rh-free catalytic converter 1991
Emerging markets introduce autocats 2000
Reduced Russian exports 1999
Refinery lock-up in South Africa 1999
End-user thrifting, Pd substitution following price spike 2008
End-user Rh stocking begins 2005
Increasing proportion of UG2 output relative to Merensky in South Africa
Disruption to mining and smelting in South Africa 2020
China 5 emissions (tighter NOx)
Russia-Ukraine conflict
Rh down 86% from all-time high
Tailpipe emissions legislation
Euro 1 July 1992
Tier 1 1994
Euro 2 Jan 1996
Euro 3 Jan 2000
Euro 4 Jan 2005
Tier 2 2007
Euro 5 Sep 2009
Euro 6 2014
China 5 2018
RDE Europe 2018
China 6 2019
Source: SFA (Oxford), Bloomberg

APPENDIX

Palladium supply-demand balance

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Primary supply									
Regional									
South Africa	2,560	2,375	2,530	2,500	2,555	1,845	2,755	2,240	2,320
Russia	2,605	2,555	2,740	2,670	2,870	2,810	2,585	2,790	2,405
Zimbabwe	325	395	395	380	385	405	395	420	440
North America	995	1,065	985	1,035	975	950	840	740	770
Other	455	420	415	395	395	385	265	270	270
Total	**6,940**	**6,810**	**7,065**	**6,975**	**7,180**	**6,395**	**6,845**	**6,460**	**6,200**
Demand & recycling									
Autocatalyst									
Gross demand	7,580	7,930	8,150	8,480	8,625	7,595	7,760	7,885	8,110
Recycling	1,605	1,710	1,920	2,035	2,175	2,010	2,380	2,095	2,040
Net demand	5,975	6,220	6,230	6,440	6,450	5,590	5,385	5,790	6,070
Jewellery									
Gross demand	245	240	215	215	215	200	215	225	235
Recycling	80	80	60	60	60	55	60	65	70
Net demand	165	165	155	155	155	145	155	160	165
Industrial demand	**1,930**	**1,900**	**1,840**	**1,840**	**1,715**	**1,640**	**1,620**	**1,515**	**1,480**
Other recycling	**430**	**390**	**380**	**370**	**365**	**335**	**415**	**365**	**350**
Gross demand	**9,755**	**10,075**	**10,205**	**10,530**	**10,555**	**9,440**	**9,595**	**9,625**	**9,825**
Recycling	**2,115**	**2,180**	**2,360**	**2,465**	**2,600**	**2,395**	**2,855**	**2,525**	**2,455**
Net demand	**7,440**	**7,650**	**7,895**	**7,840**	**7,895**	**7,785**	**6,875**	**6,565**	**6,730**
Market balance									
Balance (before ETFs)	-700	-1,090	-785	-1,090	-775	-650	105	-640	-1,165
ETFs (stock allocation)	-665	-640	-375	-560	-90	-115	50	-90	
Balance after ETFs	**-35**	**-450**	**-410**	**-525**	**-690**	**-535**	**55**	**-550**	

Source: SFA (Oxford)

Palladium demand and recycling summary

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Autocatalyst									
North America	1,855	1,935	1,850	1,860	1,815	1,460	1,475	1,495	1,650
Western Europe	1,790	1,685	1,705	1,720	1,670	1,260	1,190	1,165	1,185
Japan	745	775	800	835	870	755	725	710	700
China	1,725	1,990	2,070	2,080	2,305	2,505	2,615	2,610	2,650
India	180	220	240	315	285	240	315	390	415
RoW	1,285	1,325	1,490	1,660	1,675	1,380	1,435	1,510	1,505
Total	**7,580**	**7,930**	**8,150**	**8,480**	**8,625**	**7,595**	**7,760**	**7,885**	**8,110**
Jewellery									
North America	35	35	35	35	35	35	35	40	40
Western Europe	55	55	55	55	55	50	50	55	55
Japan	50	50	50	50	50	45	45	50	50
China	75	75	50	50	50	50	55	60	65
RoW	25	25	25	25	25	25	25	25	25
Total	**245**	**240**	**215**	**215**	**215**	**200**	**215**	**225**	**235**
Industrial									
North America	385	370	340	305	295	245	250	245	235
Western Europe	320	325	310	295	290	260	260	250	235
Japan	420	400	360	335	300	255	245	235	225
China	375	375	415	485	415	485	510	445	430
RoW	435	430	410	420	415	395	350	340	360
Total	**1,930**	**1,900**	**1,840**	**1,840**	**1,715**	**1,640**	**1,620**	**1,515**	**1,480**
Total gross demand									
North America	2,275	2,345	2,225	2,200	2,150	1,740	1,765	1,780	1,925
Western Europe	2,160	2,065	2,070	2,070	2,015	1,570	1,505	1,470	1,475
Japan	1,220	1,225	1,210	1,220	1,215	1,055	1,020	990	975
China	2,175	2,440	2,535	2,620	2,770	3,040	3,185	3,110	3,140
RoW	1,925	2,000	2,165	2,420	2,400	2,035	2,125	2,270	2,310
Total	**9,755**	**10,075**	**10,205**	**10,530**	**10,555**	**9,440**	**9,595**	**9,625**	**9,825**
Recycling									
Autocatalyst									
North America	895	960	1,060	1,135	1,190	1,130	1,300	1,015	910
Western Europe	270	260	305	330	335	300	380	285	245
Japan	125	125	145	180	200	185	205	195	205
China	115	160	165	155	165	150	180	245	300
RoW	205	205	245	240	290	240	315	350	375
Total	**1,605**	**1,710**	**1,920**	**2,035**	**2,175**	**2,010**	**2,380**	**2,095**	**2,040**
Jewellery									
Japan	20	20	20	20	20	15	15	20	20
China	60	60	40	40	40	40	45	45	50
Total	**80**	**80**	**60**	**60**	**60**	**55**	**60**	**65**	**70**
WEEE									
North America	85	80	75	70	70	60	70	60	55
Western Europe	80	75	80	80	75	70	75	70	65
Japan	170	135	130	125	120	110	120	110	100
China	25	35	35	40	45	45	60	55	60
RoW	65	60	60	60	60	55	90	70	70
Total	**430**	**390**	**380**	**370**	**365**	**335**	**415**	**365**	**350**
Total recycling									
North America	980	1,040	1,130	1,205	1,255	1,190	1,370	1,075	970
Western Europe	350	335	385	410	410	370	455	355	310
Japan	315	280	295	325	335	310	345	325	325
China	195	255	240	235	250	235	285	350	410
RoW	270	265	305	295	345	295	405	425	445
Total	**2,115**	**2,180**	**2,360**	**2,465**	**2,600**	**2,395**	**2,855**	**2,525**	**2,455**

46 Pd 106.42 Palladium

Source: SFA (Oxford)

Platinum supply-demand balance

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Primary supply									
Regional									
South Africa	4,480	4,265	4,385	4,470	4,405	3,260	4,715	3,975	4,010
Russia	710	715	720	665	710	700	640	655	610
Zimbabwe	405	490	480	465	460	480	470	495	515
North America	365	390	360	345	350	330	255	250	260
Other	200	185	185	180	185	175	125	125	130
Total	**6,165**	**6,045**	**6,125**	**6,130**	**6,105**	**4,950**	**6,210**	**5,500**	**5,520**
Demand & recycling									
Autocatalyst									
Gross demand	3,260	3,355	3,295	3,110	2,830	2,365	2,690	2,875	3,410
Recycling	1,185	1,210	1,325	1,420	1,495	1,300	1,415	1,160	1,085
Net demand	2,075	2,140	1,970	1,690	1,335	1,060	1,275	1,720	2,320
Jewellery									
Gross demand	2,835	2,510	2,450	2,245	2,090	1,560	1,780	1,445	1,470
Recycling	515	625	560	505	500	410	400	250	315
Net demand	2,325	1,885	1,890	1,740	1,595	1,150	1,380	1,195	1,155
Industrial demand	**1,840**	**1,970**	**1,845**	**1,965**	**2,010**	**1,990**	**2,170**	**2,195**	**2,310**
Hydrogen	**25**	**45**	**50**	**70**	**45**	**45**	**50**	**90**	**85**
Other recycling	**25**	**25**	**30**	**30**	**30**	**30**	**45**	**40**	**40**
Gross demand	**7,955**	**7,880**	**7,640**	**7,385**	**6,970**	**5,955**	**6,690**	**6,605**	**7,270**
Recycling	**1,720**	**1,860**	**1,915**	**1,955**	**2,020**	**1,745**	**1,860**	**1,445**	**1,445**
Net demand	**6,240**	**6,020**	**5,725**	**5,435**	**4,950**	**4,210**	**4,830**	**5,160**	**5,830**
Market balance									
Balance (before ETFs)	-75	25	400	695	1,155	740	1,380	340	-310
ETFs (stock allocation)	-240	-10	100	-240	995	505	-265	-565	
Balance after ETFs	**165**	**30**	**305**	**935**	**160**	**235**	**1,645**	**905**	

Source: SFA (Oxford)

Platinum demand and recycling summary

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Autocatalyst									
North America	480	410	390	390	375	285	375	445	505
Western Europe	1,450	1,630	1,555	1,340	1,150	805	750	775	910
Japan	510	450	435	425	400	305	290	285	320
China	145	190	215	210	230	450	660	665	855
India	180	175	180	200	160	120	185	225	230
RoW	495	500	520	540	515	400	435	485	585
Total	**3,260**	**3,355**	**3,295**	**3,110**	**2,830**	**2,365**	**2,690**	**2,875**	**3,410**

Source: SFA (Oxford)

Platinum demand and recycling summary (continued)

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Jewellery									
North America	250	265	280	280	275	210	255	265	235
Western Europe	235	240	250	255	260	175	190	175	165
Japan	340	335	340	345	330	245	260	270	270
China	1,765	1,450	1,340	1,095	945	755	875	530	570
India	180	145	175	195	210	120	135	160	165
RoW	70	70	75	75	75	55	60	50	60
Total	**2,835**	**2,510**	**2,450**	**2,245**	**2,090**	**1,560**	**1,780**	**1,445**	**1,470**
Industrial									
North America	260	390	350	350	300	230	280	335	415
Western Europe	270	280	275	295	285	260	255	270	260
Japan	95	85	65	100	105	120	100	105	100
China	650	725	645	550	620	820	1,020	910	925
RoW	560	490	505	665	700	560	515	580	610
Total	**1,840**	**1,970**	**1,845**	**1,965**	**2,010**	**1,990**	**2,170**	**2,195**	**2,310**
Hydrogen									
North America	5	10	10	15	10	10	10	10	10
Western Europe	0	5	0	0	0	0	0	10	10
Japan	15	25	30	35	15	20	25	30	30
China	0	0	0	0	0	0	0	25	20
RoW	5	5	5	20	15	10	10	15	10
Total	**25**	**45**	**50**	**70**	**45**	**45**	**50**	**90**	**85**
Total gross demand									
North America	995	1,075	1,030	1,035	965	735	920	1,050	1,175
Western Europe	1,955	2,160	2,085	1,895	1,690	1,240	1,200	1,230	1,345
Japan	955	890	870	905	850	695	680	685	720
China	2,565	2,365	2,200	1,860	1,795	2,020	2,555	2,130	2,370
RoW	1,490	1,385	1,455	1,695	1,675	1,265	1,335	1,510	1,660
Total	**7,955**	**7,880**	**7,640**	**7,385**	**6,970**	**5,955**	**6,690**	**6,605**	**7,270**
Recycling									
Autocatalyst									
North America	505	535	585	640	645	575	580	450	405
Western Europe	370	400	440	465	505	425	500	365	335
Japan	95	95	100	110	110	100	115	110	115
China	55	40	40	35	40	30	35	40	40
RoW	155	150	160	170	190	170	185	190	195
Total	**1,185**	**1,210**	**1,325**	**1,420**	**1,495**	**1,300**	**1,415**	**1,160**	**1,085**
Jewellery									
North America	5	5	5	5	5	5	5	5	5
Western Europe	5	5	5	5	5	5	5	5	5
Japan	160	150	160	145	140	110	115	105	115
China	335	460	385	340	340	285	265	125	185
RoW	5	5	5	5	10	10	10	10	10
Total	**515**	**625**	**560**	**505**	**500**	**410**	**400**	**250**	**315**
WEEE	**25**	**25**	**30**	**30**	**30**	**30**	**45**	**40**	**40**
Total recycling									
North America	520	545	600	650	660	585	595	465	415
Western Europe	380	410	450	480	520	440	515	380	350
Japan	255	245	265	260	255	210	235	220	230
China	395	500	425	380	385	320	305	170	235
RoW	165	165	175	185	205	190	210	210	215
Total	**1,720**	**1,860**	**1,915**	**1,955**	**2,020**	**1,745**	**1,860**	**1,445**	**1,445**

Source: SFA (Oxford)

Rhodium supply-demand balance

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Primary supply									
Regional									
South Africa	620	615	620	625	640	475	670	595	570
Russia	70	70	75	75	80	80	75	75	70
Zimbabwe	35	45	45	40	40	45	40	45	45
North America	30	25	25	20	20	20	20	15	15
Other	10	10	10	10	10	10	5	5	5
Total	**765**	**765**	**775**	**770**	**790**	**630**	**815**	**735**	**705**
Demand & recycling									
Autocatalyst									
Gross demand	865	835	870	915	1,025	940	935	955	990
Recycling	260	280	305	335	355	330	365	310	290
Net demand	605	555	565	580	670	605	565	645	705
Industrial demand	**155**	**180**	**155**	**210**	**170**	**135**	**120**	**105**	**90**
Other recycling	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**3**	**2**
Gross demand	**1,020**	**1,015**	**1,025**	**1,125**	**1,195**	**1,075**	**1,055**	**1,060**	**1,080**
Recycling	**265**	**280**	**305**	**340**	**355**	**335**	**370**	**310**	**290**
Net demand	**755**	**735**	**720**	**790**	**835**	**740**	**685**	**745**	**790**
Market balance									
Balance (before ETFs)	10	30	55	-20	-45	-115	130	-10	-85
ETFs (stock allocation)	-5	5	-20	-50	-15	-10	-5	0	
Balance after ETFs	**15**	**25**	**75**	**30**	**-30**	**-105**	**135**	**-10**	

Source: SFA (Oxford)

Rhodium demand and recycling summary

koz	2015	2016	2017	2018	2019	2020	2021	2022	2023f
Gross demand									
Autocatalyst									
North America	240	235	230	225	220	175	170	185	195
Western Europe	250	210	215	230	290	225	215	220	245
Japan	125	125	125	125	130	110	100	100	100
China	110	130	150	160	205	280	290	280	270
India	15	20	20	25	25	20	25	30	35
RoW	120	115	130	150	155	130	130	140	145
Total	**865**	**835**	**870**	**915**	**1,025**	**940**	**935**	**955**	**990**
Industrial									
North America	255	255	245	245	240	190	185	200	210
Western Europe	260	225	225	245	300	235	220	225	250
Japan	135	135	135	140	140	120	110	110	110
China	190	225	225	250	280	345	355	325	305
RoW	175	180	190	250	235	180	180	195	200
Total	**1,020**	**1,015**	**1,025**	**1,125**	**1,195**	**1,075**	**1,055**	**1,060**	**1,080**
Total gross demand									
North America	255	255	245	245	240	190	185	200	210
Western Europe	260	225	225	245	300	235	220	225	250
Japan	135	135	135	140	140	120	110	110	110
China	190	225	225	250	280	345	355	325	305
RoW	175	180	190	250	235	180	180	195	200
Total	**1,020**	**1,015**	**1,025**	**1,125**	**1,195**	**1,075**	**1,055**	**1,060**	**1,080**
Recycling									
Autocatalyst									
North America	150	160	165	180	190	180	200	155	140
Western Europe	45	50	55	60	65	60	70	50	45
Japan	30	35	35	45	45	40	45	40	45
China	10	5	5	5	5	5	10	15	15
RoW	25	30	35	45	50	45	45	45	45
Total	**260**	**280**	**305**	**335**	**355**	**330**	**365**	**310**	**290**

Source: SFA (Oxford)

GLOSSARY OF TERMS

BEV
Battery electric vehicle.

CARB
California Air Resources Board, or CARB, is a state-wide "clean air agency" that enforces stricter emissions laws than the federal Environmental Protection Agency.

DRC
Democratic Republic of the Congo.

ESG
Environmental, social & governance.

ETF
Exchange-traded fund.

FTA
Free trade agreement.

Gross demand
A measure of intensity of use.

HEFA
The process to produce renewable aviation fuels from a wide array of hydroprocessed esters and fatty acids.

ICE
Internal combustion engine.

IRA
The Inflation Reduction Act.

koz
A thousand troy ounces.

Load-shedding
The action of switching off parts of South Africa's electricity grid in a planned and controlled manner due to insufficient capacity or to avoid a countrywide blackout.

moz
A million troy ounces.

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

NYMEX
New York Mercantile Exchange.

OEM
Original equipment manufacturer.

OPEC+
The nations of the Organization of the Petroleum Exporting Countries, plus Bahrain, Brunei, Kazakhstan, Malaysia, Mexico, Oman, Russia, South Sudan and Sudan.

oz
Troy ounce.

PGMs
Platinum-group metals.

PHEV
Plug-in hybrid electric vehicle.

Primary supply
Mine production.

PtL/FT
Power-to-liquid and Fischer-Tropsch processes.

Secondary supply
Recycling output.

Thrifting
Using less metal in order to reduce costs.

TOCOM
Tokyo Commodity Exchange.

tpd
Metric tonnes per day.

USGS
United States Geological Survey.

WEEE
Waste electrical and electronic equipment.

ZEV
Zero-emission vehicle.

Currency symbols

$ US dollar.

METHODOLOGY

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

Gross demand is a measure of intensity of use.

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

Automotive demand is based on vehicle production data not sales.

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Heraeus Precious Metals is globally leading in the precious metals industry. The company is part of the Heraeus Group and covers the value chain from trading to precious metals products to recycling. It has extensive expertise in all platinum group metals as well as gold and silver.

With about 3,000 employees at 15 sites worldwide, Heraeus Precious Metals offers a broad portfolio of products that are essential for many industries such as the automotive, chemicals, semiconductor, pharmaceutical, hydrogen and jewelry industry.

By 2025 Heraeus Precious Metals will be the first company in the industry that operates carbon neutral.

The Heraeus Group is a broadly diversified and globally leading family-owned technology company, headquartered in Hanau, Germany. The company's roots go back to a family pharmacy started in 1660. Today, Heraeus bundles diverse activities in the Business Platforms Metals and Recycling, Healthcare, Semiconductor and Electronics as well as Industrials. Customers benefit from innovative technologies and solutions based on broad materials expertise and technological leadership.

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