19 PLATINUM-GROUP METALS

19.1 Overview

19.1.1 Overview of platinum group metals in general

Platinum Group Metals (PGMs), sometimes referred to as the platinum-group elements (PGE), comprise six elements: platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os). The platinum group metals show very similar chemical properties, while their physical properties vary. Common characteristics of the PGMs, which are the basis of most of their applications, include outstanding catalytic activity, very high resistance to corrosion and oxidation ("noble metals"), very high melting point, high density, excellent electrical conductivity, general non-toxicity (except Os), ability to form alloys, excellent resistance to wear and tarnish, and stability to high temperatures. The PGMs are considered as precious metals, like gold and silver; nevertheless, they are widely used metals and essential for certain industrial applications. The PGM are scarce natural resources that occur together in nature. Platinum and palladium are of major commercial significance, with rhodium the next most important. Given the greater commercial importance and use of platinum and palladium, there is generally much more information available on platinum and palladium than for the other three PGMs. Osmium is a little-used, toxic metal, for which there is virtually no quantitative data on any part of its value chain. For this reason, it is not feasible to carry out a quantitative criticality assessment using the methodology employed in the 2017 criticality assessment.

This factsheet deals essentially with the PGMs as a group of metals, illustrating the commonalities of the group. This "general factsheet", while their particularities are addressed in five metal "specific factsheets". Quantitative information on PGMs in this factsheet are usually aggregates of the figures shown in the specific factsheets. For further information on individual PGMs and their criticality assessment, please refer to the factsheets for platinum, palladium, rhodium, ruthenium and iridium.

Due to the geographic location of PGM reserves, the PGM mining activities are concentrated in very few countries. The lower number of mines and the high grade of specialisation required, results in a low number of companies mining and refining PGMs. In the short term, the introduction of stricter emission standards for motor vehicles is expected to contribute to the demand for platinum, palladium and rhodium used in the fabrication of autocatalysts. An increase in the adoption of fuel cells technology is expected to be supportive for platinum demand.

PGM prices are high and typically volatile because of the limited availability in nature, and the low flexibility for accommodating rapid changes in demand.

The global demand for PGMs for all applications is about 635 tonnes per year (average over the period 2016-2018).

PGMs are of great importance in many modern technologies and products. The catalytic properties of PGMs are the basis of their most important applications in emission control systems in vehicles and in industrial process catalysts for bulk-chemical manufacture and petroleum refining. Other applications include electronics, glass manufacturing, jewellery, dental and medical special alloys. There are no effective substitutes that provide the same performance as the PGMs. In many applications, a PGM can substitute for another one. Platinum and palladium can be interchanged to a certain extent in autocatalysts, depending on the prices and demand/supply for each; however, they cannot be considered fully substitutable.

The global known PGM resources are estimated to be in excess of 100,000 tonnes. South Africa hosts by far the world's most abundant resources (68% of the total), while Russia and Zimbabwe also hold a significant proportion of global PGM resources of 17% and 9%, respectively. Reserves of PGM are estimated at 17,000 tonnes, with a similarly high geographical concentration and distribution as resources. 92% of the world PGM reserves are located in South Africa, Russia, and Zimbabwe together (Mudd, Jowitt and Werner, 2018).

PGMs are scarce natural resources produced in low volumes. Global primary production of PGMs in 2017 amounted to 447 tonnes (182 tonnes platinum; 208 tonnes palladium; 23 tonnes rhodium, 34 tonnes iridium and ruthenium). The largest primary supplier of PGMs worldwide is South Africa, followed by Russia. Supply from South Africa is dominated by platinum and supply from Russia by palladium. South Africa is also the main supplier of the 'minor' PGMs: rhodium, ruthenium, and iridium. The PGM primary production is highly concentrated, as South Africa and Russia together produce around 82% of the world total, with the remainder coming predominantly from Zimbabwe and North America (Canada and United States). Less than 2 tonnes are produced annually in the EU, mainly in Finland as a by-product of nickel and copper mining.

Due to the high PGM prices, the supply of PGMs from recycling makes an important contribution to keeping up with global demand. Many parameters govern recycling efficiency for PGMs. The main secondary materials are spent automotive exhaust catalysts, spent chemical catalysts, and electronic and electrical component scrap. Automotive catalysts represent the main source of secondary material in the EU. PGM recycling from industrial applications achieves higher recycling rates in comparison to open-loop recycling of end-of-life products.

Platinum, and to a lesser extent iridium and ruthenium, are important materials for the transition to a climate economy. This materials are used in fuel cells and hydrogen technologies for energy generation and storage in transport and stationary applications.

Escalating costs, underinvestment and labour disputes in the PGM industry of South Africa are remaining concerns for the security of supply of PGMs worldwide.

19.1.2Overview of individual platinum group metals

19.1.2.1 Overview of iridium

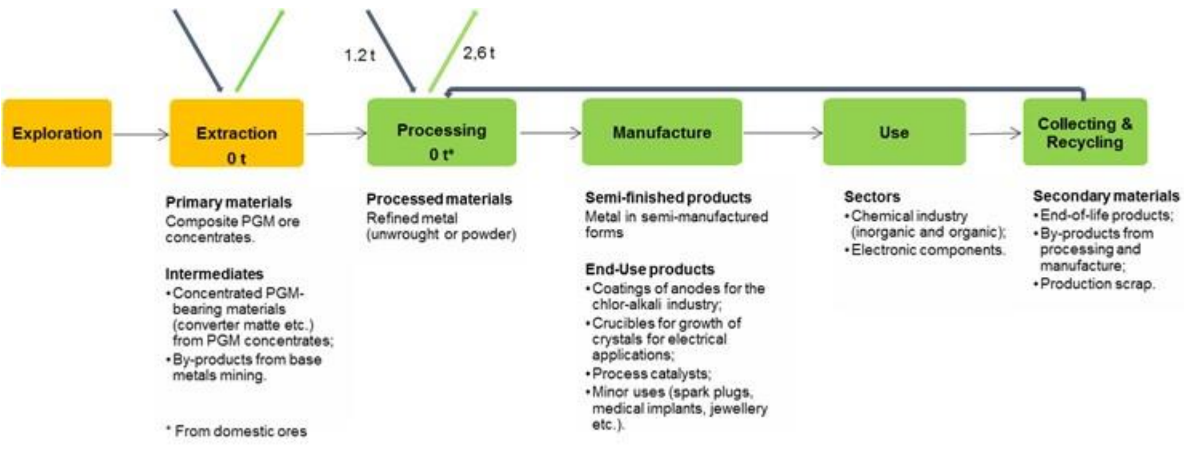


Figure 224: Simplified value chain for iridium (average 2012-2016)

Iridium (Ir, atomic number 77) is one the six chemical elements referred to as the platinum-group metals (PGM), which are, in order of increasing atomic number: ruthenium

(Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). Iridium is a silver-white metal, though with a yellowish hue, and has a very high melting point of 2,443 °C, the highest among PGM (excluding osmium). After osmium, iridium is the second most dense of the known elements with a density of 22.55 g/cm^3 (by comparison almost twice as dense as lead and three times denser than iron). It is also the most corrosion-resistant metal known. Iridium is extremely hard and brittle (6.5 hardness on the Mohs scale), over four times harder than platinum, therefore challenging to work unless it is heated to very high temperatures. Iridium has exceptional electrical conductivity (almost two times higher than platinum and palladium) and excellent biological compatibility. Because of the difficulties in fabrication, iridium is chiefly used in the form of platinum alloys as it improves considerably platinum's hardness.

This factsheet is complementary to general PGM factsheet presenting additional information and data specific to iridium where available.

The trade code used in the assessment is HS 711041 "Iridium, osmium & ruthenium, unwrought or in powder form". The relative proportion of ruthenium and iridium in the trade flows was calculated under the assumption of being proportional to their average market size in the period 2012-2016. Annual data for global ruthenium and iridium demand were sourced from Johnson Matthey statistics.

Iridium, as ruthenium, is of lower commercial importance compared to platinum, palladium, and rhodium. Global supply is highly concentrated in terms of both mine production and secondary recovery. The top importer worldwide of the "minor PGMs" (iridium, ruthenium, and osmium) in unwrought and powder form is Japan, and in semi-manufactured forms the United States and China. As concerns the leading exporting countries, for unwrought metal and powder is South Africa and Germany, and for semi-manufactured forms the UK and South Africa.

The market for iridium is small and illiquid and subject to high price volatility. In 2018, the price of iridium reached a record level of US$1,480 per troy ounce.

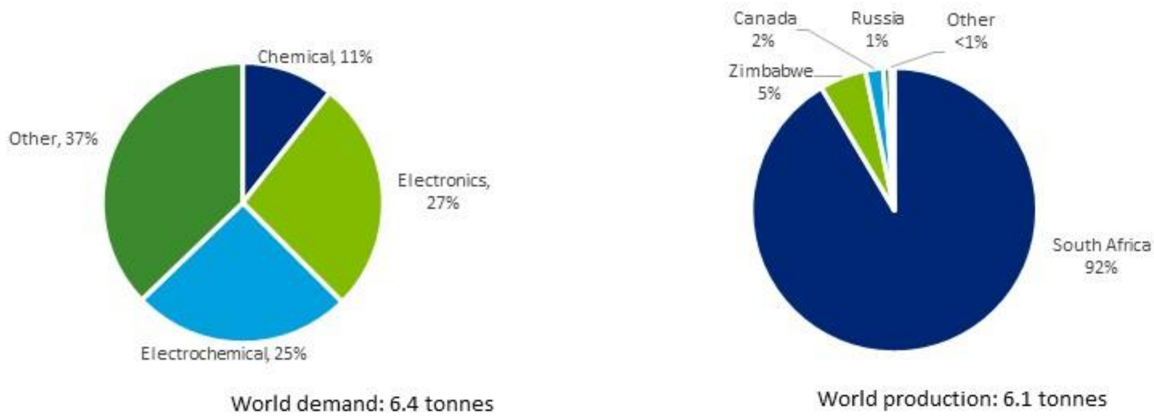


Figure 225: Global end uses of iridium (average 2012-2016), and estimated world mine production (average 2012-2016).

The world demand for iridium averaged 6.4 tonnes annually in the years 2012-2016. The import reliance for iridium from primary sources is 100%. However, the EU is an important global supplier of refined iridium metal originating from secondary materials collected domestically or imported, and the actual net import reliance is lower. In the period 2012-2016, South Africa and the United Kingdom were the main source countries for EU imports of iridium in unwrought or powder form by similar shares of almost 40% each.

The significant uses of iridium are in electronics, i.e. crucibles for growing single crystals for lasers, scanners, LEDs and other applications, anodes for the chlor-alkali industry which produces chlorine and caustic soda, and process catalysts for the chemical industry. Potential substitutes for crucibles include molybdenum and tungsten, ruthenium in the chlor-alkali industry, and rhodium for process catalysts.

South Africa hosts the majority of PGM resources with iridium occurrences. Iridium also occurs in PGM deposits in Zimbabwe and Russia. Iridium resources and reserves are not publicly available.

The annual mine production of iridium worldwide is estimated at about 6 tonnes. South Africa dominates the world mine production with a share of over 90% where iridium originates from platinum group-metal mining operations as co-product. Small quantities are also produced in mines in Zimbabwe, Canada and Russia. No primary production occurs in the EU. The end-of-life recycling input rate of iridium is approximated at 14%. Iridium is mostly recovered from process catalysts.

Applications of iridium in low-carbon technologies are identified in platinum catalysts for fuel cells (polymer electrolyte membrane), as well as in energy-efficient lighting (OLEDs).

19.1.2.2 Overview of palladium

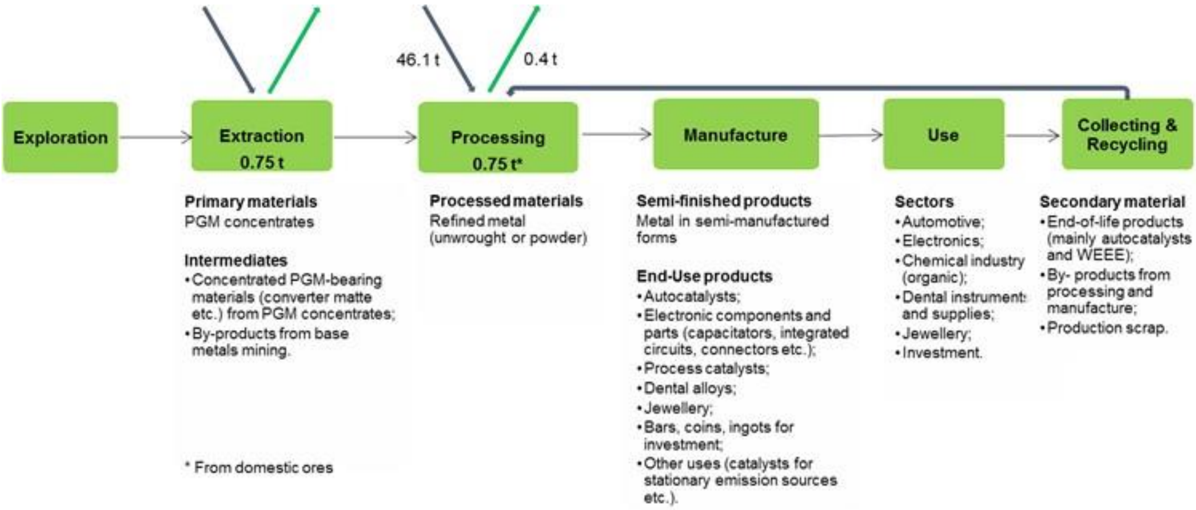


Figure 226: Simplified value chain for palladium

Palladium (Pd, atomic number 46) is one the six chemical elements of the platinum-group metals (PGM), which are, in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). Palladium is shiny silver-grey metal and the least dense of the PGM with a density of 12.02 g/cm^3 (compared to 21.45 g/cm^3 for platinum), about the same as silver. It also has the lowest melting point of the PGM (1,554 ^{o}C compared to 1,769 ^{o}C for platinum), but it is still high compared with common metals. Palladium is slightly harder than platinum (4.75 hardness on the Mohs scale) but ductile and smoothly worked when annealed. It has significant temperature stability and resistance to oxidation and corrosion, even though lower than platinum and the rest of the PGM; it oxidises in the air at 800 °C, dissolves slowly in strong acids and reacts with several nonmetallic elements on heating (e.g. sulphur). Lastly, like all PGM, palladium has unique catalytic properties, and, additionally, metallic palladium is capable of absorbing up to 900 times its volume of hydrogen. Palladium is often used as an alloy, including other PGM as alloying elements.

The trade code used in the assessment was the HS 711021 “Palladium, unwrought or in powder form”.

Palladium and platinum, are the most commercially important of the PGM. The market supply from primary sources is highly concentrated in Russia and South Africa, which have a combined share of nearly 80% of the world mine output. Russia is the leading world exporter of palladium in unwrought and powder form, followed by the UK, South Africa and the US. The palladium market remains in deficit since 2011, which is reflected in higher prices. The growth of the electric vehicle market could reduce demand for palladium over time, though hybrid technology is still reliant on these Pd catalysts to control emissions.

The price of palladium has fluctuated considerably in recent years. Since the beginning of 2016, palladium's price has surged, and it exceeded platinum's price for the first time in more than 15 years in October 2017. Palladium's price climbed at a record level of EUR 1,455 per troy ounce in September 2019, widening the price gap with platinum considerably.

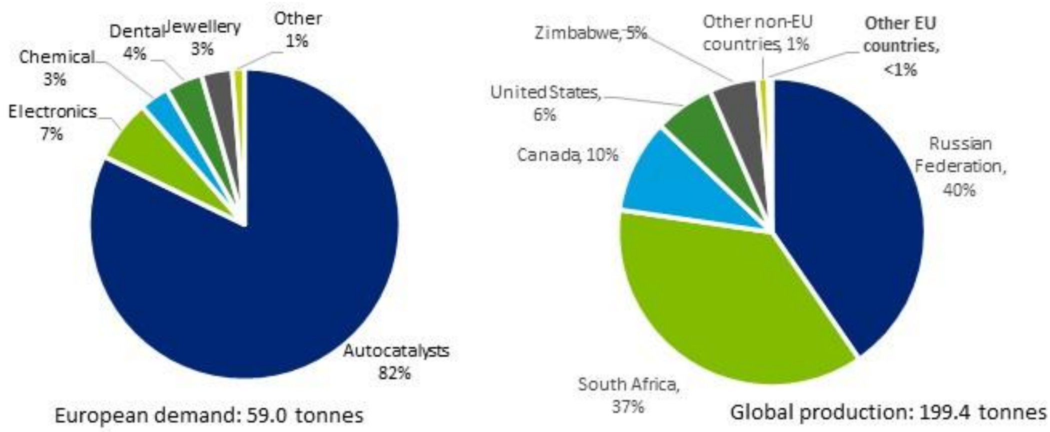


Figure 227: End uses of palladium in Europe (average 2012-2016), and world palladium mine production (average 2012-2016)

The annual palladium demand in Europe amounted to 59 tonnes, averaged over the period 2012-2016. The EU consumption of palladium metal in unwrought or powder form is estimated at 46.5 tonnes per year in the same period, mostly sourced through imports. Imports of semi-manufactured forms of palladium also contribute to the EU demand, as well as production from secondary sources. Import reliance for unwrought palladium and palladium powder is estimated to 98%, excluding consumption of refined palladium metal originating from secondary materials which is produced domestically. In the period 2012-2016, Russia (27% of the total imports) and the UK (24% of the total imports) were the main source countries for EU imports of palladium in unwrought or powder form.

By far the leading application of palladium is in catalytic converters for gasoline-powered vehicles. Besides autocatalysts, other important applications are in electronics, process catalysts for the petrochemical and chemical industry, dental alloys and jewellery. Palladium can be substituted for platinum in gasoline-engine autocatalysts.

World reserves of palladium are estimated to 7,200 tonnes in Pd content. About 44% of these reserves are located in South Africa and 41% in Russia.

The average annual mine production worldwide is estimated at 199 tonnes for the period 2012-2016. Russia is the leading mine producer with a share of 40% in the period as mentioned above, whereas South Africa is the second world producer with a share of 37% of the world mine production. EU mine production makes a small contribution to European palladium supply with an annual output of less than one tonne, of which about 97% is produced in Finland and the remainder in Poland. The secondary supply of platinum is based on the recycling of spent autocatalysts and old jewellery.

No specific low-carbon technology related to palladium is identified that can be considered a key for the transition to a climate-neutral economy by 2050.

19.1.2.3 Overview of platinum

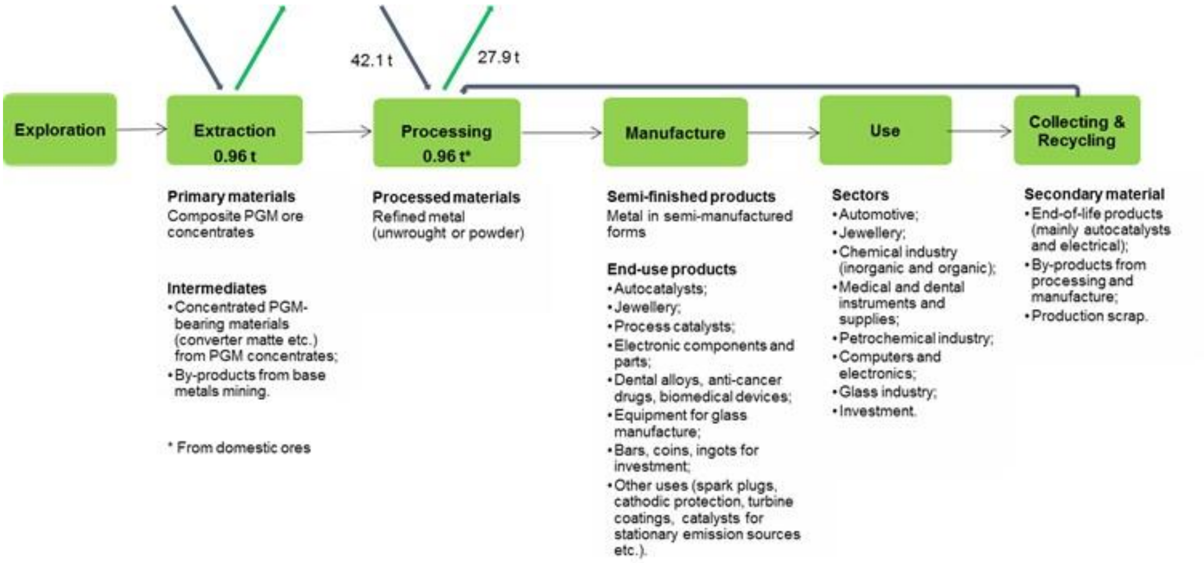


Figure 228: Simplified value chain for platinum

Platinum (Pt, atomic number 78) is one of the six chemical elements comprising the platinum-group metals (PGM). In order of increasing atomic number, the elements ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt) are clustered under the term PGM. Platinum has a density of 21.45 g/cm^3, and together with iridium and osmium are the densest known metals, being about 10% denser than gold and nearly twice as dense as silver or lead. Platinum has exceptional catalytic properties and is relatively soft (4.3 hardness in Mohs scale) and ductile, making it malleable enough to be worked into intricate shapes or stretched into fine wires. As it is extremely resistant to chemical corrosion and oxidation – it is practically unreactive - and has a high melting point of about 1,770 °C, platinum maintains its performance in even the most demanding operating conditions at high temperatures. Due to its lustrous silver-white colour and resistance to wear and tarnish, platinum is well suited for making jewellery. Platinum is mostly used as an alloy. Its working characteristics, hardness and wear properties are optimised by alloying it with other PGM such as iridium and ruthenium.

The trade code used in the assessment was the HS 711011 "Platinum, unwrought or in powder form".

Platinum and palladium are the most significant PGMs in commercial importance. The market supply of platinum from primary sources is highly concentrated in South Africa. South Africa and the United Kingdom hold the largest shares in the world market for exports of platinum in unwrought/powder form, accounting for 25% and 21% respectively of total exports by value in 2017. Germany is the largest importer globally for platinum in unwrought/powder form. In the longer term, it has been suggested that global demand may require significant increases in platinum production because of platinum's use in emerging technologies, e.g. fuel cell electric vehicles.

Since mid-2011 platinum's price is following a declining trend. In October 2017 platinum's price became lower than palladium's price for the first time since 2001. In August 2018 the monthly average price was about EUR 700 per troy ounce, the lowest since December 2008.

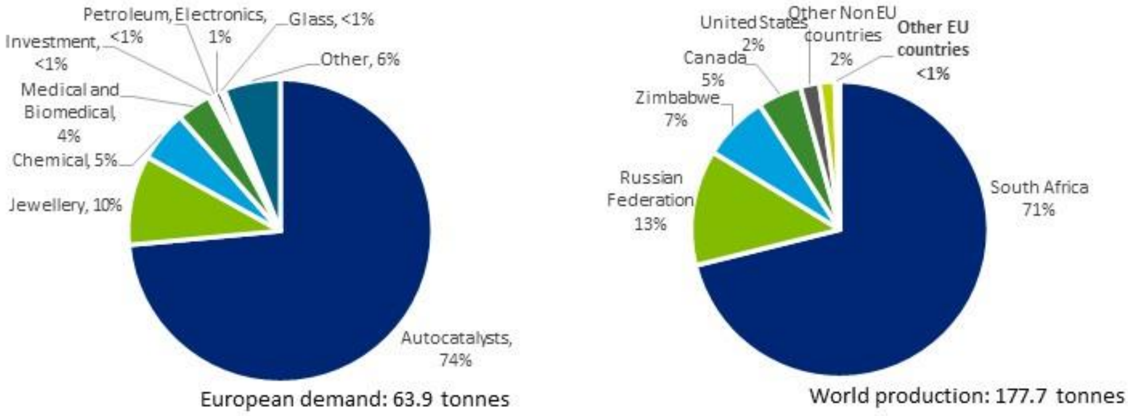


Figure 229: End uses of platinum in Europe (average 2012-2016), and world platinum mine production (average 2012-2016).

The average annual European demand for platinum was about 64 tonnes in the period 2012-2016, and the average yearly world demand was approximately 178 tonnes in the same period. EU mine production makes a small contribution to European platinum supply. The EU import reliance for platinum in unwrought or in powder form is 94%, excluding consumption of refined platinum metal originating from secondary materials which is produced domestically. However, the EU is dependent on imports of platinum waste and scrap. In the period 2012-2016, South Africa (42% of the total imports) and the UK (25% of the total imports) were the main source countries for EU imports of platinum in unwrought or powder form.

Its use in autocatalysts dominates demand for platinum. In 2018, consumption of platinum in autocatalysts accounted for 39% of global demand and 75% of European demand, reflecting the dominance of diesel vehicles in Europe in comparison with the rest of the world. Besides autocatalysts, other important applications of platinum include the use in jewellery, and as a catalyst in chemical manufacture such as nitric acid production. Palladium can be used instead of platinum in gasoline-engine catalysts with good performance, whereas for diesel engines some platinum may be substituted by palladium.

Platinum's resources and reserves are concentrated in southern Africa. The Great Dyke layered intrusion and the Bushveld Complex in South Africa are the two largest PGM deposits worldwide. Global reserves of platinum are estimated to 13 kt, with South Africa accounting for about 82%, Zimbabwe for 7%, and Russia for 6% of the total.

The average annual mine production worldwide is estimated at 178 tonnes for the period 2012-2016. South Africa is the dominant producer with a share of over 70% of the world mine production. Russia and Zimbabwe are other important producers with a share of 13% and 7%, respectively. EU mine production makes a small contribution to European platinum supply with an annual output of about one tonne, of which about 95% is produced in Finland and the remainder in Poland. The secondary supply of platinum is based on the recycling of spent autocatalysts and old jewellery.

). Platinum is a material of significance for fuel cells, a key technology for the transition to a low-carbon economy. Fuel cell electric vehicles are expected to play an important role in the achievement of a low-carbon road transport system, especially for heavy vehicles in long-distance transport. Fuel cell technology using platinum catalysts is also applicable for stationary applications to generate heat and power.

19.1.2.4 Overview of rhodium

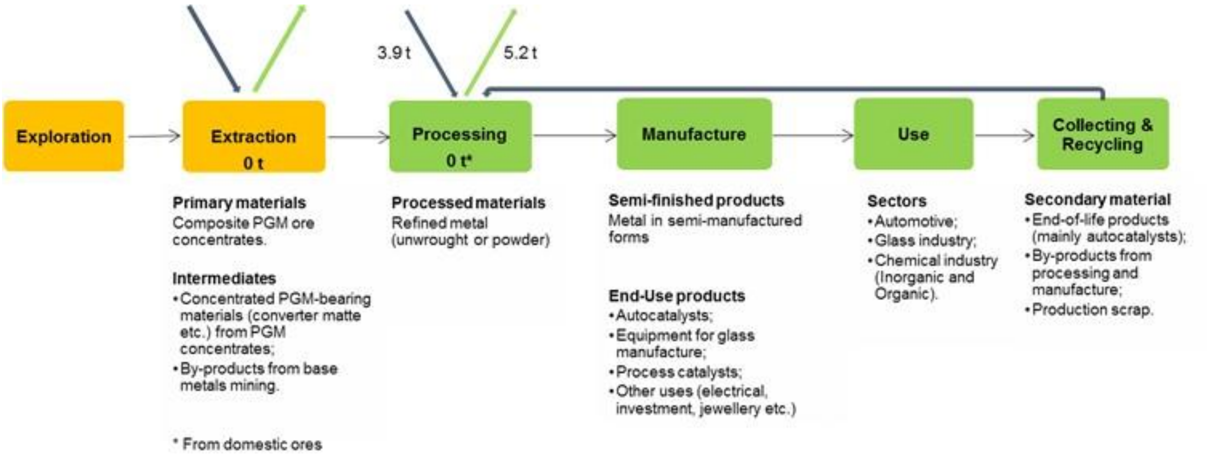


Figure 230: Simplified value chain for rhodium (average 2012-2016)

Rhodium (Rh, atomic number 45) is one of the six elements commonly referred to as the platinum group metals (PGM). The PGMs are, in order of increasing atomic number, ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). Rhodium is a silvery-white metal with excellent reflective properties. With a density of 12.41 g/cm^3, it is lighter than platinum, iridium and osmium but has a higher melting point (1,960 ^oC) than platinum and palladium. Moreover, rhodium is harder (5.5 hardness on the Mohs scale) and less malleable than these; its hardness makes it an excellent alloying element to harden platinum and palladium. Rhodium is extremely corrosion resistant and does not tarnish in the air at room temperature. It has exceptional catalytic activity, similar to platinum and platinum, and outstanding electrical conductivity, the highest among PGMs. Rhodium is predominantly used as an alloy with other PGMs.

This specific factsheet is complementary to the general PGM factsheet presenting additional information and data specific to rhodium where available.

The trade code HS 711031 "Rhodium, unwrought or in powder form" was used in the assessment.

Rhodium is the third most commercially important of the PGMs, behind platinum and palladium. The market supply is highly concentrated as South Africa holds an 80% share of the world mine output. South Africa and the UK are the leading world exporters for rhodium unwrought or in powder form. In the short-term growth in global vehicle usage and the imposition of increasingly strict emission control legislation across the world is likely to continue to increase demand for rhodium in autocatalysts. In the mid- to longer-term, the transition to electric mobility may lead to reduced demand for rhodium.

Since October 2016, the rhodium price has been rising steadily, and in September 2019 peaked to a multi-year high of USD 5,000 per oz. The significant gains in the rhodium price in 2019 coincide with projected increased demand for autocatalysts due to tighter emissions legislation and more stringent testing.

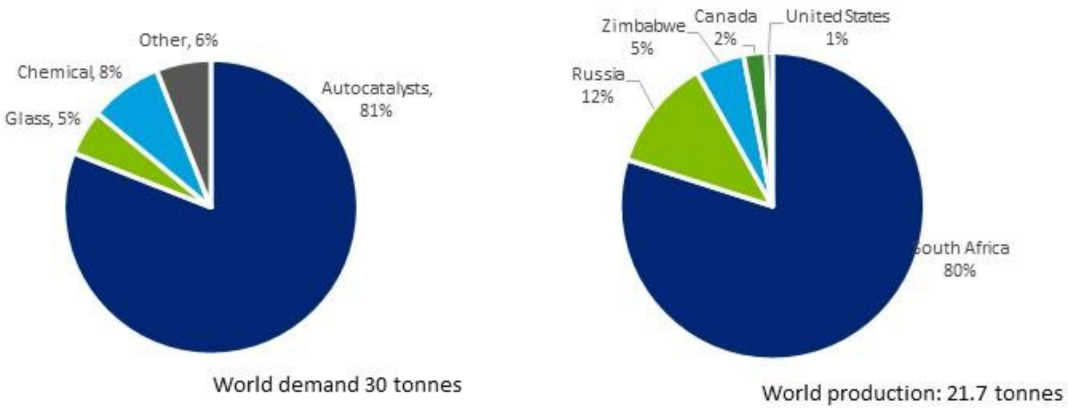


Figure 231: Global end uses of rhodium (average 2012-2016), and estimated world mine production (average 2012-2016).

The annual global demand for rhodium was 30 tonnes as an average in years 2012-2016. The import reliance for rhodium originating from primary sources is 100%. Nevertheless, the EU is an important global supplier of refined rhodium metal produced from secondary materials, collected domestically or imported, and, therefore, the actual net import reliance is lower.

Rhodium is used predominantly in autocatalysts which account for over 80% of global demand. Rhodium is also essential in the manufacture of glass and specific process catalysts for the chemicals sector (e.g. nitric acid production). Cobalt is a potential substitute in process catalysts for aldehydes production, ruthenium in catalysts for acetic acid production, and gold or iridium in glass manufacturing equipment.

The world's largest PGM mineral resources with rhodium occurrences reside in South Africa. Rhodium also occurs in notable PGM deposits in Russia and Zimbabwe.

The world rhodium mine production is estimated at 22 tonnes annually. The sheer dominance of South Africa in the primary world supply of rhodium is emphasised by its share of 80% of the world total, followed by Russia (12%) and Zimbabwe (5%), averaged for the period 2012-2016. Rhodium is produced as co-product from platinum group-metal mining operations. There is no production of rhodium from primary sources in the EU. Though, rhodium is almost entirely recycled from spent automotive catalysts, which contributes a substantial proportion of the total metal supply, a relatively higher share than for platinum and palladium. The global average end-of-life functional recycling rate ranges from 50% to 60%. In 2018, recycling accounted for 31% of rhodium global supply.

Rhodium is not assessed as a key material for the transition to net-zero greenhouse gas economy. One application in low-carbon technologies identified for rhodium is the production of fibreglass for wind turbines and automotive lightweight, as rhodium is used in platinum alloys for glass-making equipment.

19.1.2.5 Overview of ruthenium

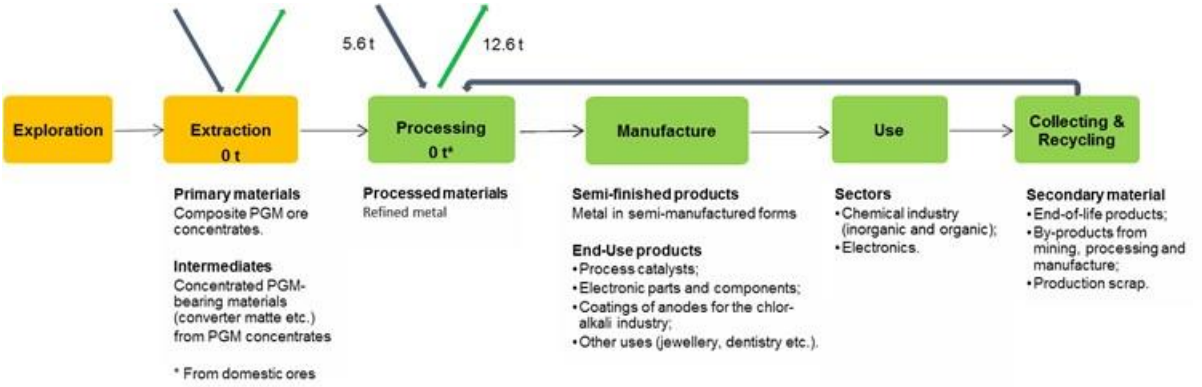


Figure 232: Simplified value chain for ruthenium (average 2012-2016)

Ruthenium (Ru, atomic number 44) is one of the six platinum-group metals (PGM). The PGM consists of the following elements in order of increasing atomic number: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). Ruthenium is the fourth of the PGM in order of commercial significance, after platinum, palladium and rhodium; however, its demand is comparable with that of rhodium in terms of quantity. Ruthenium is a shiny silver-grey metal, considerably lighter than platinum, osmium and iridium with a density of 12.45 g/cm^3. It has a very high melting point of 2,310 ^{o}C, and is exceptionally hard (hardness of 6.5 on the Mohs scale), over five times harder than platinum, as well as brittle, even after annealing at temperatures as high as 1,500 ^{o}C; therefore, the use of pure ruthenium is restricted because it is extremely difficult to work. Ruthenium is generally used as an alloying agent to platinum and palladium to improve wear resistance in electrical contacts and to impart hardness in certain jewellery alloys. Also, on account of its exceptional corrosion resistance, very good electrical and catalytic properties, ruthenium finds essential applications in the electronics and chemical industries.

This factsheet is complementary to the general PGM factsheet presenting additional information and data specific to ruthenium where available.

The trade code used in the assessment is HS 711041 "Iridium, osmium & ruthenium, unwrought or in powder form". The relative proportion of ruthenium and iridium in this total trade flow was calculated under the assumption of being proportional to their average market size in the period 2012-2016.

Ruthenium, as iridium, is of lower commercial importance compared to platinum, palladium, and rhodium. Global supply is highly concentrated in terms of both mine production and secondary recovery. The top importer worldwide of the "minor PGMs" (iridium, ruthenium, and osmium) in unwrought and powder form is Japan, and in semi-manufactured forms the US and China. As concerns the leading exporting countries, for unwrought metal and powder is South Africa and Germany, and for semi-manufactured forms the UK and South Africa.

The market for ruthenium is small and illiquid and subject to high price volatility. In 2018, the price of ruthenium climbed to a ten-year high of USD 270 per troy ounce.

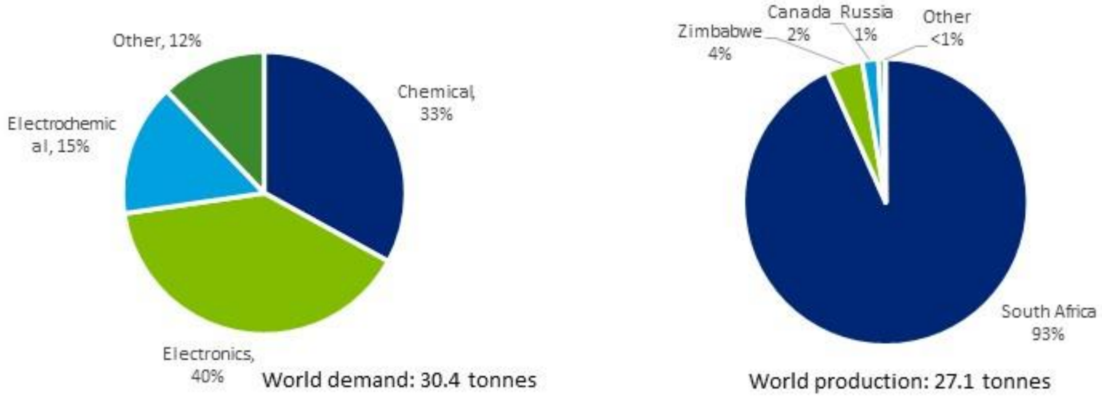


Figure 233: Global end uses of ruthenium (average 2012-2016), and estimated world mine production (average 2012-2016).

The annual global demand for ruthenium was 30.4 tonnes as an average in years 2012-2016. The import reliance for ruthenium originating from primary sources is 100%. Nevertheless, the EU is an important global supplier of refined ruthenium metal originating from secondary materials collected domestically or imported, and, therefore, the actual net import reliance is lower. In the period 2012-2016, South Africa and the UK were the main source countries for EU imports of ruthenium in unwrought or powder form by similar shares of nearly 40% each.

Currently, the primary use of ruthenium worldwide is for electronic applications, with process catalysts and electrochemical applications in the chemical industry for the manufacture of organic and inorganic chemicals the next most important. In particular, ruthenium is mainly used in anodes for the electrochemical production of chlorine and caustic soda, electrical contacts for thermostats and relays, hard disk drives, and as a catalyst in oil refining and chemical industry (e.g. ammonia synthesis). Potential substitution materials for electrical applications are other PGM (mostly palladium) and silver, and an iron-based alloy for ammonia synthesis.

South Africa hosts the majority of PGM resources with identified ruthenium occurrences. Ruthenium also occurs in PGM deposits in Zimbabwe and Russia. Data on resources and reserves for ruthenium are not available in the public domain.

The average annual mine production worldwide is estimated at about 27 tonnes for the period 2012-2016. South Africa is by far the leading producer with a share of over 90% of the world mine production where ruthenium originates as co-product from platinum group-metal mining operations. Small quantities are extracted in mines in Zimbabwe, Canada and Russia. There is no production of ruthenium in the EU from primary sources. The end-of-life recycling input rate of ruthenium is estimated at 11%. Ruthenium is mostly recovered from process catalysts.

A contribution of ruthenium for the transition to a climate-neutral economy is recognised in platinum catalysts for fuel cell technology.

19.2 Market analysis, trade and prices

19.2.1 Global market of platinum group metals in general

PGM mine production is highly concentrated in a few countries. The producing countries of PGMs are South Africa, Russia, Zimbabwe, Canada, and the United States, which account for 99% of global production. South Africa is the leading producer, with a share of about 58% of world PGM mine production in 2017. According to the British Geological Survey (BGS, 2019), the annual mine production of PGMs in 2017 was 446 tonnes, while in 2018 the annual mine production of platinum-palladium-rhodium was 412 tonnes according to Johnson Matthey (2019a). The value of PGM production at average annual prices of 2018 was US$14.8 billion, of which US$5.4 billion for platinum, US$7.2 billion for palladium, US$ 2.3 billion for rhodium, and US$0.5 billion for ruthenium and iridium (Hagelüken, 2019).

In addition to the high geographical concentration of mines, global mine production of PGMs is also dominated by few companies. The top four PGM producers are Anglo American Platinum, Norilsk Nickel, Impala Platinum, and Sibanye Stillwater. They accounted for approximately 87% of the market in 2018 (IPA Industrial expert, 2019), and maintain considerable processing assets that supply the market with refined PGMs and by-products of the PGM production (Ndlovu, 2015). A significant market player emerged in the last years is the South African company Sibanye Gold, which initially bought the Rustenburg mines in 2016 from Anglo American Platinum, and in May 2017 purchased the US Stillwater Mining Co; in June 2019, Sibanye-Stillwater was merged with Lonmin. This company currently controls 20% of the world's PGM primary production (Hagelüken, 2019), and has become the world's largest PGM producer (PWC, 2019).

In general, the PGM mining sector is vertically integrated, from mining through concentration to smelting, refining and marketing of the PGM (Hagelüken, 2019). Exceptions do exist, for example, Norilsk Nickel's metal is refined by third parties in Russia, whereas in South Africa only a part of Lonmin operations (now Sibanye-Stillwater) are integrated through to refined metal, while the remainder is refined and sold by other companies (IPA Industrial expert, 2019). Four companies dominate PGM mining in South Africa: Anglo-American Platinum, Impala Platinum, Sibanye Stillwater and Northam Platinum. Each of these runs integrated operations in South Africa, and/or has agreements with other refiners to process their metal in South Africa. About 25% of the processing of the extracted ores, from concentration to refining, was carried out by non-integrated miners (Ndlovu, 2015).

The PGM value chain is also highly concentrated in the manufacturing stage. The global PGM fabrication sector is dominated by five companies (Johnson Matthey, BASF, Umicore, Heraeus and Tanaka) that account for approximately 85% of the market of fabricated products (Ndlovu, 2015). Four of these have a strong presence in Europe. These companies run large integrated operations that derive their supplies from a combination of primary and secondary sources. They deliver a diverse range of PGM-bearing materials and products to the global market from specialised plants located in different parts of the world, including Europe (European Commission, 2017a).

Almost all PGMs derived from primary source materials (i.e. mine production) is traded in the form of refined metal produced from integrated mining/metallurgical operations. There is only minimal international trade in PGM ores and concentrates (European Commission, 2017a).

19.2.2Global market of individual platinum group metals

19.2.2.1 Global market of iridium

The demand for iridium is considerably lower than for the other PGMs, with the exception of osmium. In 2018, the annual global gross demand for iridium was 7.5 tonnes, increased by nearly 88% in comparison to 2005, with significant fluctuations. Over the 2016 to 2018 period, demand for iridium exceeded mine output, but sales from producer stocks have kept the markets supplied (Johnson Matthey, 2019a). South Africa is the dominant world producer of iridium from primary sources. The market value of iridium metal consumed in 2018 is estimated at USD 0.28 billion[180].

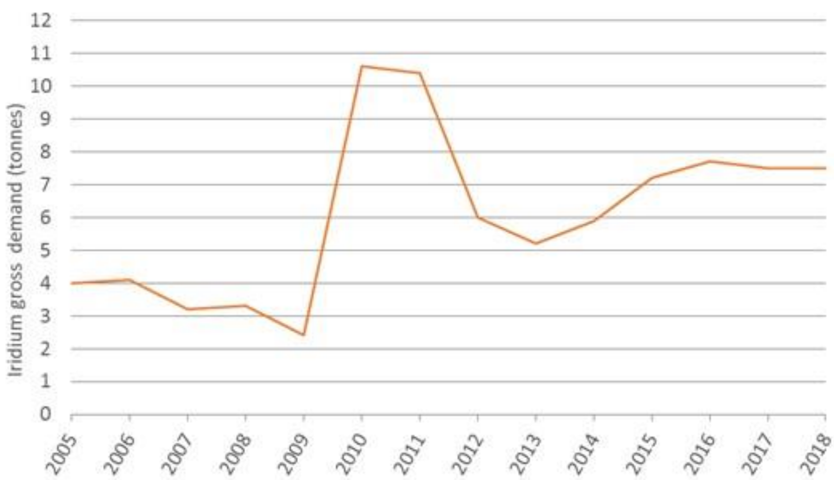


Figure 234: Global gross demand[181] for iridium from 2005 to 2018 (background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, (Johnson Matthey, 2014) for 2005-2012

Iridium has a very small and illiquid market, and the global primary supply is highly concentrated; thus, modest increases in demand or fluctuations in supply can have a significant impact on availability (Johnson Matthey, 2018). In addition, given that iridium is effectively a by-product of platinum and/or palladium extraction, its supply is closely linked to the production of the host PGM (European Commission, 2017). Furthermore, only few market participants have the capability to refine iridium from secondary sources fully, and lead times for refining are typically very long, often over 20 weeks, which may cause disruptions in the supply chain (Johnson Matthey, 2019a).

Over the 2016 to 2018 period, demand for iridium exceeded mine output, but sales from producer stocks have helped to keep the markets supplied. According to Johnson Matthey market analysis, strategic purchasing in Asia contributed to unusually large amounts of iridium shipped in 2016–2017 (Johnson Matthey, 2019a).

Almost all iridium derived from primary source materials (i.e. mine production) is traded in the form of refined products from integrated mining/metallurgical operations. There is only minimal international trade in iridium ores and concentrates (European Commission, 2017).

The Harmonised System does not separate trade flows for iridium and trade data are available only under the single HS code 711041, which consist of "iridium, osmium and ruthenium metal in unwrought or powder form". South Africa is the leading world supplier

[180] Estimated as: 219,000 oz of global gross demand in 2018 X 1,284 USD/oz average price in 2018

[181] Gross demand is the sum of manufacturer demand for metal in that application and any changes in unrefined metal stocks.

of ruthenium-iridium-osmium metal. In 2017, exports from South Africa accounted for 46% of international trade value of ruthenium+iriridium+osmium metal. Germany and the United Kingdom are also significant exporters with a share of 18% and 14% respectively of the value of global exports in 2017. Japan is the top importer of these three PGMs with 33% of global imports by value in 2017. The United Stats and the United Kingdom are also important destination countries for ruthenium+iridium+osmium metal representing 16% and 13% respectively of global imports by value.

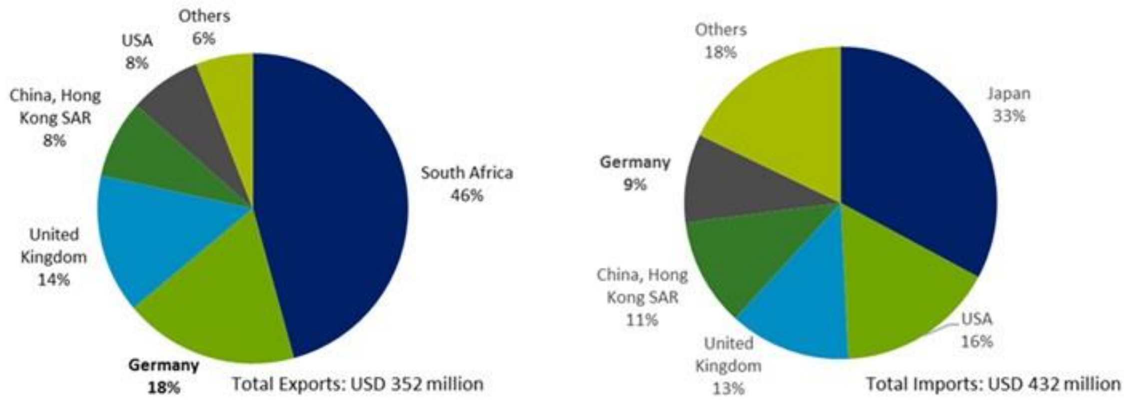


Figure 235: Top-5 iridium, osmium & ruthenium (unwrought/in powder form, HS 7110 41) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

The Harmonised System does not separate either trade flows for downstream iridium semi-finished products. Trade data are available only under the single HS code 7110 49, which comprises "iridium, osmium and ruthenium metal in semi-manufactured forms". The UK is the top world supplier of ruthenium-iridium-osmium in semi-manufactured forms with exports accounting for 35% of the total exports value in 2017. South Africa (29%) and Japan (21%) are also important exporters worldwide. The United States and China are the top destination countries for ruthenium+iridium+osmi in semi-manufactured forms accounting for 29% and 27% respectively of global imports by value in 2017. Malaysia is also a significant importer of semi-manufactured forms of these three PGM, with a share of 16% of global imports by value in 2017.

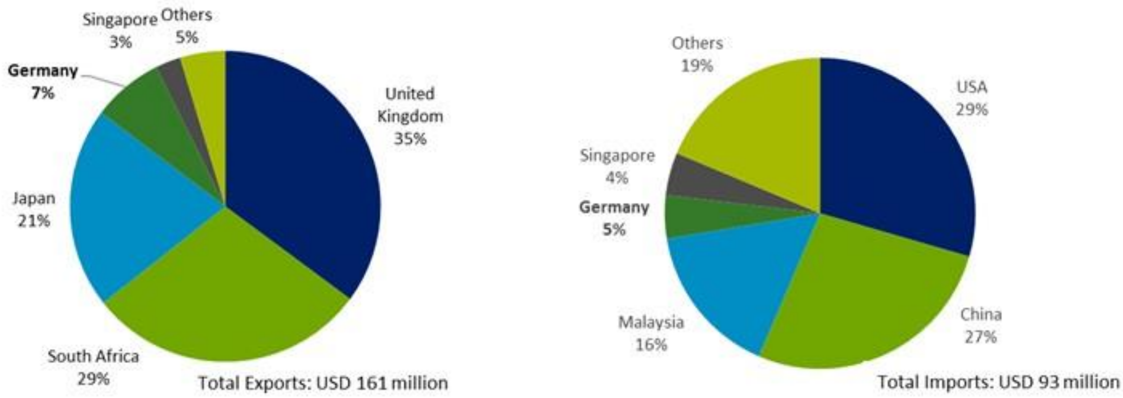


Figure 236: Top-5 iridium, osmium & ruthenium (in semi-manufactured forms, HS 7110 49) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

Concerning export taxes, quotas or export prohibition in place in 2017, Zimbabwe applied a 15% tax for HS 7110 41 "Iridium, osmium & ruthenium, unwrought or in powder form" and HS 7110 49 "Iridium, osmium & ruthenium, in semi-manufactured forms". Russia imposed an export tax of 6.5% for both codes until 31/8/2016 (OECD, 2019).

19.2.2.2 Global market of palladium

Palladium and platinum, are the most commercially important of the PGM with the most extensive range of applications.

The world mine production of palladium amounted to 217 tonnes in 2018. Russia and South Africa dominate the world supply of palladium from primary sources, with a combined share of 79% of the world mine production in 2018 (Johnson Matthey, 2019a), which highlights the market concentration. Palladium's global supply increased sharply from 1994 to 2001 following the explosion of demand, and Russian exports almost entirely drove this rise. This temporary expansion in supply was achieved mainly through significant sales from Russian state stocks (Hagelüken, 2019). The Russian production is derived almost exclusively from the underground mines extracting nickel sulphide ores in the Norilsk-Talnakh district. The output in Norilsk peaked in 2006 at 100 tonnes per year. Since then, it has fluctuated in a range of 75-90 tonnes per year, whereas sales from Russian state stocks have come to an end in 2013 (Hagelüken, 2019; Johnson Matthey, 2014; Johnson Matthey, 2019a).

Figure 237 below presents the evolution in the supply and demand of palladium from 2005 to 2018. Palladium's market is in deficit since 2011, and this reflected in poor liquidity and higher prices (Johnson Matthey, 2017; Johnson Matthey, 2018).

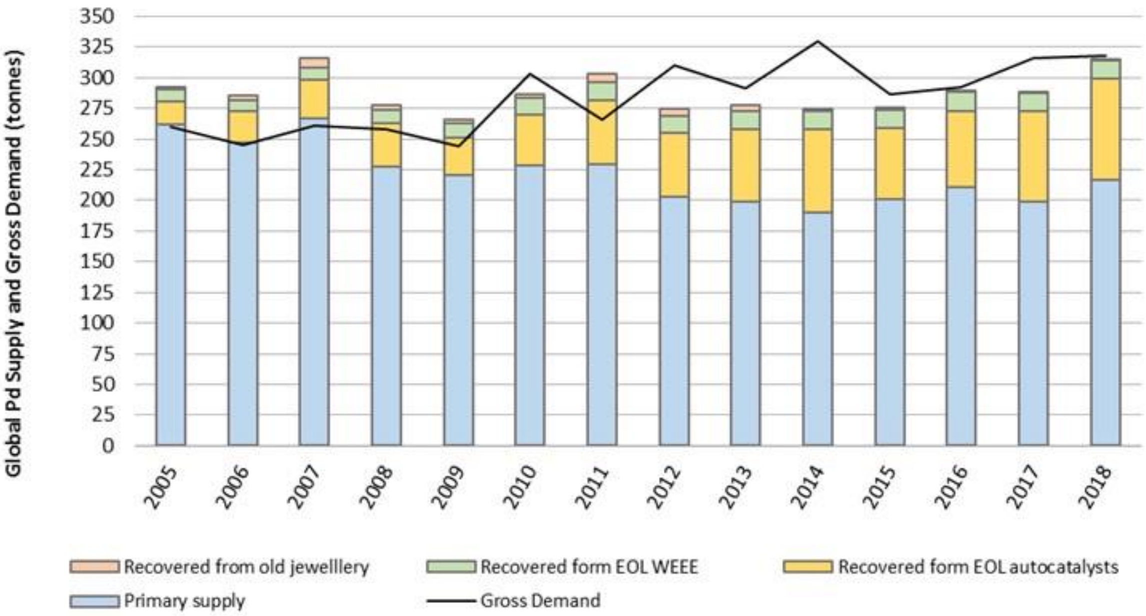


Figure 237: Global supply and demand of palladium from 2005 to 2018. Background data for 2014-2018 in (Johnson Matthey, 2019a), for 2013 in (Johnson Matthey, 2018), and for 2005-2012 in (Johnson Matthey, 2014)

The market value of the consumed palladium metal is estimated at €8.9 billion[182] for the year 2018.

Almost all palladium derived from primary source materials (i.e. mine production) is traded in the form of refined products from integrated mining/metallurgical operations. There is

[182] Estimated as: 10,220,000 oz of global gross demand in 2018 X 874 EUR/oz average price in 2018

only minimal international trade in palladium ores and concentrates (European Commission, 2017).

Russia is the most significant world supplier of palladium metal in unwrought or in powder form. Exports from Russia accounted for 26% of international trade of palladium metal in unwrought or in powder form by value in 2017 (see Figure 238). The United Kingdom and South Africa are also important exporters with a share of 16% each of global exports by value in 2017. The United States is the leading importer of accounting for 21% of global imports by value in 2017. Germany and Japan are also significant destination countries for palladium in unwrought or in powder form with a share of 17% and 16%, respectively, of global imports by value.

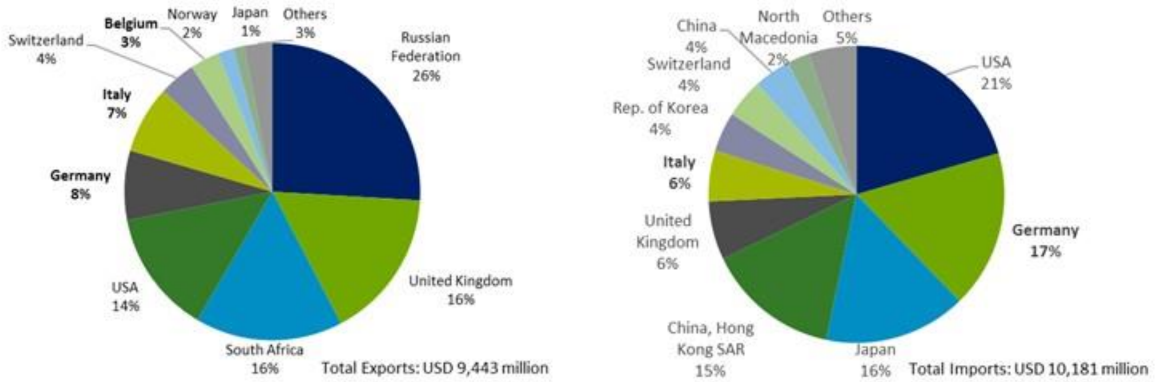


Figure 238: Top-10 palladium (unwrought/in powder form, HS 7110 21) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

The UK is the most significant market player in the international trade of palladium in semi-manufactured forms, with 44% share for both total imports value and total exports value in 2017 (see Figure 239). Along with the United Kingdom, the United States (11%), Germany (10%), Switzerland (9%) and Canada (8%) are the top-5 exporters of palladium in semi-manufactured forms worldwide. The United States (19%) and Canada (10%) are the most important importers, apart from the United Kingdom, of palladium in semi-manufactured forms.

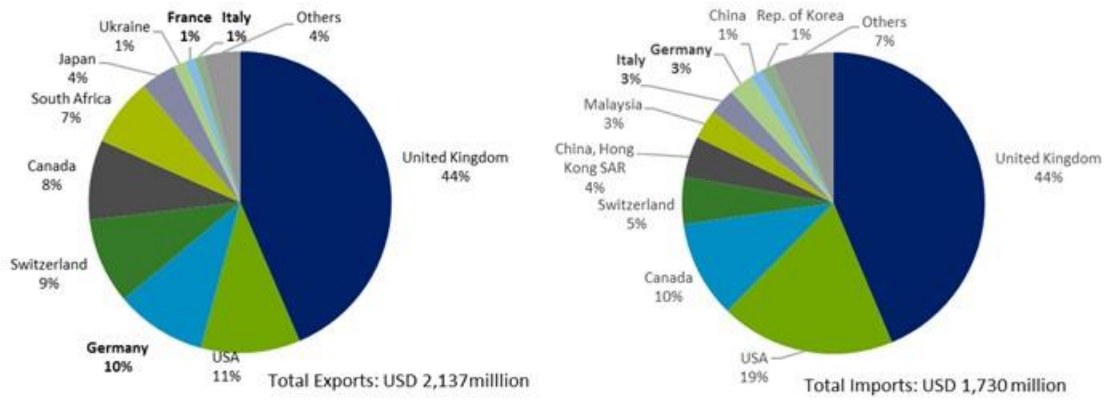


Figure 239: Top-10 palladium (in semi-manufactured forms, HS 7110 29) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019)

Regarding the most relevant export restrictions (export taxes, quotas or export prohibition) in place in 2017, Zimbabwe applied a 15% tax for HS 7210 11 "Palladium, unwrought/in powder form" and HS 7110 19 "Palladium, in semi-manufactured forms". According to the OECD inventory of export restrictions, the effect of an export tax (6.5%) imposed by Russia for both trade codes ended on 31/8/2016 (OECD, 2019).

19.2.2.3 Global market of platinum

Platinum and palladium are of major commercial significance, having the broadest range of applications of the PGM.

The world mine production in 2018 was 190 tonnes. South Africa accounted for about 73% of the total mine production, dominating the primary supply of platinum (Johnson Matthey, 2019b). South Africa's production comes from several mines, most of them underground, at the Bushveld Igneous Complex. As refining of PGMs mined in Zimbabwe is carried out in South Africa (Hagelüken, 2019), more than 80% of the global platinum supply from primary sources is controlled by South Africa.

Figure 240 shows the development of platinum supply and demand since 2005. Global platinum production from mines reached a peak in 2006 at the level of 212 tonnes driven by a significant production increase from South Africa. The platinum production increased by about 40% from 120 tonnes in 2000 to 165 tonnes in 2006. Since then, South African production has been on a downward trend and has stabilised at levels of around 140 tonnes per year in the period 2015-2018. The reasons for the decline have been problems in energy supply, difficult mining conditions, and disruptions from events such as strikes and social unrest (Hagelüken, 2019). In relation to demand, the overall platinum demand is relatively stable fluctuating approximately between 245 and 260 tonnes per year, except 2008 as a result of the financial crisis. The platinum market has been in a surplus in 2017 and 2018 after five consecutive years of deficit.

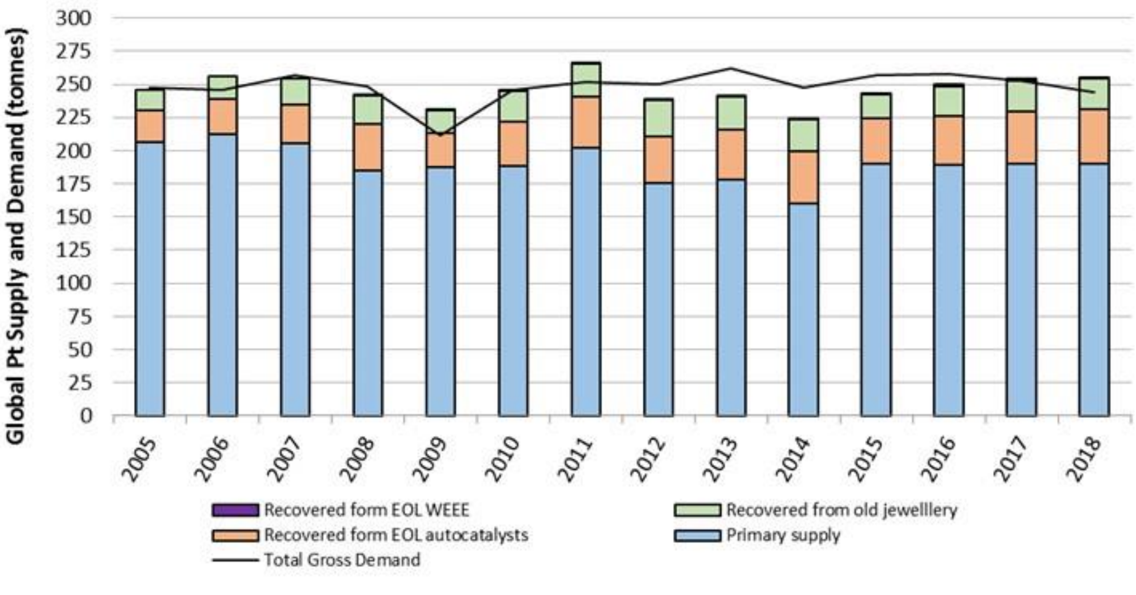


Figure 240: Global supply and demand of platinum from 2005 to 2018. Background data for 2014-2018 in (Johnson Matthey, 2019b), for 2013 in (Johnson Matthey, 2018), and for 2005-2012 in (Johnson Matthey, 2014).

The market value of platinum metal consumed in 2018 is estimated at €5.8 billion[183].

[183] Estimated as: 7,846,000 oz of global gross demand in 2018 X 744 €/oz average price in 2018

Almost all platinum derived from primary source materials (i.e. mine production) is traded in the form of refined products from integrated mining/metallurgical operations. There is only minimal international trade in platinum ores and concentrates (European Commission, 2017).

In 2017, South Africa and the United Kingdom were the main sources worldwide for imports of platinum in unwrought or in powder form, accounting for 25% and 21% respectively of the world's total exports by value (Figure 241). Italy is the third-ranked world exporter with a share of 11%.

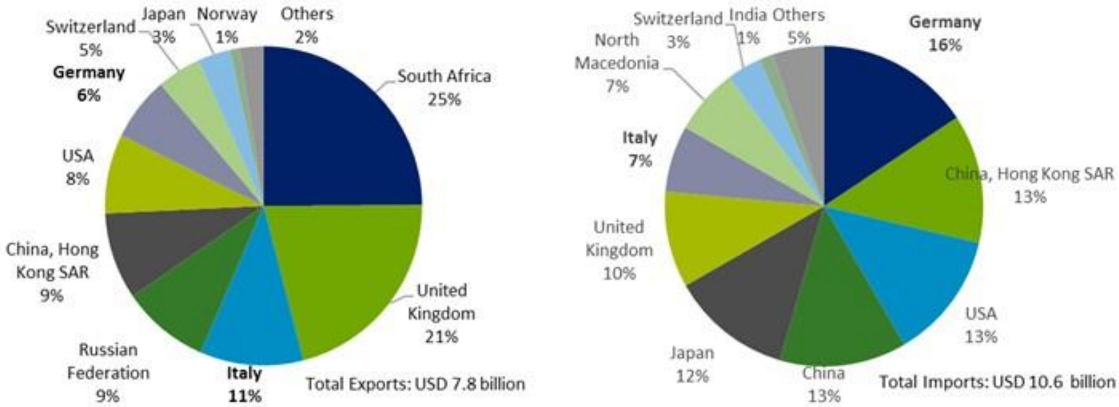


Figure 241: Top-10 platinum (in unwrought/powder form, HS 7110 11) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

South Africa and the United Kingdom are also the main sources of world's exports of platinum in semi-manufactured forms, accounting for about the two-thirds of global exports by value (see Figure 242). The main destination countries for the world trade of platinum in semi-manufactured forms are the United Kingdom and China, accounting for 33% and 16% of the world imports by value, respectively.

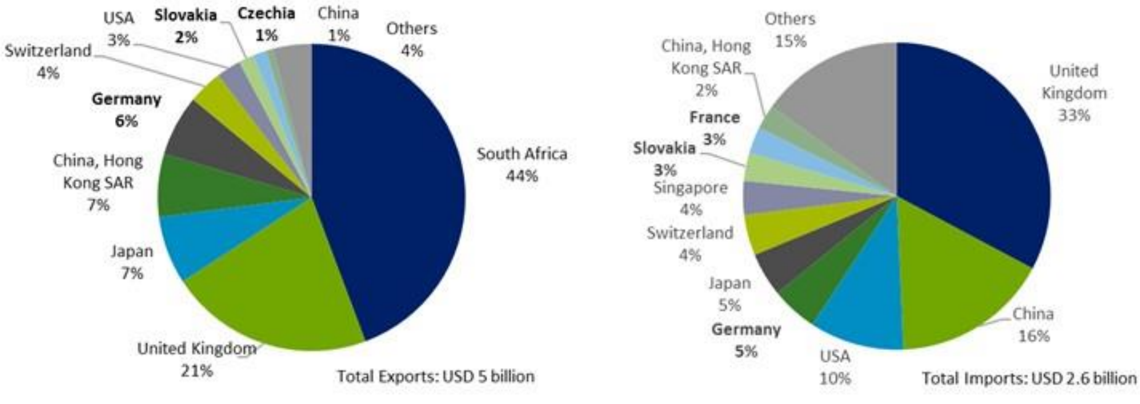


Figure 242: Top-10 platinum (in semi-manufactured forms, HS 7110 19) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019)

As regards platinum catalysts (in the form of wire cloth or grill), Germany provided almost half of world's imports, while a group of EU MS are among the top-10 export destinations of platinum catalysts (see Figure 243).

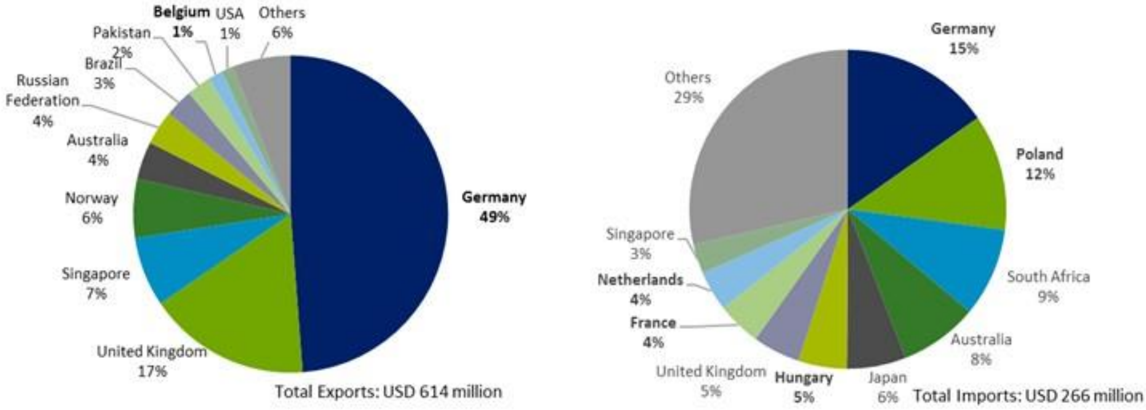


Figure 243: Top-10 platinum catalysts (in the form of wire cloth or grill, HS 7115 10) importing (left) and exporting (right) countries in 2017 by value. Data from (UN Comtrade, 2019)

Moreover, there is significant international trade of platinum-bearing waste and scrap in the EU Member States. Figure 244 shows the top importers and exporters worldwide of waste and scrap of platinum by value. The US and Germany dominate the international trade of platinum waste and scrap.

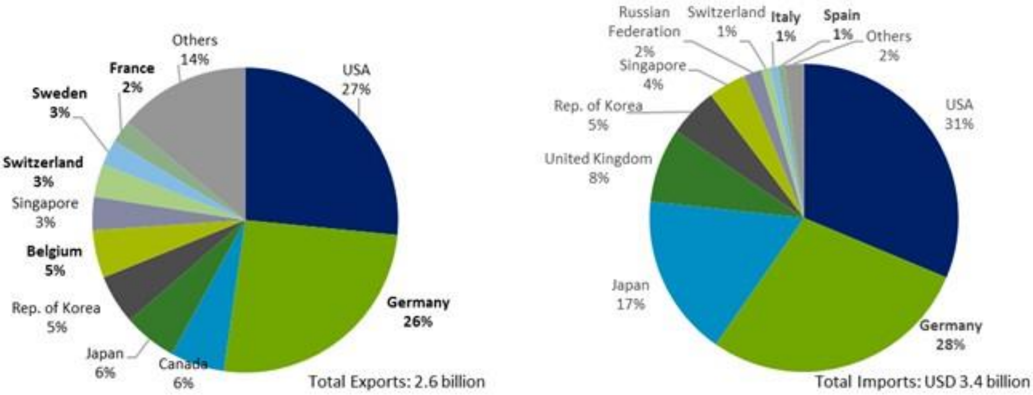


Figure 244: Top-10 platinum (Waste & scrap of platinum, HS 7112 92) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019)

Concerning the export taxes, quotas or export prohibition in place in 2017, Zimbabwe applied a 15% tax for HS 7110 11 "Platinum, unwrought/in powder form" and HS "7110 19 Platinum, in semi-manufactured forms". According to the OECD inventory of export restrictions, the effect of an export tax (6.5%) imposed by Russia for both trade codes ended on 31/8/2016 (OECD, 2019).

19.2.2.4 Global market of rhodium

After platinum and palladium, rhodium is the third most important in commercial significance among the PGMs. The world mine supply of rhodium is geographically highly concentrated. Global mine production is dominated by South Africa, with a share of 81% in 2017 (WMD, 2019). Other market players in mine supply are Russia (11%), Zimbabwe (6%) and Canada (3%).

Over the 2015 to 2018 period, rhodium's gross global annual demand ranged from 28.6 tonnes to 32.7 tonnes. In the same period, supply for primary and secondary sources exceeded demand. Gross rhodium demand reached a record of 32.7 tonnes in 2017, almost precisely matching combined primary and secondary quantities, and leaving the market in balance.

The market value of rhodium metal consumed in 2018 is estimated at US$2.3 billion[184].

Figure 245 below presents the evolution in the supply and demand of rhodium from 2005 to 2018. The rhodium market has been in surplus since 2015.

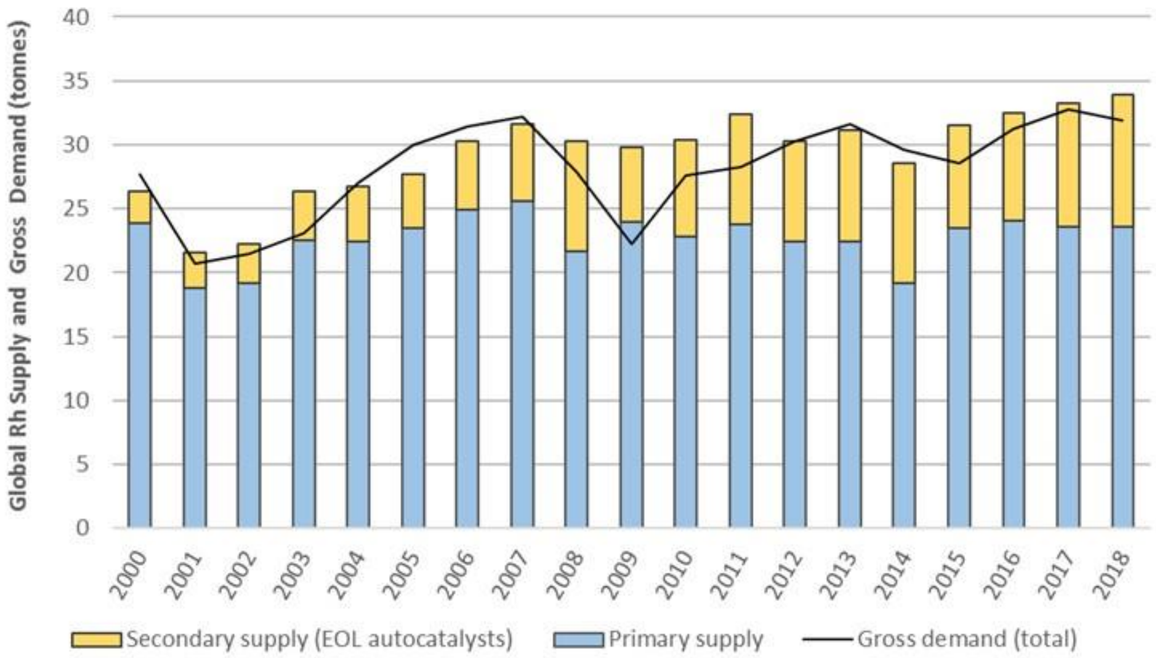


Figure 245: Global supply and gross demand[185] of rhodium from 2000 to 2018 (background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, and (Johnson Matthey, 2014) for 2000-2012).

The rhodium market is small and illiquid, and the global primary supply highly concentrated. Therefore, modest increases in demand or fluctuations in supply can have a significant impact on prices and physical availability (Johnson Matthey, 2018). Moreover, given that rhodium is effectively a by-product of platinum and palladium extraction, its supply is closely tied to the production of those PGMs (European Commission, 2017). Finally, the market availability of rhodium metal may be restricted in the short-term by capacity constrains in the secondary refining sector (Johnson Matthey, 2019a).

Almost all rhodium derived from primary source materials (i.e. mine production) is traded in the form of refined products from integrated mining/metallurgical operations. Hence, there is only minimal international trade in rhodium ores and concentrates (European Commission, 2017).

Figure 246 presents the top world importers and exporters by value in 2017 of rhodium metal in unwrought or in powder form (HS 7110 31). South Africa is the most significant exporter (31%) followed by the UK (22%), the US (15%) and Germany (13%). The US is the largest importer (27%), followed by Japan (16%), and Germany (14%).

[184] Estimated as: 1,026,000 oz of global gross demand in 2018 X 2,220 US$/oz average price in 2018

[185] Gross demand is the sum of manufacturer demand for metal in that application and any changes in unrefined metal stocks.

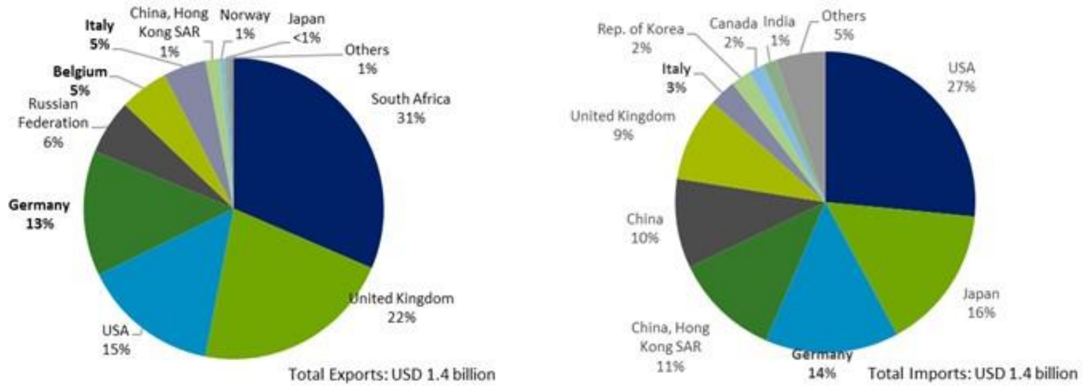


Figure 246: Top-10 rhodium (unwrought/in powder form, HS 7110 31) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

For rhodium in semi-manufactured forms (HS 7110 39), South Africa is the top supplier worldwide accounting for 79% of world exports by value in 2017, followed by the UK (9%). Malaysia is the top destination country of international trade, with a share of 33% of global imports value in 2017, followed by the United States (19%) and the United Kingdom (12%). Figure 247 shows the top world importers and exporters of rhodium in semi-manufactured forms based on trade data for code HS 7110 39.

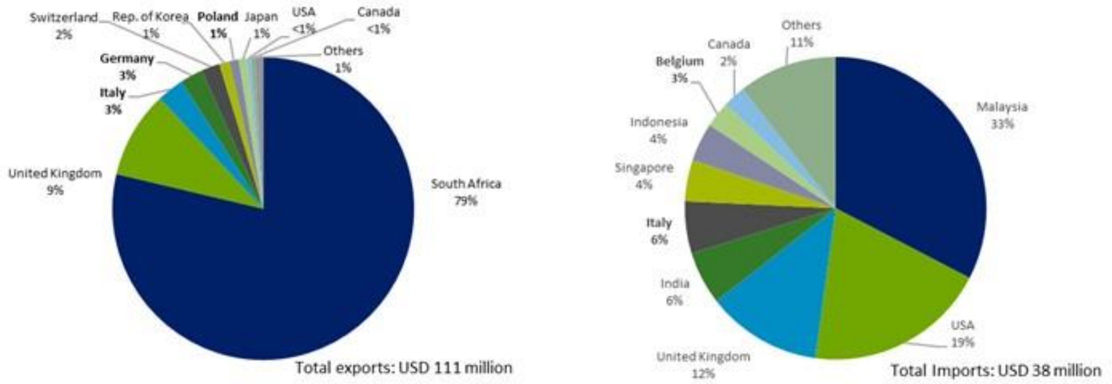


Figure 247: Top-10 rhodium (in semi-manufactured forms, HS 7110 39) importing (left) and exporting (right) countries in 2017 by value. Data from (UN Comtrade, 2019)

Regarding relevant export restrictions (export taxes, quotas or export prohibition) in place in 2017, Zimbabwe applied a 15% tax for HS 7210 31 "Rhodium, unwrought/in powder form" and HS 7110 39 "Rhodium, in semi-manufactured forms". The effect of an export tax (6.5%) imposed by Russia for both trade codes ended on 31/8/2016 (OECD, 2019).

19.2.2.5 Global market of ruthenium

Ruthenium is the fourth of the PGM in order of commercial significance, after platinum, palladium and rhodium. South Africa dominates the supply from primary sources. On the demand side, the global gross demand for ruthenium is relatively stable in the last years (2015-2018), ranging from 33.5 tonnes to 38 tonnes. Ruthenium's demand is comparable with that of rhodium in terms of quantity. Over the 2016-2018 period, demand for ruthenium exceeded mine output, but sales from producer stocks have kept the markets supplied (Johnson Matthey, 2019a). In 2018, the market value of the consumed ruthenium metal is estimated at USD 0.26 billion[186].

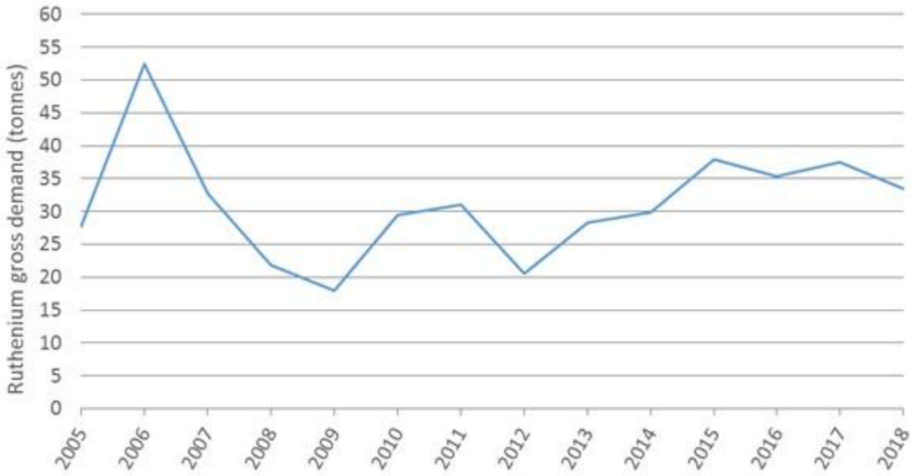


Figure 248: Global gross demand[187] for ruthenium from 2005 to 2018 (background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, (Johnson Matthey, 2014) for 2005-2012

The market for ruthenium is small and illiquid, and the global primary supply highly concentrated. As a result, modest increases in demand or fluctuations in supply can have a significant impact on availability (Johnson Matthey, 2018). In addition, given that ruthenium is effectively a by-product of platinum and/or palladium extraction, its supply is closely tied to the production of the those PGM (European Commission, 2017). Furthermore, few market participants have the capability to refine ruthenium from secondary sources fully, and lead times for refining are typically very long, often over 20 weeks. Thus, the lengthy refining process which may cause bottlenecks in the supply chain (Johnson Matthey, 2019a).

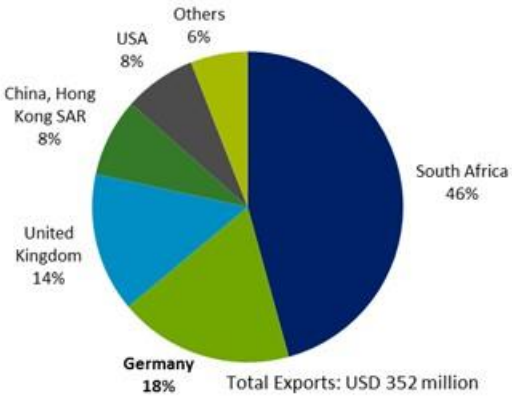
Over the 2016 to 2018 period, demand for ruthenium exceeded mine output, but sales from producer stocks have helped to keep the markets supplied. According to Johnson Matthey market analysis, strategic purchasing in Asia contributed to unusually large amounts of ruthenium shipped in 2017-2018 (Johnson Matthey, 2019a).

Almost all ruthenium derived from primary source materials (i.e. mine production) is traded in the form of refined products from integrated mining/metallurgical operations. There is only very limited international trade in ruthenium ores and concentrates (European Commission, 2017).

The Harmonised System does not separate trade flows for ruthenium metal, and trade data are available only under the single HS code 711041, which comprises "iridium, osmium and ruthenium metal in unwrought or powder form". South Africa is the leading world supplier of ruthenium-iridium-osmium metal; exports from South Africa accounted for 46% of international trade of ruthenium+iridium+osmium metal by value in 2017. Germany and the United Kingdom are also significant exporters with a market share of 18% and 14% respectively of global exports by value in 2017. Japan is the top importer of these three PGMs accounting for 33% of global imports by value in 2017. The USA and the UK are also significant destination countries for ruthenium+iridium+osmium metal with a share of 16% and 13%, respectively, of global imports by value.

[186] Estimated as: 1,076,000 oz t of global gross demand in 2018 X 241 US$/oz average price in 2018

[187] Gross demand is the sum of manufacturer demand for metal in that application and any changes in unrefined metal stocks.



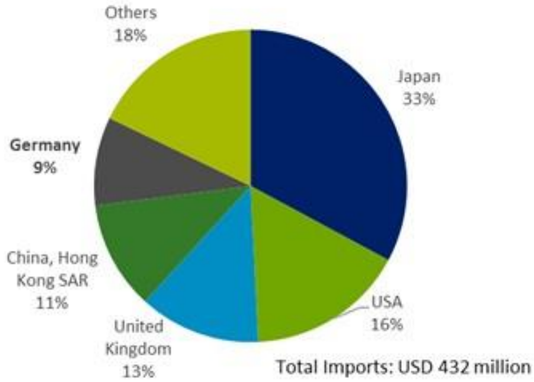
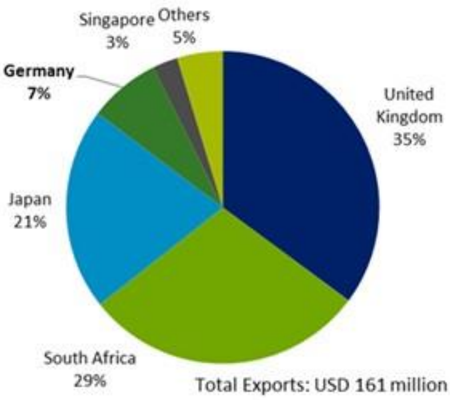


Figure 249: Top-5 iridium, osmium & ruthenium (unwrought/in powder form, HS 7110 41) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

The Harmonised System does not separate either trade flows for downstream ruthenium semi-finished products. Trade data are available only under the single HS code 7110 49, which involves "iridium, osmium and ruthenium metal in semi-manufactured forms". The United Kingdom is the top world supplier of ruthenium-iridium-osmium in semi-manufactured forms with exports accounting for 35% of the total exports value in 2017. South Africa (29%) and Japan (21%) are also important exporters worldwide. The United States and China are the top importing countries of ruthenium+iridium+osmium in semi-manufactured forms accounting for 29% and 27%, respectively, of the global imports by value in 2017. Malaysia is also a significant destination of world exports of semi-manufactured forms of these three PGM, with a share of 16% of global imports by value in 2017.



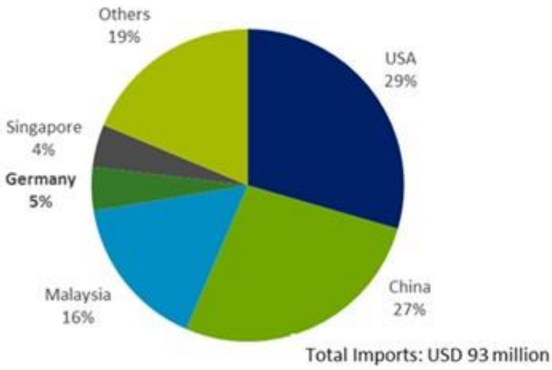


Figure 250: Top-5 iridium, osmium & ruthenium (in semi-manufactured forms, HS 7110 49) exporting (left) and importing (right) countries in 2017 by value. Data from (UN Comtrade, 2019).

Concerning export taxes, quotas or export prohibition in place in 2017, Zimbabwe applied a 15% tax for HS 7110 41 "Iridium, osmium & ruthenium, unwrought or in powder form" and HS 7110 49 "Iridium, osmium & ruthenium, in semi-manufactured forms". Russia imposed an export tax of 6.5% for both codes until 31/8/2016 (OECD, 2019).

19.2.3 General outlook for supply and demand of platinum group metals in general

19.2.3.1 Forward look of PGM supply

Given the importance of their industrial applications, the fact that PGMs are mined in only a few countries, and that are not readily substitutable, there has long been concern over security of supply of PGMs. Various actions have been taken since the late 1980s to ensure supply and mitigate the impacts of potential shortages. These have included the establishment of government stockpiles in some countries, promotion of recycling, research activities to understand deposit formation, the discovery of substantial additional mineral resources, and efforts to identify possible substitutes (European Commission, 2017a; Mudd, Jowitt and Werner, 2018).

Various studies have compared projected demand for PGMs with the amount of PGM resources that have been positively identified by mineral exploration. Along with the expected supply by recycling, it is suggested that geological availability is not an issue for PGM supply in the future. The known resources in the ground are considered sufficient, coupled with the potential for additional resource discoveries as well as for PGM extraction from different ore types, if market conditions are suitable (i.e. prices versus cost), to meet anticipated demand well for several decades (Zientek *et al.*, 2017; Mudd, Jowitt and Werner, 2018). USGS pointed to the existence of significant additional resources in under-explored areas adjacent to the Bushveld Complex in South Africa and the Great Dyke in Zimbabwe. Unexplored extensions of the Merensky Reef and the UG2 Chromitite may contain 33,000 tonnes of platinum and 32,000 tonnes of palladium in additional resources to a depth of 3 kilometres (Zientek *et al.*, 2017). The total extractable amounts of PGMs considering new technology for mining at great depths (up to 5 kilometres) may increase by more than two times in comparison with the identified resources to date (Sverdrup and Ragnarsdottir, 2016).

However, in the event of significantly higher demand, short-term supply shortages are possible despite resource availability, because of:

- As the PGM primary production is highly concentrated geographically, it is likely to be affected by social, environmental, political, and economic factors, rather than geological resource depletion (Hagelüken, 2019; Zientek *et al.*, 2017);
- PGMs are produced as by-products of nickel in Russia. Therefore, an increase in the output depends on concurrent higher nickel production;
- The development of new mines lasts several years and is associated with high financial and technical risks (Hagelüken, 2019).

In South Africa, various factors have combined in recent years to increasing concerns about the security of PGM supplies. Prominent among these are labour disputes over wages and working conditions, mining accidents which have led to shaft closures and lost production, as well as calls for nationalisation of the industry. In addition to rising wages, other costs have also increased significantly, including the price of power, water, fuel and materials. The effects of these have been exacerbated by the prolonged global recession continued economic uncertainties, low metal prices and fluctuating exchange rates (European Commission, 2017a). Since 2008, shaft closures have cut out over 37 tonnes of platinum capacity, 20 tonnes of palladium capacity and almost 6 tonnes of rhodium capacity in South Africa (Heraeus, 2019). The PGM output in South Africa fell from 311 tonnes in 2016 to 260 tonnes in 2017 (BGS, 2019), due to declining ore grades, rationalisation and shaft closures at large underground mines (European Commission, 2017a).

There has been a recent period of cost-cutting and industry restructuring, but major capital investment is needed to increase mechanisation in the mines, to develop new mining capacity, and to restore sustainable profitability and secure jobs (IPA Industrial expert, 2019). Various mines have closed or are being considered for closure, while others have changed ownership. South Africa will likely remain the dominant global supplier of PGMs, because of its vast resource base, the established mining and processing infrastructure and expertise, and the great importance of the PGM industry to the economy of South Africa. However, it is also probable that there will be less, but more modern operations employing fewer workers (European Commission, 2017a).

In the Norilsk-Talnakh area in Russia, the PGMs (chiefly palladium) are essentially a by-product of nickel mining, so it is difficult to assess the long-term availability of PGMs from these mines, especially when nickel prices remain at low levels. For many years PGM supplies from Russia were supported by sales from government stocks. Although these sales have now ceased, the stocks are now owned by the Russian central bank and, depending on prices and other factors, may provide an additional source of future supply. The other source of Russian PGM supply is alluvial mining operations in the Far East. These provide only a small proportion of Russia's output, whereas grades are reported to be falling, so their share is likely to continue to decrease as it has been since 2014 (European Commission, 2017a).

Recycling currently makes already an important contribution to PGM supply and, given favourable economic conditions and supportive legislation, the share of PGMs from secondary materials is likely to increase as end-of-life products are collected more efficiently and processed using the optimum technology (European Commission, 2017a).

19.2.3.2 Forward look of PGM demand for autocatalysts

Catalytic converters for motor vehicles will likely remain the most significant demand sector for PGM for the foreseeable future. It is also considered likely to grow further as a result of increasing vehicle sales, both light-duty and heavy-duty, and stricter emission standards and testing regimes (IPA industrial expert, 2019). Nevertheless, the projected rapid growth in battery electric vehicles (BEVs) is going to affect the demand for PGM.

Since the early 1990s, the use of platinum-rich diesel catalysts has become universal, and PGM loadings increased to meet tightening tailpipe emissions standards. Euro 6b emissions limits (introduced in September 2014 and since September 2015 enforced on all new passenger cars registered in Europe) led to a rise in the average platinum loadings in diesel autocatalyst systems in Europe (Johnson Matthey, 2015; Johnson Matthey, 2016). In 2016, the total demand for platinum from the European vehicle sector reached its highest level since 2008 (Figure 250). Autocatalysts accounted for 75% of the European demand for platinum in 2018, and diesel catalysts used in light and heavy-duty vehicles and off-road applications account for 95% of automotive platinum usage in Europe (Johnson Matthey, 2016). Despite a decline in the popularity of diesel cars in the region since 2015, Europe remains the largest global market for diesel vehicles and accounts for over half of diesel cars manufactured globally.

In the EU, Real Driving Emissions (RDE) standards are being phased in between 2017 and 2022 for both gasoline and diesel vehicles under Euro 6d legislation. These changes, which will restrict the permitted difference for NOx and PN emissions under real driving and laboratory test conditions, will have significant impacts on the diesel catalysts developed by European carmakers and have greatly increased the complexity and variety of diesel catalyst systems in use (Johnson Matthey, 2016). PGM-containing catalysts are still required in all diesel vehicles sold in Europe, but increased use of selective catalytic reduction (SCR), and combined SCR-particulate filter technologies - to tightly control NO_x and PN emissions under RDE testing - has led to a decline in average platinum (and overall PGM) loadings since 2016 (Johnson Matthey, 2019a).

The automotive industry also dominates demand for palladium and rhodium, accounting for 85% of global gross demand in 2018 (Johnson Matthey, 2019a). European demand for palladium was estimated at 64 tonnes in 2018, with nearly 59 tonnes used by the automotive industry representing a share of 92% of the total demand in Europe. In recent years, consumption of both metals has expanded ahead of growth in vehicle sales as average PGM catalyst loadings have risen to meet tighter emissions legislation. The recent introduction of the RDE testing in Europe has driven average catalyst loadings higher on most vehicles (Johnson Matthey, 2019a).

The next stage of European legislation ('Euro 7') with an expected entry into force somewhere around 2023-2025, is not yet defined but is likely to tighten emissions limits further. Implementation of these tighter regulations may lead to renewed upward pressure on PGM loadings, though the result will depend on the timing, the severity and nature of the limits.

Consideration for the future is the potential use of platinum in gasoline emissions catalysts. For gasoline-powered vehicles, palladium-rhodium three-way catalysts (TWCs) are typically employed. Platinum is also active for CO and HC oxidation and was the dominant choice of metal for these catalysts when TWCs were first developed in the mid-70s through to the early 90s, before the use of low sulphur fuel made increasing use of (cheaper) palladium-containing TWCs possible. However, the reversal in the platinum to palladium price ratio since September 2018 has led to increasing speculation over a potential switch back from palladium to platinum in gasoline catalysts. While any large scale move towards greater use of platinum in gasoline catalysts would significantly impact the demand outlook for both platinum and palladium, there remain a number of technical and practical hurdles to overcome before OEMs would be ready and confident to consider a switch (IPA industrial expert, 2019).

At the same time, internal combustion engines (ICE) will be increasingly replaced by electric vehicles of various types, driven by progressively stringent CO_2 targets around the world. Hybrid electric vehicles will still require PGM-containing catalysts to treat emissions from the ICE. But in the case of zero tailpipe emission vehicles, pure battery electric vehicles (BEVs) have no ICE and do not require a catalyst, and so their increasing use will displace PGM demand. Alongside BEVs, fuel cell electric vehicles (FCEVs), which use a platinum catalyst, will play a vital role in the decarbonisation of the transport sector. This is not only true in the passenger car segment; fuel cell vans, but buses and trucks are also increasingly seen as being a crucial part of the transition to clean forms of transportation in the heavy-duty sector (Johnson Matthey, 2018).

While BEVs are gaining far more media attention currently, most major OEMs invest in both BEV and FCEV technologies, to satisfy the varied requirements of a diverse customer base. As a rapidly evolving market, long term views differ extensively, but most automotive experts agree that the future vehicle fleet will comprise a mix of hybrids, BEVs and FCEVs. BEVs are seen as the most practical and efficient option for vehicle segments where range requirements are limited (or more frequent refuelling is a feasible option), and FCEVs particularly suitable to segments where long-range and/or high utilisation rates are desirable (Johnson Matthey, 2018). With FCEV demand, therefore, set to grow in all transport sectors, over the longer-term platinum demand in the automotive industry is expected to rise.

Demand for PGMs in the fuel cell industry will become significant in the long term only if fuel cell electric vehicles (FCEVs) obtain a sizeable share of light-duty vehicle production. Fuel cell-powered electric car production was currently approaching 10,000 per year but is predicted to grow by orders of magnitude until 2040. However, PGM demand for fuel cells and hydrogen technologies is several years away from being significant (Heraeus, 2019).

19.2.4 Outlook for supply and demand of individual platinum group metals

19.2.4.1 Outlook for supply and demand of iridium

Forward look for iridium supply

It is considered that South Africa will continue to be the leading supplier of iridium worldwide. Most PGMs in South Africa are currently mined from the UG2 Chromitite layer, Bushveld Complex, that hosts larger PGM resources than the Merensky Reef, and, additionally, it contains a higher proportion of iridium; the iridium to platinum ratio in Merensky Reef is reported 1:50, while in the UG2 the ratio is 1:20 (Angerer et al., 2016). Thus, geologic availability is considered unlikely to be problematic for the future availability of iridium from South Africa.

Primary production of iridium is linked to platinum and palladium extraction; therefore it is set to grow or decrease in line with the production of these metals. Any drastic disruption in the output of platinum and palladium from South Africa will also have an effect on iridium availability. Similarly, it is not possible to adapt supply to demand fluctuations of the "minor PGMs", e.g. because of new technological developments, with stable production of the host PGMs (Hagelüken, 2019). A short-term escalation in demand can be met from stored iridium-containing intermediate products of PGM refining (Angerer et al., 2016).

With regard to the overall supply outlook, it can be argued that platinum's output from primary sources will grow in the longer term (20 years) to keep up with the anticipated increase in platinum's demand in 2035 and beyond (see the Platinum factsheet), and therefore, iridium's supply as a co-product will increase proportionally.

Forward look for iridium demand

The outlook for iridium is firm in the short-term. The anticipated strong growth in demand for electrochemical applications is expected to support overall demand. International Maritime Organisation's (IMO's) 'International Convention for the Control and Management of Ship's Ballast Water and Sediments' requires the mandatory addition of ballast water treatment technology to new ships and in the longer term the retrofitting of existing vessels. Treatment technology, using electrodes coated with ruthenium and iridium, is one of several ballast water treatment options available (Johnson Matthey, 2019a). In the electrical sector, iridium usage in organic light-emitting diodes (OLEDs) used in displays for electronic devices (mobiles phones, TVs) is also expected to grow (Johnson Matthey, 2019a).

In addition, iridium is a material used together with platinum in fuel cells, i.e. in polymer electrolyte membrane fuel cells (PEM). In the longer term, this application represents an area of supplementary demand, but the impact will depend on the market penetration of fuel cell electric vehicles (FCEV); their number would have to grow significantly to make a significant impact. Heraeus forecasts a gradually increasing platinum demand for FCEVs from 2030 onwards, and therefore, a supplementary demand for iridium (Heraeus, 2019).

For the overall qualitative assessment of the outlook of iridium's supply and demand, it is difficult to predict with confidence the impact of the above projections.

Table 105: Qualitative forecast of supply and demand of iridium

Material	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years

Iridium	X		+	?	+	0	?	+

19.2.4.2 Outlook for supply and demand of palladium

Forward look for palladium supply

It is expected that Russia and South Africa will continue to be the leading global suppliers of palladium. Although palladium may be considered as a by-product of nickel mining in Russia, it is unlikely that this will become a constraint on palladium supply, at least in the short term.

Forward look for palladium demand

The general factors affecting the future demand for PGM in the automotive sector are discussed in the PGM factsheet.

In the short term, the imposition of increasingly strict emission control legislation across the world is likely to continue to increase demand for palladium in autocatalysts. In the longer term, the move away from carbon-based fuels for powering road vehicles may lead to reduced demand for palladium.

Forecasts on the future use of PGM and palladium up to 2035 for Europe and worldwide were developed in the context of the H2020 SCRREEN project (Tercero, 2019) (Ait Abderrahim and Monnet, 2018). The results of the base scenario show that only the use of palladium in the chemical sector is expected to grow significantly in the EU and globally in absolute terms, while dental applications are almost disappearing in the rest of the world. The application that is expected to undergo significant changes in the next two decades for palladium demand is autocatalysts. According to the base scenario for the mobility sector, a decrease in PGM and therefore palladium demand for autocatalysts by 59% from 2017 to 2035 is considered plausible. It is indicated by (Tercero, 2019) that in 2035 the overall palladium consumption is projected to be 191 tonnes globally and 34 tonnes in Europe (of which 21 tonnes for autocatalysts). These projections can be compared with the global demand for palladium in 2018, i.e. 318 tonnes globally and 64 tonnes in Europe, as reported by (Johnson Matthey, 2019a).

Also, two different deployment scenarios were considered for electric vehicles in Europe's transportation sector ("Tech 2" and "Tech 3") as described in the JRC report by (Blagoeva *et al.*, 2016), which were updated and adjusted. According to the more conservative scenario "Tech 2", which assumes a strong market penetration by hybrid electric vehicles (HEVs) and a slower decrease in market share of gasoline-fuelled cars, the demand for palladium in autocatalysts is decreasing significantly from 52 tonnes in 2017 (84% of EU consumption) to 20 tonnes in 2035 (61% of EU consumption), which is very close to the base scenario. In this scenario, the total European demand for palladium in 2035 is projected to be 33 tonnes. In the "Tech 3" scenario, which suggests a rapid breakthrough of the more advanced technologies of plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV), palladium demand for autocatalysts drops from 52 tonnes in 2017 (84% of EU consumption) to 14 tonnes in 2035 (52% of EU consumption), with a total European palladium consumption of 27 tonnes in 2035.

In another study, it has been suggested that global demand for palladium will increase due to emerging technologies (Marscheider-Weidemann et al., 2016). The main palladium-containing future technologies identified are the micro-electric capacitors and seawater desalination. The demand for palladium from emerging technologies is estimated to increase fivefold from 2013 to 2035, i.e. from 20 tonnes in 2013 to 100 tonnes in 2035.

It is difficult to predict future palladium demand for jewellery and investment as it varies considerably by country in response to cultural attitudes and changing metal prices (European Commission, 2017).

For the overall qualitative assessment for the outlook of palladium's demand, it is challenging to forecast if the ongoing increase in loadings in catalytic converters will offset the decrease in demand by the lower number of ICE vehicles in 5 years from now. For the qualitative estimation of palladium's demand in 10 and 20 years, the forecasts developed by the SCRREEN project are applied (Tercero, 2019)

Table 106: Qualitative forecast of supply and demand of palladium

Material	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Palladium	X		?	-	-		-	-

19.2.4.3 Outlook for supply and demand of platinum

Forward look for platinum supply

It is considered that South Africa will continue to be the leading global supplier of platinum.

Forward look for platinum demand

General factors affecting the future demand for PGM in the automotive sector are also discussed in the PGM factsheet.

With the expected transformation of the transport sector from a combustion engine-based system towards electric mobility, the overall use of platinum will undergo significant changes in the next decades, and these changes will be more severe for Europe since European platinum demand is much more dependent on autocatalysts than the demand in the rest of the world is (Tercero, 2019).

In the short term, the imposition of increasingly strict emission control legislation worldwide is likely to increase demand for platinum in autocatalysts. In the longer term, the move away from carbon-based fuels for powering road vehicles will lead to reduced demand for platinum in catalytic converters. However, if fuel cell vehicles achieve significant market penetration in the future, platinum demand in the automotive sector will likely rise over the longer term.

It is difficult to predict future platinum demand for jewellery and investment as it varies considerably by country in response to cultural attitudes and changing metal prices. However, in recent years platinum jewellery demand (which accounts for the vast majority of PGM use in the jewellery sector) has been in decline. A progressively weaker platinum price (and, since 2015 its discount to gold) has challenged the consumer perception of platinum as the premium jewellery metal in the largest market of China. Intense competition from alternative metals, as well as the luxury market at large, have also acted to dampen demand. While interest in platinum jewellery in India has grown strongly in recent years (albeit from a low base), this has, so far at least, failed to offset the decline in the Chinese market. (IPA industrial expert, 2019)

Industrial consumption of platinum in chemicals, glass and petroleum refining has been at historically elevated levels over the last decade, due to a large extent to significant investment in new plants and expansions by China and Chinese-owned plants in other regions (Johnson Matthey, 2019b).

Forecasts on the future use of platinum and other PGM until 2035 for Europe and worldwide were developed in the context of the H2020 SCRREEN project (Tercero, 2019) (Ait Abderrahim and Monnet, 2018). The base scenario, which does not takes into account fuel cell electric vehicles (FCEVs) as a possible alternative to internal combustion engine (ICE) cars, results in a constant drop of platinum use in Europe from 2017 to 2035 due to the steady decline of the autocatalyst sector, i.e. from 53 tonnes in 2017 (Johnson Matthey, 2019b) to 23 tonnes in 2035. Platinum use in chemical and other applications is predicted to increase slightly but stays on a low level, while other sectors are expected to be stagnant until 2035. In this scenario, the overall consumption of platinum projected for Europe in 2035 is 45 tonnes. Results of the global forecast are similar. However, the growth of chemical and other uses is even stronger worldwide, almost balancing the decreasing demand for autocatalysts from about 101 tonnes in 2017 (Johnson Matthey, 2019b) to 42 tonnes in 2035. The global platinum consumption for 2035 is predicted to be 223 tonnes, and this can be compared with the worldwide demand for platinum in 2018 of 248 tonnes (Johnson Matthey, 2019b).

In order to take into account different scenarios for the deployment of electric vehicles in Europe, the two scenarios ("Tech 2" and "Tech 3") described in the JRC report by (Blagoeva et al., 2016) were considered and adjusted. In the more conservative "Tech 2" scenario assuming a strong market penetration of HEVs and only very slowly increasing shares of the more advanced technologies of BEVs and especially FCEVs, the overall platinum demand in Europe starts to increase again in 2025 (72 tonnes in 2017, 75 tonnes in 2035). In the "Tech 3" scenario, which assumes a more rapid introduction rate and stronger market penetration of BEVs and FCEVs, European platinum demand increases quickly, surpassing the level of 2017 already in 2023 and rising even further to 100 tonnes in 2035. However, both scenarios predict a decreasing platinum demand in Europe for the next five years due to progressing market penetration of electric vehicles and a consequently shrinking requirement for autocatalysts in vehicles with internal combustion engines (Tercero, 2019).

In the global context, the forecasted rise of demand because of platinum's use in emerging technologies may require significant increases in platinum production. The projected rise of demand is estimated up to 110 tonnes in 2035 by (Marscheider-Weidemann et al., 2016), driven by fuel cell electric vehicles that may require up to about 90 tonnes per year of platinum, depending on the market penetration. This can be compared with the global mine production of platinum in 2017 of 182 tonnes (WMD 2019).

For the overall qualitative assessment for the outlook of platinum's demand, it is uncertain if the ongoing increase in loadings in catalytic converters will offset the decrease in demand by the lower number of ICE vehicles in 5 years from now. For the qualitative estimation of platinum's demand in 10 and 20 years, the forecasts developed by the SCRREEN project are applied (Tercero, 2019). As concerns supply, it is assumed that geological availability of PGM in South Africa is such that there will be no restriction in supply if significant increases in platinum production are required.

Table 107: Qualitative forecast of supply and demand of platinum

Material	**Criticality of the material in 2020**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Platinum	x		?	0	+	+	+	+

19.2.4.4 Outlook for supply and demand of rhodium

Forward look of rhodium supply

It is considered that South Africa will continue to be the main global supplier of rhodium. Nevertheless, it is reported that rhodium supplies from South Africa are forecast to decline as shaft closures at Lonmin and Impala Platinum are implemented, and as some other UG2 operations are near the end of their lives. The UG2 reef is richer in rhodium than other PGM ores mined in South Africa, so the depletion and closure of UG2 operations will be particularly significant for rhodium supply. Growth in autocatalyst recycling may not be enough to offset the future contraction in mine production of rhodium. The scope for growth in rhodium recovery from autocatalysts is lower for rhodium than for palladium due to rhodium thrifting programmes in the past, particularly on North American and European cars (Johnson Matthey, 2019a).

Forward look of rhodium demand

The short-term outlook for demand is positive as car manufacturers are increasing PGM loadings in response to tighter emissions legislation and more stringent testing. According to Johnson Matthey projections, the autocatalyst demand is expected to increase by 10% in 2019, and the global rhodium demand to reach record levels (Johnson Matthey, 2019a). The major drivers of the increased rhodium demand for autocatalysts will be China and Europe. In China, a step-change in loadings on vehicles is underway due to a regulatory tightening. In Europe, an upward trend in rhodium loadings is expected as a result of more stringent testing of passenger vehicles. In particular, from September 2019 all new passenger cars sold in Europe will have to comply with Euro 6d-TEMP standards, which require vehicles to demonstrate NOx and particle number (PN) emissions compliance in Real Driving Emissions (RDE) testing as well as in laboratory tests. The final phase of Euro 6d will be implemented starting in January 2020, further limiting permitted NO_x emissions. At the same time, from January 2019 new in-service conformity regulations apply intended to ensure that catalyst systems meet RDE standards not just at the point that the vehicle is put into service, but for most of its lifetime. Because rhodium is a particularly effective catalyst for NOx, the impact of Euro 6d legislation on rhodium demand has been particularly significant (Johnson Matthey, 2019a). However, despite demand from the automotive sector is set to rise strongly due to increased rhodium loadings within the next 1-2 years, the absolute increase in rhodium's demand for autocatalysts in the near future will depend on gasoline car production and the market penetration of electric vehicles, so the trend is considered uncertain in 5 years from now.

In the mid- to longer-term, rhodium's demand is expected to undergo significant changes due to turning away from vehicles with internal combustion engines towards the use of electric vehicles. The H2020 SCRREEN project (Tercero, 2019) (Ait Abderrahim and Monnet, 2018) developed forecasts on the future use of PGMs up to 2035 for Europe and worldwide. In the base scenario for the global rhodium demand, a sharp decrease in demand for autocatalysts is predicted while the other sectors (chemical, glass and other uses) show a rising demand until 2035. The overall rhodium consumption is contracted by about 18% from 32.7 tonnes in 2017 (Johnson Matthey, 2019a) to 27 tonnes in 2035. The projection is similar for Europe as in 2035 rhodium demand decreases by 33% compared to 2017 to 2.7 tonnes, consisting of 48% for autocatalysts, 29% for the glass industry, 20% for chemical and 3% for other uses.

In order to take into account different scenarios for the penetration of electric vehicles in the European automobile sector, the two scenarios ("Tech 2" and "Tech 3") described in the JRC report by (Blagoeva *et al.*, 2016) were considered and adjusted. The "Tech 2" scenario, consisting of a slightly slower decreasing market share of gasoline-fuelled cars and an intense market penetration of hybrid electric vehicles (HEV), results in significant lower demand for rhodium in autocatalysts in the EU, from 3.2 tonnes in 2017 to 1.3 tonnes in 2035, as an autocatalyst is needed only for 72% of new cars in 2035; the overall European demand for rhodium in 2035 totals also 2.7 tonnes in this scenario. In the "Tech 3" scenario, which assumes rapid uptake rates for advanced electric vehicles (EVs), i.e. (BEVs and PHEVs), the share of new cars containing an internal combustion engine and, therefore, requiring an autocatalyst in 2035 is only 49%. Hence, the rhodium demand for autocatalysts is forecasted to drop from 3.2 tonnes in 2017 to 0.8 tonnes in 2035 with a total European rhodium consumption of 2.3 tonnes of rhodium in 2035 (Tercero, 2019).

The qualitative forecast for the world supply and demand for rhodium is presented in Table 108.

Table 108: Qualitative forecast of supply and demand of rhodium

Material	Criticality of the material in 2020		Demand forecast			Supply forecast		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Rhodium	X		?	-	-	0/-	0/-	0/-

19.2.4.5 Outlook for supply and demand of ruthenium

Forward look for ruthenium supply

It is considered that South Africa will continue to be the main global supplier of ruthenium. Most PGMs in South Africa are today mined from the UG2 Chromitite layer, Bushveld Complex, which hosts larger PGM resources than the Merensky Reef. As long as the UG2 ore contains a higher proportion of ruthenium than the Merensky Reef, the future availability of ruthenium from South Africa is considered unlikely to be problematic in terms of geological availability.

On the other hand, as ruthenium is a co-product of platinum and palladium production, a drastic disruption in the output of these host PGMs from South Africa poses a risk for future ruthenium supply. Likewise, it is not possible in practice to adapt supply to demand fluctuations, e.g. because of new technological developments, with stable production of the host PGMs (Hagelüken, 2019). A short-term escalation in demand can be met from stored ruthenium-bearing intermediate products of PGM refining (Angerer *et al.*, 2016).

The recycling rate of ruthenium from consumer products is currently very low. Given favourable economic, technical and regulatory conditions improved ruthenium recovery from sources such as WEEE might be envisaged (European Commission, 2017). A recent price-related increase in recycling of ruthenium old catalysts may continue in the future (Johnson Matthey, 2019a).

As concerns the overall outlook of supply, it can be expected that the projected significant increase in platinum's demand in 2035 (see Platinum factsheet) will be met by increased output from primary sources, and therefore, ruthenium's availability as a co-product will be increased proportionally. It is also assumed, that the current trend of high prices for ruthenium will be maintained in the short-term, and, therefore, supply from secondary sources will grow contributing to overall supply in the short-term (5 years).

Forward look for ruthenium demand

The outlook for ruthenium in the short-term is firm. Demand for hard disk drives, which are based on perpendicular magnetic recording in which ruthenium plays an important role, is expected to grow even though their share in the market is declining from the competing solid-state (flash) drives (Johnson Matthey, 2019a). For catalytic applications, demand growth is also expected because of new caprolactam and adipic acid capacity in China; there is also a potential for new ruthenium demand arising from the commercialisation of new catalytic processes (Johnson Matthey, 2019a). For electrochemical applications, a growth in demand should also be anticipated due to the mandatory fitment of ballast water treatment technology to new ships required by the International Maritime Organisation's (IMO's) 'International Convention for the Control and Management of Ship's Ballast Water and Sediments'; in the longer term, existing ships will also need to be retrofitted. Treatment technology, using electrodes coated with ruthenium and iridium, is one of several ballast water treatment options available (Johnson Matthey, 2019a). In the longer term (20 years), a supplementary demand for ruthenium can be anticipated from 2030 onwards due to the growing market penetration of fuel cell electric vehicles (FCEVs) (Heraeus, 2019).

For the overall qualitative assessment of the outlook of ruthenium's supply and demand, it is difficult to predict with confidence the impact of the above projections, especially in the 10 years horizon (see Table 109).

Table 109: Qualitative forecast of supply and demand of ruthenium

Material	**Criticality of the material in 2020**		**Demand forecast**			**Supply forecast**		
	Yes	No	5 years	10 years	20 years	5 years	10 years	20 years
Ruthenium	X		+	?	+	+	?	+

19.3 EU Trade

19.3.1 General EU trade of platinum group metals

Figure 251 presents the physical trade flows of PGMs in unwrought and powder form. It is apparent that after a period of decline (2010-2013), imports are continuously increasing from 2014 onwards; in 2018 total imports amounted to about 190 tonnes, close to the highest level that has been recorded since 2010 (203 tonnes). It is also apparent that the EU, after a period of net exports (2011-2014), has become again a net importer of PGMs in unwrought or in powder form since 2015. In 2013, in which the lowest level of imports is observed, demand for platinum and palladium in Europe was also at its lowest level in the period 2010-2018, i.e. about 110 tonnes when it typically ranges from 120-125 tonnes.

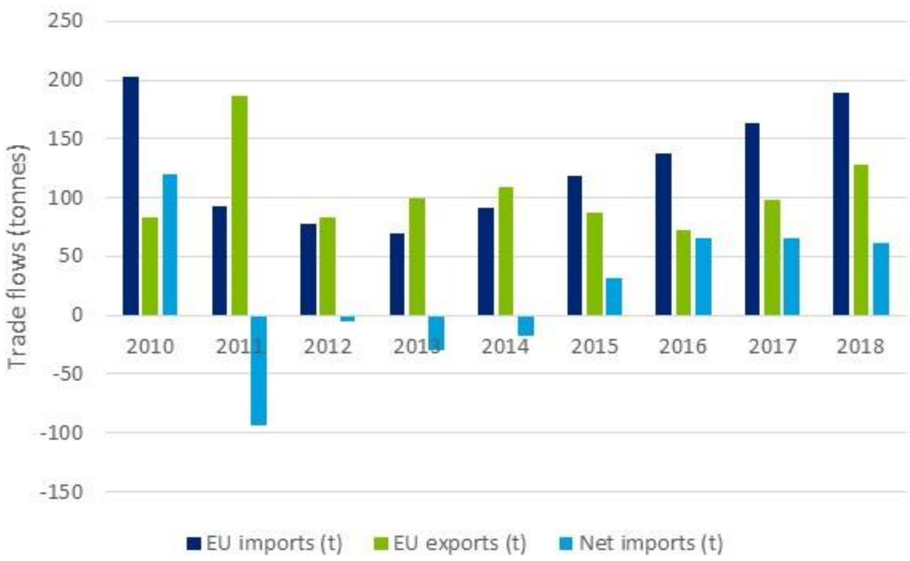


Figure 251: Trends in extra-EU trade for all PGMs in unwrought and powder form. Data[188] from (Eurostat, 2019a)

As regards trade of PGMs in semi-manufactured forms, imports of PGMs from extra-EU countries outweighed exports significantly from 2010 to 2015 (see Figure 252). The spikes in the trade balance observed in 2012 and 2013 are due to unusually high amounts of PGMs imported from the United Kingdom in those years. Imports of semi-manufactured forms of PGM were the highest in 2013 during the period 2010-2018 (see Figure 252). In 2016 and 2017, trade flows were relatively balanced. The EU became a net exporter for the first time in 2018 within the timeframe 2010-2018, as exports increased considerably.

[188] For trade codes: 7110 11"Platinum, unwrought/in powder form", HS 7110 21"Palladium, unwrought/in powder form", HS 7110 31"Rhodium, unwrought/in powder form", 7110 41"Iridium, osmium & ruthenium, unwrought/in powder form"

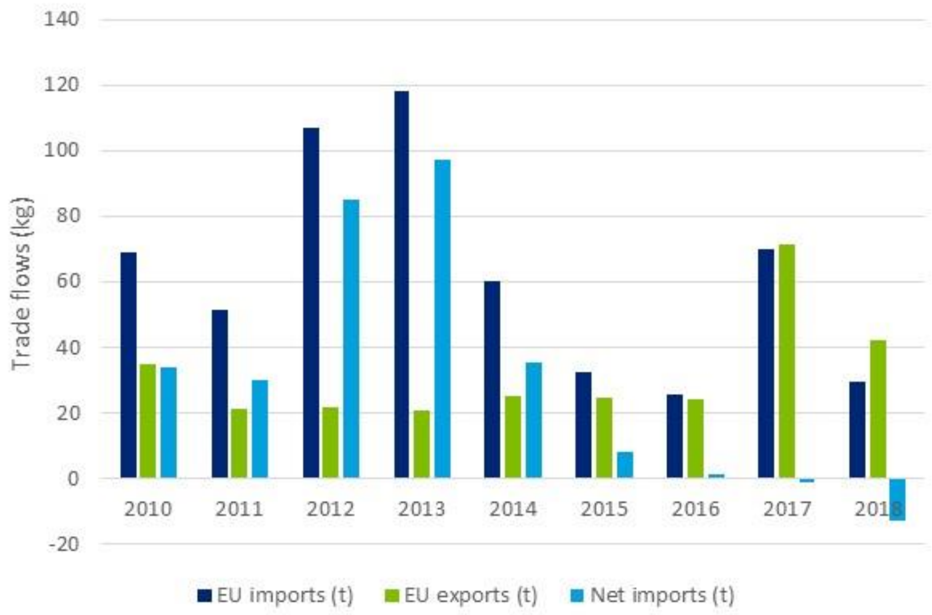


Figure 252: Trends in extra EU trade for all PGMs in semi-manufactured forms. Data[189] from (Eurostat, 2019a)

Figure 253 demonstrates the overall EU-extra trade balance by value for all PGMs in unwrought, powder and semi-manufactured forms. It is noted that in spite of the steady increase of imports value from 2013 to 2017, the EU-extra trade balance is generally negative (except for 2012 and 2013). Furthermore, the trade balance is significantly more negative in the latter years (2015-2018). These trends can be attributed to increasing quantities of imports, in combination with palladium's rising price and growing demand in Europe.

[189] For trade codes: HS 7110 19 "Platinum, in semi-manufactured forms", HS 7110 29 "Palladium, in semi-manufactured forms", HS 7110 39 "Rhodium, in semi-manufactured forms", HS 7110 49"Iridium, osmium & ruthenium, in semi-manufactured forms"

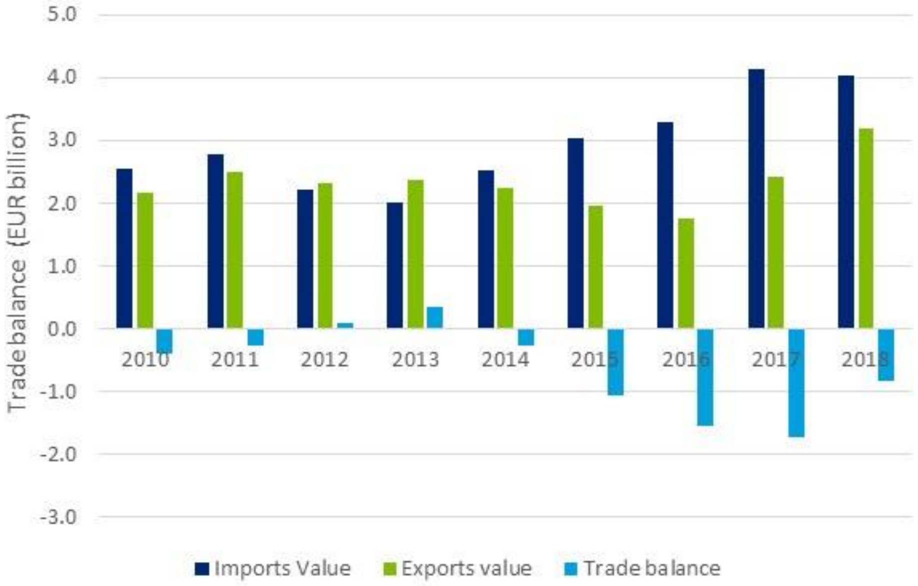


Figure 253: Trends in extra-EU trade balance for all PGMs in unwrought, powder and semi-manufactured form. Data from (Eurostat, 2019a)

South Africa, the United States, Russia, United Kingdom and Switzerland are the chief suppliers of PGMs to the EU (Figure 254). Switzerland, in particular, has traditionally been a central point of PGM storage and distribution by producers, traders and bankers and has significant precious metal refining capacity. Major platinum and palladium exchange-traded funds, which are based on physical holdings of these metals, are also located in Switzerland (European Commission, 2017a).

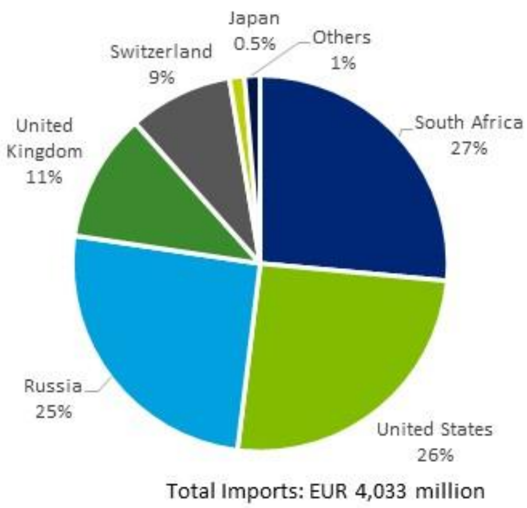


Figure 254: Sources of EU imports in 2018 for PGM in unwrought, powder and semi-manufactured form by value. Data from (Eurostat, 2019a)

Figure 255 reflects the distribution of EU imports value by product category. Palladium products have a dominant position in the value of EU imports, with a total share of 54%, followed by platinum (35%), rhodium (9%), and iridium, osmium & ruthenium (2%).

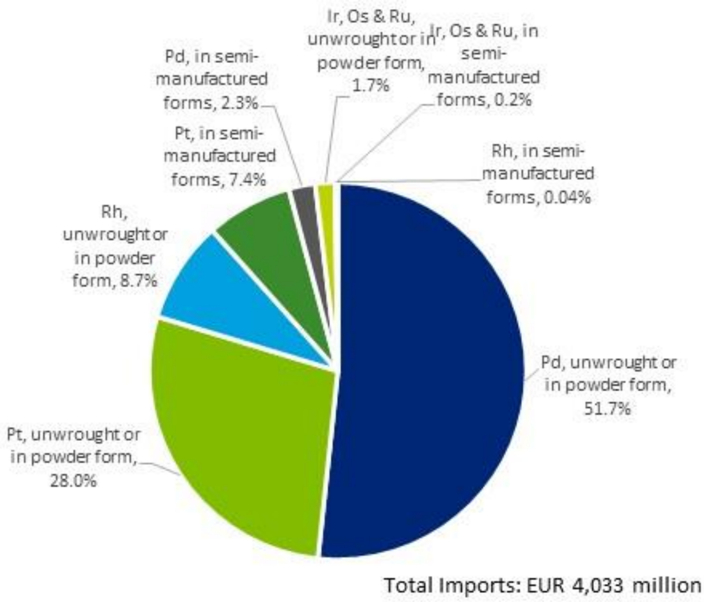


Figure 255: EU imports value in 2018 by PGM product group in unwrought, powder and semi-manufactured form. Data from (Eurostat, 2019a)

19.3.2EU trade of individual platinum group metals

19.3.2.1 EU trade of iridium

As discussed in section 19.3.1, PGMs are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For iridium, trade data were analysed for trade codes HS code 7110 41 "Iridium, osmium and ruthenium in unwrought or powder form", and HS 7110 49 "Iridium, osmium and ruthenium metal in semi-manufactured forms". The relative proportion of iridium in the EU trade flows in the above aggregated trade codes was estimated by assuming trade flows for osmium to be negligibly small and, thus, set to zero. Also, by considering that the disaggregated trade flows for ruthenium and iridium are proportional to their world demand. The relative size of their markets was derived from data published by (Johnson Matthey, 2019a), and has been calculated at 83% ruthenium and 17% iridium, as an average over the 2012-2016 period.

In all years from 2012 to 2016, the EU was a net exporter of iridium in unwrought or powder form. Net exports averaged to 1.5 tonne per year. As it is demonstrated in Figure 256, the evolution of EU net exports since 2013 is towards lower levels, due to declining exports. For iridium in semi-manufactured forms, the EU was also a net exporter on average in years 2012-2016 (Figure 256). From the above figures, it is concluded that that the EU is a considerable world supplier of refined iridium; however, it is not possible to determine how much of this metal was derived from primary or secondary sources.

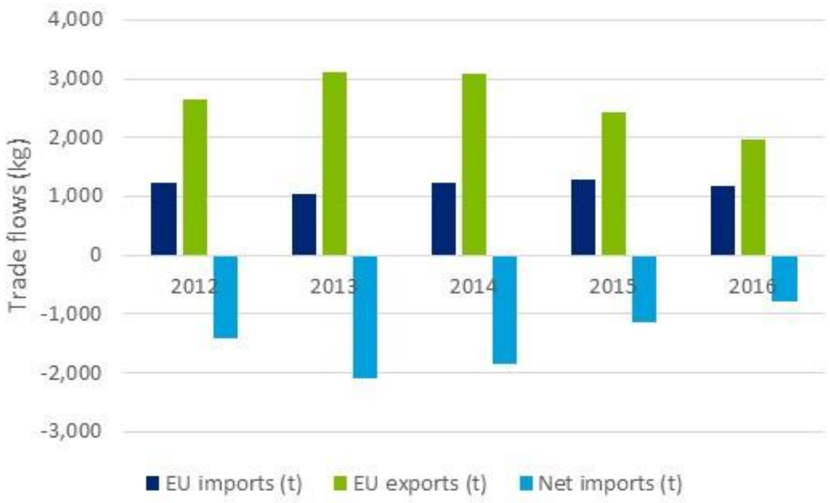


Figure 256: Estimated EU trade flows for iridium in unwrought or powder form. Background data from (Eurostat, 2019a, Johnson Matthey, 2019a)

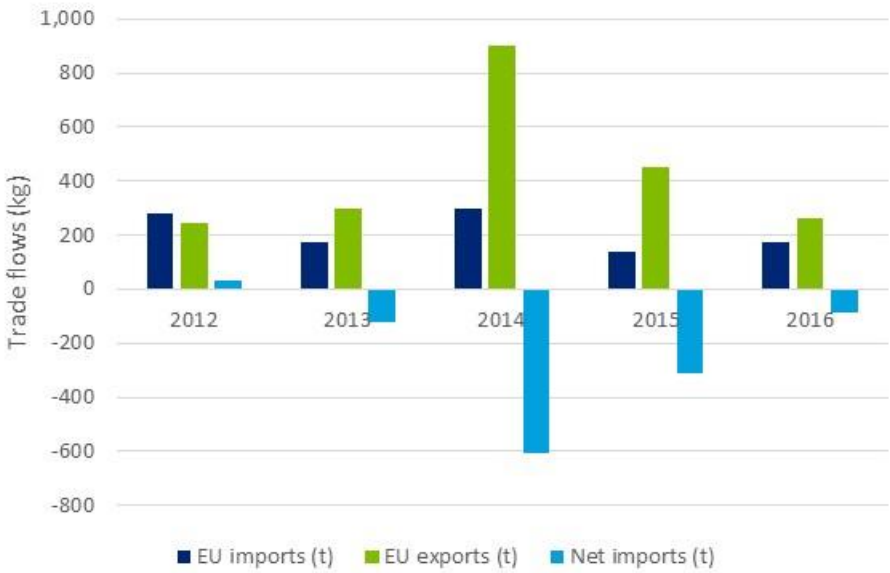


Figure 257: Estimated EU trade flows for iridium in semi-manufactured forms, Background data from (Eurostat, 2019a, Johnson Matthey, 2019a).

EU imports of iridium, in unwrought or powder form, averaged to about 1.2 tonnes per annum between 2012 and 2016. The key sourcing countries were South Africa (39%), the UK (38%), and Japan (11%) (Figure 258). In the same period, the average annual EU exports amounted to about 2.6 tonnes of iridium metal, in unwrought or powder form. Singapore was the top destination of exports (75% of the total), followed by the US (9%).

The annual average EU imports of iridium in semi-manufactured forms were about 0.2 tonnes from 2012 to 2016. The United States was the main source country (52%), followed by the United Kingdom (23%) and Switzerland (10%) (Figure 258). In the same period, the EU exported annually about 0.4 tonnes of iridium in semi-manufactured forms. Turkey (48%) was the major destination of EU exports, followed by Brazil and Singapore (13% each).

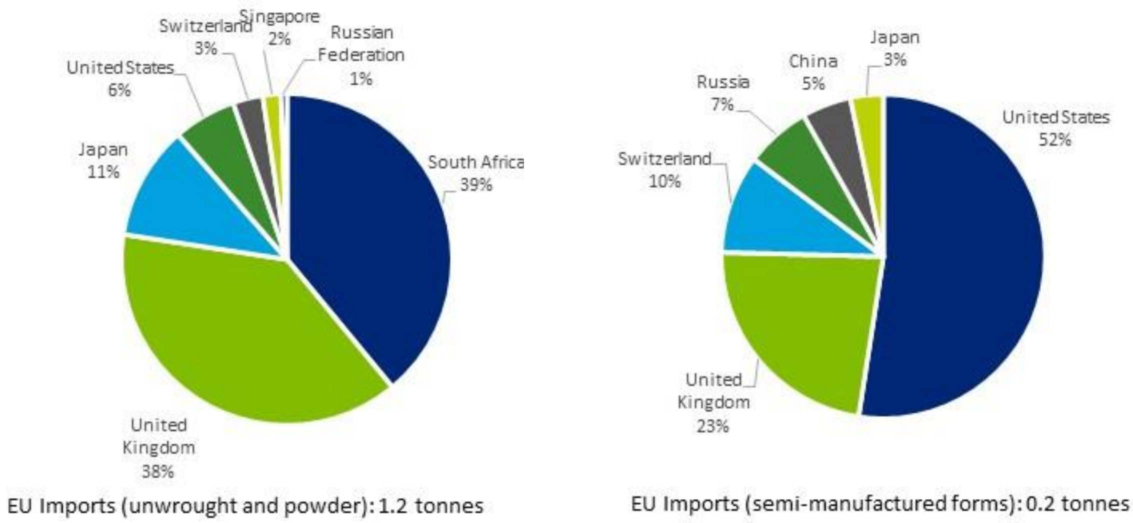


Figure 258: Origin countries for EU imports of iridium metal in unwrought or powder form (left), and in semi-manufactured forms (right), average 2012-2016. Background data from (Eurostat, 2019a, Johnson Matthey, 2019a).

In 2017, there were no export taxes, quotas or export prohibition in place between the EU and its suppliers for HS 7110 41 "Iridium, osmium & ruthenium, unwrought or in powder form" and HS 7110 49 "Iridium, osmium & ruthenium, in semi-manufactured forms". The EU and South Africa have a trade agreement in place (European Commission, 2019).

19.3.2.2 EU trade of palladium

As discussed in section 19.3.1, the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For palladium, trade data are available for palladium metal in unwrought or powder form (HS code 7110 21), and in semi-manufactured forms (HS 7110 29).

During the period 2012-2016, the EU was a net importer of palladium metal. The EU imported about 46.1 tonnes of palladium in unwrought or powder form on average over the 2012-2016 period, whereas it exported only 0.4 tonnes (see Figure 259). Imports of palladium in unwrought or powder form have increased significantly from 2013 to 2016 by 50%. The primary sources of EU imports of palladium metal were Russia, the United Kingdom, Switzerland, the USA, and South Africa (see Figure 259). The main destination of EU exports for unwrought palladium or in powder form was the US (36% of the total).

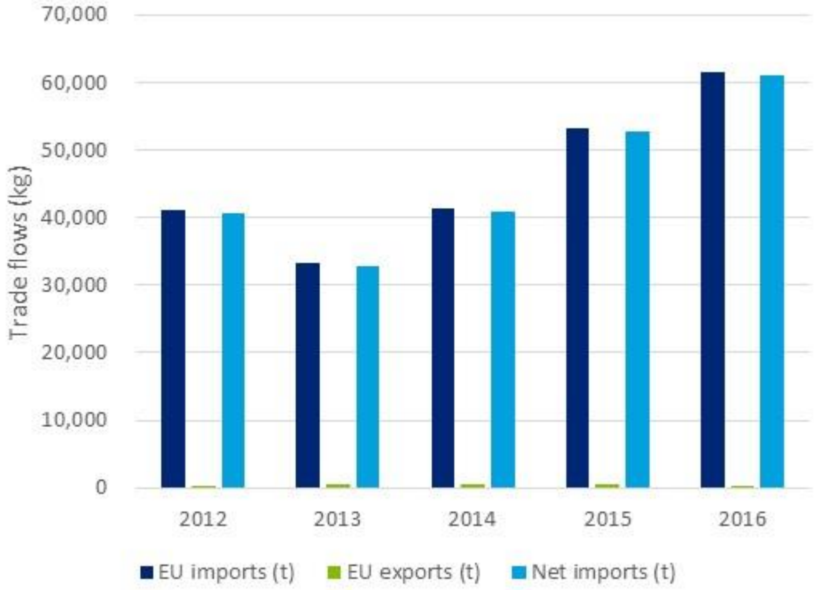


Figure 259: EU trade flows for palladium in unwrought or powder form (HS 7110 21), 2012–2016. Data from (Eurostat, 2019a)

Similarly, the EU was a net importer for palladium in semi-manufactured forms as the annual average net imports amounted to 7.6 tonnes over the period 2012-2016. A surge of imports can be noted in Figure 260 for the year 2014, which is due to a particularly high amount of material (about 33 tonnes) imported from the United Kingdom in that year. The main origins of imports for palladium in semi-manufactured forms was the United Kingdom, the United States, and Switzerland (see Figure 261). The annual average EU exports for palladium in semi-manufactured forms reached 8.3 tonnes per annum between 2012 and 2016. The main destinations for these exports were the US (37%), Switzerland (23 %) and the United Kingdom (13%).

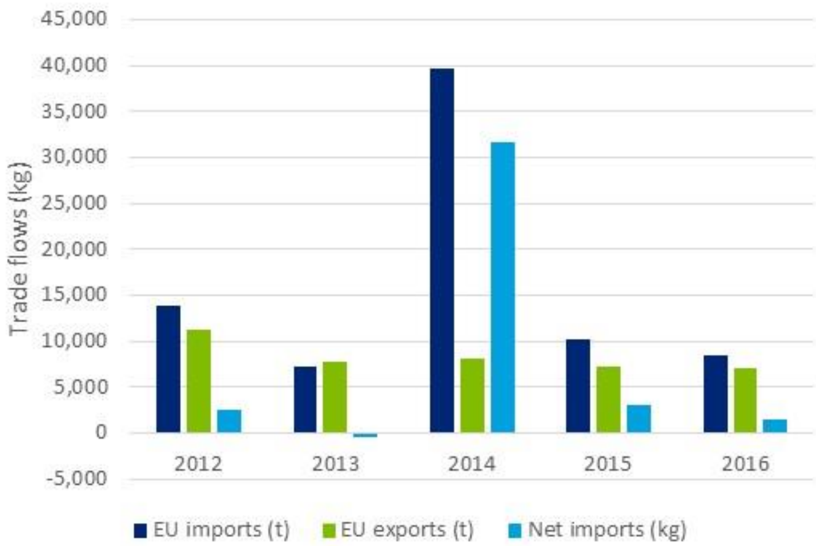


Figure 260: EU trade flows for palladium in semi-manufactured forms (HS 7110 29), 2012-2016. Data from (Eurostat, 2019a)

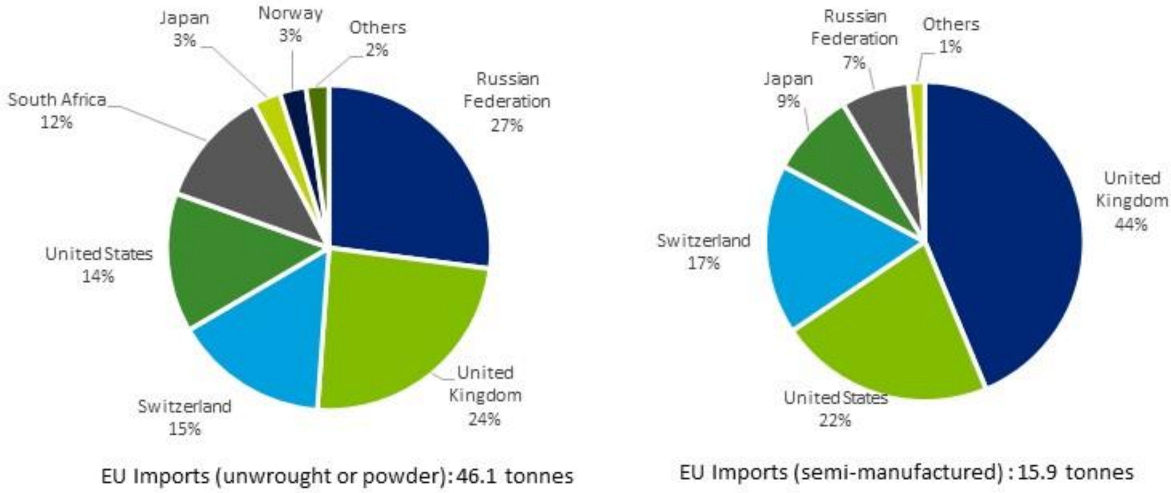


Figure 261: Origin countries for EU imports of palladium in unwrought or powder form (left), and in semi-manufactured forms (right), average 2012-2016. (Eurostat, 2019a)

In 2017, there were no export taxes, quotas or export prohibition in place by EU's suppliers for HS 7110 21 "Palladium, unwrought/in powder form" and HS 7110 29 "Palladium, in semi-manufactured forms" (OECD, 2019). The EU and South Africa have a trade agreement in place (European Commission, 2019).

19.3.2.3 EU trade of platinum

As discussed in section 19.3.1, the PGM are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For platinum, trade data are available for platinum in unwrought or powder form (HS code 7110 11), platinum in semi-manufactured forms (HS 7110 19), platinum waste and scrap (HS code 7112 92), and platinum catalysts in the form of wire cloth or grill (HS code 7115 10).

The EU was a net importer of platinum metal over the period 2012-2016. On average, the EU imported about 42.1 tonnes per year of platinum in unwrought or powder form, while it exported 27.9 tonnes per year. A gradual and significant increase in the amount of imports took place from 2012 to 2016 (see Figure 262). Imports in 2016 surged by about 150% compared to 2012, with South Africa contributing to the higher amount of the increase (one-third of the overall rise). EU imports and exports remained relatively balanced in the period 2012-2014. Nevertheless, a substantial increase in EU net imports took place in 2015 and 2016, due to declining exports. The primary sources of EU imports of platinum metal were South Africa, the United Kingdom, the United States, and Switzerland (see Figure 262). The main destinations of EU exports for unwrought platinum or platinum in powder form were the United Kingdom (33%), the United States (29%), and Switzerland (22%).

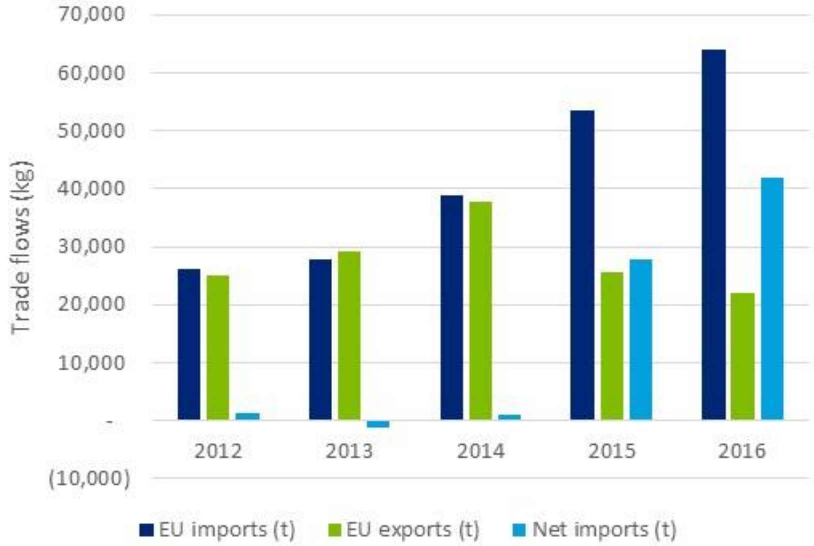


Figure 262: EU trade flows for platinum in unwrought or powder form (HS 7110 11), 2012–2016. Data from (Eurostat, 2019a)

Concerning platinum in semi-manufactured forms, the EU was also a net importer over the period 2012-2016 as the annual net imports averaged to 39.3 tonnes (see Figure 263). Imports were particularly high in 2012 and 2013 due to increased amounts received from the United Kingdom (81 tonnes and 100 tonnes, respectively). United Kingdom was the dominant sourcing country for the EU imports of platinum in semi-manufactured forms accounting for 80% of the 50.8 tonnes of total imports (see Figure 264). The average EU exports for platinum in semi-manufactured forms were 11.5 tonnes per annum between 2012 and 2016, and the main destinations were the United States (38%), the United Kingdom (26%), and Switzerland (14%).

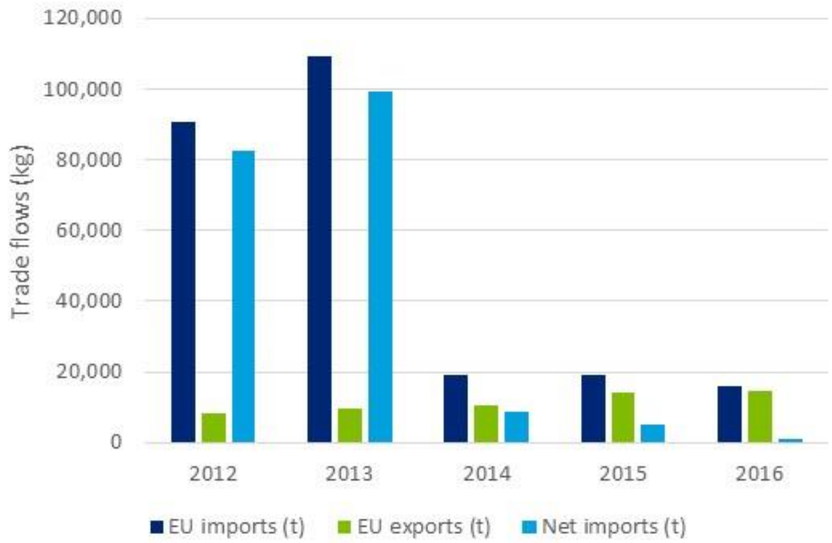


Figure 263: EU trade flows of platinum in semi-manufactured forms (HS 7110 19), 2012-2016. Data from (Eurostat, 2019a)

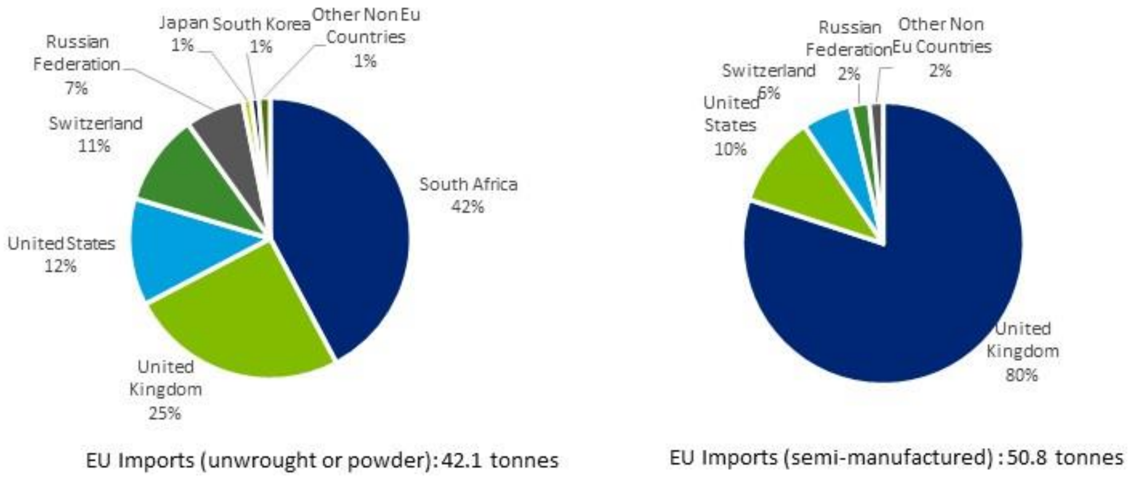


Figure 264: Origin countries for EU imports of platinum in unwrought or powder form (left), and in semi-manufactured forms (right), average 2012-2016. Data from (Eurostat, 2019a)

There is also significant international trade of platinum-bearing waste and scrap in the EU Member States. Figure 265 presents the relevant trade flows in terms of volume from 2010 to 2016, and Figure 266 shows the top importers and exporters worldwide of waste and scrap of platinum by value in 2017 (including intra-EU trade). As it is demonstrated by Figure 265, EU-extra imports of waste and scrap of platinum prevail over imports to a large extent.

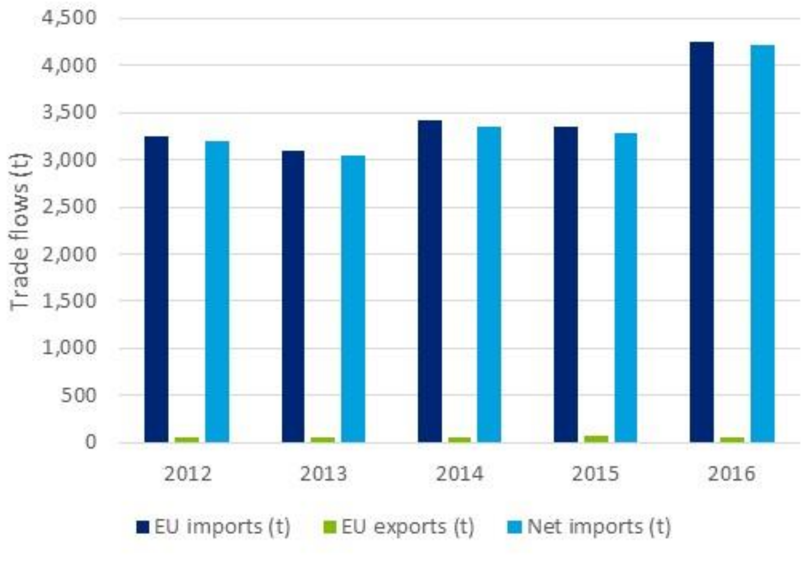


Figure 265: EU trade flows of waste and scrap of platinum (HS 7112 92), 2012-2016. Data from (Eurostat, 2019a)

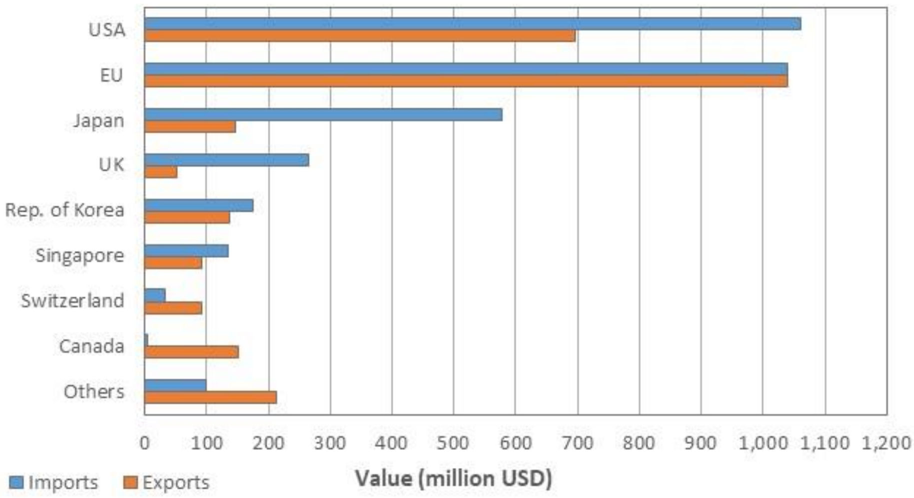


Figure 266: Global trade of platinum waste and scrap (HS 7112 92) in 2017 by value. Data from (UN Comtrade, 2019)

In 2017, there were no export taxes, quotas or export prohibition in place imposed by EU's suppliers for HS 7110 11 "Platinum, unwrought/in powder form" and HS 7110 19 "Platinum, in semi-manufactured forms". The EU and South Africa have a trade agreement in place (European Commission, 2019).

19.3.2.4 EU trade of rhodium

As discussed in section 19.3.1, the PGMs are traded in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For rhodium, trade data are available for rhodium metal in unwrought or powder form (HS 7110 31), and in semi-manufactured forms (HS 7110 39). In the years 2012-2016, the EU was a net exporter for both rhodium in unwrought or powder form and rhodium in semi-manufactured forms.

The EU imported on average 3.9 tonnes per year and exported 5.2 tonnes per year of rhodium in unwrought/powder form; thus the net exports averaged to 1.3 tonnes annually. In the period 2012-2014 exports prevailed significantly over imports, whereas in 2014-2015, the trade balance is almost neutral (see Figure 267). South Africa was the predominant source of EU's imports of rhodium in unwrought/powder form, accounting for 45% of the total imports (see Figure 269). The United Kingdom (21%), Russia (17%) and the United States (13%) were also important trade partners.

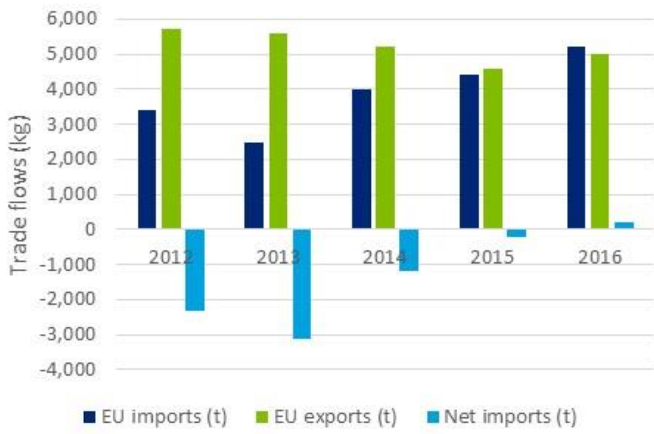


Figure 267: EU trade flows for rhodium in unwrought or powder form (HS 7110 31), 2012–2016 (Eurostat, 2019a)

For rhodium in semi-manufactured forms, the annual average imports amounted to 0.8 tonnes and the yearly average exports to one tonne, resulting in average yearly net exports of 0.2 tonnes (with high fluctuations) (see Figure 268). Vietnam was the major source for EU imports of rhodium in semi-manufactured forms, mainly due to a massive import flow in 2015.

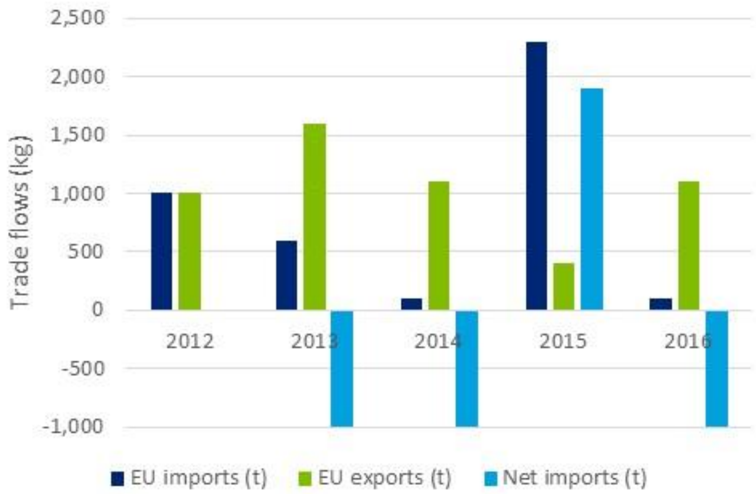


Figure 268: EU trade flows for rhodium in semi-manufactured forms (HS 7110 39), 2012-2016 (Eurostat, 2019a)

Figure 269 presents the sources of EU imports of rhodium.

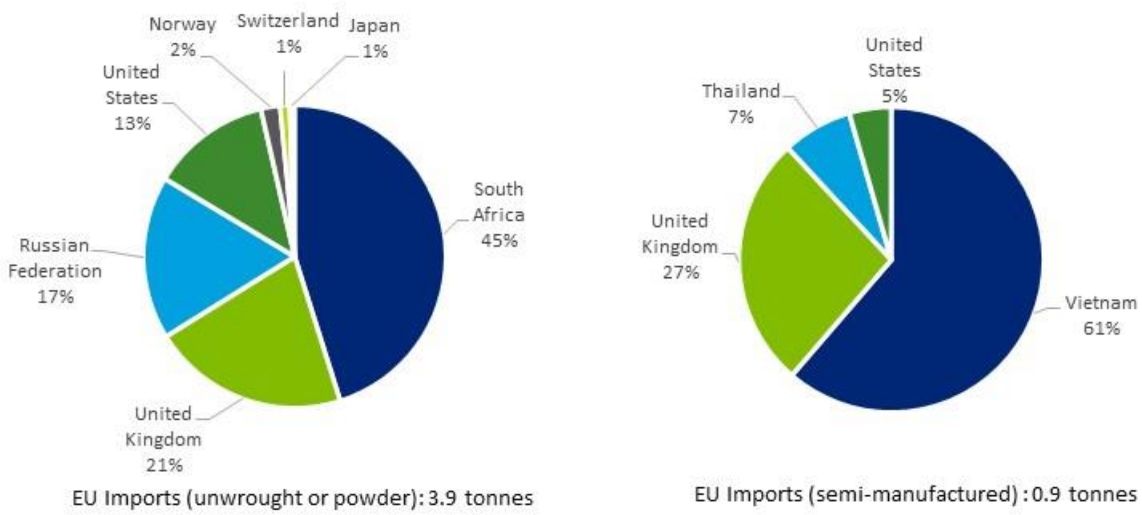


Figure 269: Origin countries for EU imports of rhodium in unwrought or powder form (left), and in semi-manufactured forms (right), average 2012-2016 (Eurostat, 2019a)

In 2017, there were no export taxes, quotas or export prohibition in place by EU's suppliers for HS 7210 31 "Rhodium, unwrought/in powder form" and HS 7110 39 "Rhodium, in semi-manufactured forms" (OECD, 2019). The EU and South Africa have a trade agreement in place (European Commission, 2019).

19.3.2.5 EU trade of ruthenium

As discussed in section 19.3.1, PGMs are traded in the EU in a variety of forms – as metal in unwrought or powder form, in semi-manufactured forms and various intermediate products and wastes. For ruthenium, trade data were analysed for HS code 7110 41 (which includes iridium, osmium and ruthenium in unwrought or powder form), and for trade code HS 7110 49 (which includes iridium, osmium and ruthenium metal in semi-manufactured forms). The proportion of ruthenium in the EU trade flows was estimated by assuming trade flows for osmium to be negligible small, thus set to zero. In addition, by considering that the disaggregated trade flows for ruthenium and iridium are proportional to their world demand. The relative size of their markets was derived from data published by (Johnson Matthey, 2019a), and has been estimated at 83% ruthenium and 17% iridium, as an average over the 2012-2016 period.

In all years from 2012 to 2016, the EU was a net exporter of ruthenium in unwrought or powder form (see Figure 270). The average annual net exports amounted to 7 tonnes; however, since 2013 the trade balance is declining due to decreasing exports. For ruthenium in semi-manufactured forms the EU was also a net exporter on average in years 2012-2016 (Figure 271). From the the figures, it is concluded that that the EU is a significant world supplier of refined ruthenium; however, it is not possible to determine how much of this metal was derived from primary or secondary sources.

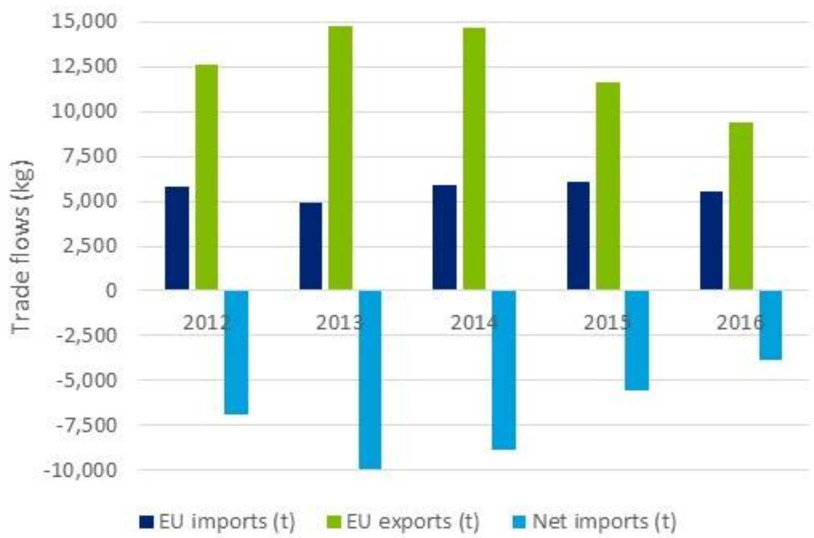


Figure 270: Estimated EU trade flows for ruthenium in unwrought or powder form. Background data from (Eurostat, 2019a; Johnson Matthey, 2019a)

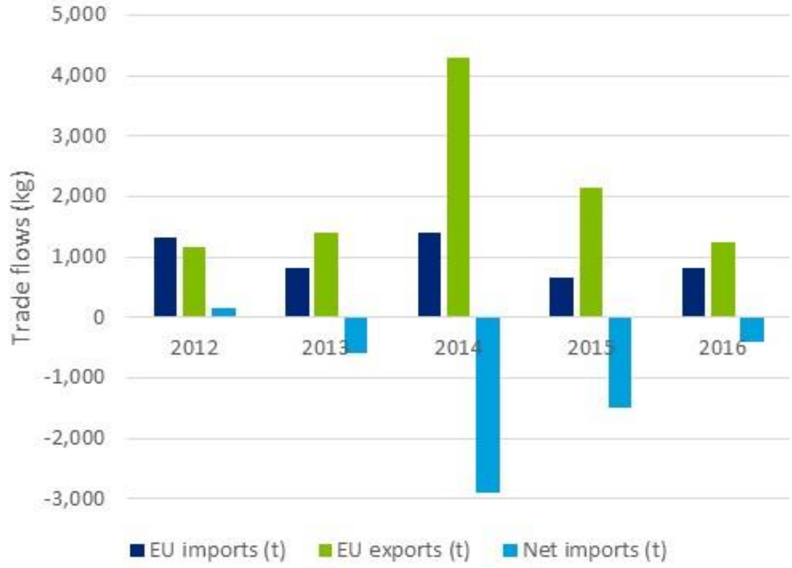


Figure 271: Estimated EU trade flows for ruthenium in semi-manufactured forms, Background data from (Eurostat, 2019a; Johnson Matthey, 2019a)

The average annual EU imports of ruthenium, in unwrought or powder form, were about 5.6 tonnes between 2012 and 2016. The sources of these imports were South Africa (39%), the United Kingdom(38%), and Japan (11%) (Figure 272). During the same period, the EU exported annually about 12.6 tonnes of ruthenium metal, in unwrought or powder form. Singapore was the top destination of exports (75% of the total), followed by the United States (9%).

The average annual EU imports of ruthenium in semi-manufactured forms were about 1.0 tonne from 2012 to 2016. The United States was the main source (52%), followed by the United Kingdom (23%) and Switzerland (10%) (Figure 272). In the same period, the EU exported annually about 2.1 tonnes of ruthenium in semi-manufactured forms. Turkey (48%) was the major destination of EU exports, followed by Brazil and Singapore (13% each).

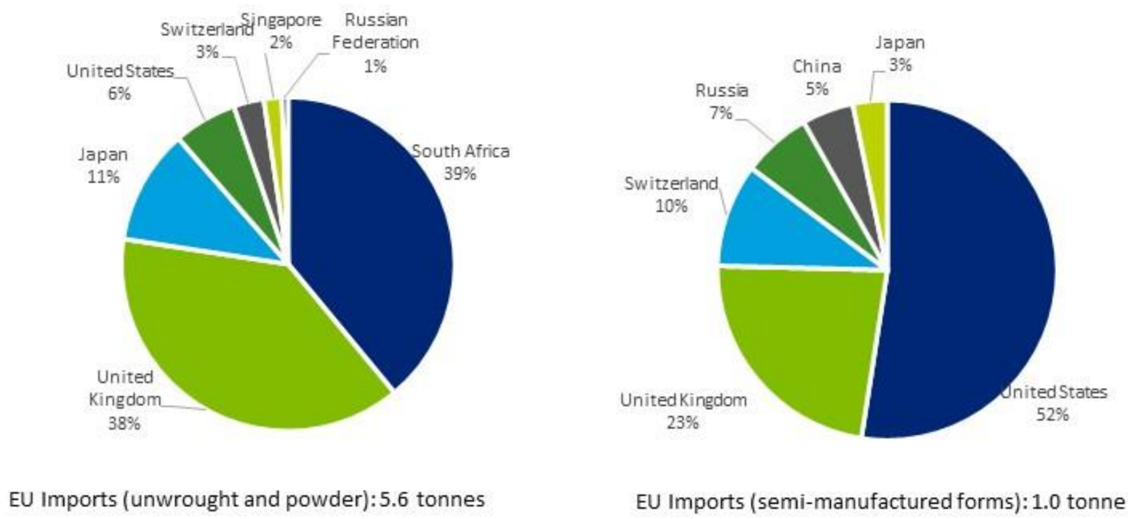


Figure 272 : Origin countries for EU imports of ruthenium metal in unwrought or powder form(left), and in semi-manufactured forms (right), average 2012-2016. Background data from (Eurostat, 2019a; Johnson Matthey, 2019a).

No export taxes, quotas or export prohibition are reported to be in place by EU’s suppliers for HS 7110 41 “Iridium, osmium & ruthenium, unwrought or in powder form” and HS 7110 49 “Iridium, osmium & ruthenium, in semi-manufactured forms”. The EU and South Africa have a trade agreement in place (European Commission, 2019).

19.4 Prices and price volatility

19.4.1 Prices and price volatility of platinum group metals in general

PGM prices are high due to the limited availability in nature and in the market. Prices are sensitive to volatility because of a small buffering stock-in-use in society and low flexibility for accommodating rapid changes in demand (Sverdrup and Ragnarsdottir, 2016).

PGM are bought and sold in various ways. Platinum and palladium are typically exchange-traded with several daily market prices quoted for the pure (min. 99.9%) metals in US$ per troy ounce. For example, the London Metal Exchange (LME) delivers daily prices for platinum and palladium on behalf of the London Bullion Market Association. Johnson Matthey also publishes daily prices based on the company's quoted prices for its customers of wholesale quantities of platinum group metals set by its trading desks in the U.S., Hong Kong and the UK. The price is for the metal in sponge form with minimum purities of 99.95% for platinum and palladium, and 99.9% for rhodium, iridium and ruthenium. Platinum and palladium are also traded over-the-counter. Other platinum group metals are more commonly traded through long-term supply contracts and individual trades between large consumers and suppliers and trading houses (European Commission, 2014).

The evolution of prices for each PGM is presented in the individual PGM factsheets. In general, the price development of the PGM used in autocatalysts is the result of the interaction between market, catalytic technology and availability of raw materials (Hagelüken, 2019). Moreover, the price volatility observed for the PGM is due to various events that could affect global supply and demand. Some are associated with government policies and legislation such as the widespread adoption of catalytic converters in the mid-1970s which led to a surge in PGM demand (Hagelüken, 2019). Others are related to the changing global economic conditions such as the worldwide recession of 2008. Other events are related to supply disruption in mineral production such as miners' strikes in South Africa (1986, 2011, and 2012), and the power supply disruption in South Africa in 2008 when the South African mining industry briefly shut down almost all its operations (Zientek et al., 2017).

19.4.2 Prices and price volatility of individual platinum group metals

19.4.2.1 Prices and price volatility of iridium

Unlike platinum and palladium, iridium is not traded on the major metal exchanges. Iridium is generally sold through long-term supply contracts between fabricators and mines. Johnson Matthey is the main fixer of the iridium price publishing quoted prices set by the company's trading desks in the United States, Hong Kong and the United Kingdom for wholesale quantities of platinum group metals. The price is for the metal in sponge form with a minimum purity of 99.9% iridium (European Commission, 2017).

The price of iridium has experienced considerable volatility in recent years in response to changing industrial demand. In the 1990s, iridium price had a tenfold increase from US$60 per troy ounce in 1996 to US$575 per troy ounce in 2019, as it was first used in 1996 for iridium-coated catalytic converters in Japan (Hagelüken, 2019). Nevertheless, the subsequent price evolution is not related to autocatalysts. Over the first decade of the 2000s, the price varied between about US$100 and US$400 per troy ounce. However, in early 2010, it began to rise rapidly, peaking in late 2011 at approximately US$1,085 per troy ounce. This sharp increase can be attributed chiefly to a rapid and significant expansion of demand for iridium crucibles by the electrical sector (European Commission, 2017). However, the high level of demand from the electronics industry was not sustained, and the price fell back sharply to about US$400 per troy ounce in late 2013. Reduced demand from the chlor-alkali industry in China also contributed to the falling price in this period (European Commission, 2017). Since the second half of 2016, the iridium price has risen sharply from US$520 to US$1,480 per troy ounce in October 2018 at an all-time high (a price gain of 185 %). The price rise is attributed to supply fluctuations of refined metal, increased industrial demand in 2017 for crucibles from the electrical sector and for the coating of anodes in the electrochemical sector, as well as due to strategic purchasing in Asia in 2016-2017; in 2018 the price rose sharply despite lower demand in comparison to 2017 (Johnson Matthey, 2018); Johnson Matthey, 2019a). Iridium's price has remained stable to this record level until September 2019 (see Figure 273), reflecting a modest improvement in market liquidity, probably due to some additional recycling activity in the chemicals sector and growth in refined output (Johnson Matthey, 2019a).

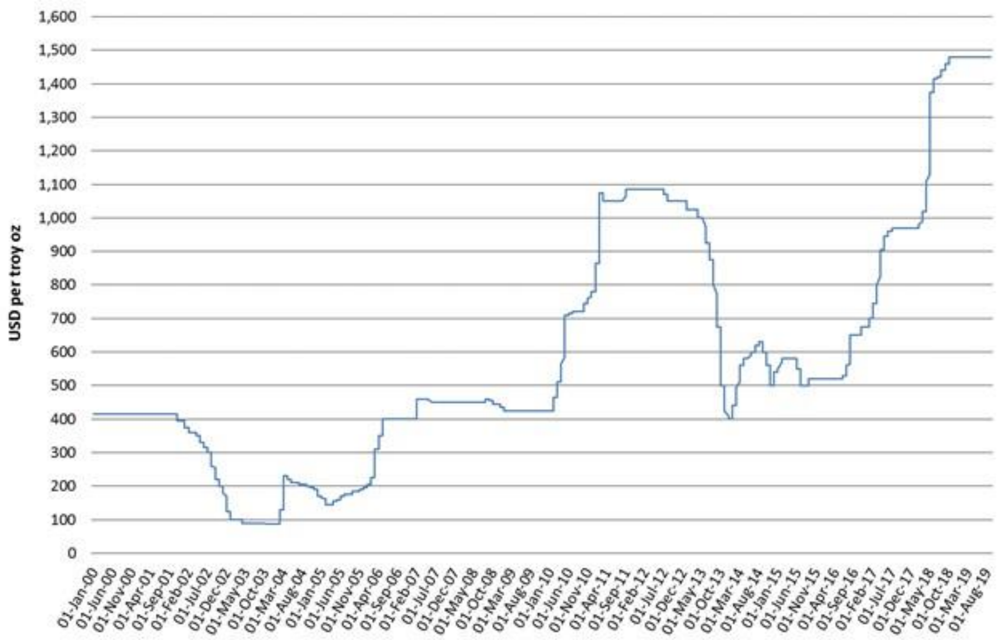


Figure 273. Iridium price trend, January 2000 – September 2019, Johnson Matthey quoted daily prices (US$/oz[190]), sponge, min. 99.9%, London. Data from (Johnson Matthey, 2019d)

19.4.2.2 Prices and price volatility of palladium

Palladium is typically exchange-traded. Pure palladium (minimum 99.95 %) prices are quoted daily in US dollars per troy ounce in a number of international exchange markets. It is also traded through London on a 24-hour basis in over-the-counter (OTC) transactions between miners, central banks, governments, fabricators, investors, hedge funds and refiners. From December 2014, a new benchmark price is set twice daily, called the "London Metal Bullion Association (LMBA) Palladium Price", via an auction process taking place in the OTC market in London (LBMA, 2019). The prices are administered and distributed by the London Metals Exchange (LME) via a custom-built electronic auction platform. The new reference prices replace the data of the London Platinum Fixing Company (LPPFCL). In the spot market, palladium is sold for cash and immediate delivery in sponge, plate or ingot form. Palladium is also traded through long-term supply contracts between fabricators and miners.

[190] 1 troy ounce (oz t) = 31.10348 g

The price of palladium has fluctuated considerably in recent years. From 1995 to 2001 palladium dominated the autocatalysts sector as it substituted platinum in gasoline vehicles (e.g. in the classical European 3-way catalyst with a Pt/Rh ratio of 5:1) driven by technical developments in catalyst technology and improved fuel qualities (Hagelüken, 2019). At the same time, Russia temporarily blocked palladium exports in 1999 and 2000 (Zientek et al., 2017). The result of strong demand and supply disruption was that palladium's price rose sharply in the late 1990s reaching its peak in January 2001 at around €1,100 per troy ounce, and palladium became more expensive than platinum. However, this trend was not sustained as high prices brought about substitution by platinum (Hagelüken, 2019), which in combination with increasing supply (Schmidt, 2015), made the palladium's price to fall steeply at levels as low as €150 per troy ounce in May 2003. A new substitution cycle was triggered again in 2008 when the price differential between the two PGM became very high (Hagelüken, 2019). After the global economic recession in 2008, palladium's price had a continually rising trend, with short-term drops during the second semester of 2011 and 2015. Since the beginning of 2016, palladium's price has surged dramatically, and in October 2017 surpassed platinum's price for the first time since 2001. Palladium's price climbed at a record level of €1,455 per troy ounce in September 2019, widening considerably the price premium to platinum (see Figure 274).

According to Johnson Matthey's data, palladium's market is in deficit since 2011 (see Figure 274), and this reflected in poor liquidity and higher prices (Johnson Matthey, 2017; Johnson Matthey, 2018). Demand for palladium in autocatalysts is experiencing a steady increase since 2009, and surged to an all-time high record of 271 tonnes in 2018, more than doubled in comparison to 2009 (126 tonnes). In contrast, platinum demand for autocatalysts in the same period increased from 68 tonnes in 2009 to 99 tonnes in 2018. The diesel emissions scandal in Europe is considered a factor that resulted in an increasing trend towards gasoline vehicles, thus in higher palladium demand for autocatalysts compared to platinum, as well as the partial substitution of platinum by palladium in diesel catalysts (DERA, 2017; Hagelüken, 2019).

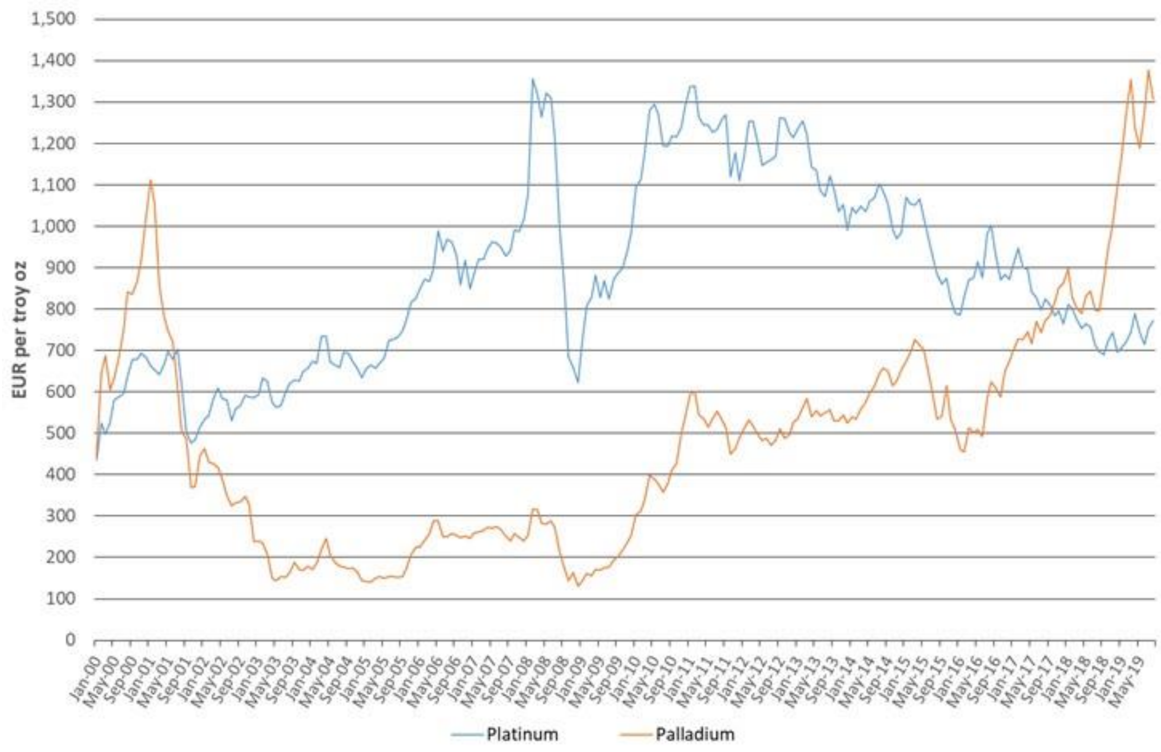


Figure 274: Palladium and Platinum (99.95%) price trend from January 2000 to August 2019, LBMA afternoon monthly average, in warehouse (€/oz t[191]). Data from (LPPM, 2019)

The long-term prices of palladium are shown in Figure 275. The price curve shows real prices.

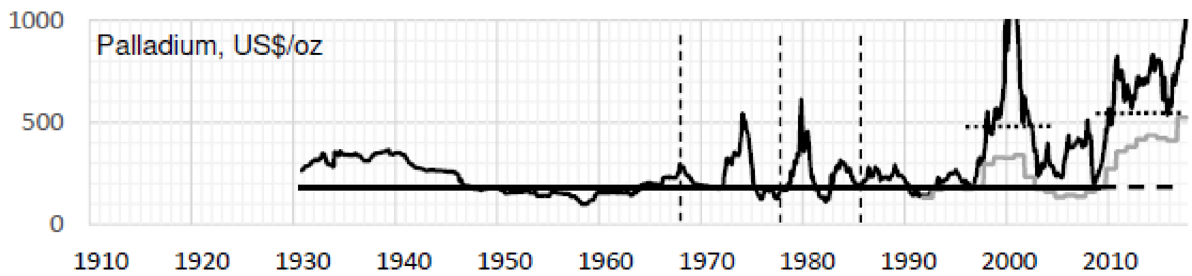


Figure 275: Palladium prices in US$ per troy ounce. Vertical dashed line indicate breaks in price specification.(Buchholz *et al.* 2019)

19.4.2.3 Prices and price volatility of platinum

Platinum is typically exchange-traded in international markets with a number of daily market prices (e.g. the London Platinum and Palladium Market and the Johnson Matthey base price) quoted for the pure metal (minimum 99.95 %) in US dollars per troy ounce. Furthermore, platinum is also traded through London on a 24-hour basis in over-the-counter (OTC) transactions between miners, central banks, governments, fabricators, investors, hedge funds and refiners. From December 2014, a new benchmark price is determined twice daily, called the "London Metal Bullion Association (LMBA) Platinum Price", via an auction process taking place in the OTC market in London. The prices are

[191] 1 troy ounce (oz t) = 31.10348 g

administered and distributed by the London Metals Exchange (LME) via a custom-built electronic auction platform. The new reference prices replace the data of the London Platinum Fixing Company (LPPFCL). In the spot market, platinum is sold for cash and immediate delivery in sponge, plate or ingot form. Platinum is also traded through long-term supply contracts between fabricators and miners.

The price of platinum has experienced a high degree of volatility in recent years. After a long period of relative stability during the 1990s at price levels of around US$400 per troy ounce (Hagelüken, 2019), platinum's price demonstrated an upward trend in the years after 2000, peaking at an all-time record high of about €1,360 per troy ounce in February 2008, following the widespread use of platinum in exhaust catalysts for diesel-fueled vehicles as well the expectations for fuel cell technology development. However, at the onset of the global economic recession in 2008, the price fell sharply within a few months to around €620 per troy ounce in December 2008. With the recovery of the global economy, the price of platinum increased as a result of increased demand, supply shortages and speculation by investors, reaching a peak of about €1,340 per troy ounce in February 2011 (Schmidt, 2015). Since then, platinum's price has been volatile following a downward path. In October 2017 platinum's price became lower than palladium's price for the first time since 2001 (see Palladium factsheet), and in August 2018 the monthly average price was about €700 per troy ounce, the lowest since December 2008.

According to the market data of supply and demand published by Johnson Matthey, the sustained declining trend cannot be attributed to market surplus as the platinum market remained in an overall deficit from 2012 to 2016, moving to a modest surplus only in 2017 (see Figure 276). The diesel crisis and the resulting trend towards gasoline vehicles, as well as partial substitution of platinum by palladium in diesel catalysts, affected the increased demand for palladium in comparison to platinum (DERA, 2017).

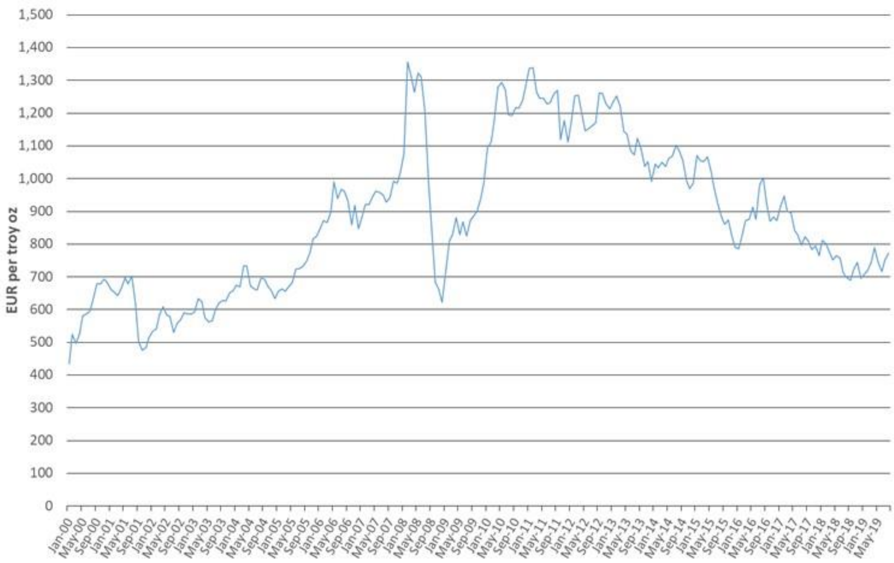
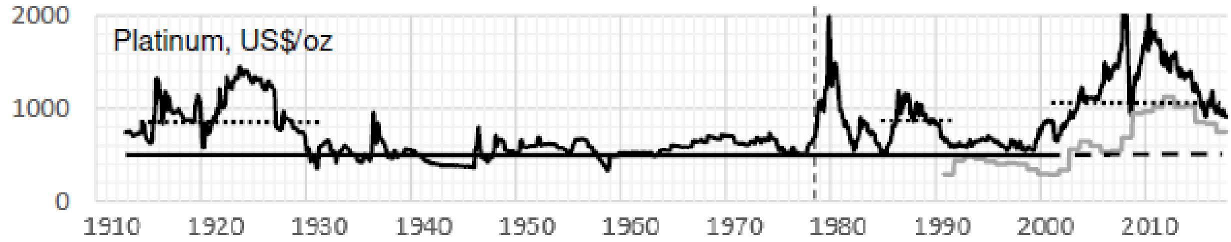


Figure 276: Platinum (99.95%) price trend from January 2000 to August 2019, LBMA afternoon monthly average, in warehouse (€/oz t[192]). Data from (LPPM, 2019)

[192] 1 troy ounce (oz t) = 31.10348 g

The long-term prices of platinum are shown in Figure 277



The price curve shows real prices.

Figure 277: Platinum prices in US$ per troy ounce. Vertical dashed line indicate breaks in price specification.(Buchholz *et al.* 2019)

19.4.2.4 Prices and price volatility of rhodium

Unlike platinum and palladium, rhodium is not traded on the major metal exchanges. Rhodium is generally sold through long-term supply contracts between fabricators and mines. Johnson Matthey is the main fixer of the rhodium price, publishing daily prices from its trading desks in the United States, Hong Kong and the United Kingdom. The price is for the metal in sponge form with a minimum purity of 99.9% rhodium (European Commission, 2017).

Rhodium has experienced extreme price volatility in recent years (see Figure 278). Prices increased in the late 1990s, reaching about US$2,600 per troy ounce in mid-2000 (Zientek *et al.*, 2017). In 2003, the average price for rhodium was only US$530 per troy ounce. In response to the rapidly growing demand for autocatalysts, especially in Asian markets (Zientek *et al.*, 2017), the price rose steadily from 2004 onwards, peaking a particularly high rate of more than US$10,000 per troy ounce in July 2008. However, with the onset of the global economic recession and decreasing demand, it fell sharply by 90% to about US$1,000 per troy ounce by the end of 2008. Following a short recovery in 2010 up to US$3,000 per troy ounce, rhodium's price followed a general downward trend. Between 2013 and the third quarter of 2017, rhodium's price fluctuated between US$640 per troy ounce and US$1260 per troy ounce, as a result of weak industrial demand and improved supply situation (European Commission, 2017), as well as due to the spread of diesel vehicles which do not require rhodium in diesel oxidation catalysts (DOC) and particulate filters (DPF) (Hagelüken, 2019).

Since mid-2017, the rhodium price has been rising steadily, and almost increased by eight times to an eleven-year high of around US$5,000 per troy ounce in September 2019, well above gold and other PGMs; notably, from May 2019 to September 2019, the monthly average price of rhodium surged by 67% from about US$3,000 per ounce to nearly US$4,900 per ounce. According to Johnson Matthey, the price increase in 2017 is not attributed to supply shortage or increased demand by a specific industrial sector, but speculative and strategic purchasing of rhodium, especially in Asia, which had a significant impact in metal availability (Johnson Matthey, 2018). In 2018, the rhodium price continued climbing steadily by 45%, reaching an eight-year high of US$2,600 per ounce in December 2018, despite a market overall surplus suggesting that market participants and perhaps industrial consumers (automotive and industrial companies) purchased and held rhodium in anticipation of future demand growth (Johnson Matthey, 2019a). Within 2019, rhodium price has been rising steeply, reaching US$5,000 per ounce in September 2019, the highest since September 2008, and almost doubled in comparison to December 2018. It is noted that the impressive growth in rhodium price in 2019 coincides with a forecasted increasing demand for autocatalysts due to tighter emissions legislation and more stringent testing (see section 1.2.1.2).

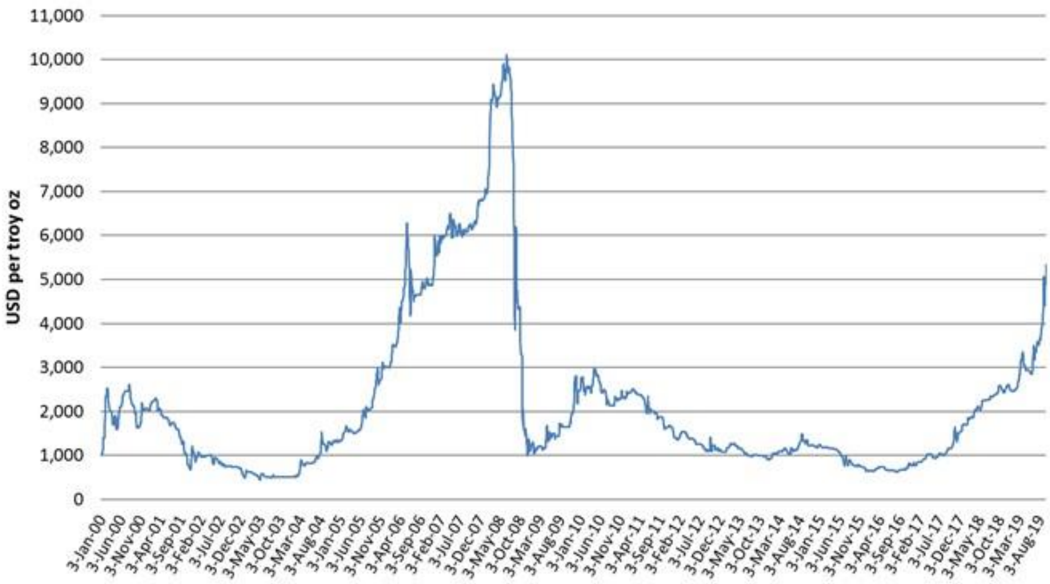


Figure 278. Rhodium price trend, January 2000-September 2019, Johnson Matthey quoted daily prices (US$/oz t[193]), sponge, min. 99.9%, London. Data from (Johnson Matthey, 2019d)

19.4.2.5 Prices and price volatility of ruthenium

Unlike platinum and palladium, ruthenium is not traded on the major metal exchanges. Ruthenium is generally sold through long-term supply contracts between fabricators and mines. Johnson Matthey is the main fixer of the ruthenium price, publishing daily prices from its trading desks in the United States, Hong Kong and the United Kingdom quoted for customers of wholesale quantities of platinum group metals. The price is for the metal in sponge form with a minimum purity of 99.9% ruthenium (European Commission, 2017).

The price of ruthenium has experienced significant fluctuations in recent years (Figure 279). From levels between US$30-40 per troy ounce in 2003, the price followed an upward trend peaking at about US$850 per troy ounce in February 2007, as a result of increased ruthenium usage in electronics, especially in computer hard disk drives (Zientek et al., 2017). However, with the onset of the global economic recession, it fell back to US$75 per troy ounce in early 2009. Following a brief recovery in 2010, the price has further declined to US$40 per troy ounce at the beginning of 2017, which is the onset of a constant rise to the level of US$270 per troy ounce at the end of 2018, reaching a ten-year high. According to (Johnson Matthey, 2018), the rise of ruthenium price in 2017 is attributed to steady industrial demand and strategic purchasing in Asia, while in 2018 the factors contributing to price increase were again strategic purchasing in Asia and fluctuations in supply from primary and secondary refiners, even though demand was lower in comparison to 2017 (Johnson Matthey, 2019a). From mid-2018, ruthenium prices have stabilised (Figure 279) reflecting a modest improvement in market liquidity, probably due to some additional recycling activity in the chemicals sector and an improvement in refined output (Johnson Matthey, 2019a).

193 1 troy ounce (oz t) = 31.10348 g

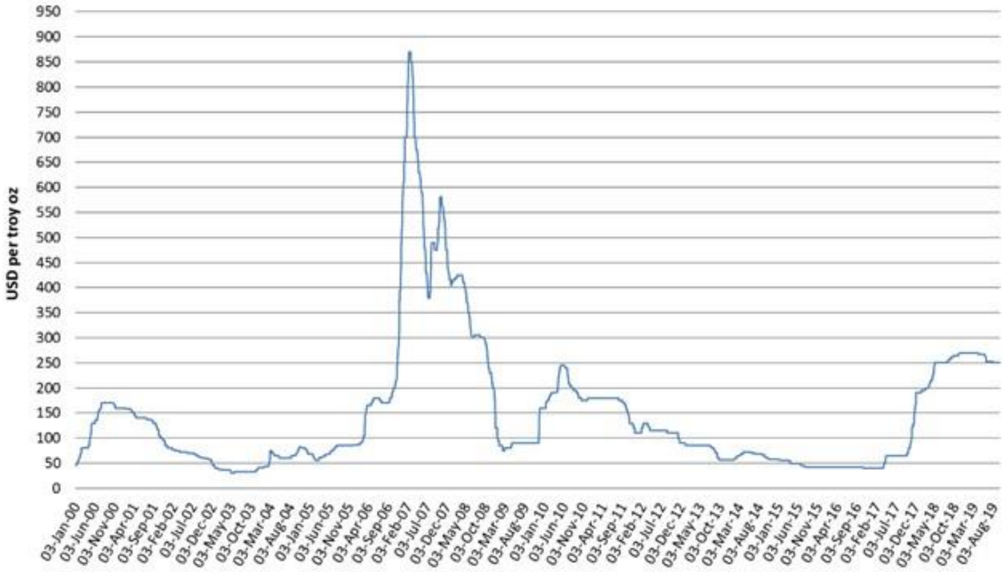


Figure 279. Ruthenium price trend, January 2000 – September 2019, Johnson Matthey quoted daily prices (US$/oz t[194]), sponge, min. 99.9%, London. Data from (Johnson Matthey, 2019d)

[194] 1 troy ounce (oz t) = 31.10348 g

19.5 Demand

19.5.1 EU demand and consumption

Detailed regional demand data is available for platinum and palladium, as compiled by Johnson Matthey. Figure 280 below presents the evolution of European gross demand[195] for platinum and palladium. In 2018, the European demand for platinum and palladium was 125 tonnes, accounting for about 23% of the worldwide consumption (562 tonnes) for these two PGMs (Johnson Matthey, 2019a); the majority (83%) was consumed in autocatalysts. The total world demand for PGMs amounted to approximately 635 tonnes in 2018 (see Figure 280). In the last five years, the global PGM demand ranged from 617 in 2015 to 646 tonnes in 2017, which was the all-time record at this point in time.

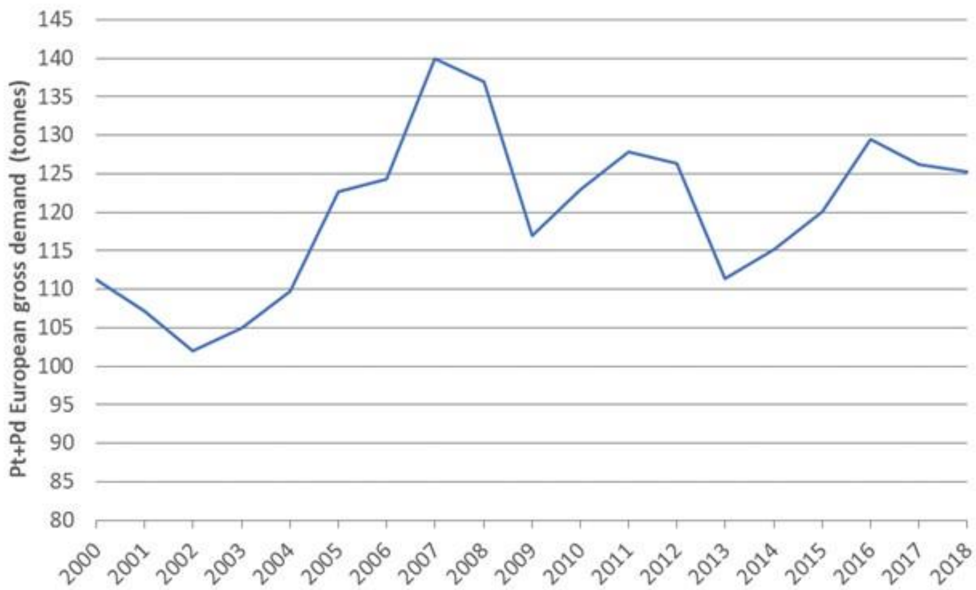


Figure 280: Gross demand in Europe for PGM (platinum+palladium) from 2000 to 2018, Background data from (Johnson Matthey, 2019a) (2014-2018), (Johnson Matthey, 2018) (2013), and (Johnson Matthey, 2014) (2005-2012).

[195] Gross demand is the sum of manufacturer demand for metal in that application and any changes in unrefined metal stocks.

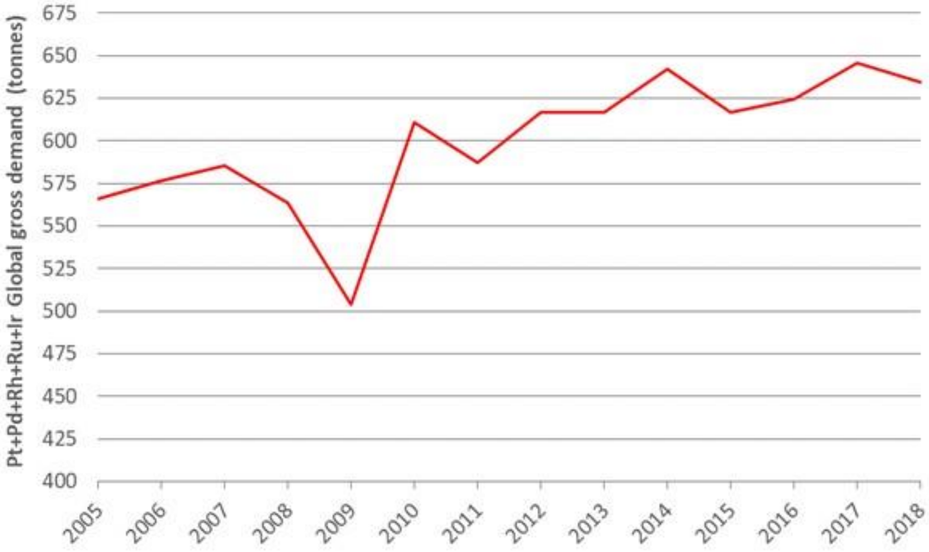


Figure 281: Global total gross demand for PGMs (platinum+palladium+rhodium+ruthenium+iridium) from 2005 to 2018. Background data from (Johnson Matthey, 2019a) (2014-2018), (Johnson Matthey, 2018) (2013), and (Johnson Matthey, 2014) (2005-2012).

Information on consumption for each platinum-group metal is provided in sections 19.5.1.1 – 19.5.1.5.

19.5.1.1 EU demand and consumption of iridium

Given the diversity of forms in which iridium is traded, the limited scope of trade data specific to iridium and the absence of any distinction between iridium metal derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of iridium. The import reliance is 100% for iridium supplied from primary sources.

Gross global demand for iridium in 2018 was 7.5 tonnes (Johnson Matthey, 2019a). In 2016, iridium demand in Europe amounted to approximately 0.9 tonnes, which was about 14% of global demand (Johnson Matthey, unpublished data in European Commission (2017)).

19.5.1.2 EU demand and consumption of palladium

Given the diversity of forms in which palladium is traded, the lack of production statistics for refined palladium in the EU, and the absence in trade statistics of distinction between platinum derived from primary and secondary sources, it was not possible to determine a single reliable figure for the overall EU consumption of palladium.

The EU apparent consumption of palladium metal in unwrought or in powder form is estimated at 46.5 tonnes per year, as an average over the period 2012-2016. Net imports represent 45.7 tonnes per year, and the domestic production from primary sources (0.8 tonnes per year) the remainder (assuming that it was refined to palladium metal domestically). Based on these figures, the net import reliance as a percentage of apparent consumption for refined palladium in unwrought or in powder form is 98%. The consumption from metal produced domestically from secondary sources is not accounted for in these figures, in other words, the actual EU import reliance for palladium metal in unwrought/powder form is expected to be lower.

According to background data published by Johnson Matthey (Johnson Matthey, 2019), the average annual European demand for palladium, for all uses except investment, was 59 tonnes in the period 2012-2016. In 2018, palladium demand in Europe surged to 68.3 tonnes, and the majority (86%) was used in autocatalysts. Electronics (4%) and manufacture of chemicals (4%) were the second and third-ranked applications, respectively. Investment items contributed to the European demand with 4.4 tonnes in 2018 (i.e. recycling or sales). In the last five years, the European demand for palladium represents a share of between 17% and 20% of the global demand (Johnson Matthey, 2019).

19.5.1.3 EU demand and consumption of platinum

Given the diversity of forms in which platinum is traded, the absence of production statistics for refined platinum in the EU, and the absence in trade statistics of distinction between platinum derived from primary and secondary sources, it was not possible to determine a single reliable figure for the overall EU consumption of platinum.

The EU apparent consumption of platinum metal in unwrought or in powder form is estimated at 15.1 tonnes per year, as an average over the period 2012-2016. Net imports represent 14.1 tonnes per year, and the domestic production from primary sources of about one tonne made up the remainder (assuming that it was refined to platinum metal domestically). Based on these figures, the net import reliance as a percentage of apparent consumption for refined palladium in unwrought or in powder form is 94%. However, it has to be noted that the consumption related to the significant EU production from secondary sources is not accounted for in the above figures.

According to background data published by Johnson Matthey (Johnson Matthey, 2019b), the average annual European demand for platinum, for all uses except investment, was 63.7 tonnes in the period 2012-2016. In 2018, platinum demand in Europe amounted to 64.5 tonnes, and the majority (71%) was used in autocatalysts. Jewellery (9%) and chemicals manufacture (6%) were the second and third most important applications, respectively. Investment items contributed to the European platinum demand with 3.2 tonnes in 2018 (i.e. recycling or sales). In the last five years, the European demand for platinum represents a share of between 24% and 30% of the total global demand.

19.5.1.4 EU demand and consumption of rhodium

Given the diversity of forms in which rhodium is traded, and the absence of production statistics for refined rhodium production in the EU, it was not possible to determine a single reliable figure for the EU consumption of rhodium. According to data provided by Eurostat, the EU appears to be a net exporter of rhodium for rhodium in unwrought or in powder form, as well as in rhodium in semi-manufactured forms.

Gross global demand for rhodium in 2018 was 31.8 tonnes (Johnson Matthey, 2019a). In 2015, rhodium demand in Europe amounted to approximately 5 tonnes, which was about 16% of global demand, and the majority was used in autocatalysts (Johnson Matthey unpublished data in European Commission (2017)).

19.5.1.5 EU demand and consumption of ruthenium

Given the diversity of forms in which ruthenium is traded, the limited scope of trade data specific to ruthenium and the absence of any distinction between ruthenium metal derived from primary and secondary source materials, it is not possible to determine a single reliable figure for EU consumption of ruthenium. The import reliance is 100% for ruthenium supplied from primary sources.

Gross global demand for ruthenium in 2018 was 33.5 tonnes (Johnson Matthey, 2019a). In 2016, ruthenium demand in Europe amounted to approximately 2.5 tonnes, which was about 8% of global demand, mainly used in industrial applications (Johnson Matthey unpublished data in European Commission (2017)).

19.5.2Uses and end uses

19.5.2.1 Uses and End Uses of PGMs in general

Because of their unique properties, PGMs are fundamental components in a broad range of modern technologies. All the PGMs, commonly in combination with one another or with other metals, can act as catalysts which are exploited in a wide range of applications. The most significant application across the group is associated with automotive catalysts for emissions control. Other important uses accounting for smaller proportions are jewellery, catalysts for chemical processes, and electronic/electrical applications. It is also worth noting that the PGMs are used in very small quantities in the various applications; for instance, the average PGM loading for a EURO 5 light-duty diesel catalyst system is 7-8 grams, whereas the catalyst system contains 2-3 grams in a EURO 5 light-duty gasoline vehicle (IPA, 2015c). An overview of PGM demand by end-use sector is given in Figure 282.

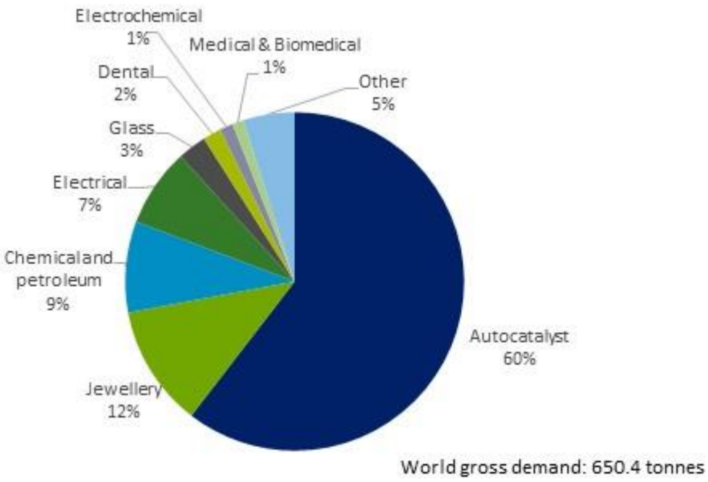


Figure 282: Global gross demand[196] for PGMs (platinum+palladium+rhodium+ruthenium+iridium) by end uses in 2018. Background data from (Johnson Matthey, 2019a)

Given the different properties of each PGM, many applications are specific to individual PGMs. Figure 283 presents the structure of PGM demand per application. The demand for each metal of the platinum group by application is presented in the specific PGM factsheet, where also further information is provided.

[196] Investment is not included given that the global gross demand has been negative in 2018, i.e. -15.7 tonnes

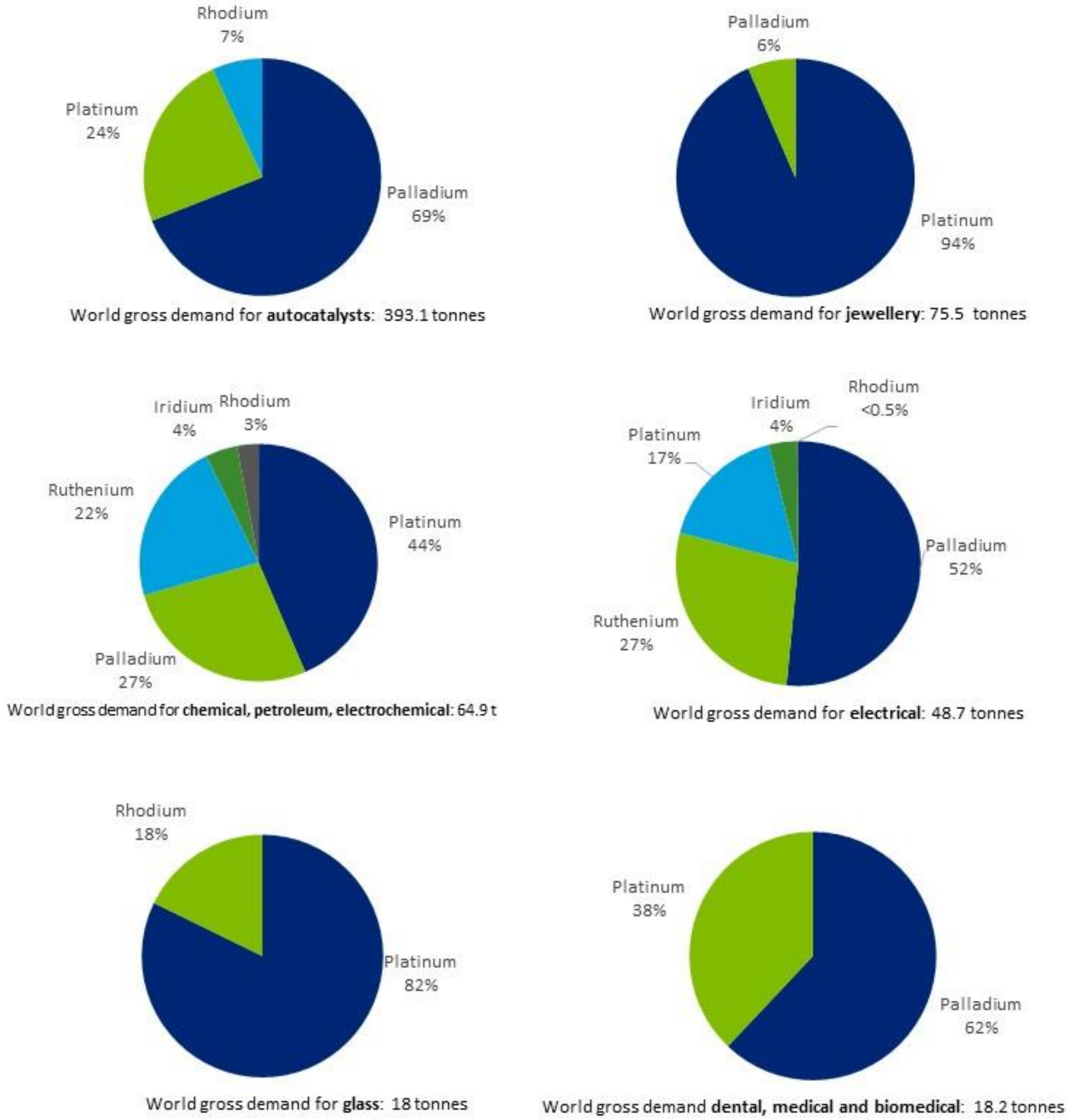


Figure 283: PGM global demand by sector and material in 2018. Background data from (Johnson Matthey, 2019a)

A short presentation of the PGM applications is given below (European Commission, 2014; European Commission, 2017a); further information is provided in the specific PGM factsheets:

- *Autocatalysts*: Autocatalysts are by far the most important application of PGM. Platinum, palladium and rhodium are essential for the function of catalytic converters to reduce emissions from gasoline and diesel engines, i.e. hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter (PM). The activity of PGMs enables the reactions to occur at low-temperature conditions, and their durability allows catalytic converters to perform over the life of the vehicle (IPA, 2015a). Palladium accounts for 69% of the global PGM gross demand in autocatalysts, and platinum and rhodium for 24% and 7%, respectively.

Figure 284 illustrates the development of PGM demand for autocatalysts; figures for platinum and palladium refer to European demand, and figures for rhodium to global demand.

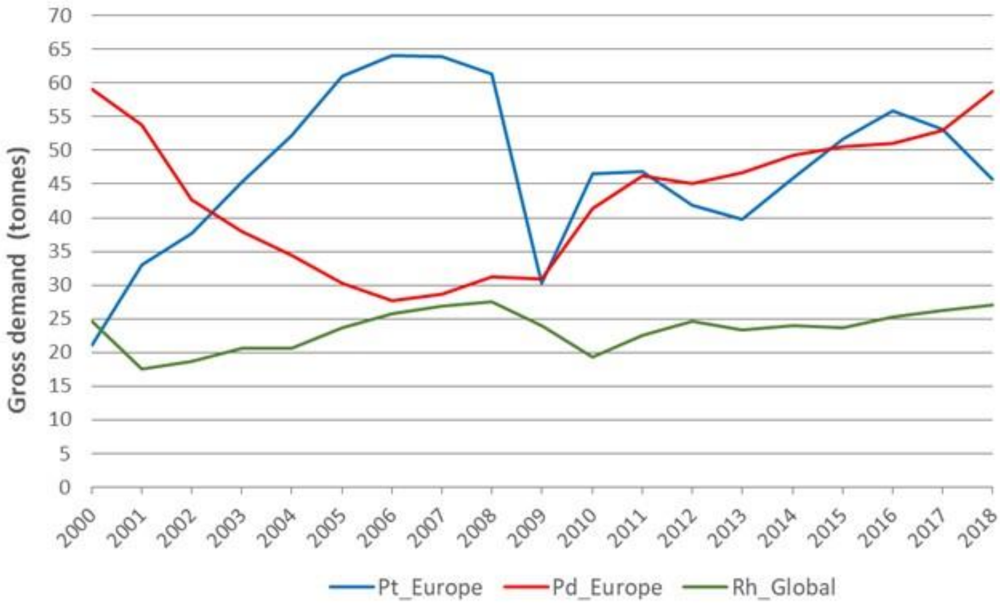


Figure 284: Development of PGM demand for autocatalysts in Europe (platinum, palladium), and globally (rhodium), 2000–2018 (background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, and (Johnson Matthey, 2014) for 2005-2012).

- *Jewellery*: The value and physical properties of PGMs means they are suitable and desirable for high-value jewellery, which accounts for 12% of their consumption (see Figure 283). Platinum is by far the most commonly used PGM in jewellery, followed by palladium (see Figure 283);
- *Catalysts in chemical, electrochemical and petrochemical applications*: PGMs are widely used as catalysts in the industrial sector, primarily in chemical manufacture and petroleum refining. Their properties and high value mean they are particularly suitable for catalytic processes, where only a small quantity of the metal can have a large impact on production and they can generally be recovered at the end of the process. All PGMs are employed as catalysts on an industrial scale (se Figure 283). Platinum is used as a catalyst in a variety of processes, with the most important being petroleum refining (where it is in some applications combined with rhenium) and nitric acid production. Palladium and rhodium are both used in the production of several plastics and polymer precursors. Ruthenium is used in ammonia production, as well as with iridium in electrochemical processes;
- *Electronics*: PGMs have various uses in the electronics industry. Both platinum and palladium are used in the manufacture of some printed circuit boards. The use of palladium in electronics has grown with the miniaturisation of components for applications such as mobile phones where palladium is used in multilayer ceramic capacitors. Platinum and ruthenium find specific uses in computer hard disk drives, and iridium is linked to the manufacturing process for LEDs and organic LEDs;
- *Glass*: PGMs are used in the manufacture of some glass types when high processing temperatures are used. Their high melting point, strength and resistance to corrosion make them suitable for this purpose. Both platinum and rhodium are employed in the production of glass fibre, LCD manufacture and some other types of glass (but not for bottle glass);
- *Medical industry and dental*: PGMs, mainly palladium, find uses in dental applications, specifically in alloys for fillings and bridges. They are also used in components in medical scanners, sensors and drugs;

- *Investments*: Due to their high value, platinum and palladium are also used for investment purposes such as in exchange-traded funds (ETFs). Investment in the other PGMs is relatively small. Investment can be both a source of supply (i.e. recycling or sales) and a component of demand (i.e. purchases).

19.5.2.2 Uses and end uses of individual PGMs

Uses and end-uses of iridium

The predominant applications of iridium are in crucibles for growing single crystals for electronics, and dimensionally stable anodes for the electrochemical production of chlorine and sodium hydroxide. In 2018, electrochemical applications accounted for 29%, electrical applications for 24%, and chemical applications for 8% of the global gross demand (see Figure 285). A range of other minor uses, including spark plugs and medical implants, accounted for almost 40% of the global gross demand. There are no specific data for the applications of iridium in Europe.

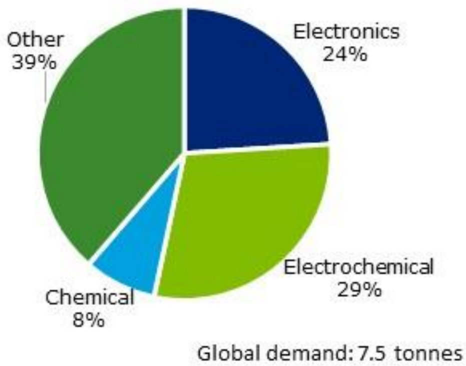


Figure 285: Global end uses of iridium in 2018. Background data from (Johnson Matthey, 2019a)

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 110.

Table 110: Iridium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat, 2019c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Electronics	C26 - Manufacture of computer, electronic and optical products	65,703	C2611 - Manufacture of electronic components
Chemical	C20 - Manufacture of chemicals and chemical products	105,514	C2014 - Manufacture of other organic basic chemicals
Electrochemical	C20 - Manufacture of chemicals and chemical products	105,514	C2013 - Manufacture of other inorganic basic chemicals
Other			C2931 - Manufacture of electrical and electronic equipment for motor vehicles

The applications of iridium are described below:

- *Electronics/Electrical.* On account of its high melting point and resistance to chemical attack, iridium is a highly suitable material for high-temperature crucibles utilised to grow synthetic, high-purity single crystals, especially of metal oxides, which are used by the electronics industry in several applications. Examples are the Yttrium Aluminium Garnet (YAG) crystals for lasers, the LSO and GSO crystals for medical scanners and X-ray scanners for baggage and container screening, sapphire that provides as a substrate for the production of gallium nitride which is used for light-emitting diodes (LEDs) increasingly utilised in flat-screen displays and portable electronic equipment (European Commission, 2017), and lithium tantalate crystals used as the substrate for filters in mobile phones (Johnson Matthey, 2018). Iridium can also be used in the organic light-emitting diodes (OLEDs) technology (Moss et al., 2013);

- *Electrochemical.* Iridium and ruthenium oxides are employed in coatings for anodes in the electrochemical production of chlorine and sodium hydroxide by the chlor-alkali industry. Iridium is also used in coatings of anodes used in electrogalvanising, electrowinning, as well as of electrodes employed in the process of electrolytic chlorination of water and ballast water treatment (together with ruthenium). The relative quantities of ruthenium and iridium used in these applications differ (Johnson Matthey, 2019a);
- *Chemical industry.* Iridium's catalytic properties enable its use in the manufacture of chemicals as iridium catalysts to promote hydrogenation, acetic acid synthesis and hydroformylation for the production of aldehydes. Iridium can also be used in conjunction with platinum in a few niche reforming applications in oil refining;
- *Other.* Iridium is also employed in a range of other applications. In the automotive industry, it is used mainly as a component in exhaust emission control systems of gasoline direct injection (GDI) engines and alloys for high-performance spark plugs. Due to its biological compatibility, oxidation resistance, durability and electrical conductivity, electrodes for medical implants such as heart pacemakers, aura and retinal implants, neuromodulation and neurostimulation devices, are made of platinum-iridium alloys. Moreover, iridium isotopes are the active ingredient in platinum radiotherapy (brachytherapy) implants for cancer treatment. Platinum-iridium alloys are also used in jewellery and for high-temperature equipment required for the manufacture of glass. Due to its unique corrosion resistance and hardness, iridium has been used in platinum alloys to set standards in weights and measures (e.g. the international prototype standard kilogram of mass and the standard metre were made from an alloy containing 90% platinum and 10% iridium). Finally, iridium is used, together with platinum, as a catalyst for hydrogen generation for fuel cells.

Uses and end-uses of palladium

The patterns of end uses of palladium are similar in Europe in comparison to the global context.

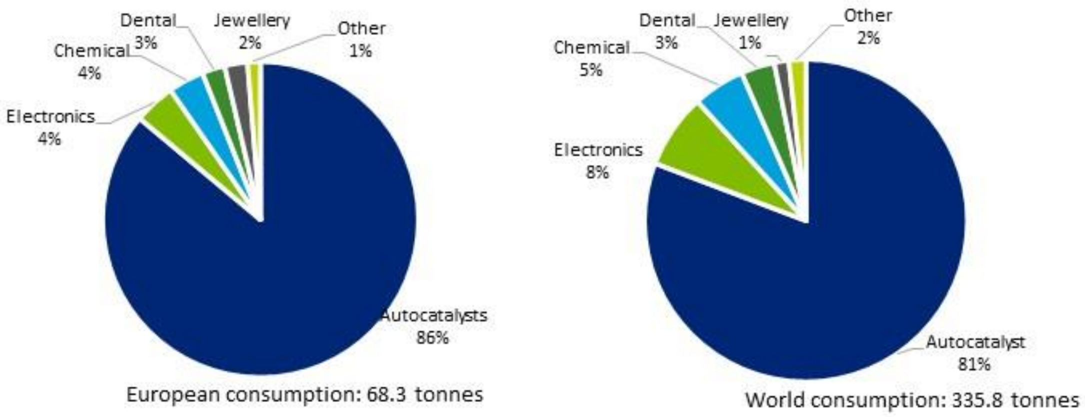


Figure 286: End uses of palladium in Europe in 2018 (left), and global end uses of palladium in 2018 (right). Background data from (Johnson Matthey, 2019)

European palladium demand is strongly dominated by its use in catalytic converters for vehicles. In 2018, autocatalysts represented a share of 86% of the total consumption of about 68 tonnes. The other applications contributed with 4% each for electronics and chemicals, 3% dental and 2% jewellery (Johnson Matthey, 2019). The global demand for palladium in 2018 was approximately 336 tonnes. The predominant global use was in autocatalysts, which accounted for 81% of demand. The remainder was used chiefly in electrical/electronics, chemical, dental and jewellery applications.

The above figures for demand do not include investment, as the demand for palladium investment items has been negative in 2018. The trend of selling palladium investment items in the global market is prevailing since 2013.

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 111.

Table 111: Palladium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat, 2019c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603	C2932 - Manufacture of other parts and accessories for motor vehicles
Electronics	C26 - Manufacture of computer, electronic and optical products	65,703	C2611 - Manufacture of electronic components
Chemical	C20 - Manufacture of chemicals and chemical products	105,514	C2015 - Manufacture of fertilisers and nitrogen compounds
Dental	C32 - Other manufacturing	39,160	C3250 - Manufacture of medical and dental instruments and supplies
Jewellery	C32 - Other manufacturing	39,160	C3212 - Manufacture of jewellery and related articles
Investment	There is no NACE code associated with investment and therefore no related value-added		

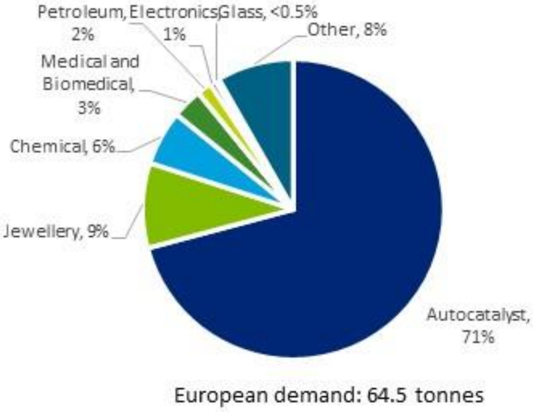
The applications of platinum, which are also discussed briefly in the PGM factsheet, are described below:

- *Autocatalysts*. Palladium is used as the dominant active ingredient (in combination with rhodium) in catalytic converters to control polluting exhaust emissions of unburnt hydrocarbons, carbon monoxide and oxides of nitrogen from gasoline-powered vehicles. Nowadays, autocatalysts are capable of eliminating 98% of harmful emissions from engine exhausts, and the risk of capacity loss through poisoning by the sulphur and lead present in the fuels has been considerably reduced. Moreover, palladium's use in diesel-powered vehicles has been growing the last years and manufacturers increase the proportion of palladium to platinum on diesel catalysts, in particular after the availability of fuel with a very low sulphur content (under 10 ppm) and the development of catalysed particulate filters (DPF), in which palladium enables high-temperature regeneration to take place without damaging the catalyst. The quantities and proportions of platinum and palladium used in autocatalysts have varied considerably over time in response to technological changes and price variations. According to (European Commission, 2017), close to 90% of palladium in autocatalysts is used for light-duty gasoline engines, with the remainder used in light-duty diesel;

- *Electrical*. Palladium coatings, electrodeposited or chemically plated, are widely used in electronic components as an effective and long-lasting plating on account of palladium's electrical conductivity and durability. It's most important use is in multi-layer ceramic capacitors (MLCC), especially for demanding applications such as automotive engine management systems, broadcasting equipment, defence and aerospace electronics, medical devices, and consumer electronics requiring high reliability. Smaller amounts of palladium are used in the conductive Ag-Pd tracks of hybrid integrated circuits (HIC), primarily used by the automotive sector. Additional applications in the electronics industry are for plating connectors, as an alternative material to gold, as an alternative to Sn-Pb solder. Pd-containing tiny components exist in virtually every type of electronic device, each component containing only a fraction of a gram of metal;
- *Chemical industry*. Industrial palladium catalysts are very effective in chemical reactions that require hydrogen exchange between two reactants, such as those producing butadiene and cyclohexane, the raw materials for synthetic rubber and nylon. Other applications of palladium-based catalysts include the production of terephthalic acid, hydrogen peroxide and high-purity hydrogen. Also, palladium is used by the petrochemical industry to catalyse the hydrocracking process;
- *Jewellery*. In jewellery, palladium is commonly used either as an alloying addition to platinum and gold (white gold) or as palladium jewellery itself;
- *Dental*. Palladium is an essential component of alloys used for dental restorations such as inlays, bridges and crowns. Palladium provides strength, stiffness and durability to the dental alloy while the other metals of the alloy (i.e. gold, silver, zinc and copper in varying proportions) improve malleability. In low gold alloys used in dentistry, palladium content typically ranges from 50% to 80% by weight. The use of Pd-containing alloys varies widely from country to country depending on customer preferences;
- *Investment*. Palladium, like platinum and rhodium and similar to gold and silver, is also used for investment in the form of physical (e.g. collectable and bullion coins, bars) or financial assets (e.g. exchange-traded funds). Unlike platinum, almost all palladium investment is accounted for by exchange-traded funds (ETFs);
- *Other*. Other applications include palladium catalysts to control pollution from non-road engines and stationary sources, archival and museum suitable photographic prints, palladium-zeolite ethylene scavenger for fruit and vegetable storage, hydrogen storage, and hydrogen purification in the form of Pd-Ag membranes.

Uses and end-uses of platinum

There are some notable differences between patterns of platinum use in Europe and the rest of the world.



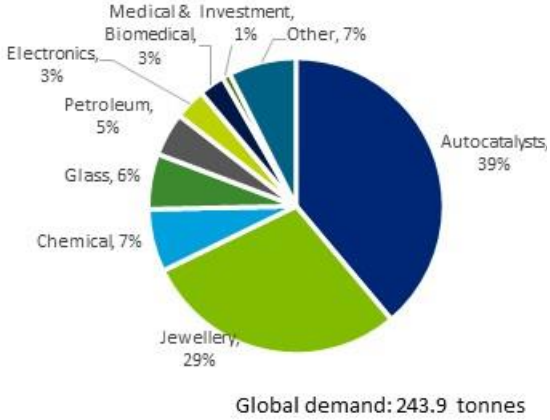


Figure 287: End uses of platinum in Europe in 2018 (left), and global end uses of platinum in 2018 (right). Background data from (Johnson Matthey, 2019b)

In Europe, the demand of platinum is strongly dominated by autocatalysts, reflecting the dominance of diesel-powered vehicles in the European fleet compared with the rest of the world; in 2018, platinum demand for autocatalysts represented a share of 71% of the total consumption of about 65 tonnes in Europe, and almost half (48%) of the total platinum demand worldwide for autocatalysts (Johnson Matthey, 2019b). The share of autocatalysts in the world demand of platinum is much lower (39%). The second most important use of platinum is in jewellery, which also shows a marked difference between Europe and the rest of the world. Jewellery accounted for about 29% of world platinum demand in 2018, compared with close to 9% in Europe. This difference can be attributed to the growing market for platinum jewellery in China, Japan and India (European Commission, 2017). Chemical manufacture represents the third most important application, with a 6% share of platinum demand in Europe and 7% globally in 2018.

Demand for investment in Europe has been negative in 2013, 2014, 2015, and 2018 as investors returned their platinum holdings to the market. In contrast, the level of global investment demand for platinum fluctuated considerably between 2011 and 2018 but remained positive(Johnson Matthey, 2016; Johnson Matthey, 2019b).

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 112.

Table 112: Platinum applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat, 2019c)

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603	C2932 - manufacture of other parts and accessories for motor vehicles
Jewellery	C32 - Other manufacturing	39,160	C3212 - manufacture of jewellery and related articles
Chemical	C20 - Manufacture of chemicals and chemical products	105,514	C2013 - manufacture of other inorganic basic chemicals; C2014 - manufacture of other organic basic chemicals; C2015 - manufacture of

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
			fertilisers and nitrogen compounds
Medical	C32 - Other manufacturing	39,160	C3250 - manufacture of medical and dental instruments and supplies
Petroleum	C19 - Manufacture of coke and refined petroleum products	17,289	C1920 - manufacture of refined petroleum products
Electronics	C26 - Manufacture of computer, electronic and optical products	65,703	C2620 - manufacture of computers and peripheral equipment; C2640 - manufacture of consumer electronics; C2680 - manufacture of magnetic and optical media
Glass manufacture	C23 - Manufacture of other non-metallic mineral products	57,255	C2311 – manufacture of flat glass
Investment	There is no NACE code associated with investment and therefore, no related value-added.		

Platinum's unique physical and chemical properties have been exploited for a wide range of applications. The applications of platinum, which are also discussed briefly in section 19.5.2.1, are the following (Johnson Matthey, 2019a, IPA, 2012, Gunn, 2014, BRGM, 2014):

- *Autocatalysts.* Platinum is the principal active component in catalytic converters and filters fitted to diesel-powered vehicles to reduce harmful exhaust emissions. Emissions of hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) are eliminated by over 98%. Platinum-rich autocatalysts oxidise any unburnt HC and CO to water and carbon dioxide. Their use became universal in diesel engines due to the more oxidising environment of a diesel exhaust stream and the lower operating temperatures in comparison with gasoline engines, as well as because of the higher sulphur tolerance of platinum. Also, various systems employing platinum or platinum-palladium filters have been developed for diesel vehicles to trap soot particles from exhaust emissions and oxidise the soot to carbon dioxide;
- *Jewellery.* Platinum alloys (e.g. Pt 96% - Cu 4%, Pt 95% - Pd 5%) are widely used to make fine jewellery. Today, platinum is a trendy metal for bridal or fashion jewellery;
- *Chemical industry*. Many chemical processes employ platinum-based catalysts for the production of bulk and speciality chemicals. A significant application is the use of a platinum catalyst in the conversion of ammonia to nitric oxide, which is the first step in the process of nitric acid production. Among nitric acid's downstream uses is the production of nitrogen fertilisers, explosive-grade ammonium nitrate, adipic acid for making nylon, toluene diisocyanate for manufacturing polyurethane etc. Another important application of platinum catalysts is in the manufacture of specific silicones. Platinum is also employed in the production of paraxylene (PX) which is an intermediate in the production of PET used for plastics and polyester textiles. Lastly, platinum is used in the pharmaceutical industry as a selective hydrogenation agent;

- *Medical and dental.* The use of platinum in the medical sector comprises pharmaceuticals and biomedical components. In particular, platinum is an active ingredient in anti-cancer drugs as certain compounds (i.e. cisplatin, carboplatin and oxaliplatin) are effective in the treatment of a range of cancers by inhibiting cell division. In addition, on account of its excellent biocompatibility, outstanding resistance to oxidation, durability and electrical conductivity combined with its radio-opacity, platinum is an ideal material for electrodes in temporary or permanent biomedical implants such as heart pacemakers and defibrillators, aural and retinal implants, neuromodulation devices, brachytherapy implants, catheters for arteries and coronary stents (with chromium). Lastly, platinum is used in dental restorative alloys usually mixed with gold or silver in varying ratios (e.g. high gold alloys with around 10% of platinum by weight), although to a lesser extent than palladium;
- *Petroleum industry*. Platinum-based catalysts are indispensable for crude oil refining. In particular, they are used in the catalytic reforming process in oil refineries to reform naphtha into high octane blending components for gasoline (i.e., reformates). The substrate of the catalyst (e.g. alumina) is coated with Pt solutions, and the platinum content of the catalyst usually is less than 0.6% by weight;
- *Electrical/electronics*. In the electronics industry, platinum is a critical component of the magnetic coating on hard disks that increase their data storage capacity. It is also used in high-temperature thermocouples, in fuel cells as a catalyst, and multilayer ceramic capacitors (MLCC), even though to a lesser extent than palladium;
- *Glass industry.* Special containers and other equipment (e.g. pipes, linings, nozzles, drawing dies) fabricated from platinum and platinum-rhodium alloys are employed in glass manufacturing to handle molten glass, i.e. to line vessels that contain, channel and form molten glass. On account of platinum's high melting point and resistance to corrosion by molten glass, such equipment can withstand the harsh conditions in glassmaking while maintaining the purity of the glass. Platinum-based equipment is employed in the manufacture of speciality glass such as reinforcement fibreglass, glass for liquid crystal display (LCD) and plasma screens, ceramic glass, optical & ophthalmic glass and container glass;
- *Investment*. Due to its physical property of being practically unreactive and its scarcity in the earth’s crust, and similar to gold and silver, platinum is acceptable as an investment asset and means of exchange. Several different investment products have been introduced to meet demand, including either physical assets (e.g. bars, coins) or financial assets (e.g. exchange-traded funds). Financial assets make investments simpler as they allow investors to own platinum, without the difficulties associated with holding the metal physically;
- *Other.* A range of other platinum applications include electrode tips of automotive and aviation spark plugs, oxygen sensors in car exhaust systems for efficient fuel management, ignition wires in airbag inflation devices, platinum-aluminide coatings on turbine blades to provide protection against corrosion and high-temperatures, platinum-clad anodes for cathodic protection of sea vessels, use of platinum catalysts in emission control from stationary sources (e.g. combustion plants), electrodes in carbon monoxide sensors, archival and museum suitable photographic prints, standards in weights and measures etc.

Uses and end-uses of rhodium

Autocatalysts is the predominant application of rhodium, accounting for over 80% of total gross demand in 2018. Other areas in which rhodium is essential are the manufacture of glass and the chemicals sector.

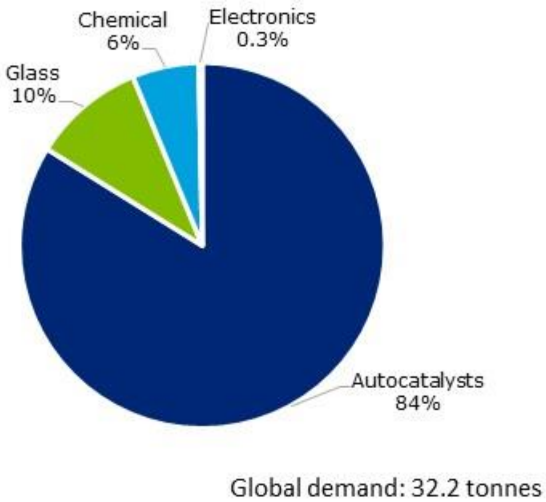


Figure 288: Global end uses of rhodium in 2018. Background data from (Johnson Matthey, 2019a)

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 113.

Table 113: Rhodium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat, 2019c)

Applications	**2-digit NACE sectors**	**Value added of NACE 2 sector (millions €)**	**4-digit NACE sectors**
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603	C2932 - Manufacture of other parts and accessories for motor vehicles
Glass	C23 - Manufacture of other non-metallic mineral products	57,255	C2311 - Manufacture of flat glass
Chemical	C20 - Manufacture of chemicals and chemical products	105,514	C2015 - Manufacture of fertilisers and nitrogen compounds
Electronics	C27 - Manufacture of electrical equipment	80,745	C2712 - Manufacture of electricity distribution and control apparatus

The applications of rhodium are described below:

- *Autocatalysts*. Global demand for rhodium is dominated by catalytic converters to remove harmful emissions from vehicle exhaust gases. Its catalytic qualities (outstanding activity and selectivity) and strength are essential for improving the converters' effectiveness. Rhodium is employed along with palladium in three-way catalysts for gasoline engines to catalyse the reduction of nitrogen oxides (NO_x) to nitrogen, and which account for more than 95% of total autocatalyst usage of rhodium (Johnson Matthey, 2015). Rhodium is indispensable for the function of gasoline catalytic converters due to its ability to maintain a high conversion of NOx in the exhaust gases;
- *Glass*. On account of rhodium's high melting point, hardness, temperature stability and corrosion resistance, alloying platinum with rhodium in various proportions (from 5% up to 30% rhodium) increases strength and extends the life of platinum-

based tooling used by the glass manufacture sector in a broad range of glass products (e.g. fibreglass, LCD glass);

- *Chemical industry*. Rhodium is used in conjunction with other metals in long established formulations to catalyse specific chemical processes for the manufacture of various organic and inorganic chemicals. Platinum-rhodium alloys in the form of gauze catalysts are used in the catalytic oxidation of ammonia to produce nitric oxide, which is the input material for the production of nitric acid. Many complex rhodium compounds have also been developed for use as catalysts in the production of various organic chemicals such as aldehydes, acetic acid production and hydrogenation reactions;
- *Other*. Electrodeposition of rhodium gives hard and reflective surfaces used in the manufacture of mirrors for optical instruments. A range of other minor uses includes investment (e.g. bars and ETFs), plating of jewellery (e.g. white gold) for an improved finish, mammography x-ray machines, Pt-Rh alloys for high-temperature thermocouples, spark plug tips.

Uses and end-uses of ruthenium

The predominant application of ruthenium is in electronic components and products, such as hard disk drives and contacts for thermostats and relays, which accounted for 40% of global gross demand in 2018 (Figure 289). The remainder was used in chemical process catalysts (25%) and electrochemical applications (18%). A range of other minor uses, accounted for 17% of the total, including spark plugs, jewellery, dentistry and superalloys. There are no specific data for the uses of ruthenium in Europe. The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Figure 289.

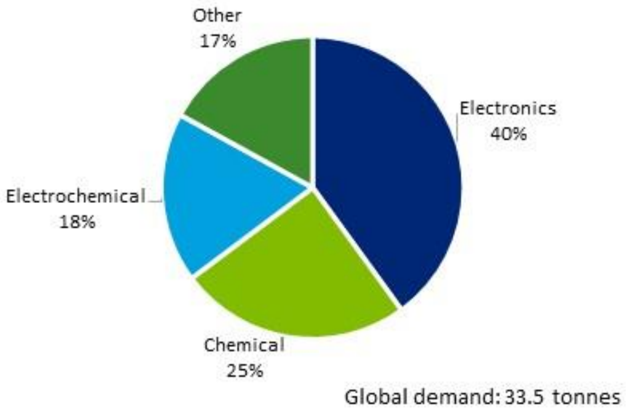


Figure 289: Global end uses of ruthenium in 2018. Background data from (Johnson Matthey, 2019a)

Table 114: Ruthenium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat, 2019c)

Applications	**2-digit NACE sectors**	**Value added of NACE 2 sector (millions€)**	**4-digit NACE sectors**
Electronics	C26 - Manufacture of computer, electronic and optical products	65,703	C2620 - Manufacture of computers and peripheral equipment
Chemical	C20 - Manufacture of chemicals and chemical products	105,514	C2014 - Manufacture of other organic basic chemicals

			C2013 - Manufacture of other inorganic basic chemicals
Electrochemical	C20 - Manufacture of chemicals and chemical products	105,514	C2013 - Manufacture of other inorganic basic chemicals

The applications of ruthenium are described below:

- *Chemical.* Ruthenium catalysts are employed in the production of a variety of speciality chemicals, as well as in the production of bulk inorganic and organic chemical commodities, i.e. the Cativa acetic acid process, the Kellogg Advanced Ammonia Process (KAAP), and the manufacture of caprolactam and adipic acid as feedstocks for synthetic polymer production (process applied in China) (Johnson Matthey, 2019a).
- *Electrical* A platinum-ruthenium alloy plays an important role in the complex structure of layered materials in hard disk drives which apply the perpendicular magnetic recording (PMR) technology to increase the data storage capacity per unit area. Ruthenium is also alloyed to palladium alloys to increase resistance to abrasion in electrical contact surfaces for thermostats and relays. It is also used in resistors in electronic circuits;
- *Electrochemical.* Ruthenium oxides and ruthenium-iridium oxides are used as coatings of the titanium anodes employed by the chlor-alkali process for the electrochemical production of chlorine and sodium hydroxide. Smaller electrochemical uses, in combination with iridium, include the coatings of electrodes employed by devices for the electrolytic chlorination of swimming pools and ballast water treatment on ships, as well as in electrowinning in base metal refineries. The relative quantities of ruthenium and iridium used in these applications vary (Johnson Matthey, 2019a);
- *Other.* Small amounts of ruthenium are sometimes added to platinum and palladium alloys used in jewellery and dentistry to impart hardness. In the Fischer-Tropsch process for bioenergy generation, ruthenium is used in a cobalt-based catalyst at low levels (Moss *et al.*, 2011). Other small uses are found in platinum-ruthenium electrodes for fuel cells and fountain pen nibs.

19.6 Substitution

19.6.1 Substitution of platinum group metals in general

(Nassar, 2015) presented a detailed review of the potential for PGM substitution in the major commercial applications of the PGMs. He concluded that in most applications, substitution is either not possible or impractical for various technical or economic reasons. Where substitutes are available, these are most commonly other PGMs or nickel, cobalt and gold. Moreover, the fact that the PGMs are co-products produced together from the same ores means that the supply of the various PGMs is coupled and thus their ability to substitute for one another in the event of supply disruption is limited. Overall it was concluded that the potential for PGM substitution in most high-volume applications is limited.

In general, the best and commonly the only available substitute is of one PGM for another. Substitution among PGM may occur when the price differential is large enough, as it had happened in the 2000 to 2001 period when the high palladium price stimulated substitution by platinum. For the same reason, nickel and copper were also substituted for palladium in certain electronics applications, albeit with some reduction in performance (Gunn, 2014). Gold is another possible substitute for PGMs, but its price has deterred its widespread use for this purpose (European Commission, 2017a).

At present, there are virtually no effective and economical alternatives to PGMs in autocatalysts. Some substitution is possible for diesel engines where a certain amount of platinum may be substituted by palladium. In addition, the PGMs perform important roles as catalysts in the manufacture of various chemicals, both organic and inorganic, and in petroleum refining. In many cases, the catalyst is a mixture of more than one PGM and other metals, which has been optimised over a long period. Consequently, there is a little practical incentive to substitute the PGM unless the prevailing economic conditions make it important to do so. Furthermore, substituting PGMs in closed-loop applications offers little economic benefit as life cycle losses in these applications are very small (European Commission, 2017a).

Substitution or the thrifting of the PGMs, i.e. using less material in an application with little or no reduction in performance, has long been an objective because of the prevailing high prices and the general designation of PGMs as 'critical' in many parts of the world. For example, autocatalysts have become more efficient, and smaller quantities of PGMs are required to achieve the same performance. However, the amounts used have remained nearly constant as emission standards have become increasingly stringent (Gunn, 2014). Considerable research is in progress which aims to either reduce or replace the use of PGMs in various applications (European Commission, 2017a). For example, the EC-funded Partial-PGM project is aiming to achieve a reduction of more than 35% of PGMs used in a hybrid three-way catalytic converters (TWC)/Gasoline Particulate Filter (GPF) for gasoline vehicles, either by increasing performance or by replacement with transition metals (Partial-PGMs, 2019). Another EC-funded project, CritCat, aims to develop substitutes based on ultra-small transition metal nanoparticles for PGM-based catalysts used in chemical processes and emerging energy-conversion technologies (CritCat, 2019).

Potential substitutes for applications of the individual PGMs are reviewed in the five specific PGM factsheets.

19.6.2 Substitution of individual platinum group metals

19.6.2.1 Substitution of iridium

(Nassar, 2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. Given that the PGM are co-products, in the event of a supply disruption of iridium, the ability to substitute it with other PGM is likely to be limited. Similarly, given that iridium production is highly concentrated in southern Africa, it would not be easy to bring new supply on stream quickly because the level of production is dependent on that of the 'paying' metals, platinum and palladium (European Commission, 2017).

In the electrical industry where iridium is used in crucibles for the growth of high-purity single crystals of metal oxides, possible substitutes include molybdenum and tungsten (Nassar, 2015). However, the performance of molybdenum crucibles that can be used to grow sapphire and yttrium aluminium garnet crystals is considered poor (Graedel *et al.*, 2015b). Data on the market share of these alternative materials are not available.

In the chlor-alkali industry, the membrane technology, which is gradually replacing alternative methods of chlorine manufacture, uses anodes based on a mixture of iridium and ruthenium. No information exists on the relative proportions of each PGM used for neither this purpose nor the degree to which one can be substituted by the other. Many other anode compositions have been patented, but few are in commercial use (Nassar, 2015). For example, ruthenium and ruthenium-tin oxide coatings are an alternative to the ruthenium-iridium coatings in the anodes used by the chlor-alkali industry (Graedel *et al.*, 2015b). For other chemical applications in which iridium is used as a process catalyst, it is reported that a rhodium catalyst is used in the Monsanto acetic acid synthesis process (Graedel *et al.*, 2015b).

Finally, in certain applications in which iridium is used as an alloying agent with platinum, elements other than iridium may be used in the platinum alloy (Graedel et al., 2015b).

On a scale of 0 to 100[197], iridium's substitution index has been assessed as 69 by (Graedel *et al.*, 2015a).

19.6.2.2 Substitution of palladium

The high price of palladium and the perceived possibility of future supply disruptions have led to considerable interest in finding alternatives to palladium in many applications. (Nassar, 2015) reviewed the possibilities for elemental substitution of the PGM in their main uses. For palladium, the potential substitutes are other PGM, gold or base metals, although these may have associated price or performance penalties.

Given that the PGM are co-products, in the event of a supply disruption of palladium, the ability to substitute it with platinum is likely to be limited. For particular applications of palladium, the following potential substitutes are identified (Graedel *et al.*, 2015a):

- In autocatalysts, platinum and palladium can only substitute for each other being equally effective at controlling emissions from gasoline-powered vehicles (Graedel *et al.*, 2015a; Tercero *et al.*, 2018). Palladium has been substituted for platinum in most gasoline-engine catalytic converters because of the historically lower price for palladium relative to that of platinum (USGS, 2019). About 25% of palladium can routinely be substituted for platinum in diesel catalytic converters; the proportion can be as much as 50% in some applications (USGS, 2019);
- In electronics, nickel-based multilayer ceramic capacitors can be used in place of those based on palladium with good performance (Graedel *et al.*, 2015a).

[197] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.

- Platinum jewellery alloyed with elements other than palladium is considered a substitute with good performance Substitute refers to platinum jewellery alloyed with elements other than palladium with good performance(Graedel *et al.*, 2015a);
- In dental restorations, alloys with palladium as an alloying agent can be replaced by nickel-based metal alloys (Graedel *et al.*, 2015a);
- In process catalysts for chemical and petroleum applications, nickel catalysts might be used in the hydrogenation of alkynes to alkenes, indirect synthesis of hydrogen peroxide, and in hydro-cracking and hydro-treating. Performance is assessed as adequate (Graedel *et al.*, 2015a);
- Palladium used in coins and exchange-traded funds may be substituted by gold, silver, and platinum as an alternative medium for investing (Graedel *et al.*, 2015a). The level of substitution depends on many factors, chiefly to price because, unlike other applications, palladium investment is strongly price-elastic (European Commission, 2017);
- In other applications, such as in control of industrial emissions and oxygen sensors, other PGM can be used instead of palladium(Graedel *et al.*, 2015a).

On a scale of 0 to 100[198], palladium's substitution index has been assessed as 39 by (Graedel *et al.*, 2015b).

19.6.2.3 Substitution of platinum

The high price of platinum and the perceived possibility of future supply disruptions have led to considerable interest in research for substitute materials (European Commission, 2017; Nassar, 2015) reviewed the options for elemental substitution of the PGM in their main applications. For platinum, the potential substitutes are other PGM or base metals, although these may have associated price or performance penalties. Given that the PGM are co-products, in the event of a supply disruption of platinum, the ability to substitute it with palladium is likely to be limited. For particular applications of platinum, the following potential substitutes are listed below:

- In autocatalysts, the only viable substitution option is replacement of platinum with palladium (and vice versa) (Tercero *et al.*, 2015). In most gasoline-engine catalytic converters, palladium has been substituted for platinum because of the historically lower price for palladium relative to that of platinum. In diesel catalytic converters, palladium can replace for up to 25% of platinum (the proportion can be as much as 50% in some applications), but not completely (USGS, 2019; Graedel *et al.*, 2015a). This may occur when the price differential between the metals is large enough (European Commission, 2017);
- Although the substitution of platinum in jewellery is possible, in practice, cultural attitudes and historical factors are restricting factors (European Commission, 2017). Palladium can substitute platinum as a jewellery metal and alloying agent in white gold (Graedel *et al.*, 2015a);
- In the investment sector platinum used in bars, coins, and exchange-traded funds may be substituted by gold, silver, and platinum as an alternative medium for investing (Graedel *et al.*, 2015b). The level of substitution depends on many factors, chiefly to price because, unlike other applications, platinum investment is strongly price-elastic (European Commission, 2017);
- In process catalysts for the production of chemicals, cobalt oxide can substitute platinum in the production of nitric acid with adequate performance. In petroleum refining processes, molybdenum oxide-based catalysts that were used in the older reforming process are potential substitutes but with poor performance (Graedel *et al.*, 2015b);

[198] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.

- For glass manufacturing equipment, iridium is a possible substitute but with reduced performance (Graedel *et al.*, 2015b);
- Palladium-based alloys as alternatives to platinum-based alloys in dental and biomedical applications with adequate performance (Graedel *et al.*, 2015b);
- In electrical applications, iron-palladium and cobalt-palladium alloys in thin films have been investigated for use in computer hard disk drives (Graedel *et al.*, 2015b);
- In other applications, including stationary pollution control, spark plugs and oxygen sensors, and corrosion-resistant coatings, other PGM can presumably be used in some of these Other platinum-group metals can likely be used in some of these other applications (Graedel *et al.*, 2015b).

On a scale of 0 to 100[199], platinum's substitution index has been assessed as 66 by (Graedel *et al.*, 2015a).

19.6.2.4 Substitution of rhodium

The high price of rhodium, its price volatility and the perceived possibility of future supply disruptions have led to considerable interest in finding alternatives in many applications.

(Nassar, 2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. For rhodium, the potential substitutes are other PGM, gold or base metals, although these may have associated price or performance penalties. Given that the PGMs are co-products, in the event of a supply disruption of rhodium, the ability to substitute it with other PGMs is likely to be limited. According to (Graedel *et al.*, 2015b):

- There are no effective substitutes for rhodium in *autocatalysts* for the control of NO_X emissions. According to (European Commission, 2017), although rhodium substitution might be possible, there is generally little economic or technical incentive to do so, especially as the catalysts are recycled very efficiently;
- In *chemical applications*, cobalt is a potential substitute for process catalysts used in the conversion of alkenes to aldehydes. Ruthenium is a competing material in catalysts for acetic acid production (Cativa process) (Johnson Matthey, 2019a);
- For *glass manufacturing equipment* where rhodium is used as an alloying agent with platinum, the use of platinum either alone or with an alloying agent other than rhodium, such as gold or iridium, is a potential substitute;
- For *electrical applications*, in which rhodium is used as an alloying agent with platinum in thermocouples, nickel is a possible substitute in type K and type N thermocouples that can be used in oxidising or inert atmospheres up to 1,260 °C;
- In *other applications*, including electroplating onto metal surfaces, such as jewellery, to provide protection and finishing, rhodium coatings are noted as being superior to all other platinum-group metal coatings in terms of hardness, mechanical and chemical stability, and reflectivity.

On a scale of 0 to 100[200], rhodium's substitution index has been assessed as 96 by (Graedel *et al.*, 2015a).

19.6.2.5 Substitution of ruthenium

(Nassar, 2015) reviewed the possibilities for elemental substitution of the PGM in their main applications. Given that the PGM are co-products, in the event of a supply disruption of ruthenium, the ability to substitute it with other PGM is likely to be limited. Similarly, given that ruthenium production is highly concentrated in South Africa, it would not be

[199] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.
[200] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.

easy to bring new supply on stream quickly because the level of production is dependent on that of the 'paying' metals, platinum and palladium (European Commission, 2017).

Ruthenium has uses in many electrical components and products. In some of these, substitution by other PGM (iridium, rhodium and palladium) and by silver are possible, but there are no data on market share. An example is oxides of iridium that can substitute for oxides of ruthenium in thick film resistors pastes (Graedel *et al.*, 2015b). Nevertheless, substitution with iridium and rhodium is very unlikely because of their much higher price, and their lower production levels but palladium's availability is several times higher, which means that it might be used as a substitute, despite its higher price (CRM experts, 2019).

Likewise, some substitutes exist where ruthenium is used as a process catalyst in chemical manufacture, but there is no information on the relative proportions of each and the degree to which one can be substituted by the other (European Commission, 2017). For example, in the majority of ammonia synthesis plants, a magnetite-based catalyst is used (Graedel *et al.*, 2015b). This is longer-established synthesis route which competes with the Kellogg Advanced Ammonia Process (KAAP) which utilises ruthenium (Johnson Matthey, 2019a). However, the ammonia synthesis process that uses a ruthenium catalyst is thought to be 20 times more effective than the process that uses the magnetite catalyst (Nassar, 2015). In the chlor-alkali industry iridium-based coatings of dimensionally stable anodes are an alternative to ruthenium-coated anodes (Graedel *et al.*, 2015b); yet, iridium is much more expensive and less available than ruthenium which makes substitution very unlikely (CRM experts, 2019). Finally, other precious metals can presumably be used in most of the other applications in which ruthenium is used as an alloying element (Graedel *et al.*, 2015b).

On a scale of 0 to 100[201], ruthenium's substitution index has been assessed as 63 by (Graedel *et al.*, 2015a).

[201] On this scale, zero indicates that exemplary substitutes exist for all major uses and 100 indicates that no substitute with even adequate performance exists for any of the major uses.

19.7 Supply

19.7.1 EU supply chain

19.7.1.1 EU supply chain of PGMs in general

Refineries in the EU process a wide range of PGM-bearing materials originating from European and overseas sources. These include end-of-life products (e.g. autocatalysts jewellery, WEEE) and manufacturing waste (new scrap). By-products from the non-ferrous mining, processing and manufacturing industries also contribute to the EU supply. These include concentrates, slags, mattes, flue dust, ash, slimes and other residues (European Commission, 2017a). Figure 290 presents the total PGM production in the EU for both primary and secondary sources.

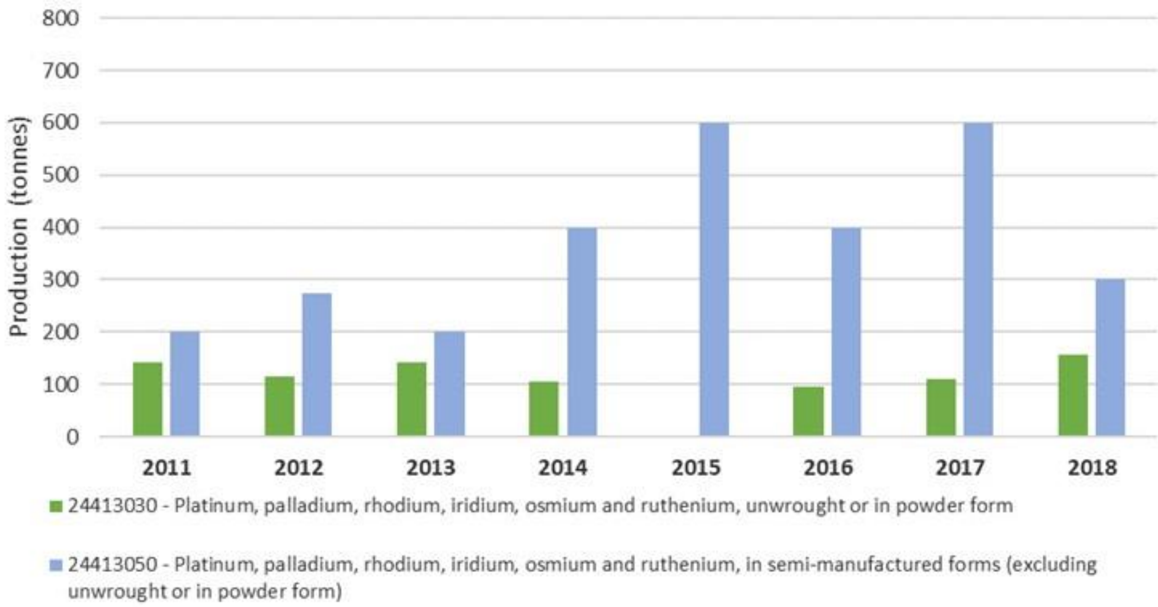


Figure 290: Production sold of PGM in various forms in EU. Data[202] from Eurostat Prodcom (Eurostat, 2019b)

PGMs are supplied to the EU market in many different forms. They are generally traded as unwrought metal, in fine powders, in semi-manufactured forms, and as base metals containing PGMs. They are also supplied in various components and final products (e.g. catalysts, jewellery) (European Commission, 2017b). Most of the PGM imports from primary sources are concentrated materials after a first refining stage. The second refining step commonly takes place in Europe (e.g. Belgium, Germany, Norway and the United Kingdom), undertaken by several companies specialised in the refining process (BIO Intelligence Service, 2015; European Commission, 2014).

In the case of catalytic converters, the PGM precursor salts are used to finely disperse the PGMs on an aluminium oxide honeycomb, which is then used within the catalytic converter. Manufacturing of these does occur within the EU by specialist manufacturers, as does placing into vehicles by assemblers. In other applications, the salts or the purified metal may be used depending on particular requirements. For example, metal is supplied to the jewellery and electronics industry, with the consequent stages occurring within the EU linked to the manufacturing base in these applications. Production of metal also occurs

[202] Values presented for PRC 24413030 in 2016 and 2017 are estimates (adjusted on the basis of the production value). The reported production for PRC 24413030 in 2015 is not presented due to low robustness. Data reported for PRC 24413050 are rounded values due to confidentiality (except of the value in year 2012).

within the EU, as a follow on stage from salt production. This involves heat treatment of the metal salts to produce pure PGMs. Alloying between PGMs may take place at this stage. Supply to the chemicals sector is often in the salts form, where other chemicals and catalysts are derived from these precursor materials. Overall, these supply chains are similar to that seen above for the automotive sector, with EU activity across all stages after the initial mining and processing (European Commission, 2014).

EU sourcing of PGMs from primary sources

A very small amount of mine production of PGMs takes place in the EU. The Kevitsa mine in northern Finland operated by Boliden produces PGM (platinum and palladium) as a by-product of nickel and coppermining. The annual average head grade of the ore ranges from 0.29 parts per million (ppm) to 0.36 ppm for platinum, and between 0.19 ppm and 0.22 ppm for palladium. In 2018, the metal production was 1,576 kilogram of platinum and 1,157 kilogram of palladium in polymetallic concentrates containing nickel, copper, gold, platinum, palladium, and cobalt (Boliden, 2019a). Boliden's smelters, the Harjavalta copper-nickel smelter in Finland and the Rönnskär copper-lead smelter in Sweden, produce annually a PGM concentrate of 2 to 3 tonnes each as an intermediate for further refining. At the Rönnskär smelter, precious metals are also recovered from electronic scrap, which is used in the process to a great extent (Boliden, 2019a).

KGHM in Poland produces minor quantities of platinum and palladium from residual copper slimes generated by the electrolytic refining of ores extracted at the Lubin mines (Lauri *et al.*, 2018; KGHM, 2019); metal is recovered at the Glogow refinery (S&P Global, 2018). The annual production is typically less than 100 kilogram of platinum+palladium (WMD 2019).

Lastly, PGM might be recovered from nickel-copper concentrates produced in the Aguablanca mine in Spain; however, no PGM recovery is taking place (Lauri *et al.*, 2018).

Heraeus in Germany refines metal for the minor PGMs under an agreement with Northam Platinum from South Africa (IPA Industrial expert, 2019).

It is not possible to determine from publicly available data the import flows and the sourcing countries of PGM-containing materials originating from primary sources, e.g. concentrated intermediates for further refining, base metals mattes, etc.

EU sourcing of PGMs from secondary sources

Europe has a strong position in recycling and refining of PGM with major industrial actors. The principal industries in Europe, refining all forms of PGM-containing waste stream from manufacturing residues to end-of-life products, are Umicore and Johnson Matthey. Other companies in the PGM refining sector operating in Europe include, but are not limited to, BASF, Heraeus, Safina and Vale Europe (Sundqvist Ökvist *et al.*, 2018).

Umicore's Hoboken plant in Antwerp, Belgium, currently recovers base, precious and special metals, and provides related supplies. The production capacity for platinum and palladium is 25 tonnes per annum in each case, and for rhodium 5 tonnes per annum, in the form of high purity powder (minimum 99.95%), known as "sponge". Iridium and ruthenium are also available as a powder/sponge, with a purity of 99.9% (Umicore, 2019a). Umicore's precious metal recovery currently focuses chiefly on recyclable materials and industrial by-products such as electronic scrap, spent automotive and industrial catalysts refining of complex, incineration bottom ashes and other precious metals containing materials, rather than metal concentrates (Umicore, 2019b; European Commission, 2017a).

19.7.1.2 EU supply chain of individual PGMs

EU supply chain of iridium

The overall EU supply chain of PGM is described in the general PGM factsheet.

The supply chain for iridium is complex and challenging to quantify. Iridium supplies are derived from both primary and secondary sources. Refineries in the EU process a wide range of iridium-bearing materials emanating from European and overseas sources. These include end-of-life products and manufacturing waste (new scrap). By-products and residues from the non-ferrous mining, processing and manufacturing industries also contribute to supply.

There is no production of iridium from mines in the EU. Therefore, the EU is 100% reliant on imports for iridium originating from primary sources (European Commission, 2017). However, as the EU is a significant producer of refined iridium from primary and, mainly, from secondary materials collected domestically or imported, the actual import dependency is lower.

EU supply chain of palladium

The overall EU supply chain of PGM is described in the general PGM factsheet.

The supply chain for palladium is complex and challenging to quantify. Palladium supplies are derived from both primary and secondary sources. Refineries in the EU process a wide range of palladium-bearing materials coming from European and overseas sources. These include end-of-life products and manufacturing waste (new scrap). By-products and residues from the non-ferrous mining, processing and manufacturing industries also contribute to supply.

EU mine production makes a small contribution (ca. 0.8 tonnes, average 2012–2016) to EU palladium supply. About 97% is produced in Finland and the remainder in Poland. The net import reliance as a percentage of apparent consumption for palladium in unwrought or in powder form is estimated at 98%.

The palladium flows through the EU economy are illustrated in Figure 291.

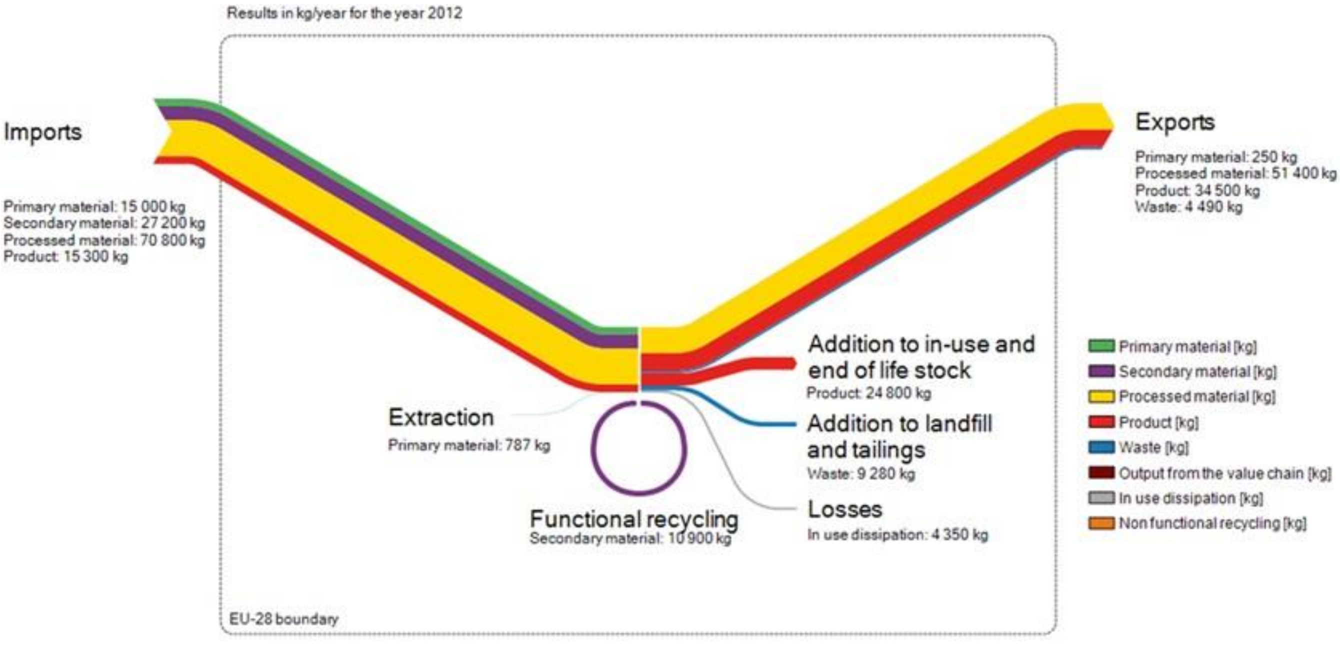


Figure 291: Simplified MSA of palladium flows in the EU for 2012. (BIO Intelligence Service, 2015a)

EU supply chain of platinum

The overall EU supply chain of PGM is described in the general PGM factsheet.

The supply chain for platinum in the EU is complex and challenging to quantify. Platinum supplies are derived from both primary and secondary sources. Refineries in the EU process a wide range of platinum-bearing materials emanating from European and overseas sources. These include end-of-life products and manufacturing waste (new scrap). By-products and residues from the non-ferrous mining, processing and manufacturing industries also contribute to supply.

EU mine production makes a small contribution (ca. 1.0 tonne, average 2012–2016) to EU platinum supply. About 95% is produced in Finland and the remainder in Poland. The net import reliance as a percentage of apparent consumption for platinum in unwrought or in powder form is estimated at 94%.

The platinum flows through the EU economy are illustrated in Figure 292.

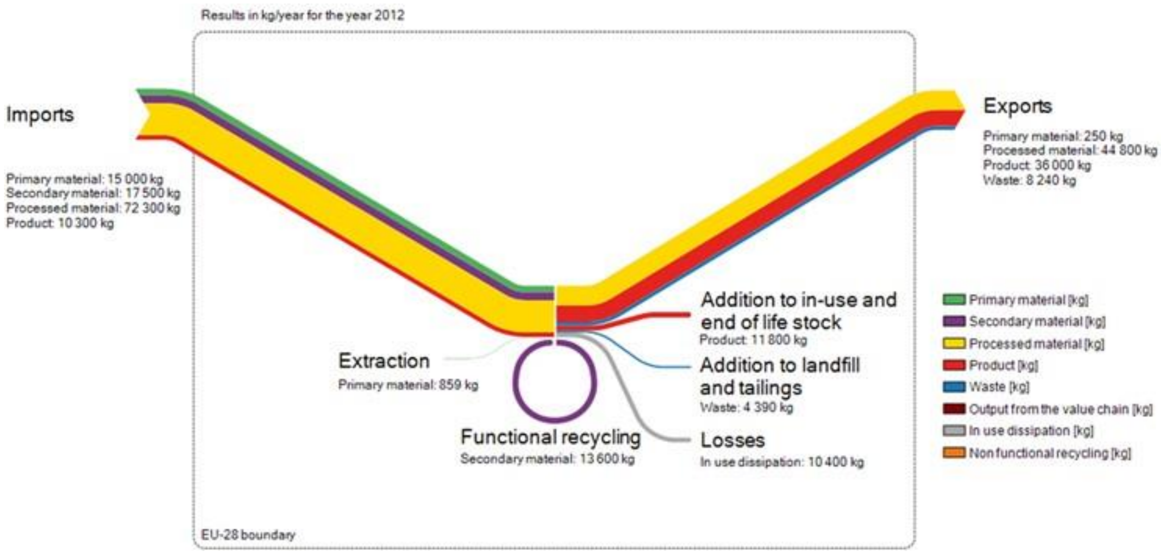


Figure 292: Simplified MSA of platinum flows in the EU for 2012. (BIO Intelligence Service, 2015a)

EU supply chain of rhodium

Figure 293 shows the rhodium flows through the EU economy.

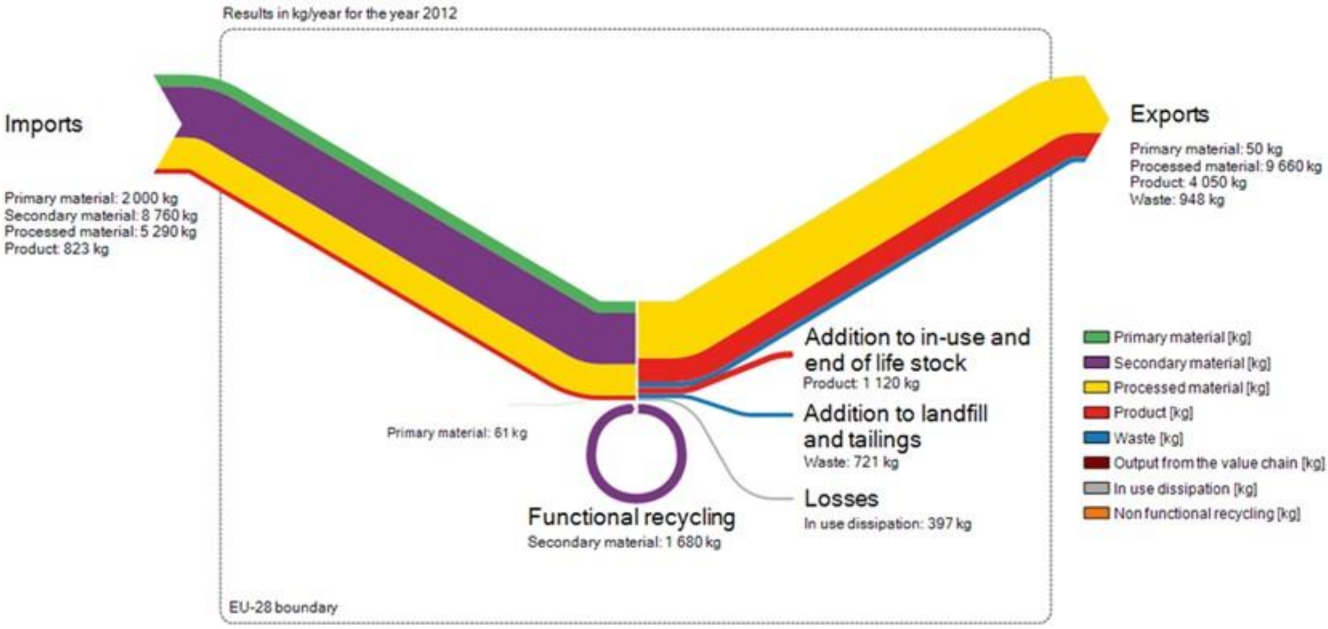


Figure 293: Simplified MSA of rhodium flows in the EU for 2012. (BIO Intelligence Service, 2015a)

The overall EU supply chain of the PGMs is described in the general PGM factsheet. The supply chain for rhodium is complex and challenging to quantify. Rhodium supplies originate from both primary and secondary sources. Refineries in the EU process a wide range of rhodium-bearing materials emanating from European and overseas sources. These include end-of-life products, chiefly autocatalysts, and manufacturing waste (new scrap). By-products and residues from the non-ferrous mining, processing and manufacturing industries also contribute to supply.

There is no production of rhodium from mines in the EU; thus, the EU is 100% reliant on imports for rhodium derived from primary sources (European Commission, 2017). Nevertheless, as the EU is a significant producer of refined rhodium from primary and, mainly, from secondary materials collected domestically or imported, the actual dependency on imports is lower.

EU supply chain of ruthenium

The supply chain of the PGMs is described in the general PGM factsheet. The supply chain for ruthenium in the EU is complex and challenging to quantify. Ruthenium supplies are derived from both primary sources and secondary sources. Refineries in the EU process a wide range of ruthenium-bearing materials emanating from European and overseas sources. These include end-of-life products and manufacturing waste (new scrap). By-products and residues from the non-ferrous mining, processing and manufacturing industries also contribute to the supply (European Commission, 2017).

There is no production of ruthenium from mines in the EU; hence, the import reliance is 100% for ruthenium originating from primary sources (European Commission, 2017). Nevertheless, the EU is a significant producer of refined ruthenium from primary and, mainly, secondary materials collected domestically or imported, hence, the actual import dependency is lower.

19.7.2Supply from primary materials

19.7.2.1 Geology, resources and reserves

Geology, resources and reserves of PGMs in general

Geological occurrence: The PGMs are among the rarest elements on Earth. Their abundance in the Earth's upper continental crust ranges from 0.022 parts per billion (ppb) for iridium to 0.52 ppb for palladium. According to data reported by (Rudnick and Gao, 2014), the overall PGM (for platinum palladium, osmium, iridium, and ruthenium) abundance in the upper continental crust is 1.5 ppb, and in the bulk continental crust 3.7 ppb. PGMs are enriched in ultramafic rocks, such as peridotite, in which platinum and palladium concentrations are commonly 10-20 ppb (BGS, 2009).

The six PGMs occur together in nature, typically associated with nickel and copper. They are predominantly found either in base-metal sulphide minerals, or in a wide variety of PGM-bearing minerals bonded with one another, with other metals in alloy form, or with elements such as sulphur, arsenic, antimony and tellurium; hence, they are mined simultaneously from the same ore deposit as the main or by-product. In the cases, they are the main product, platinum or palladium is the main economic driver supporting the extractive operations while the other PGMs are by-products that make a minor revenue contribution. When PGMs are produced as a by-product (e.g. of nickel production), they are making a significant contribution to the overall economics of the operation (Yang *et al.*, 2018).

Enrichment of PGM concentrations occurs in deposits of several types developed in a limited range of geological settings. Mineable deposits of PGMs are scarce, and most PGM-bearing ores are extremely low-grade. Ore grades range typically from 1 to 10 grams (PGE and gold content) per tonne in the main commercial deposits in South Africa, Russia, and Zimbabwe (Zientek *et al.*, 2017). Deposits associated with commercial grades of PGM are of several types, mainly found in mafic or ultramafic rocks where the PGMs have been concentrated as a result of igneous processes (Mudd, Jowitt and Werner, 2018). The majority of global PGM resources and reserves are hosted in two deposit classes: the PGM-dominant class and the nickel-copper sulphide class.

The PGM-dominant class has platinum as the main economic product, generally with lesser amounts of palladium and rhodium production. Two types of PGM-dominant ores account for the majority of PGM production, the Merensky Reef type and the Chromitite reef type, both of which are best developed in the Bushveld Igneous Complex in South Africa (Gunn, 2014). The Merensky Reef type comprises extensive, laterally continuous, thin layers (termed 'reefs') in large layered mafic-ultramafic intrusions. Current mill-head grades of the Merensky Reef are typically 4-7 parts per million (ppm) of "6E" (i.e. combined platinum+palladium+rhodium+ruthenium+iridium+gold) or 4-6 ppm of combined platinum, palladium, rhodium and gold ("4E"), with a platinum-palladium-ratio between 2.0 : 1 and 2.5 : 1 at the largest operating mines (IPA Industrial expert, 2019). Similar deposits are mined in the Great Dyke in Zimbabwe and the Stillwater Complex in the United States. The Chromitite reef type has a similar morphology to the Merensky Reef, but it comprises thin continuous layers of chromite. Typical mined 4E grades (i.e. platinum+palladium including rhenium, and gold) are in the range 2.5 ppm to 4 ppm with a palatinum-palladium-ratio of 2 : 1 (IPA Industrial expert, 2019) and significantly higher amounts of rhodium, ruthenium and iridium in comparison to the Merensky Reef (Hagelüken, 2019). The most important development of this type of mineralisation is found in the UG2 Chromitite in the Bushveld Igneous Complex, which is the largest repository of known PGM resources in the world.

A third type of platinum-palladium-bearing mineralisation, which is gaining in economic importance, is known as the Contact type. PGM grades typically range from 1 ppm to

4 ppm, and copper and nickel are produced as by-products because of the low-grade mineralisation. This type is best developed on the northern limb of the Bushveld Igneous Complex, known as the Platreef, although other deposits assigned to this class are also found in Canada, United States and Finland (Portimo). Finally, a fourth type of PGM-dominant deposits is the dunite pipes (e.g. Onverwacht, Bushveld Complex in South Africa), with high-grade platinum mineralisation in dunites, typical grades ranging from 3 ppm to 2,000 ppm platinum+palladium, but largely worked out and no longer mined (Viljoen, 2016, Gunn, 2014).

The nickel-copper-dominant deposits, in which the PGMs are associated with sulphide ores (mainly pyrrhotite, chalcopyrite and pentlandite), are found in various geological settings related to a range of igneous processes. This type of deposits is mined primarily for the value of nickel and copper, but with a significant contribution to their value by cobalt, gold, silver, PGMs etc., which are recovered as by-products when they occur at economically recoverable amounts. PGM grades can be up to 10 ppm, with a platinum-palladium- ratio less than one (Gunn, 2014, Hagelüken, 2019). The deposits mined in the Norilsk-Talnakh district of the Taimyr Peninsula in Russia is the most important example. Norilsk is one of the world's largest producers of nickel and, as some of the ores are very rich in PGM, it is the largest palladium producer in the world and an important platinum producer. The average grade of reserves is 5.54 ppm 6E (4.25 ppm palladium and 1.13 ppm platinum), with a platinum-palladium- ratio ranging typically from 0.2 to 0.4 in the different ore fields and deposits (Nornickel, 2018). Other economically important resources of PGM in magmatic nickel-copper sulphide deposits are found in the Sudbury Igneous Complex of Canada, the Kambalda area of Western Australia, the Pechenga district of Russia and Jinchuan in China (Gunn, 2014).

The 'minor' PGMs (rhodium, ruthenium, iridium and osmium) are generally present in platinum-palladium ores in tiny amounts, rarely exceeding a few per cent of the total PGM content. However, the proportion of iridium, rhodium and ruthenium in the UG2 ore is significantly greater than in the Merensky Reef, and it may exceed 20% (IPA Industrial expert, 2019). Consequently, as mining of the UG2 has increased markedly in recent decades, so the potential availability of these PGMs has enlarged (European Commission, 2017a).

The H2020 SCRREEN project provided a compilation of the available information on the geological occurrences of PGMs in Europe (Lauri *et al.*, 2018). The main points are summarised below:

- In Finland, PGM occurrences are identified in a number of deposits. In most cases, the PGMs are only potential companion or minor by-products. The most important are located in the PGM-dominant, layered intrusion-hosted deposits of the Arctic Platinum Project in northern Finland grading on average at 1.47 ppm palladium and 0.36ppm platinum (Arctic Platinum, 2019). Notable PGM occurrences are found in the magmatic nickel and nickel-copper deposits of Kevitsa and Sakatti;
- In Bulgaria and Greece, the Elatsite and the Skouries porphyry copper deposits respectively are reported to be enriched in PGMs, though at very low levels (the grade of Elatsite deposits is at 0.0197 ppm platinum+palladiumcontaining around 7 tonnes of platinum+palladium, and the average grade of the Skouries 2 deposit is at 0.047 ppm platinum+palladium containing about 23 tonnes platinum+palladium). As the dominant PGM minerals are associated with copper sulphides, they will probably follow copper in processing and could be recovered at the refinery stage as by-products;
- In Poland, the minor PGM production from the Lubin mines indicates the PGM potential of the Kupferschiefer deposits;
- In Germany, PGM mineralisation similar to that in the Polish Kupferschiefer has been described within the Mansfeld/Sangerhausen district;

- In Portugal and Spain, mafic-ultramafic intrusion-hosted nickel deposits may contain a small PGM potential in the Ossa-Morena and Aguablanca zones respectively, that could be recovered as by-products. A low grade of PGM is associated with the sulphide minerals of the nickel-copper ore extracted in Aguablanca mine in Spain grading at 0.47 ppm PGM; in 2011 the deposit contained about 85 tonnes palladium and 2 tonnes platinum. However, there is no information regarding how much of the Pt and Pd is retained in the nickel and copper concentrates and whether they are actually recovered at the refining stage;
- PGM are potentially contained within copper-nickel occurrences in mafic-ultramafic rocks in Cyprus, and nickel and nickel-copper deposits in Sweden.
- Greenland hosts both reef-type mineralisation and dunite-related PGM occurrences.

Global resources and reserves*:* It is difficult to obtain reliable global resource and reserve estimates for the PGMs as a group, or individual members of the group. Obstacles are the variability between reporting standards used, the fact that the PGM mineralisation may be aggregated in different and incomparable ways (i.e. platinum+palladium+rhodium or platinum+palladium+rhodium+gold), and because of the dynamic nature of resources and reserves being subject to continual revision, as exploration and mining proceed and market conditions change. Furthermore, the terms reserves and resources are often confused and used incorrectly, thus making compilations on national or regional scales complicated (European Commission, 2017a).

The United States Geological Survey (USGS) estimates global PGM resources to be more than 100,000 tonnes contained metal (USGS, 2019). (Mudd, Jowitt and Werner, 2018) summarised global PGM mineral resources in a detailed study of publicly available data for 2015 as reported by companies. A figure of 105,682 tonnes of total mineral resources of contained PGMs ("4E" data, i.e. consisting of platinum+palladium+rhodium+gold) is derived. Approximately two-thirds (68%) of the total PGM resources are located in South Africa, followed by Russia (17%), and Zimbabwe (9%). Likewise, the French Geological Survey compiled company data for 2012 and estimated global resources of PGM (platinum+palladium+rhodium) at 93,530 tonnes of which 71% was located in South Africa, 15% in Russia and 8% in Zimbabwe (BRGM, 2014).

Table 115: World resources of PGMs

	Source: (BRGM, 2014)		**Source: (Mudd, Jowitt and Werner, 2018)**	
	Year 2012		**Year 2015**	
Country	**PGM[203] Resources (tonnes)**	**Percentage of total (%)**	**PGM[204] Resources (tonnes)**	**Percentage of total (%)**
South Africa	66,749	71	72,201	68
Russia	14,071	15	17,793	17
Zimbabwe	7,764	8	9,184	9
USA	1,683	2	2,438	2
Canada	1,718	2	2,059	2
Finland	NA	NA	891	1
Greenland	NA	NA	469	<0.5
Australia	NA	NA	274	<0.5
Other countries	1,544	2%	352	<0.5
World total	93,530	100	105,682	100

[203] Pt+Pd+Rh

[204] Pt+Pd+Rh+Au

Global reserves of PGMs are estimated at 69,000 tonnes by the United States Geological Survey, with over 90% located in South Africa (Table 116). However, according to (Mudd, Jowitt and Werner, 2018), in 2015 global reserves of PGMs (platinum+palladium+rhodium+gold) were 16,775 tonnes, of which 64% were found in South Africa, 23% in Russia, 4% in Zimbabwe and 4% in the United States. Similarly, the French Geological Survey (platinum+palladium+rhodium) estimated a global PGM reserve of 14,582 tonnes based on company data for 2012. About 70% of the reserves was located in South Africa, 15% in Russia and 7% in Zimbabwe (BRGM, 2014). The above differences are due to the fact that the USGS reports much larger reserves for PGM in South Africa; 63,000 tonnes of PGMs are quantified by the USGS as South African reserves for the year 2018, while according to data compiled by (BRGM, 2014) and (Mudd, Jowitt and Werner, 2018), South African reserves are about 10,500 tonnes. The above differences compared to the USGS assessment is due to the fact that the USGS values for South Africa are derived from national reporting, despite not being strictly code-based reserves (Mudd, Jowitt and Werner, 2018).

Table 116: World reserves of PGM

	Source: (USGS, 2019)		**Source: (Mudd, Jowitt and Werner, 2018)**	
	Year 2018		Year 2015	
Country	**PGM Reserves (tonnes)** (rounded)	**Percentage of total (%)**	**PGM Reserves (tonnes)**	**Percentage of total (%)**
South Africa	63,000	91	10,790	64
Russia	3,900	6	3,932	23
Zimbabwe	1,200	2	747	5
USA	900	1	727	4
Canada	310	<1	504	3
Finland	NA	-	75	<0.5
World total	69,000	100	16,775	100

EU resources and reserves: PGM mineral resources and reserves compliant with an international reporting code are reported for Finland (Lauri *et al.*, 2018)(FODD, 2017). In particular:

- *The Arctic Platinum* Project in South Lapland holds the largest PGM single resource, with the PGM-dominant deposits of Konttijärvi and Ahmavaara jointly having a total (NI-compliant) resource of 225 tonnes palladium and 52 tonnes platinum (FODD, 2017);
- Other PGM resources occur in the following large, nickel-copper -dominant deposits: the active *Kevitsa* nickel-copper mine, with PERC-compliant reserves at 25 tonnes platinum and 16 tonnes palladium at the end of 2018 (Boliden, 2019b); the *Sakatti* deposit with indicated and inferred resource of 22 tonnes palladium and 28 tonnes platinum (JORC-compliant); possibly, the active *Talvivaara* mine with non-compliant inferred PGM resource of 38 tonnes palladium and 28 tonnes platinum.

According to the Fennoscandian Ore Deposit database, at the end of 2017, 34 deposits in Finland contained a total resource of 717 tonnes palladium and 285 tonnes of platinum.

Geology, resources and reserves of individual PGMs

19.7.2.1.1.1 Geology, resources and reserves of iridium

Geological occurrence: The geological occurrence of iridium is also discussed in the general PGM Factsheet.

The PGM are among the least abundant elements in the Earth's crust. Iridium is one of the rarest metals in nature, with an abundance in the Earth's crust reported as 0.037 parts per billion (ppb) by weight, and in the upper crust 0.022 ppb (Rudnick and Gao, 2014). The iridium grade in PGM ores is significantly lower than that of platinum and palladium.

Iridium is a co-product of platinum and palladium. The majority of iridium is derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the Great Dyke in Zimbabwe, in which iridium is produced as a co-product from platinum mining. According to background data sourced from (S&P Global, 2018a) (S&P Global, 2018b), iridium occurrence is associated with the 54% of the total global platinum+palladium resources and reserves, of which the PGM-dominant deposits account for about 79% (split into 73% in South Africa and 6% in Zimbabwe), whereas the nickel-copper -dominant deposits account for 21% (split into 20% in Russia and 1% in Canada).

No information is available for iridium geological occurrences or iridium concentration in PGM deposits in the EU.

Global resources and reserves*:* There are no global or national resource or reserve data for iridium in the public domain. Iridium data are typically presented in combination with other PGM (see PGM factsheet for more details).

EU resources and reserves: Resources of iridium do not exist in the EU, or are not available in the public domain.

19.7.2.1.1.2 Geology, resources and reserves of palladium

Geological occurrence: The geological occurrence of palladium is also discussed in the general PGM factsheet.

The abundance of palladium in the Earth's crust is reported by various sources to range from 1.5 parts per billion (ppb) by weight (Rudnick and Gao, 2014) to approximately 5 ppb (BGS, 2009), whereas in the upper crust the average abundance is reported as 0.52 ppb (Rudnick and Gao, 2014).

Of the deposits in operation worldwide, palladium is mostly a by-product; however, the main product, to which palladium is associated, varies across countries. Palladium is predominantly a by-product of nickel and copper mining in the Russian Federation, Canada and Finland. In South Africa and Zimbabwe, palladium is mostly a co-product of platinum mining, while in the United States palladium is the main product mined from PGM-dominant deposits. In 2017, 49% of the world's palladium mine production was associated with Ni-Cu-dominant deposits and 51% with PGM-dominant deposits (background data from (S&P Global, 2018)).

The geological occurrence of palladium in the EU is discussed in0.

Global resources and reserves: Palladium resources are typically reported in combination with other PGM, most commonly with platinum and sometimes with rhodium and/or gold. See the PGM factsheet for more details. Some mining companies publish separate resource and reserve data for palladium in individual deposits. An estimate based on data published by the French Geological Survey (BRGM) and Norilsk Nickel is that global reserves of palladium are 7,200 tonnes in palladium content in 2017, with most of them located in South Africa (43.5%) and Russia (40.8%). Table 117 presents the estimate for global reserves of palladium.

Table 117: World reserves of palladium in 2017 (BRGM, 2017a) (Nornickel, 2018)

Country	**Palladium Reserves (tonnes of Pd content)** (rounded values)	**Percentage of the total (%)**
South Africa	3,130	43.5
Russian Federation[205]	2,940	40.8
United States	450	6.3
Zimbabwe	370	5.1
Canada	280	3.9
Other countries (unspecified)	30	0.4
World total	7,200	100

EU resources and reserves: Table 118 and Table 119 show available data for palladium resources and reserves.

Table 118: Palladium resources data in the EU

Country	**Classification**	**Quantity (million tonnes of ore)**	**Grade (g/t)**	**Reporting code**	**Reporting date**	**Source**
Finland	Measured	23.6	0.11	PERC	12/2018	(Boliden, 2019)
	Indicated	114.9	0.09		12/2018	(Boliden, 2019)
	Inferred	19.2	0.08		12/2018	(Boliden, 2019)
Finland[1,2]	All (Measured-Indicated-Inferred)	312.8	0.79	NI 43-101	12/2017	(FODD, 2017)
Finland[2]	All (Measured-Indicated-Inferred)	1,989	0.09	JORC	12/2017	(FODD, 2017)
Finland[2]	Historic Resource Estimate	214.7	1.11	None	12/2017	(FODD, 2017)
Sweden	Historic Resource Estimate	0.2	0.4	None	12/2017	(FODD, 2017)

[1]NI 43-101 compliant resources of the Kevitsa (Boliden) mine are not included, as they are reported separately in the table
[2]Mineral resources of closed mines, as the FODD database indicates them, are included.

Table 119: Palladium reserves data in the EU

Country	**Classification**	**Quantity (million tonnes of ore)**	**Grade (g/t)**	**Pd content (t)**	**Reporting code**	**Reporting date**	**Source**
Finland	Proven	62.5	0.12	7.5	PERC	12/2018	(Boliden, 2019)
	Probable	66.1	0.14	8.8			

[205] Background data from (Nornickel, 2018)

19.7.2.1.1.3 Geology, resources and reserves of platinum

Geological occurrence: The geological occurrence of platinum is also discussed in the general PGM factsheet.

As all PGMs, platinum is a scarce natural resource. Platinum's abundance in Earth's crust is reported from 1.5 ppb by weight (Rudnick and Gao, 2014) to approximately 5 ppb (BGS, 2009), whereas in the upper crust as 0.5 ppb (Rudnick and Gao, 2014).

In addition to the significant resources derived from mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the nickel sulphide deposits in Russia and elsewhere, platinum is also known to be enriched to potentially economic concentrations in several other geological settings (Gunn, 2014). Small-scale production from placer deposits has taken place for many decades in the Urals and the Russian Far East, in Colombia, Alaska and New Zealand. High tenor platinum values are also known in Alaskan-Ural type complexes, in ophiolites and hydrothermal veins, but these are not currently worked for platinum. Low-grade platinum enrichments are also well known in laterites, unconformity-related gold-uranium deposits, porphyry deposits, black shales and carbonatites and other alkaline complexes. These settings have not been the source of platinum production to date, but platinum might in the future become available as a by-product of other metals in deposits of these types.

Concerning the main deposits in operation globally, platinum is mostly the main product mined in South Africa and Zimbabwe, where palladium and other PGM are the secondary co-products. In the Russian Federation and Canada platinum is typically a by-product of copper and nickel, but produced at lower quantities than palladium. In the United States, platinum is a co-product of palladium production. In 2017, 83% of the world platinum mine production was associated with PGM-dominant deposits and 17% with nickel-copper-dominant deposits (background data from(S&P Global, 2018)).

The geological occurrence of platinum in the EU is discussed in chapter 0.

Global resources and reserves*:* Platinum resources are typically reported in combination with other PGM, most commonly with palladium and sometimes with rhodium and/or gold (See the PGM factsheet for more details). Some mining companies publish separate resource and reserve data for platinum in individual deposits. According to data published by the French Geological Survey (BRGM), global reserves of platinum are estimated to 13,000 tonnes in 2017 (BRGM, 2017b), with most of them located in South Africa (81.7%), followed by Zimbabwe (7.3%) and Russia (5.9%). Table 120 presents the estimated global reserves of platinum.

Table 120: World reserves of platinum in 2017. (BRGM, 2017b)

Country	**Platinum Reserves (tonnes of Pt content)** (rounded values)	**Percentage of the total (%)**
South Africa	10,620	81.7
Zimbabwe	950	7.3
Russian Federation	780	5.9
United States	210	1.6
Canada	210	1.6
Other countries (unspecified)	230	1.9
World total	13,000	100

EU resources and reserves: Available data for platinum resources and reserves are shown in Table 121 and Table 122 below.

Table 121: Platinum resources data in the EU

Country	Classification	Quantity (million tonnes of ore)	Grade (g/t)	Reporting code	Reporting date	Source
Finland	Measured	23.6	0.17	PERC	12/2018	(Boliden, 2019)
	Indicated	114.9	0.14		12/2018	(Boliden, 2019)
	Inferred	19.2	0.13		12/2018	(Boliden, 2019)
Finland[1,2]	All (Measured-Indicated-Inferred)	312.8	0.19	NI 43-101	12/2017	(FODD, 2017)
Finland[2]	All (Measured-Indicated-Inferred)	1,989	0.05	JORC	12/2017	(FODD, 2017)
Finland[2]	Historic Resource Estimates	126.3	0.77	None	12/2017	(FODD, 2017)

[1]NI 43-101 compliant resources of the Kevitsa (Boliden) mine are not included, as they are reported separately in the table
[2]Mineral resources of closed mines, as the FODD database indicates them, are included.

Also, the European Minerals Yearbook reports 5.08 Mtonnes of indicated, JORC-compliant resources in Greenland at a grade of 0.06 grams per tonne (g/t) (Minerals4EU 2019).

Table 122: Platinum reserves data in the EU

Country	Classification	Quantity (million tonnes of ore)	Grade (g/t)	Pt content (t)	Reporting code	Reporting date	Source
Finland	Proven	62.5	0.18	11.3	PERC	12/2018	(Boliden, 2019)
	Probable	66.1	0.21	13.9			

19.7.2.1.1.4 Geology, resources and reserves of rhodium

Geological occurrence: The geological occurrence of rhodium is also discussed in the general PGM Factsheet

The PGMs are among the rarest elements in the Earth's crust; rhodium is a scarce metal with an abundance of approximately 1 ppb by weight in the Earth's crust (BGS, 2009). The rhodium grade in PGM ores is lower than that of platinum and palladium.

Rhodium is a co-product of platinum and palladium mining. Over 80% of rhodium's world primary production is derived from PGM-dominant deposits in South Africa, in which PGMs are the main economic components. In particular, the major part of rhodium is extracted from the mafic-ultramafic Bushveld Igneous Complex in South Africa, namely from two horizons: the Merensky Reef and the UG2 Chromitite. The UG2 Chromitite deposit of the Bushveld Complex is particularly rich in rhodium (0.3-0.6 ppm) (Gunn, 2014), and accounts for more than half of total rhodium production from South Africa (Johnson Matthey, 2016). Other sources of rhodium are the PGM-dominant deposit of Great Dyke in Zimbabwe, as well as the nickel-copper sulphide deposits in Canada (Sudbury) and Russia (Norilsk) where rhodium is extracted as a by-product together with other PGM (Gunn, 2014). According to background data from (S&P Global, 2018a)(S&P Global, 2018b), the platinum-palladium deposits with rhodium occurrences account for 91% of the global joint platinum+palladium resources and reserves, of which the PGM-dominant deposits represent approximately 84% (split into 79% in South Africa and 5% in Zimbabwe), and the nickel-copperNi-Cu-dominant deposits account for 16% (divided in 12% in Russia and 4% in North America).

In the EU, rhodium grades of about 0.1 ppm are reported in two small, non-exploited deposits in Finland (Paasivara, Ala-Penikkavaara) having a total, non-compliant resource estimate of 780 kilogram of rhodium (FODD, 2017). In Europe, exploration drillings in the past have intersected rhodium-rich mineralisation of up to 1.0 ppm platinum+palladium+rhodium in Greenland (Lauri *et al.*, 2018).

Global resources and reserves*:* Global or national resource or reserve data for rhodium are not available in the public domain. Rhodium data are generally presented in combination with other PGMs, most commonly platinum and palladium, and sometimes with gold. In the general PGM factsheet, more information about mineral resources and reserves is provided.

EU resources and reserves: The following table presents available data on rhodium resources in the EU. Rhodium reserves do not exist.

Table 123: Rhodium resources data for the EU

Country	Classification	Quantity (million tonnes of ore)	Grade (g/t)	Reporting code	Reporting date	Source
Finland[206]	Historic Resource Estimates	8.6	0.11	None	12/2017	(FODD, 2017)

19.7.2.1.1.5 Geology, resources and reserves of ruthenium

Geological occurrence: The geological occurrence of ruthenium is also discussed in the general PGM factsheet.

The PGM are among the least abundant elements, and ruthenium is one of the rarest metals in nature. Its abundance in the Earth's crust is reported to be 0.57 ppb by weight and in the upper crust 0.34 ppb (Rudnick and Gao, 2014). The ruthenium content in PGM ores is significantly lower than that of platinum and palladium.

Ruthenium is a co-product of platinum and palladium. The principal primary sources of ruthenium are the PGM-dominant deposits located in mafic-ultramafic igneous complexes like the Bushveld Igneous Complex in South Africa and the Great Dyke in Zimbabwe, where ruthenium is produced as a co-product of platinum mining. According to background data from (S&P Global, 2018a)(S&P Global, 2018b), ruthenium's occurrence is reported for the 51% of the global joint platinum+palladium resources and reserves, of which the PGM-dominant deposits account for 78% (split into 72% in South Africa and 6% in Zimbabwe), whereas the nickel-copper -dominant deposits account for 22% (split into 21% in Russia and 1% in Canada).

No information is available for geological occurrences of ruthenium in PGM deposits in the EU.

Global resources and reserves*:* There are no global or national resource or reserve data for ruthenium in the public domain. Data for ruthenium are typically presented in aggregated form with other PGMs (seechapter 0).

EU resources and reserves: Resources of iridium do not exist in the EU, or are not reported in the public domain.

[206] Mineral resources of closed mines, as reported by the FODD database, are included

19.7.2.2 Mining and metallurgical extraction

Exploration and new mine development projects in the EU

Active exploration projects are registered in Finland and Sweden by (S&P Global, 2018). The most advanced one, currently at pre-feasibility/scoping stage, is the palladium-rich polymetallic (platinum-palladium-gold-copper-nickel) Arctic Platinum Project in northern Finland (Arctic Platinum, 2019).

Mining of PGMs

PGM-bearing deposits are typically mined by underground or, less usually, by open-pit methods. The selection depends on size, grade and morphology of the orebody.

Most of the PGM mines in South Africa operate at depth below 500 metres and up to 2.2 kilometres. Mining is labour-intensive by conventional drilling and blasting techniques, though attempts are being made to introduce more mechanisation into the workplace, as the PGM-rich layers are very narrow (typically less than one metre thick) (IPA, 2015d, European Commission, 2017a, Hagelüken, 2019). Underground mining is also employed at the Norilsk-Talnakh mines in Russia and several sites in Zimbabwe, Canada and the United States (European Commission, 2017a).

Surface mines are generally cheaper and safer to operate than underground mines. Open-pit mining is most appropriate for near-surface (< 100 metres depth), lower-grade, steeply dipping, or massive ore bodies where large-scale surface excavations would not cause significant environmental impact (European Commission, 2017a). Examples of surface mining operations include the Mogalakwena mine in South Africa (Merschel and Krämer, 2018), and Norilsk-I "South Cluster" operations in Russia which involve both open-cast and underground mining (IPA Industrial expert, 2019).

As PGMs are mined at very low concentrations compared with most other metals, a number of mineral processing steps are required after mining to increase the PGM content. A range of physical and chemical concentration techniques are applied based on the mineralogical features of the individual ore including crushing and milling, froth flotation, and in some cases magnetic separation and dense media separation (BGS, 2009). Concentration is typically carried out at, or close to, the mine site (Gunn, 2014). Subsequent smelting and refining may be carried out at or near the mine, or concentrate may be transported to a centralised facility for processing to metal.

Different processes are used for processing sulphide-poor ores (i.e. Merensky and UG2) and sulphide-rich ores (e.g. Norilsk). In the PGM-dominant deposits, the crude ore is initially crushed and ground to facilitate separation of PGM-bearing and gangue minerals. Magnetic or dense media separation can also be applied after comminution to optimise recovery, depending on the associated minerals (sulphides, chromite or silicates). Subsequently, the liberated sulphide mineral grains which host the PGM are concentrated by froth flotation (Gunn, 2014). The grades of the mined ores from the Bushveld Igneous Complex, the world's chief source of PGMs, are generally in the range 2-5 ppm of combined platinum+palladium. The typical grades currently mined are about 3-4 ppm platinum+palladium in the Merensky Reef and 2-3 ppm platinum+palladium in UG2 (IPA Industrial expert, 2019). In general, for most mining companies or projects the average ore grades have been gradually declining, which is a function of the mix of reef types mined (Merensky/UG-2/Platreef) and the economics of mining, i.e. shallower but lower grade ores versus deeper but higher grade ores (Mudd, Jowitt and Werner, 2018).

Typical grades of the concentrate range from 100 ppm to 200 ppm PGM (Merschel and Krämer, 2018), but can be up to 1,000 ppm PGM (Johnson Matthey, 2019b); grades of 2,100 ppm PGM for concentrates from the Stillwater operations in the United States are also reported (Yang *et al.*, 2018).

Nickel-copper -dominant ores are treated differently due to their higher sulphide content and different mineralogy; several processing routes are applied as sulphide concentration, and ore texture vary considerably (Gunn, 2014).

Metallurgical extraction of PGMs

Metallurgical processing and refining to produce high-purity PGM products is a complex, costly, and lengthy process; it may take up to six months to produce refined metal from the time the first PGM-bearing ore is extracted at the mine (IPA, 2015e). The applied techniques differ from company to company (Yang *et al.*, 2018), the details of which are not disclosed as commercial secrets (Gunn, 2014).

19.7.2.2.1.1 Enrichment of concentrates

The PGM concentrates are too low-grade to be refined directly and have to undergo an enrichment step prior to refining. However, their value is so high that this enrichment step has to ensure minimum losses (Yang *et al.*, 2018). The enrichment process typically consists of a pyrometallurgical and a hydrometallurgical step (Yang *et al.*, 2018). This process typically occurs close to the mining site due to the large tonnages of materials that require processing (European Commission, 2014).

For PGM concentrates produced by the PGM-dominant ores of South Africa, the following processes are generally applied (Yang *et al.*, 2018, Merschel and Krämer, 2018, Gunn, 2014, Jones, 2005):

(i) Smelting and matte production: The dried flotation concentrate is smelted in electric furnaces at temperatures about 1,350 °C, although higher temperatures maybe are needed for UG2 concentrates (Gunn, 2014). The PGM and base-metal sulphides accumulate in a matte, while a slag containing unwanted minerals is discarded. The matte is then transferred to converters where it undergoes a process known as converting. This involves blowing air, or oxygen, into the matte to oxidise contained iron and sulphur. Silica is added to the matte to react with the oxidised iron to form a slag that can be easily removed, while the sulphur is collected from the off-gas to produce sulphuric acid. The converter matte consists of copper and nickel sulphide with smaller quantities of iron sulphides, cobalt and PGM. This is usually cast into ingots and is then sent to the base metal treatment plant. The typical PGM content of the converter matte is 0.2-0.4% PGM by weight (Merschel and Krämer, 2018);

(ii) PGM concentrate production: The matte is transferred to the base metal refinery where it is magnetically separated and leached over several stages to separate base metals (e.g. nickel and copper). After the final leaching stage, a PGM concentrate is produced containing about 50% to 70% PGMs+gold (Merschel and Krämer, 2018).

Where PGMs are a by-product of nickel and copper production from nickel-copper-dominant ores, such as those in Russia and Canada, different treatments are applied due to the higher sulphide content and different mineralogy. The metallurgical process is designed around the main product (typically nickel) while maximising PGM recoveries (Yang *et al.*, 2018, Gunn, 2014).

The concentrate produced in Russia (Norilsk) undergoes roasting, smelting, and conversion to a copper-nickel- PGM matte. The matte is then treated in the base metal refinery by oxidation pressure leaching to produce concentrates of copper, nickel and cobalt. The copper concentrates, which contain all the PGMs and gold, are further treated by a combination of copper extractive metallurgy techniques, i.e. smelting to copper blisters and refining by electrowinning, to separate copper. The anode slimes are then combined with nickel slimes and other PGM-bearing concentrates and smelted again to produce a PGM-bearing matte, which is pressure-leached to produce separately a concentrate of silver, a second one containing palladium and platinum, and a third one with the rest of the PGM (Gunn, 2014). Different processing routes are applied to nickel and copper PGM-bearing concentrates produced elsewhere. The various extractive metallurgy circuits used generate anode slimes and carbonyl process residues rich in PGMs, gold, and other metals, which are sent for PGM refining.

19.7.2.2.1.2 Refining

The PGM-bearing concentrate is transferred from the base metal refinery to the precious metal refinery for separation and purification of the PGMs and gold. Refining is known to involve a series of hydrometallurgical steps to separate and purify the PGMs.

The PGM concentrate is dissolved in hydrochloric acid and the six PGM are refined to a high level of purity by selective precipitation, or separation using a combination of techniques such as solvent extraction, distillation and ion-exchange. Gold and palladium are the first to be extracted, and rhodium usually the last. Iridium, ruthenium and osmium are separated at the end of the separation process, therefore, if there is no demand, part of these intermediates can be stored for future use (Angerer *et al.*, 2016). In South Africa, the time between the mining of the ore and production of pure metal typically ranges from around six weeks for palladium and up to 20 weeks for rhodium (Johnson Matthey, 2019b). Nickel, copper, cobalt, and silver may be obtained in the refining process as co-products. The refined PGMs have a purity of over 99.95%, and can be produced in several forms: ingot, grain or a fine powder known as "sponge".

19.7.2.3 World and EU mine production

PGM mine production for 2017 is summarised in Figure 294. South Africa is the leading PGM supplier from primary sources accounting for 58% of the world's mine production. South Africa is the dominant world supplier of platinum and the 'minor' PGM, i.e. rhodium, ruthenium, iridium and osmium, and the second world producer of palladium. Russia is the second PGM world producer accounting for about 24% of total production in 2017, and it is the top world producer of palladium. The rest of the notable world producers consists of Zimbabwe, Canada and the US.

The world primary production of PGMs has remained relatively constant since 2010 ranging from 443 to 467 tonnes annually, though, with a noteworthy reduction in 2014 (Figure 295). South African production of platinum was hit by widespread strike action in 2014 when a six-month stoppage at western Bushveld operations resulted in the loss of over one million ounces of platinum production (Johnson Matthey, 2019a). However, South African production has been broadly stable since 2015 despite the closure of several high-cost shafts during this period (IPA Industrial expert, 2019).

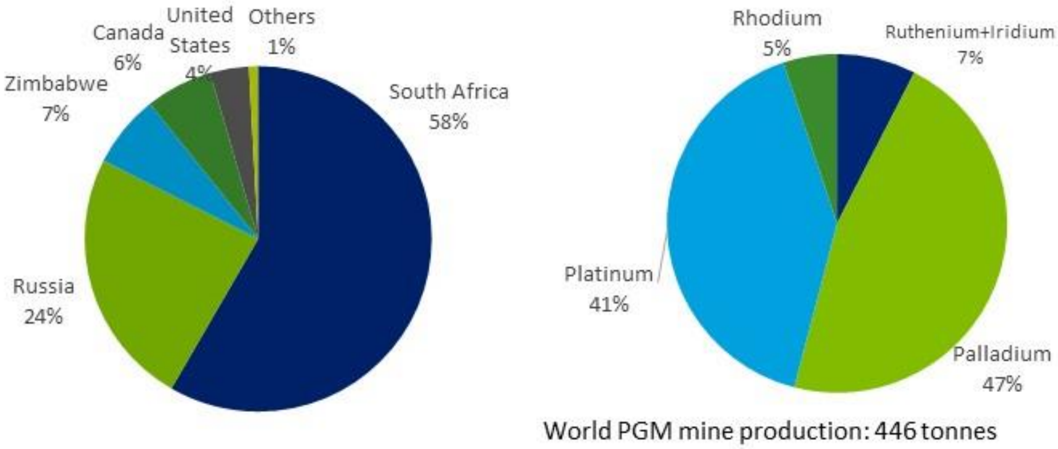


Figure 294: World mine production of PGM in 2017 per country (left) and per material (right). Background data[207] from (WMD 2019) (BGS, 2019)

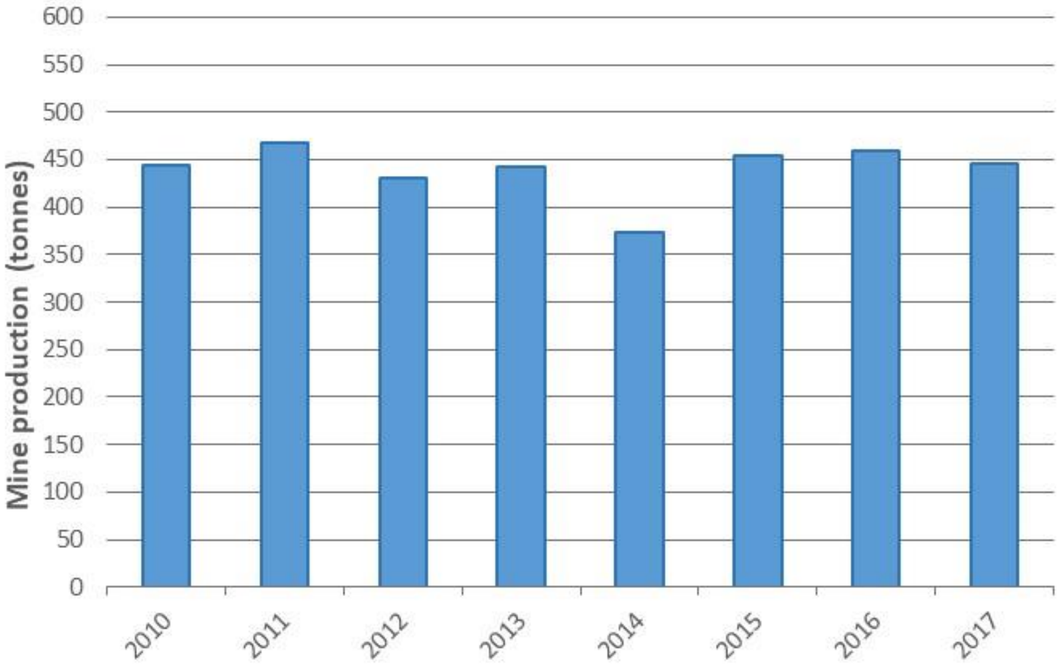


Figure 295: Evolution of world mine production of PGMs from 2010 to 2017. Background data from (WMD 2019) (BGS, 2019)

World and EU mine production of iridium

The world production of iridium is estimated to approximately six tonnes, much less than the annual production of the other PGM. Iridium supply is strongly dominated by South Africa, which accounted for about 92% of the total. Zimbabwe, Canada and Russia are contributing to the remainder of the global mine production with 5%, 2% and 1% respectively. There is no production of iridium from mines in the EU.

[207] WMD is the source for platinum, palladium and rhodium mine production. For other PGM, BGS was used as the source ("Other platinum metals") after adjusting the values reported with the Rh mine production reported by WMD

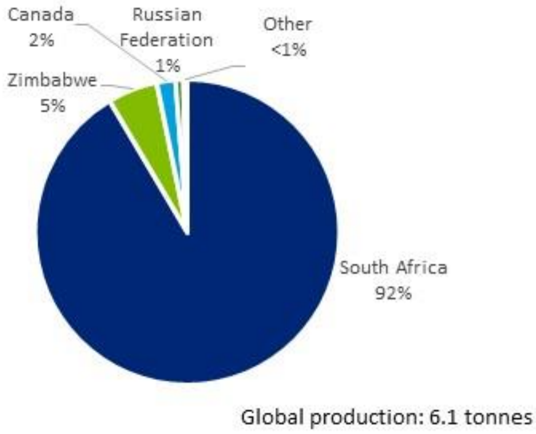


Figure 296: The distribution of global mine production of iridium. Average for the years 2012-2016. Estimation based on background data from (BGS, 2019) (WMD 2019) (Johnson Matthey, 2019a) (Girolami, 2012)(European Commission, 2017)

World and EU mine production of palladium

The annual average world mine production of palladium in the period 2012-2016 was about 199 tonnes. Russia was the leading world producer with a share of 40% of the total. South Africa was the second most important producer (37% of total), followed by Canada (10%), the United States (6%), and Zimbabwe (5%). EU production accounts for only 0.4% of the global output.

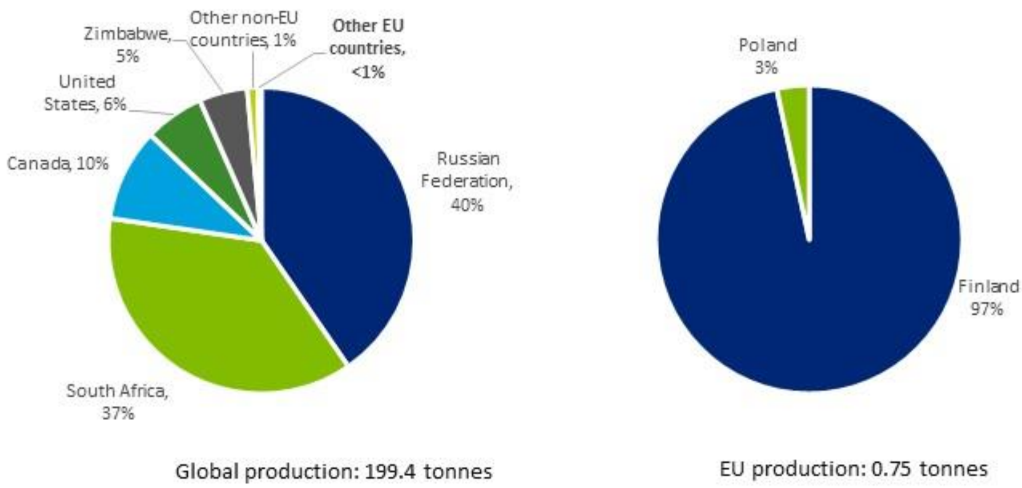


Figure 297: World and EU mine production of palladium (average 2012-2016). Data from (WMD 2019) (BGS, 2019)[208]

World and EU mine production of platinum

The annual average world mine production of platinum for the period 2012-2016 was about 178 tonnes. Global supply is dominated by South Africa, which accounted for about 71% of the total. Russia was the second most important producer (13% of total), followed by Zimbabwe (7%) and Canada (5%). Extraction in the EU accounts for only 0.5% of the global production.

[208] for China

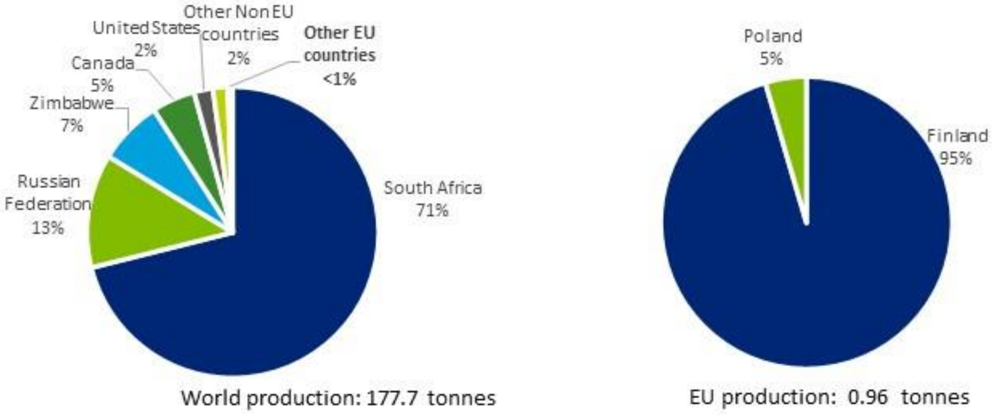


Figure 298: World and EU mine production of platinum (average 2012-2016). Data from (WMD 2019) (BGS, 2019)[209]

World and EU mine production of rhodium

The average annual world mine production of rhodium for the period 2012-16 was approximately 21.7 tonnes. Global supply is dominated by South Africa, which accounted for about 80% of the total. Russia was the second most important producer (12% of total), followed by Zimbabwe (5%), Canada (2%) and the United States (1%).

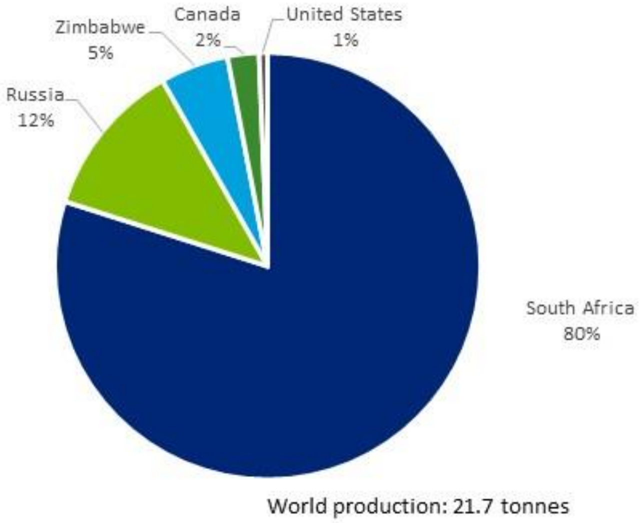


Figure 299: The distribution of global mine production of rhodium, average 2012–2016. Data from (WMD 2019)

World and EU mine production of ruthenium

The annual average mine production of ruthenium for the period 2012-2016 is estimated to about 27 tonnes. Global supply is strongly dominated by South Africa, which accounted for about 93% of the total. Zimbabwe was the second most important producer (4% of total), followed by Canada (2%), and Russia (1%) (Figure 300). There is no production of ruthenium from mines in the EU.

[209] For China

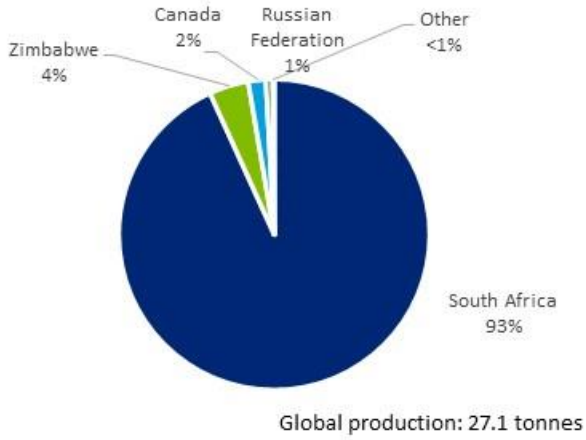


Figure 300: The distribution of global mine production of ruthenium. Average for the years 2012-2016. Estimation based on background data from (BGS, 2019) (WMD 2019) (Johnson Matthey, 2019a) (Girolami, 2012)(European Commission, 2017)

19.7.3Supply from secondary materials/recycling

19.7.3.1 Supply of PGMs in general from secondary materials

The PGMs are highly recyclable in technical terms due to their noble characteristics and durability in use, as well as because very high recovery rates of the metal content can be achieved once the PGM-containing scrap reaches a modern refining facility. In this case recovery rates for platinum and palladium of over 95% are technically attainable with current state-of-the-art techniques, while for rhodium, iridium and ruthenium the metallurgical yields are somewhat lower but still high (Hagelüken, 2014, Gunn, 2014, Sundqvist Ökvist *et al.*, 2018). In addition to the technical viability of recycling, secondary production from end-of-life products is attractive from an economic point of view as the PGM, like all precious metals, have a high intrinsic value (Hagelüken, 2014). Therefore, the potential for effective recycling is generally excellent, except in some applications and/or when used in minimal amounts (UNEP, 2011).

Besides the positive impact to the security of supply, PGM recycling brings environmental benefits. Secondary production of PGMs has lower environmental impacts than primary production due to the much higher PGM concentration in many end-of-life products compared to the low ore grades. For example, an autocatalyst may contain up to 2,000 g/t of PGM in the ceramic catalyst brick, and computer motherboards contain around 80 g/t palladium. This is significantly higher compared to 2-6 g/t of average grade in most PGM mines (Hagelüken, 2012)(IPA, 2015f).

The supply of PGMs from secondary materials is well established and has been growing steadily in recent years (see Figure 301) helping to manage the supply and demand dynamics and maintain the market in balance. Recycled platinum, palladium, and rhodium provide a significant proportion of the total supply, which is sufficient to balance the market closing the gap between mine production and consumption (Zientek et al., 2017). In 2018, about 29% (173 tonnes) of the global supply of Pt+Pd+Rh was obtained through recycling (Johnson Matthey, 2019a), while in 2005 this proportion was 13% (74.5 tonnes) (Johnson Matthey, 2014). Concerning ruthenium and iridium, it is considered that the proportion of the metal supply produced from recycling is lower than for platinum, palladium, and rhodium, while literature does not acknowledge osmium being recycled in an industrial scale.

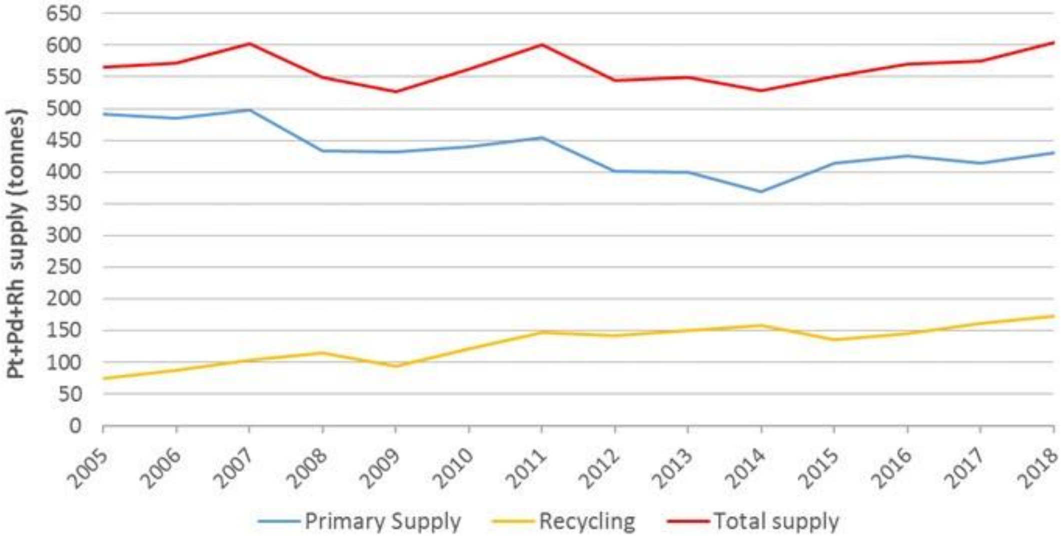


Figure 301: Global supply of PGM (Pt+Pd+Rh) from mine production and recycling (2005–2018). Background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, and (Johnson Matthey, 2014) for 2005-2012.

Technical challenges in the recycling of PGMs do exist, especially for complex products such as vehicles and computers. However, the main barrier to the effective recycling of PGM lies in ensuring that end-of-life products are collected appropriately and enter an efficient recycling chain. In open-loop recycling of end-of-life consumer products the rate achieved is critically dependent on numerous factors, such as the prevailing price and a host of others (e.g. market mechanism, consumer behaviour, relevant legislation) that influence the collection efficiency (Hagelüken, 2012)(Hagelüken, 2014). For example, declining steel scrap prices (as those prevailing between 2014 and 2016) affect negatively the number of end-of-life vehicles worldwide reaching scrapyards, leading to longer lifetime of vehicles and lower volumes of spent catalytic converters being removed for processing. Also, low PGM prices have a short-term adverse effect on recovery from autocatalysts as they may lead to stockpiling of catalyst scrap by collectors (Johnson Matthey, 2016)(Johnson Matthey, 2017)(Johnson Matthey, 2018). In the EU, the recycling of autocatalysts is impacted by the End-of-Life Vehicles (ELV) Directive (2000/53/EC), and Directive 2005/64/EC on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability, while the recycling of electronics is stimulated by the EU Waste Electrical & Electronic Equipment (WEEE) Directive (Directive 2012/19/EU).

Recycling of automotive catalysts is the most important contributor to secondary supply. 95% of the PGM content of spent autocatalysts can be recovered during the refining process using state-of-the-art recycling technologies (IPA, 2015f), and the global average recycling rate is estimated to be 50-60% (European Commission, 2017b). The contribution of autocatalysts' recycling to the security of supply is higher for rhodium. In the period 2014-2018, between 27% and 33% of total global demand for rhodium was supplied by autocatalysts recycling, whereas for platinum the proportion was 14-17% and for palladium 21-26%.

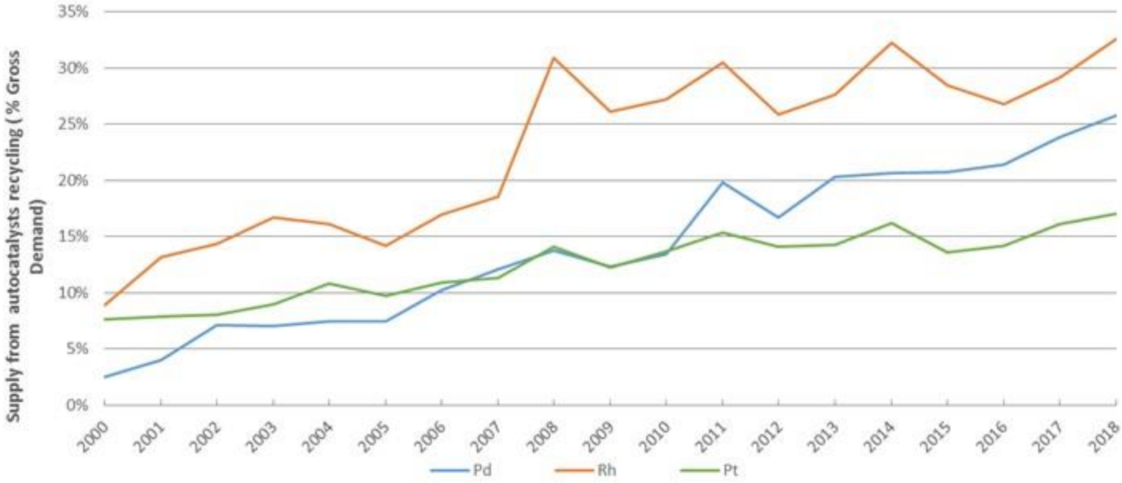


Figure 302: Contribution of autocatalysts recycling to platinum group metals world market balance (2000-2018). Background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, and (Johnson Matthey, 2014) for 2005-2012

Besides autocatalysts, other materials from end-of-life products, notably jewellery and electronic scrap, are used as feedstock to PGM recycling processes. Consumer items, such as automotive catalysts, jewellery scrap and electronic equipment, all rich in PGMs, may or may not enter the recycling stage. This forms an 'open-loop' system, in which losses of PGMs tend to be higher than in a closed-loop system, where PGM materials are collected at a very high rate or enter secondary production directly from industrial processes. Recycling rates in open-loop recycling are correspondingly lower, e.g. 5-10% in waste electrical and electronic equipment (WEEE).

PGM recycling from industrial applications typically follows a closed-loop system, in which the metal usually remains in the ownership of the industrial user, and metal recovered from scrap is subsequently reused in the same application (Hagelüken, 2012) (Johnson Matthey, 2019a). Typical examples are spent process catalysts used in the chemical and oil refining industry, as well as glassmaking equipment. New metal supply is only required to cover small life cycle losses and increased demand from market growth and new applications. End-of-life recycling rates in industrial applications are well over 80% (Hagelüken, 2014).

In some other cases, PGM uses are dissipative (e.g. medical applications, spark plugs, sensors) and are not available for recycling. In contrast, jewellery and investment items reach very high recycling rates due to their high value and PGM concentration (Hagelüken, 2012).

A complementary source of PGMs and other precious metals are industrial by-products of the non-ferrous metals mining, processing and manufacturing industries. These include various intermediate products and residues such as complex mining concentrates, slags, mattes, flue dust, ash, slimes and production waste from the electronics, glass, jewellery and chemical industries (European Commission, 2017a).

Secondary production processes vary widely depending on the specific material or combination of materials treated, the contaminants to be removed and the particular mix of PGMs for separation from any batch of feedstock (Cusano et al., 2017). The first step in secondary production is typically the pre-treatment of the feedstock (e.g. segregation, crushing, grinding, thermal treatment). The PGM-containing materials are then either smelted to a metal matte or dissolved to bring the PGMs into a solution. The concentrated

PGM output is further refined to recover individual metals separately in a pure form, identical in quality and purity to those from primary production. Although PGMs are relatively inert, the chemical properties and the reactivity of their compounds vary, allowing a variety of separation techniques to be used such as chemical precipitation, chemical dissolution, liquid-liquid extraction, distillation of tetroxides, ion exchange, electrolytic processes, pyrolysis or reduction of metallic chloride compounds to pure metal sponges. PGM refining is complex, and individual process stages may have to be repeated to achieve the required purity. PGM are generally refined together with gold and silver.

19.7.3.2 Supply of individual PGMs from secondary materials

Supply of iridium from secondary materials

Recycling makes an important and growing contribution to global PGM supply (see chapter 19.7.3.1).

Most iridium is used in closed-loop industrial applications (including process catalysts and electrodes) where losses are low and recycling rates high. A recycling rate of 40–50% is reported by (UNEP, 2011) and (Hagelüken, 2014) as typical. In most consumer goods the recycling rate of iridium is very low because it is used either in dissipative applications, such as spark plug tips or in medical implants which are not recovered at the end of life (European Commission, 2017). In spent electrodes, much of the ruthenium and iridium is dissipated during use, so only a small proportion of the original metal can be recovered (Johnson Matthey, 2019a). The global average end-of-life functional recycling rate is estimated to range from 20% to 30%, the fraction of secondary (scrap) metal in the total input to metal production to range between 15% and 20% (recycled content), and the share of old scrap in the total scrap flow (old scrap ratio) to be above 80% (UNEP, 2011; Hagelüken, 2014). Based on these data, and published by (Mathieux *et al.*, 2017), the estimated end-of-life recycling input rate (EoL-RIR) used in the assessment is 14%.

Table 124 provides an overview of the recycling rates by end-use sectors.

Table 124: Global end-of-life recycling rates (%) for iridium by end-use sector. (Hagelüken, 2014; UNEP, 2011)

Average EoL recycling rate	Vehicles[1]	Electronics	Industrial applications[2]	Dental	Other[3]	Jewellery and coins
20-30	0	0	40-50	not applicable	5-10	not applicable

[1] Autocatalysts, spark plugs, excluding car electronics
[2] Including process catalysts/electrochemical, glass
[3] Including decorative, medical, sensors, crucibles

In addition to recycling from end-of-life products, refineries also process iridium-bearing manufacturing wastes (new scrap) (European Commission, 2017).

Supply of palladium from secondary materials

The high value of palladium makes it attractive for recycling and sophisticated technology has been developed that permits highly effective recovery from a variety of waste streams, notably autocatalysts and waste electrical and electronic equipment (WEEE). As discussed in the PGM factsheet, recycling makes a significant and growing contribution to global PGM supply, contributing to the market balance of scarce natural resources.

It is believed to be significant international trade in palladium-bearing waste and scrap, but Eurostat data are not available to ascertain the volumes involved (European Commission, 2017).

The secondary supply of palladium from EOL products complements substantially the primary (mine) supply and balances partially the market deficit since 2012. According to Johnson Matthey data, in 2018 palladium recovered from end-of-life products reached an all-time high record accounting for 31% (excluding closed-loop recycling) of the global palladium supply by volume. By far the majority of the recycling volumes for palladium come from the recycling of spent automotive catalysts, ranging between 21% and 26% of the worldwide palladium supply during the last five years (2014-2018). Palladium's recovery from waste electrical and electronic equipment also contributes to global supply accounting for about 5% of the total supply. In 2018, supply from the recycling of autocatalysts represented 84% of the total quantity recovered from EOL products, with electronics (15%) and old jewellery (1%) making up the remainder.

The end-of-life recycling rate of the PGM varies considerably by country and by application (European Commission, 2017). An overview of the recycling rates by end-use sectors is provided in Table 125.

Table 125: Global end-of-life recycling rates (%) for palladium by end-use sector (Hagelüken, 2014; UNEP, 2011)

Average EOL recycling rate[1]	Vehicles[2]	Electronics	Industrial Applications[3]	Dental	Other[4]	Jewellery and coins[4]
60-70	50-55	5-10	80-90	15-20	15-20	90-100

[1] Excluding jewellery and coins
[2] Autocatalysts, spark plugs, excluding car electronics
[3] Including process catalysts/electrochemical, glass
[4] Including decorative, medical, sensors, crucibles
[5] Including medals and silverware

Different estimations exist for the recycling indicators of palladium. (UNEP, 2011) and (Hagelüken, 2014) reported that the global average end-of-life functional recycling rate ranges from 60% to 70%, the fraction of secondary (scrap) metal in the total input to metal production is 50% (recycled content), and the share of old scrap in the total scrap flow (old scrap ratio) to be above 80%. According to statistics published yearly by Johnson Matthey, in the period 2014-2018, the proportion of total palladium global supply covered by recycling ranges from 27% to 31% (Johnson Matthey, 2019); these data refer to open-loop recycling from post-consumer scrap. According to data collected in the MSA study carried out by (BIO Intelligence Service, 2015a), the end-of-life functional recycling rate in the EU in 2012 was 47%, and the end-of-life recycling input rate (EoL-RIR) 9%.

The EoL-RIR used in the criticality assessment was 28%, as it is derived from background data published by (Johnson Matthey, 2019) and averaged over the period 2012-2016.

Besides open-loop recycling from end-of-life products, palladium is also recovered in closed-loop industrial processes.

In addition to recovery from end-of-life products, palladium is also recovered from a range of intermediate products and wastes from smelting, refining and manufacturing processes.

Supply of platinum from secondary materials

The high value of platinum, combined with its relative scarcity, makes it attractive for recycling. Sophisticated technology has been developed that permits highly effective recovery of platinum from a variety of waste streams, mainly autocatalysts and old jewellery. As discussed in the PGM factsheet, recycling makes a significant and growing contribution to global platinum supply, contributing to the market balance of scarce natural resources.

The secondary production of platinum contributes substantially to the global market supply, offsetting partially the weaker mine supply after 2011 and the market deficit in 2012-2016. The majority of the recycling volumes of platinum originates from spent automotive catalysts and jewellery. According to Johnson Matthey data, in 2018 the global supply of platinum from secondary sources accounted for the 26% of the total primary and secondary supply (excluding closed-loop recycling), of which 63% came from autocatalysts, and old jewellery (35%) and electronics (2%) made up the remainder. In the last five years (2014-2018), the share of the world platinum supply covered from the recycling of autocatalysts ranged from 14% to 18%, from old jewellery from 7% to 11%, while waste electrical and electronic equipment recycling covered 0.4% of the worldwide supply.

The end-of-life recycling rate of the PGM varies considerably by country and by application (European Commission, 2017). An overview of the recycling rates by end-use sectors is provided in Table 126.

Table 126: Global end-of-life recycling rates (%) for platinum by end-use sector (Hagelüken, 2014) (UNEP, 2011)

Average EoL recycling rate[1]	Vehicles[2]	Electronics	Industrial Applications[3]	Dental	Other[4]	Jewellery and coins[5]
60-70	50-55	0-5	80-90	15-20	10-20	90-100

[1] Excluding jewellery and coins
[2] Autocatalysts, spark plugs, excluding car electronics
[3] Including process catalysts/electrochemical, glass
[4] Including decorative, medical, sensors, crucibles
[5] Including medals and silverware

Several estimations are available for the recycling indicators of platinum. It is reported by (UNEP, 2011) and (Hagelüken, 2014) that the global average end-of-life functional recycling rate ranges from 60% to 70% (see Table 126), the fraction of secondary (scrap) metal in the total input to metal production is 50% (recycled content), and the share of old scrap in the overall scrap flow (old scrap ratio) to be above 80%. According to statistics published yearly by Johnson Matthey, in the period 2014-2018, the contribution of recycling to global platinum supply ranges from 22% to 29% (Johnson Matthey, 2019b); these data refer to open-loop recycling from post-consumer scrap. According to data provided by (BIO Intelligence Service, 2015a), the end-of-life functional recycling rate in the EU was 54% in 2012, and the end-of-life recycling input rate 11%.

The EOL-RIR used in the criticality assessment was 25%, as it is derived from background data published by (Johnson Matthey, 2019b) and averaged over the period 2012-2016.

In addition to open-loop recovery from end-of-life products, platinum is also recovered in closed-loop industrial processes, e.g. in glass manufacturing where old platinum equipment is recycled and turned into new tooling (WPIC, 2019).

Along with end-of-life products, platinum is also recovered from a range of intermediate products and wastes from smelting, refining and manufacturing processes (European Commission, 2017).

Supply of rhodium from secondary materials

As discussed in the PGM Factsheet recycling makes a significant and growing contribution to global PGM supply, contributing to the market balance of scarce natural resources. The high value of rhodium makes it attractive for recycling. Rhodium is mainly recycled from spent automotive catalysts for which sophisticated technologies are well established for rhodium recovery.

The recycling of spent autocatalysts makes a vital contribution to the rhodium market balance and security of supply. Recycling from other end-of-life products is negligible (Johnson Matthey, 2018). According to Johnson Matthey data (Johnson Matthey, 2019a), rhodium recovered from autocatalysts accounted for 31% of global supply and 33% of global gross demand in 2018, reflecting a higher contribution of autocatalysts recycling to market balance in comparison with palladium and platinum. The secondary supply of rhodium depends on several factors such as the overall number of the collected end-of-life vehicles and the availability of scrap containing rhodium, which varies by region as car markets and consumer preferences are different. Also, the rhodium loadings in catalysts at the time of their manufacture have an impact. For instance, the increase in rhodium usage in palladium-rhodium three-way catalysts that occurred during the early 2000s with substantially higher average rhodium loadings, and the rhodium thrifting in gasoline catalysts because of the 2007-2008 price spike (Johnson Matthey, 2018; Johnson Matthey, 2017; Johnson Matthey, 2016).

Different estimates are available for the recycling indicators of rhodium. (UNEP, 2011) and (Hagelüken, 2014) reported that the global average end-of-life functional recycling rate ranges from 50% to 60% (see Table 127), the fraction of secondary (scrap) metal in the total input to metal production is 40% (recycled content), and the share of old scrap in the overall scrap flow (old scrap ratio) to be above 80%. According to statistics published annualy by Johnson Matthey, recycling (open-loop recycling from post-consumer scrap) contributed between 27% and 31% of the global supply (primary+secondary) of rhodium in the last five years (2014-2018) (Johnson Matthey, 2019a). On the other hand, according to data provided by the MSA study of rhodium (BIO Intelligence Service, 2015a), the end-of-life recycling rate in the EU in 2012 was 62%, and the end-of-life recycling input rate only 9%. In the criticality assessment, the value of 28% was used as the EoL-RIR (average of years 2012 to 2016) derived from background data published by (Johnson Matthey, 2019a).

An overview of the recycling rates by end-use sectors is provided in Table 127.

Table 127: Global end-of-life recycling rates for rhodium by end-use sector (UNEP, 2011; Hagelüken, 2014)

Average EOL recycling rate[1]	Vehicles[2]	Electronics	Industrial Applications[3]	Dental	Other[4]	Jewellery and coins[5]
50-60	45-50	5-10	80-90	Not applicable	30-50	40-50

[1] Excluding jewellery and coins
[2] Autocatalysts, spark plugs, excluding car electronics
[3] Including process catalysts/electrochemical, glass
[4] Including decorative, medical, sensors, crucibles
[5] Including medals and silverware

In addition to recycling from end-of-life products, rhodium is also recovered from a range of intermediate products and wastes from smelting, refining and manufacturing processes (European Commission, 2017).

Supply of ruthenium from secondary materials

Recycling makes a significant and growing contribution to global PGM supply. The PGM supply from secondary materials is also discussed in the PGM factsheet.

Ruthenium is mainly recycled from process catalysts. A small contribution to ruthenium's recycling comes from manufacturing wastes and residues such as spent targets, physical vapour deposition (PVD) shield scrap, machining parts and turnings, as well as ruthenium-containing chemicals, solutions, and other chemical scraps (Umicore, 2019c). The very small amount of ruthenium in computer hard disk drives does not have sufficient value to ensure the economic viability of recycling (UNEP, 2011). In spent electrodes, much of the ruthenium and iridium is dissipated during use, so only a small proportion of the original metal can be recovered (Johnson Matthey, 2019a). Closed-loop recycling can achieve very high levels of ruthenium recovery. In open-loop recycling of consumer products, the rate achieved is generally much lower (European Commission, 2017).

Ruthenium differs from the other platinum-group metals because of its low price and complex chemistry. Ruthenium's price has been too low in the five-year period from 2013 to 2017 to allow the recovery of metal from spent process catalysts, as the refining process was uneconomic, especially for catalysts with a low ruthenium content or where process losses are high. However, the price gains in late 2017 have made recycling more cost-effective and stimulated the recovery of ruthenium from spent process catalyst, which were stockpiled in anticipation of higher prices (Johnson Matthey, 2019a). Nevertheless, much of the ruthenium is lost from the electrodes during use, so only a small proportion of the original metal can be recovered (Johnson Matthey, 2018).

According to (UNEP, 2011) and (Hagelüken, 2014), the global average end-of-life functional recycling rate (EoL-RR) for ruthenium was estimated to range from 5% to 15%, the fraction of secondary (scrap) metal in the total input to metal production to range between 50% and 60% (recycled content), and the share of old scrap in the total scrap flow (old scrap ratio) to be less than 20%. The high recycled content for ruthenium is due to the high availability of new scrap (UNEP, 2011). The end-of-life recycling input rate (EoL-RIR) used in the assessment is estimated to 11% as it is approximated from the above-estimated recycling data and presented by (Mathieux *et al.*, 2017).

(UNEP, 2011) and (Hagelüken, 2014)also provide an overview of the recycling rates by end-use sectors (see Table 128). The global end-of-life recycling rate of ruthenium in electronics and other uses is estimated less than 5%, while in industrial applications a rate of 40-50% is more typical.

Table 128: Global end-of-life recycling rates (%) for ruthenium by end-use sector. (Hagelüken, 2014; UNEP, 2011)

Average EOL recycling rate	Vehicles	Electronics	Industrial applications[1]	Dental	Other[2]	Jewellery and coins
5-15	not applicable	0-5	40-50	not applicable	0-5	not applicable

[1] Including process catalysts/electrochemical, glass
[2] Including decorative, medical, sensors, crucibles

19.8 Other considerations

19.8.1 Environmental and health and safety issues

PGM mining is a capital, energy and labour-intensive process. The International Platinum Group Metals Association (IPA) carried out in 2013 the first-ever industry-wide Life Cycle Assessment (LCA) study. The study quantifies the environmental impacts of both primary and secondary production of PGMs (platinum, palladium and rhodium) for a variety of categories, as well as the fabrication of catalytic converters using PGM and the use of these autocatalysts in a EURO 5 diesel and gasoline vehicle. The Life Cycle Inventory (LCI) dataset is based on data collected from industry, having 2010 as the reference year. The study covers all the main technologies for the production of PGM "from cradle to gate" and is highly representative of the industry. The key findings of the study are (Bossi and Gediga, 2017, IPA, 2015c):

- Power consumption during mining and ore beneficiation is the major environmental impact (72%) of the production of PGM due to the low ore grade, high electricity demand in the mines and concentrators, difficult mining conditions and hard coal dominance in the South African power grid mix. A further 27% of the impacts come from smelting and refining of PGMs;
- Only 1% of impacts are attributed to recycling. The much lower impact of secondary production is due to various reasons, including the enormous difference in the concentration of PGMs between primary and secondary sources;
- The benefits from the use of PGM-based automotive catalysts offset the impacts of PGM production. A reduction of emissions of pollutants, including CO, HC, NO_x and PM, of up to 97% is achieved, which corresponds to over 1.3 tonnes of avoided emissions in one EURO 5 gasoline plus one EURO 5 diesel vehicle in use over 160,000 kilometres each.

The summary results are presented in Table 129.

Table 129: Summary results of the Life Cycle Impact Assessment for the average production of 1 gram of PGM (IPA, 2015c)

	Platinum	**Palladium**	**Rhodium**
Global Warming potential (kg CO_2-eq/g)	33	25	30
Primary energy demand (MJ/g)	387	304	346

The mining industry in South Africa has made significant strides in improving safety in the last years. The overall number of fatalities declined by 88% from 1993 to 2016. In 2018, the platinum sector had a 59% decrease in the number of fatalities, from 29 in 2017 to 12 in 2018, but a 10% increase in the number of injuries (from 1,048 in 2017 to 1,154 in 2018). For a proper assessment, longer time series are required, given the anecdotic character of these accidents. The mining sector of South Africa has set itself the goal of zero-harm by December 2020 (Minerals Council of South Africa, 2019b, Minerals Council of South Africa, 2019c).

EU occupational safety and health (OSH) requirements exist to protect workers' health and safety. Employers need to identify which hazardous substances they use at the workplace, carry out a risk assessment and introduce appropriate, proportionate and effective risk management measures to eliminate or control exposure, to consult with the workers who should receive training and, as appropriate, health surveillance[210].At EU level, occupational exposure limit values[211] (OELs) are set for platinum to prevent occupational diseases or other adverse effects in workers exposed to platinum in the workplace. Workers' and employers organisations should be kept informed by member states about the indicative occupational exposure limit values[212] (IOELVs) (Skowroń 2017), which is set for platinum at Community level[213] by Directive 91/322/EEC: 1 mg/m^3 (measured or calculated in relation to a reference period of eight hours).

19.8.2Contribution to low-carbon technologies

The contribution of PGMs to low-carbon technologies is discussed in this section, with a focus on palladium and platinum. In the following, particular contributions of iridium, rhodium and ruthenium are provided.

Fuel cells that operate at low temperatures need catalysts to accelerate electrochemical processes, and the usual choice of catalyst is platinum. Platinum and other PGM (ruthenium and iridium) are used in fuel cells for the same reasons as they are in the automotive and chemical industries; they are excellent catalysts, and they are robust under a fuel cell's harsh operating conditions (Heraeus, 2019).

High-temperature fuel cells do not generally require platinum catalysts. Polymer electrolyte membrane fuel cells (PEMFC) operate at low temperatures and, therefore, require platinum as a catalyst on both the cathode and the anode. The PGM-containing PEMFC is well-suited for the production of hydrogen and powering vehicles. Other fuel-cell technologies requiring platinum are direct methanol fuel cells (DMFC), and phosphoric acid fuel cells (PAFC) (Moss *et al.*, 2013). In PEM-based electrolysers, platinum catalysts typically contain also ruthenium and iridium (Heraeus, 2019) (Angerer *et al.*, 2016). Ruthenium is also often included in the anode of DMFC operating at low temperature with catalysts made of platinum (Moss *et al.*, 2013).

Fuel cell electric vehicles (FCEVs) are expected to play an important role in the transition to a net-zero carbon transport sector, in particular in long-distance transport, e.g. for long-haul heavy goods vehicles and coaches, provided that the necessary hydrogen refuelling station infrastructure is deployed. To avoid generating carbon at the point of use, fuel cells must be fuelled with hydrogen which can be produced in various ways from a range of sources. Overall carbon emissions are zero or close-to-zero if hydrogen is produced from carbon-neutral energy, by using water electrolysis or natural gas with carbon capture and storage (CCS) (European Commission, 2018). For water electrolysis in particular, which is the reverse of a fuel cell, using renewable electricity avoids carbon emissions during hydrogen generation. This hydrogen is then a form of renewable energy storage and can be used to generate power again when required, or for heating, transportation, and industrial applications. Stationary fuel cells can be used at various scales to generate heat and power, whether within homes or for commercial operations, or even at grid-scale (IPA Industrial expert, 2019).

Various technologies to store, transport and purify hydrogen also use PGM. For example, liquid organic hydrogen carriers (LOHC) are alternately hydrogenated and dehydrogenated to store and release hydrogen. Depending on the specific technology and carrier molecule,

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[210] https://ec.europa.eu/social/main.jsp?catId=148

[211] "OEL means the limit of the time-weighted average of the concentration of a chemical agent in the air within the breathing zone of a worker in relation to a specified reference period" (Skowroń 2017)

[212] as set out by Council Directive 98/24/EC

[213] IOELVs from Directive 91/322/EEC, which was based on an earlier legal framework (Directive 80/1107/EEC), are being scientifically reviewed, as foreseen in art. 3 of the abovementioned Directive 98/24/EC.

platinum catalysts may be used for these processes (Auer et al., 2019). In another example, palladium-based membranes can be used to separate and purify hydrogen from a hydrogen-containing gas mixture, because palladium has the unique property of allowing the preferential permeation of hydrogen (Burkhanov *et al.*, 2011).

Platinum and rhodium alloys are employed in the manufacture of glass-making equipment for the production of fibreglass, which is used to build wind turbines for renewable energy generation, and in automotive lightweight to improve fuel efficiency (IPA Industrial expert, 2019).

Contribution to low-carbon technologies by iridium

Iridium is an effective catalyst in fuel cells and hydrogen technologies involving polymer electrolyte membrane (PEM) electrolysers, where it is used in combination with platinum (Angerer *et al.*, 2016; Heraeus, 2019). The generated hydrogen may be used to power fuel cell electric vehicles (FCEV). Iridium is also employed in organic light-emitting diodes (OLEDs), an alternative low energy lighting technologies to the commonly used LEDs.

Contribution to low-carbon technologies by rhodium

A contribution of rhodium can be considered the production of fibreglass for wind turbines and automotive lightweight, as it is used in platinum alloys for glass-making equipment.

Contribution to low-carbon technologies by ruthenium

Ruthenium is a material employed by PEM fuel cell (PEMFC) technology for both transport (fuel cell electric vehicles), and stationary applications for hydrogen generation and storage. Ruthenium is used in PEMFC to protect platinum catalysts from poisoning by trace carbon monoxide in the hydrogen fuel (Heraeus, 2019). Finally, the use of ruthenium in alloys for aircraft turbine blades can improve strength, durability and resistance to creep, thus allowing the engines to operate at higher temperatures while burning fuel more efficiently. Ruthenium has a remarkable effect on titanium's corrosion resistance which is improved a hundred times by the addition of just 0.1% of ruthenium (IPA, 2019).

19.8.3Socio-economic issues

South Africa, the top platinum, rhodium, iridium and ruthenium supplier in the world, has a low governance level for the "political stability and absence of violence/terrorism" component of governance, while the average of the six worldwide governance indicators (WGI) is on a medium level (World Bank, 2018).

Concerning the mining sector, platinum group metals mining is an integral part of the South Africa economy (Baxter, 2019). In 2018 the PGM industry employed directly 167,000 people (Minerals Council of South Africa, 2019a), though, down from 191,000 people in 2013 (IPA, 2015b) and over 200,000 in 2006 (Baxter, 2019). According to the International Platinum Group Metals Association (IPA) companies provide staff with training, permanent housing, health monitoring and create opportunities for local businesses (IPA, 2015b), while employers in the PGM sector enjoy growing, and higher salaries in comparison to other sectors (IPA Industrial expert, 2019). However, unsafe working conditions and long strikes in the main PGM mining companies are also documented (Buratovic *et al.*, 2017). In 2012, following a wildcat strike and violent disputes at the Lonmin mine in Marikana, 46 people, mainly employees, died in the event that became known as "the Marikana tragedy" (Chinguno, 2013)(Cairncross and Kisting, 2016). In 2014, due to major strike operations at western Bushveld owned by Anglo American, Impala Platinum and Lonmin stopped for six months (Johnson Matthey, 2019a); the 2014 strike was a major contributor to the jobs losses that followed (IPA Industrial expert, 2019).

Currently, the PGM industry in South Africa is facing challenges due to domestic labour strife, flat new-mine supply and weaker demand, the increased growth of recycling, declining productivity and rapidly escalating costs (Baxter, 2019). According to the Minerals Council of South Africa, at the end of 2018, more than 65% of PGM operations, representing 52% of PGM production, were marginal or loss-making at prevailing prices, putting in danger around 90,000 jobs. Electricity costs have increased by more than 500% in the period 2008 to 2018, and a further increase of about 30% in production costs is anticipated up to 2021 due to electricity tariff increases (IPA Industrial expert, 2019). After years of underinvestment, it is suggested that significant capital investment is needed to secure jobs (IPA Industrial expert, 2019).

The governance of Russia, the leading global producer of palladium, has been assessed as low, i.e. for the governance components "political stability and absence of violence/terrorism", "rule of law" and "control of corruption" it ranks between the 10^{th} and the 25^{th} percentile. In the component "voice and accountability" its ranking dropped from the 43^{rd} percentile in 1996 to the 19^{th} in 2017 (World Bank, 2018).

The social sustainability of the mining industry in Russia is poorly investigated. Some studies focus on the impact of mining on local communities, especially in Northern areas and in the Arctic. In this context, mining is seen both as an opportunity for employment and prosperity and as a thread for what concerns environmental impacts and indigenous rights. Despite a large number of mining areas and activities in Russia, company-community conflicts are rare, and the social acceptance of mining in Russia is high (Tiainen, Sairinen and Sidorenko, 2015; Pettersson *et al.*, 2015; Suopajärvi *et al.*, 2016).

Zimbabwe, which accounts for 7% of the global PGM primary supply, has an even more critical situation, as its governance indicators are very low. Also, it is ranked near the bottom of the 2017 Resource Governance Index categorised as having "failing" governance. This means the country has almost no framework in place to ensure that resource extraction benefits society (NRGI, 2017). Similarly, Zimbabwe ranks very low on rankings of corruption perceptions (157 of 180 countries) and state fragility (10 of 178 countries) (Transparency International, 2017; The Fund for Peace, 2019).

19.9 Comparison with previous EU assessments

19.9.1 Comparison with previous EU assessments on PGMs in general

In the criticality assessments of 2011 and 2014, the PGMs were treated as a single group. Platinum, palladium, and, to a lesser extent, rhodium had the highest impact on the measured criticality of the group because these metals have much greater economic importance than the other PGMs, while more data are available to assess their supply risk. In the current and the 2017 assessment, the criticality of the five PGMs was assessed individually using the revised methodology. These assessments are discussed in the specific PGM factsheets. Osmium was not assessed because of the very small size of its market and the lack of any quantitative data on its supply and demand. The SR and EI score for the group of PGMs were calculated through an arithmetic average of the SR and EI scores of platinum, palladium, iridium, rhodium and ruthenium, respectively.

The results of this review and earlier assessments are shown in Table 130.

Table 130: Economic importance and supply risk results for PGMs in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011);(European Commission, 2014); (European Commission, 2017a)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
PGM	6.7	3.6		6.6	1.2		5.0	2.5		5.7	2.4

The results are not comparable to the 2011 and 2014 EU criticality assessments due to the revision of the methodology for assessing economic importance and supply risk introduced in 2017. The averaged Supply Risk (SR=2.4) is marginally lower compared to the 2017 assessment. The trend is mainly attributed to the higher EOL-RIR used in the current assessment for platinum and palladium.

The average Economic Importance (EI) indicator (EI=5.7) is higher in the current assessment in comparison to the previous exercise of 2017. The main parameter affecting the result is the increased value-added of NACE 2 sector "C29 - Manufacture of motor vehicles, trailers and semi-trailers", which corresponds to the application of autocatalysts, the most significant application for PGM in Europe.

19.9.2 Comparison with previous EU assessments on individual PGMs

19.9.2.1 Comparison with previous EU assessments on iridium

The assessment has been performed using the revised methodology introduced in the 2017 assessment. The supply risk (SR) has been analysed at the extraction stage of the value chain using only the global HHI calculation. The approach applied is the same as the 2017 assessment, even though the stage of the value chain assessed was cited as "processing/refining stage". It is considered more appropriate to classify the stage evaluated as the "mining stage" because the HHI was calculated on the basis of mine production of primary PGM, allocated where the initial mining took place rather than the location of refining (although this coincides to a large degree). The EU HHI does not contribute to the calculation of the Supply Risk due to lack of appropriate trade data from official sources for import flows of primary materials, i.e. PGM-bearing concentrates or mattes.

The processing/refining stage was not assessed in the current exercise because publicly available statistics on refinery production from primary and secondary sources do not exist. In addition, the complexity of trade flows of intermediate iridium-bearing materials is such that would require an in-depth analysis highly incompatible with a criticality assessment. Finally, it is not possible to determine the actual supply to the EU because the trade data published by official sources do not differentiate between iridium derived from primary and secondary sources.

The results of this review and earlier assessments are shown in Table 131.

Table 131: Economic importance and supply risk results for iridium in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011);(European Commission, 2014); (European Commission, 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
PGM	6.7	3.6		6.6	1.2		5.0	2.5		5.7	2.4
Iridium[214]	-	-		-	-		4.3	2.8		4.2	3.2

Iridium was not assessed separately in the previous critical raw materials studies of 2011 and 2014 as the PGMs were treated as a single group. The calculated Supply Risk (SR=3.2) is higher than the 2017 assessment due to the increased share of South Africa, the top producing country (92% in the current assessment in comparison to 85% in the 2017 assessment). The results of the Economic Importance indicator appear marginally lower in the current evaluation due to a decreased contribution in the calculation of EI of the NACE 2 sector ‘C20 - Manufacture of chemicals and chemical products’, which has a higher value-added than the NACE 2 sector ’C26 - Manufacture of computer, electronic and optical products’. It is noted that in the calculation of the EI of iridium in the current assessment, the share of the applications of iridium denoted as ‘Other’ is large (39%) and it was allocated among the three major identified applications (electronics, electrochemical and chemical) rather than attributing to the 2-digit NACE sector ‘C29 - Manufacture of motor vehicles, trailers and semi-trailers’, to reflect the use of iridium in spark plugs and vehicle exhaust systems as in the 2017 assessment.

19.9.2.2 Comparison with previous EU assessments on palladium

The assessment has been performed using the revised methodology introduced in the 2017 assessment. The calculation of the Supply Risk (SR) was carried out at the extraction stage of the value chain using only the global HHI calculation. The approach applied is the same as the 2017 assessment, even though the stage of the value chain assessed was cited as “processing/refining stage”. It is considered more appropriate to classify the stage assessed as the “mining stage” because the HHI was calculated on the basis of mine production of primary PGM, allocated where the initial mining took place rather than the location of refining (although this coincides to a large degree). The EU HHI does not contribute to the calculation of the Supply Risk due to lack of appropriate trade data from official sources for import flows of primary materials, i.e. PGM-bearing concentrates or mattes.

The processing/refining stage was not assessed in the current exercise as publicly available statistics on refinery production from primary and secondary sources do not exist. Besides, palladium is contained in a variety of complex intermediate products that would require an in-depth analysis which is incompatible with a criticality assessment. Finally, the actual supply to the EU cannot be determined because the trade data published by official sources do not distinguish between platinum metal derived from primary and secondary sources.

[214] In the 2011 and 2014 assessments the PGM were considered as a single group which included iridium. In the 2017 and the current assessment iridium was considered as a single metal.

The results of this review and earlier assessments are shown in Table 132.

Table 132: Economic importance and supply risk results for palladium in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011);(European Commission, 2014); (European Commission, 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
PGM	6.7	3.6		6.6	1.2		5.0	2.5		5.7	2.4
Palladium[215]	-	-		-	-		5.6	1.7		7.0	1.3

In the previous critical raw materials studies of 2011 and 2014, palladium was not assessed individually as the PGMs were treated as a single group. The calculated Supply Risk (SR=1.3) is lower in the current assessment due to a higher EoL-RIR. In particular, the EoL-RIR value of 28% was used in the criticality assessment as derived from industrial data published by (Johnson Matthey, 2019), while in the previous one the value of 10% was used based on background data from the MSA study of palladium (BIO Intelligence Service, 2015). Also, the concentration of supply from primary sources has been decreased, i.e. the share of Russian Federation fell from 46% in the 2017 exercise to 40% in the current assessment. This is mainly due to the significant effect on supply that sales from Russian state stocks had in the 2017 assessment, having 2010-2014 as the reference period. In particular, sales from Russian state stocks contributed a significant proportion of the total supply of palladium in the period 2010-2011 but faded out later on. The SR indicator for palladium is the lowest among the PGMs as global supply is more balanced in comparison to platinum, rhodium, ruthenium, and iridium.

The result of the Economic Importance (EI) indicator is higher in the current assessment due to a greater share of the most significant application (autocatalysts) for palladium in Europe, i.e. from 76% in the 2017 assessment to 87% in the current criticality evaluation, and a rise of the value-added of the corresponding NACE 2 sector "C29 - Manufacture of motor vehicles, trailers and semi-trailers". The increase in the value-added for NACE 2 sector C29 in terms of the 28 Members States is 14% (in the current assessment the average of value-added for years 2012-2016 was used, in contrast to the previous exercise referring to the year 2013).

19.9.2.3 Comparison with previous EU assessments on platinum

The assessment has been performed using the revised methodology introduced in the 2017 assessment. The calculation of the Supply Risk (SR) was carried out at the extraction stage of the value chain using only the global HHI calculation. The approach applied is the same as in the 2017 assessment, even though the stage of the value chain assessed was cited as "processing/refining stage". It is considered more appropriate to classify the stage evaluated as the "mining stage" because the HHI was calculated based on mine production of primary PGM, allocated where the initial mining took place rather than the location of refining (although this coincides to a large degree). The EU HHI does not contribute to the calculation of the Supply Risk due to lack of appropriate trade data from official sources for import flows of primary materials, i.e. PGM-bearing concentrates or mattes.

The processing/refining stage was not assessed in the current exercise as statistical data on refinery production from primary and secondary sources are not available in the public domain. Also, platinum is contained in a variety of complex intermediate products that would require an in-depth analysis which goes beyond the criticality assessment. Finally, the actual supply to the EU cannot be determined because the trade data published by

[215] In the 2011 and 2014 assessments the PGM were considered as a single group which included palladium. In the 2017 and the current assessment palladium was considered as a single metal.

official sources do not discriminate between platinum metal derived from primary and secondary sources.

The results of this review and earlier assessments are shown in Table 133.

Table 133: Economic importance and supply risk results for platinum in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011);(European Commission, 2014); (European Commission, 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
PGM	6.7	3.6		6.6	1.2		5.0	2.5		5.7	2.4
Platinum[216]	-	-		-	-		4.9	2.2		5.9	1.8

In the previous critical raw materials studies of 2011 and 2014, platinum was not assessed as the PGMs were treated as a single group. The calculated Supply Risk (SR=1.8) is lower in the current assessment due to a higher EoL-RIR. In particular, the EoL-RIR value of 25% was used in the assessment as derived from industrial data published by (Johnson Matthey, 2019b), while in the 2017 assessment the value of 11% was used for the EoL-RIR based on background data from the MSA study of platinum(BIO Intelligence Service, 2015). The results of the Economic Importance (EI) indicator are higher in the current assessment due to a greater share of the most important application for platinum in Europe (autocatalysts) and a strong rise of the value-added of the corresponding NACE 2 sector "C29 - Manufacture of motor vehicles, trailers and semi-trailers". The increase in the value-added for NACE 2 sector C29 in terms of the 28 Members States is 14% (in the current assessment the average of value-added for years 2012-2016 was used, while in the previous exercise the value-added for the year 2013).

19.9.2.4 Comparison with previous EU assessments on rhodium

The assessment has been performed using the revised methodology introduced in the 2017 assessment. The supply risk (SR) has been analysed at the extraction stage of the value chain using only the global HHI calculation. The approach applied is the same as for the 2017 assessment, even though the stage of the value chain assessed was cited as "processing/refining stage". It is considered more appropriate to classify the stage assessed as "mining stage" because the HHI was calculated based on mine production of primary PGMs, allocated where the initial mining took place rather than the location of refining (although this coincides to a large degree). The EU HHI does not contribute to the calculation of the Supply Risk due to lack of appropriate trade data from official sources for import flows of primary materials, i.e. PGM-bearing concentrates or mattes.

The processing/refining stage was not assessed in the current exercise because publicly available statistics on refinery production from primary and secondary sources do not exist. Also, the complexity of trade flows of intermediate rhodium-bearing materials is such that would require an in-depth analysis incompatible with a criticality assessment. Finally, the actual supply to the EU cannot be determined because the trade data published by official sources do not differentiate between rhodium derived from primary and secondary sources.

The results of this and earlier assessments are presented in Table 134.

[216] In the 2011 and 2014 assessments the PGM were considered as a single group which included platinum. In the 2017 and the current assessment platinum was considered as a single metal.

Table 134: Economic importance and supply risk results for rhodium in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011);(European Commission, 2014); (European Commission, 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
PGM	6.7	3.6		6.6	1.2		5.0	2.5		5.7	2.4
Rhodium[217]	-	-		-	-		6.6	2.5		7.4	2.1

Rhodium was not assessed separately in the previous critical raw materials studies of 2011 and 2014 as the PGM were treated as a single group, only. The calculated Supply Risk (SR=2.1) is lower than the 2017 assessment due to a higher EoL-RIR used (28% instead of 24%) and a slightly smaller market share of the top producing country (i.e. South Africa). The results of the Economic Importance indicator are higher in the current assessment due to a substantial increase of the value-added of NACE 2 sector "C29 - Manufacture of motor vehicles, trailers and semi-trailers" which represents by far the most important application for rhodium. The relative increase in the value-added for NACE 2 sector C29 in terms of the EU28 Members States is 14% (in the current assessment the average value-added for years 2012-2016 was used, while in the previous exercise the value-added for the year 2013).

19.9.2.5 Comparison with previous EU assessments on ruthenium

The assessment has been performed using the revised methodology introduced in the 2017 assessment. The supply risk (SR) has been analysed at the extraction stage of the value chain using only the global HHI calculation. The approach applied is the same as the 2017 assessment, even though the stage of the value chain assessed was cited as "processing/refining stage". It is considered more appropriate to classify the stage evaluated as "mining stage" because the HHI was calculated on the basis of mine production of primary PGMs, allocated where the initial mining took place rather than the location of refining (although this coincides to a large degree). The EU HHI does not contribute to the calculation of the Supply Risk due to lack of appropriate trade data from official sources for import flows of primary materials, i.e. PGM-bearing concentrates or mattes.

The results of this review and earlier assessments are shown in Table 135.

Table 135: Economic importance and supply risk results for ruthenium in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011);(European Commission, 2014); (European Commission, 2017)

Assessment	2011			2014			2017			2020	
Indicator	EI	SR		EI	SR		EI	SR		EI	SR
PGM	6.7	3.6		6.6	1.2		5.0	2.5		5.7	2.4
Ruthenium[218]	-	-		-	-		3.5	3.4		4.1	3.4

[217] In the 2011 and 2014 assessments the PGM were considered as a single group which included rhodium. In the 2017 and the current assessment rhodium was considered as a single metal.

[218] In the 2011 and 2014 assessments the PGM were considered as a single group which included ruthenium. In the current assessment, ruthenium was considered as a single material

Ruthenium was not assessed individually in the assessments of 2011 and 2014 as the PGM were treated as a single group. The calculated Supply Risk (SR=3.44), rounded to SR=3.4) is unchanged from the 2017 assessment as the shares of the global production have remained the same, the EoL-RIR used in the two assessments is also the same and no other changes occurred that may have an effect according to the methodology for calculating the SR.

The results of the Economic Importance (EI) indicator appear higher in the current assessment in comparison to the 2017 assessment. The increase is due to a greater contribution in the calculation of EI of the NACE 2 sector 'C20 - Manufacture of chemicals and chemical products', which has a higher value-added than the NACE 2 sector 'C26 - Manufacture of computer, electronic and optical products'.

19.10 Data sources

This section describes the sources used:

- for the PGM factsheet (general and per individual PGM): section 19.10.2
- for the criticality assessments of the individual PGMs: section 19.10.3

In addition, the data availability and quality is assessed quantitatively: section

19.10.1 Assessment of the availability and quality of data sources

19.10.1.1 Data sources on iridium

There is very little data publicly available for iridium.

Data are not published for the world mine and refinery production of iridium, neither for its global supply. For years 2012 to 2015, production figures were estimated by taking into account mine production data for the category "Other Platinum Metals" (i.e. excluding Pt and Pd) published by the British Geological Survey (BGS, 2019) in combination with production data for rhodium published by 'World Mining Data' (WMD 2019). Furthermore in order to achieve the breakdown between ruthenium and iridium mine production, it was assumed that the annual worldwide output of osmium is 500 kg as reported by (Girolami, 2012) and that ruthenium's and iridium's production is proportional to the size of their markets; data for ruthenium and iridium demand are published by (Johnson Matthey, 2019a). For the year 2016, unpublished production data provided by Johnson Matthey in (European Commission, 2017) were used.

There is no trade code specific to iridium ores and concentrates. The most relevant CN8 code would be 2616 90 00 "Precious metal ores and concentrates excluding silver". However, this code reports data for several precious metals, and it is, therefore, inappropriate to use in the assessment.

Trade data for iridium metal are not available separately. Data for iridium metal in unwrought or powder form is aggregated with osmium and ruthenium under CN code 7110 41 00. Data were extracted from Eurostat, and iridium and ruthenium flows were disaggregated assuming zero trade flows for osmium and in accordance with the relative size of their markets. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials.

Demand data published by Johnson Matthey was the source for the end uses of iridium. The EoL-RIR used was derived from background data provided by UNEP.

19.10.1.2 Data sources on palladium

Mine production data were sourced from 'World Mining Data' published by the Austrian Ministry for Sustainability and Tourism and the International Organising Committee for the World Mining Congress Austrian Ministry of Science, Technology and Commerce. Data for Chinese primary production were sourced from the British Geological Survey, as were not included in the 'World Mining Data' datasets. Data are not available in the public domain for the global refinery production of palladium.

There is no trade code specific to palladium ores and concentrates. The most relevant CN8 code would be 2616 90 00 "*Precious metal ores and concentrates excluding silver*". However, this code reports data for several precious metals, and it is, therefore, inappropriate to use in the assessment.

Trade data for palladium in unwrought or in powder form was sourced from Eurostat Comext using the CN code 7110 21 00. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials.

The source for the end uses of palladium was European demand data published by Johnson Matthey. The EoL-RIR was derived from worldwide recycling data published by Johnson Matthey.

19.10.1.3 Data sources on platinum

Mine production data were sourced from 'World Mining Data' published by the Austrian Ministry for Sustainability and Tourism and the International Organising Committee for the World Mining Congress Austrian Ministry of Science, Technology and Commerce. Data for Chinese primary production were sourced from the British Geological Survey, as were not included in the 'World Mining Data' datasets. Data are not available in the public domain for the global refinery production of platinum.

There is no trade code specific to platinum ores and concentrates. The most relevant CN8 code would be 2616 90 00 *"Precious metal ores and concentrates excluding silver"*. However, this code reports data for several precious metals, and it is, therefore, inappropriate to use in the assessment.

Trade data for platinum in unwrought or in powder form was sourced from Eurostat Comext using the CN code 7110 11 00. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials.

The source for the end uses of palladium was European demand data published by Johnson Matthey. The EoL-RIR was derived from worldwide recycling data published by Johnson Matthey.

19.10.1.4 Data sources on rhodium

Mine production data of rhodium were sourced from 'World Mining Data' published by the Austrian Ministry for Sustainability and Tourism and the International Organising Committee for the World Mining Congress Austrian Ministry of Science, Technology and Commerce. Data are not available in the public domain for the global refinery production of rhodium.

There is no trade code specific to rhodium ores and concentrates. The most relevant CN8 code would be 2616 90 00 *"Precious metal ores and concentrates excluding silver"*. However, this code reports data for several precious metals, and it is, therefore, inappropriate to use it in the assessment.

Trade data for rhodium in unwrought or in powder form was sourced from Eurostat Comext. The source for the end uses of rhodium was global demand data published by Johnson Matthey. The EoL-RIR was derived from worldwide recycling data published by Johnson Matthey.

19.10.1.5 Data sources on ruthenium

There is very little data publicly available for ruthenium.

Data are not available in the public domain for the world mine and refinery production of ruthenium, neither for its global supply. For the period 2012-2015, production figures were estimated by taking into account production data for the category "Other Platinum Metals" (i.e. excluding platinum and palladium) published by the British Geological Survey (BGS, 2019) in combination with production data for rhodium published by 'World Mining Data'

(WMD 2019). Furthermore in order to achieve the breakdown between ruthenium and iridium mine production, it was assumed that the annual worldwide output of osmium is 500 kilograms as reported by (Girolami, 2012) and that ruthenium's and iridium's production is proportional to the size of their markets; data for ruthenium and iridium demand are published by (Johnson Matthey, 2019a). For the year 2016, unpublished production data provided by Johnson Matthey in (European Commission, 2017) were used.

There is no CN8 code specific to ruthenium ores and concentrates. The most relevant CN8 code would be 2616 90 00 "Precious metal ores and concentrates excluding silver". However, this code reports data for several precious metals, and it is, therefore, inappropriate to use in the assessment.

Trade data for ruthenium metal are not available separately. Data for ruthenium metal in unwrought or powder form is aggregated with osmium and ruthenium under CN code 7110 41 00. Data were extracted from Eurostat, and iridium and ruthenium flows were disaggregated assuming zero trade flows for osmium and in accordance with the relative size of their markets. The trade data include metal from all sources, both primary and secondary. It is not therefore possible to identify the source of the metal and the relative contributions of primary and secondary materials.

The end uses of ruthenium were sourced by global demand data published by Johnson Matthey. The EoL-RIR used in the assessment was derived from background data published by UNEP.

19.10.2 Data sources used in the factsheet

Ait Abderrahim, A. and Monnet, A. (2018) Report on major trends affecting future demand for critical raw materials. SCRREEN project D.2.2. Available at: http://scrreen.eu/results/

Angerer, G. et al. (2016) Rohstoffe für die Energieversorgung der Zukunft: Geologie – Märkte – Umwelteinflüsse. München. Available at: https://www.acatech.de/publikation/rohstoffe-fuer-die-energieversorgung-der-zukunft-geologie-maerkte-umwelteinfluesse/

Arctic Platinum (2019) Suhanko Arctic Platinum Oy. Available at: https://suhanko.com/ (Accessed: 21 November 2019).

Auer, F. et al. (2019) 'Boosting the activity of hydrogen release from liquid organic hydrogen carrier systems by sulfur-additives to Pt on alumina catalysts', Catalysis Science & Technology. The Royal Society of Chemistry, 9(13), pp. 3537–3547. doi: 10.1039/C9CY00817A.

Baxter, R. (2019) 'A new strategy for the platinum sector. Minerals Council South Africa'. Available at: https://www.mineralscouncil.org.za/downloads/send/19-latest/718-a-new-strategy-for-the-platinum-sector

BGS (2009) 'Minerals profile. Platinum'. British Geological Survey - Natural Environment Research Council, pp. 1–32. Available at: http://www.bgs.ac.uk/mineralsUK/statistics/mineralProfiles.html

BGS (2019) World mineral statistics data, British Geological Survey. Available at: https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

BIO Intelligence Service (2015a) Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials. Available at: https://ec.europa.eu/jrc/en/scientific-tool/msa

BIO Intelligence Service (2015b) 'Study on Data Inventory for a Raw Material System Analysis Meeting Report – Notes of the fourth Expert workshop for PGMs, Magnesium, Natural Graphite, Indium and Germanium.', pp. 1–5.

Blagoeva, D. et al. (2016) Assessment of potential bottlenecks along the materials supply chain for the future deployment of low-carbon energy and transport technologies in the EU. Wind power, photovoltaic and electric vehicles technologies, time frame: 2015-2030. doi: 10.2790/08169.

Boliden (2019a) Boliden 2018 Annual and sustaibability Report. Available at: https://www.boliden.com/investor-relations/reports-and-presentations/annual-reports

Boliden (2019b) Summary tables of mineral resources and mineral reserves, 31 December 2018. Available at: https://www.boliden.com/operations/exploration/mineral-reserves-and-mineral-resources (Accessed: 22 September 2019).

Bossi, T. and Gediga, J. (2017) 'The Environmental Profile of Platinum Group Metals', Johnson Matthey Technology Review, 61(2), pp. 111–121. doi: 10.1595/205651317x694713.

BRGM (2014) Panorama 2012 du marché des platinoïdes. BRGM/RP-63169-FR, BRGM/RP-63169-FR.

BRGM (2017a) Fiches de criticité. Le palladium (Pd). Available at: http://www.mineralinfo.fr/page/fiches-criticite

BRGM (2017b) Fiches de criticité. Le platine (Pt). Available at: http://www.mineralinfo.fr/page/fiches-criticite

Buchholz P., Wellmer F.W., Bastian D., Liedtke M. (2019) Leaning against the wind: Low price benchmarks for acting anticyclically in the metal markets. Mineral Economics. https://doi.org/10.1007/s13563-019-00199-y

Buratovic, E. et al. (2017) Controversial Materials based raw materials.

Burkhanov, G. S. et al. (2011) 'Palladium-based alloy membranes for separation of high purity hydrogen from hydrogen-containing gas mixtures', Platinum Metals Review, 55(1), pp. 3–12. doi: 10.1595/147106711X540346.

Cairncross, E. and Kisting, S. (2016) 'Platinum and gold mining in South Africa: The context of the Marikana massacre', New Solutions, 25(4), pp. 513–534. doi: 10.1177/1048291115622027.

Chinguno, C. (2013) 'Marikana Massacre and Strike Violence Post-Apartheid', Global Labour Journal, 4(2), pp. 160–166. doi: 10.15173/glj.v4i2.1138.

CritCat (2019) Rational design of future catalyst materials, CritCat H2020 project website. Available at: http://www.critcat.eu/ (Accessed: 5 October 2019).

CRM experts (2019) 'Feedback and comments submitted after the CRM validation workshop'.

Cusano, G. et al. (2017) JRC Science for Policy report. Best Available Techniques (BAT) Reference Document for the main Non-Ferrous Metals Industries. doi: 10.2760/8224.

DERA (2017) 'Chart des Monats, Oktober 2017. Preisparität zwischen Platin und Palladium'. Available at: https://www.deutsche-rohstoffagentur.de/DERA/DE/Publikationen/Chart_des_Monats/cdm_node.html

Eurostat (2019a). Comext database. Available at: http://epp.eurostat.ec.europa.eu/newxtweb/

Eurostat (2019b). Prodcom database. Statistics on the production of manufactured goods (PRODCOM NACE Rev.2), Prodcom - Statistics by Product. Available at: https://ec.europa.eu/eurostat/web/prodcom (Accessed: 14 July 2019).

Eurostat (2019c) Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E). Available at: https://ec.europa.eu/eurostat/en/web/products-datasets/-/SBS_NA_IND_R2 (Accessed: 7 July 2019).

European Commission (2011) Critical raw materials. Available at: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en (Accessed: 8 July 2019).

European Commission (2014) Report on critical raw materials for the EU - Critical raw materials profiles. Available at: https://ec.europa.eu/docsroom/documents/11911/attachments/1/translations/en/renditions/pdf

European Commission (2017a) Study on the review of the list of critical raw materials. Critical Raw Material Factsheets. European Commission. doi: 10.2873/398823.

European Commission (2017b) Study on the review of the list of critical raw materials. Non-Critical Raw Materials Factsheets. European Commission. doi: 10.2873/876644.

European Commission (2018) In-depth analysis in support of the Commission Communication COM(2018)/773. 'A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy'. Available at: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

European Commission (2019) Negotiations and agreements. Available at: http://ec.europa.eu/trade/policy/countries-and-regions/negotiations-and-agreements/ (Accessed: 7 July 2019).

FODD (2017) Fennoscandian Mineral Deposits, Fennoscandian Ore Deposit database. V.2017. Available at: http://en.gtk.fi/informationservices/databases/fodd/index.html (Accessed: 9 August 2019)

Girolami, G. (2012) 'Osmium weighs in', Nature Chemistry, 4(11), p. 954. doi: 10.1038/nchem.1479.

Graedel, T. et al. (2015a) 'On the materials basis of modern society', Proceedings of the National Academy of Sciences, 112(20). doi: 10.1073/pnas.1312752110.

Graedel, T. et al. (2015b) 'On the materials basis of modern society. Supporting information file', Proceedings of the National Academy of Sciences of the United States of America. National Academy of Sciences, pp. 6295–300. doi: 10.1073/pnas.1312752110.

Gunn, G. (2014) 'Platinum-group metals', in Gunn, G. (ed.) Critical Metals Handbook. British Geological Survey, John Wiley & Sons, American Geophysical Union, pp. 284–311.

Hagelüken, C. (2012) 'Recycling the platinum group metals: A European perspective', Platinum Metals Review, 56(1), pp. 29–35. doi: 10.1595/147106712X611733.

Hagelüken, C. (2014) 'Recycling of (critical) metals', in Gunn, G. (ed.) Critical Metals Handbook. British Geological Survey, John Wiley & Sons, American Geophysical Union, pp. 41–69.

Hagelüken, C. (2019) 'Die Märkte der Katalysatormetalle Platin, Palladium und Rhodium – Teil 1', Metall - Fachzeitschrift für Metallurgie, 10/19(October). Available at: https://www.gdmb.de/en/gdmb-verlag-gmbh/for-readers/metall/contents/2019/

Heraeus (2019) Heraeus Precious metals. The Platinum Standard 2019. Available at: https://www.heraeus.com/en/hpm/hpm_home/heraeus_precious_metals.html

IPA (2012) 25 Prominent and Promising Applications using Platinum Group Metals. Available at: https://ipa-news.com/index/pgm-applications/

IPA (2015a) 'PGM Fact Sheets. Autocatalysts and Platinum Group Metals'. International Platinum Group Metals Association. Available at: https://ipa-news.com/index/platinum-group-metals/pgm-fact-sheets.html?PHPSESSID=fbf597ae219fd0e3294f9614a883e22f

IPA (2015b) 'PGM Fact Sheets. Socio-Economic Development in the PGM Industry'. International Platinum Group Metals Association, pp. 1–10. Available at: https://ipa-news.com/index/platinum-group-metals/pgm-fact-sheets.html?PHPSESSID=fbf597ae219fd0e3294f9614a883e22f

IPA (2015c) 'PGM Fact Sheets. The Life Cycle Assessment of Platinum Group Metals'. International Platinum Group Metals Association, pp. 1–7. Available at: https://ipa-news.com/index/platinum-group-metals/pgm-fact-sheets.html?PHPSESSID=fbf597ae219fd0e3294f9614a883e22f

IPA (2015d) 'PGM Fact Sheets. The Primary Production of Platinum Group Metals'. International Platinum Group Metals Association. Available at: https://ipa-news.com/index/platinum-group-metals/pgm-fact-sheets.html?PHPSESSID=fbf597ae219fd0e3294f9614a883e22f

IPA (2015e) 'PGM Fact Sheets. The Primary Production of Platinum Group Metals'. International Platinum Group Metals Association - PGM Fact Sheets. Available at: https://ipa-news.com/index/platinum-group-metals/pgm-fact-sheets.html (Accessed: 4 October 2019).

IPA (2015f) 'PGM Fact Sheets. The Secondary Production and Recycling of Platinum Group Metals'. International Platinum Group Metals Association, pp. 1–6. Available at: https://ipa-news.com/index/platinum-group-metals/pgm-fact-sheets.html?PHPSESSID=fbf597ae219fd0e3294f9614a883e22f

IPA industrial expert (2019) Comments and feedback received after the CRM validation workshop on Forward look: Demand, Supply, and Other Considerations.

Johnson Matthey (2014) Market data tables 2004-2013. Available at: http://www.platinum.matthey.com/services/market-research/market-data-tables (Accessed: 8 October 2019).

Johnson Matthey (2015) PGM Market Report. November 2015. November 2015, pp. 1–32. Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Johnson Matthey (2016) PGM Market Report. November 2016. Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Johnson Matthey (2017) PGM Market report. May 2017, Johnson Matthey Technology Review. doi: 10.1595/205651316X692121.

Johnson Matthey (2018) PGM Market Report. May 2018. Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Johnson Matthey (2019a) PGM market report. May 2019. Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Johnson Matthey (2019b) Production - South Africa, Johnson Matthey website. Available at: http://www.platinum.matthey.com/about-pgm/production/south-africa (Accessed: 4 October 2019).

Johnson Matthey (2019c) Applications, Johnson Matthey website. Available at: http://www.platinum.matthey.com/about-pgm/applications (Accessed: 12 October 2019).

Johnson Matthey (2019d) Price charts. Available at: http://www.platinum.matthey.com/prices/price-charts# (Accessed: 22 September 2019).

Jones, R. (2005) 'An overview of Southern African PGM smelting', Nickel and Cobalt 2005: Challenges in Extraction and Production, 44th Annual Conference of Metallurgists, Calgary, Alberta, Canada, (21-24 August), pp. 147–178. Available at: http://www.mintek.co.za/Pyromet/Files/2005JonesPGMsmelting.pdf

KGHM (2019) Precious metals., KGHM Corporate Website. Available at: https://kghm.com/en/our-business/products/precious-metals-0 (Accessed: 4 October 2019).

Lauri, L. et al. (2018) Identification and quantification of primary CRM resources in Europe. SCRREEN project D3.1. Available at: http://scrreen.eu/results/

LBMA (2019) London Bullion Market Association (LBMA). Bullion Market. Available at: http://www.lbma.org.uk/the-london-bullion-market (Accessed: 22 September 2019).

LPPM (2019) London Platinum & Palladium Market (LPPM). LBMA Platinum and Palladium price data. Available at: https://www.lppm.com/data/ (Accessed: 22 September 2019).

Marscheider-Weidemann, F. et al. (2016) Rohstoffe fur Zukunftstechnologien 2016 - DERA Rohstoffinformationen 28. Edited by D. R. (DERA) in Der and B. für G. und R. (BGR). Berlin.

Mathieux, F. et al. (2017) Critical raw materials and the circular economy - Background report. EUR 28832 EN, Publications Office of the European Union, Luxembourg. doi: 10.2760/378123.

Merschel, G. and Krämer, D. (2018) DERA Rohstoffinformationen. Hydrometallurgical extraction of platinum and palladium from oxidized PGE ores of the Bushveld Complex, South Africa – short report.

Minerals Council of South Africa (2019a) 'Facts and Figures. 2018 Edition'. Available at: https://39k5cm1a9u1968hg74aj3x51-wpengine.netdna-ssl.com/wp-content/uploads/2019/07/2018_NHPCO_Facts_Figures.pdf

Minerals Council of South Africa (2019b) 'Factsheet. Safery in mining', pp. 1–6.

Minerals Council of South Africa (2019c) 'Safety in the mining industry. Performance at a glance', pp. 1–2.

Minerals4EU (2019) European Minerals Yearbook. Available at: http://minerals4eu.brgm-rec.fr/m4eu-yearbook/theme_selection.html

Moss, R. L. et al. (2011) Critical Metals in Strategic Energy Technologies, JRC-scientific and strategic reports, European Commission Joint Research Centre Institute for Energy and Transport. doi: 10.2790/35600.

Moss, R. et al. (2013) Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector, JRC82322. doi: 10.2790/46338.

Mudd, G. M., Jowitt, S. M. and Werner, T. T. (2018) 'Global platinum group element resources, reserves and mining – A critical assessment', Science of The Total Environment. Elsevier, 622–623, pp. 614–625. doi: 10.1016/J.SCITOTENV.2017.11.350.

Nassar, N. (2015) 'Limitations to elemental substitution as exemplified by the platinum-group metals', Green Chemistry, (17), pp. 2226–2235. doi: 10.1039/x0xx00000x.

Ndlovu, J. (2015) 'Anglo American Platinum: Precious Metals Supply. Presentation given at EC International Conference, Exchange of good practices on metal by-products recovery. Technology and policy challenges. Brussels, 12-13 November 2015.', pp. 1–21. Available at: http://ec.europa.eu/DocsRoom/documents/14045/attachments/1/translations/en/renditions/native

Nornickel (2018) Annual Report 2017. Available at: https://ar2017.nornickel.com/#about (Accessed: 22 September 2019).

NRGI (2017) '2017 Resource Governance Index', p. 28. Available at: http://www.resourcegovernance.org/countries/africa/tanzania/overview

OECD (2019) Export Restrictions on Industrial Raw Materials. Available at: https://qdd.oecd.org/subject.aspx?Subject=ExportRestrictions_IndustrialRawMaterials (Accessed: 5 July 2019).

Partial-PGMs (2019) Development of novel, high-performance hybrid TWV/GPF automotive after-treatment systems by rational design: substitution of PGM and Rare Earth materials, Partial-PGMs H2020 project website. Available at: http://www.partial-pgms.eu/ (Accessed: 6 October 2019).

Pettersson, M. et al. (2015) 'License to Mine: A Comparison of the Scope of the Environmental Assessment in Sweden, Finland and Russia', Natural Resources, 06(04), pp. 237–255. doi: 10.4236/nr.2015.64022.

PWC (2019) South Africa Mine in 2019. In transition.

Rudnick, R. L. and Gao, S. (2014) Composition of the Continental Crust, Treatise on Geochemistry: Second Edition. Elsevier Ltd. doi: 10.1016/B978-0-08-095975-7.00301-6.

S&P Global (2018a) S&P Global Market Intelligence database. Metals & Mining Properties. Palladium, S&P Global Market Intelligence.

S&P Global (2018b) S&P Global Market Intelligence database. Metals & Mining Properties. Platinum, S&P Global Market Intelligence.

Schmidt, M. (2015) Rohstoffrisikobewertung – Platingruppenmetalle. Platin, Palladium, Rhodium. DERA Rohstoffinformationen 26, DERA Rohstoffinformationen. Berlin. Available at: https://www.deutsche-rohstoffagentur.de/DERA/DE/Downloads/studie_Platin_2015.pdf?__blob=publicationFile&v=2

Skowroń, J. (2017). Occupational exposure limit values. *OSHWiki, Available at:* http://oshwiki.eu/index.php?title=Occupational_exposure_limit_values&oldid=247440, accessed: 29.01. 2020

Sundqvist Ökvist, L. et al. (2018) Production technologies of critical raw materials from secondary resources. SCRREEN project D.4.2. Available at: http://scrreen.eu/results/

Suopajärvi, L. et al. (2016) 'Social sustainability in northern mining communities: A study of the European North and Northwest Russia', Resources Policy. Elsevier Ltd, 47, pp. 61–68. doi: 10.1016/j.resourpol.2015.11.004.

Sverdrup, H. U. and Ragnarsdottir, K. V. (2016) 'A system dynamics model for platinum group metal supply, market price, depletion of extractable amounts, ore grade, recycling and stocks-in-use', Resources, Conservation and Recycling. Elsevier B.V., 114, pp. 130–152. doi: 10.1016/j.resconrec.2016.07.011.

Tercero, L. (2019) Report on the future use of critical raw materials. SCRREEN project D.2.3. Available at: http://scrreen.eu/results/

Tercero, L. et al. (2015) Critical Raw Materials Substitution Profiles, CRM _Innonet. Available at: http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-4455718.pdf

Tercero, L. et al. (2018) Critical Raw Material substitution profiles. SCRREEN project D5.1., SCRREEN - D5.1. Available at: http://scrreen.eu/wp-content/uploads/2018/05/SCRREEN-D5.1-CRM-profiles.pdf

The Fund for Peace (2019) Fragile States Index. Available at: https://fragilestatesindex.org/ (Accessed: 21 October 2019).

Tiainen, H., Sairinen, R. and Sidorenko, O. (2015) 'Governance of Sustainable Mining in Arctic Countries: Finland, Sweden, Greenland & Russia', in Arctic Yearbook, pp. 132–157.

Transparency International (2017) Corruption Perceptions Index 2017. Available at: https://www.transparency.org/news/feature/corruption_perceptions_index_2017 (Accessed: 21 October 2019).

Umicore (2019a) Precious metals refining. Metals & Products. Precious Metals, Umicore webpage. Available at: https://pmr.umicore.com/en/metals-products/precious-metals/ (Accessed: 23 September 2019).

Umicore (2019b) Recyclables, Umicore website. Available at: https://pmr.umicore.com/en/recyclables/ (Accessed: 11 October 2019).

Umicore (2019c) From Ag to Zn, Umicore website - All the metals used or recycled at Umicore. Available at: https://www.umicore.com/en/about/elements/ (Accessed: 4 October 2019).

UN Comtrade (2019) International Trade Statistics Database. Available at: https://comtrade.un.org/ (Accessed: 8 July 2019).

UNEP (2011) Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel., Group. doi: ISBN 978-92-807-3161-3.

USGS (2019) Mineral Commodity Summaries 2019. U.S Geological Survey. doi: 10.1007/978-3-540-47108-0-4.

Viljoen, M. (2016) 'The Bushveld Complex: Host to the World's Largest Platinum, Chromium and Vanadium Resources. Episodes', Episodes, 39(2), pp. 239–268.

WMD (2019) World Mining Data 2019, Reichl, C.; Schatz, M; Zsak, G. Iron and Ferro Alloy Metals, non Ferrous Metals, Precious Metals, Industrial Minerals, Mineral Fuels. Austrian Federal Ministry of Sustainability and Tourism. [online] Available at: www.en.bmwfw.gv.at/Energy/WorldMiningData/Seiten/default.aspx

World Bank (2018) Aggregate Governance Indicators 1996-2017, Worldwide Governance Indicators. Available at: http://info.worldbank.org/governance/WGI/#home (Accessed: 7 July 2019).

WPIC (2019) 'Platinum recycling'. World Platinum Investment Council. Available at: https://www.platinuminvestment.com/about/60-seconds-in-platinum/2019/10/02

Yang, J. et al. (2018) Production technologies of critical raw materials from primary resources. SCRREEN project D.4.1. Available at: http://scrreen.eu/results/

Zientek, M. et al. (2017) 'Platinum-Group Elements. U.S. Geological Survey Professional Paper 1802-K', in Schulz, K. J. et al. (eds) Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply. US Geological Survey, pp. N1–N92. Available at: https://doi.org/10.3133/pp1802

19.10.3 Data sources used in the criticality assessment of the individual PGMs

BGS (2019) World mineral statistics data, British Geological Survey. Available at: https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

European Commission (2017) *Study on the review of the list of critical raw materials. Critical Raw Material Factsheets*. European Commission. doi: 10.2873/398823.

Eurostat Comext (2019) *Easy Comext database*. Available at: http://epp.eurostat.ec.europa.eu/newxtweb/.

Johnson Matthey (2018) *PGM Market Report. May 2018*. Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

Johnson Matthey (2019) *PGM Market report. May 2019*. Available at: http://www.platinum.matthey.com/services/market-research/pgm-market-reports

UNEP (2011) *Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel.*, *Group*. doi: ISBN 978-92-807-3161-3.

WMD (2019) World Mining Data 2019, Reichl, C.; Schatz, M; Zsak, G. Iron and Ferro Alloy Metals, non Ferrous Metals, Precious Metals, Industrial Minerals, Mineral Fuels. Austrian Federal Ministry of Sustainability and Tourism. [online] Available at: www.en.bmwfw.gv.at/Energy/WorldMiningData/Seiten/default.aspx

19.11 Acknowledgments

This factsheet was prepared by the JRC. The authors would like to thank the Ad Hoc Working Group on Critical Raw Materials, as well as experts participating in SCRREEN workshops for their contribution and feedback, in particular Mr Julian Köhle (IPA), Mr Christian Hagelüken (Umicore), Mr Rupen Raithatha and Ms Alison Cowley (Johnson Mattey), Mr Antoine Monnet (LGI Consulting), and Ms Barbara Forriere (Renault - Nissan – Mitsubishi).