Horizon 2020 Programme

SCRREEN2

This project has received funding from the European

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Start date: 2020-11-01 Duration: 36 Months

SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

PLATINUM GROUP METALS

AUTHOR(S):

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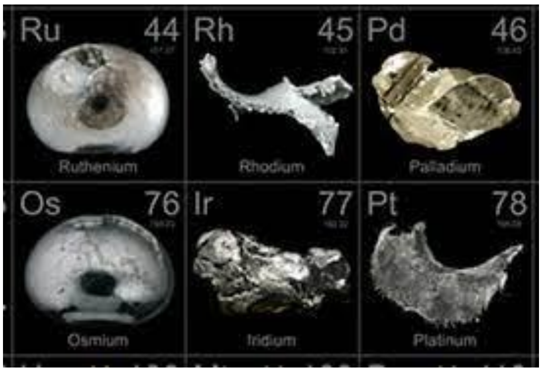
PLATINUM GROUP METALS (PGM)

OVERVIEW



Platinum Group Metals (PGMs), or platinum-group elements (PGE), comprise six elements: platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os). The PGMs 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.

Table 1. PGM supply and demand in metric tonnes, 2016-2020 average

	Global production (Mine production)	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
Iridium/ Ruthenium/ Osmium	**35,1 tonnes**	South Africa 93,5% Zimbabwe 4,9%	17,25 tonnes	49%	South Africa 31,4% UK 31,1% USA 13% Japan 10% Switzerland 6%	
Palladium	**213 tonnes**	Russia40% South Africa 36% Canada 9,9%	20 tonnes	9%	USA 29,7% Russia 28,9% UK 21,8% South Africa 10,6% Switzerland 5,9%	
Platinum	**185 tonnes**	South Africa 70,8% Russia 12% Zimbabwe 8%	72 tonnes	39%	UK 51,5% South Africa 17,8% Switzerland 8,4% Russia 7%	
Rhodium	**23 tonnes**	South Africa 81% Russia 10% Zimbabwe 6%	Negative value...		South Africa 36,6% UK 27,4% Russia 13,4% USA 11% Mexico 10%	

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

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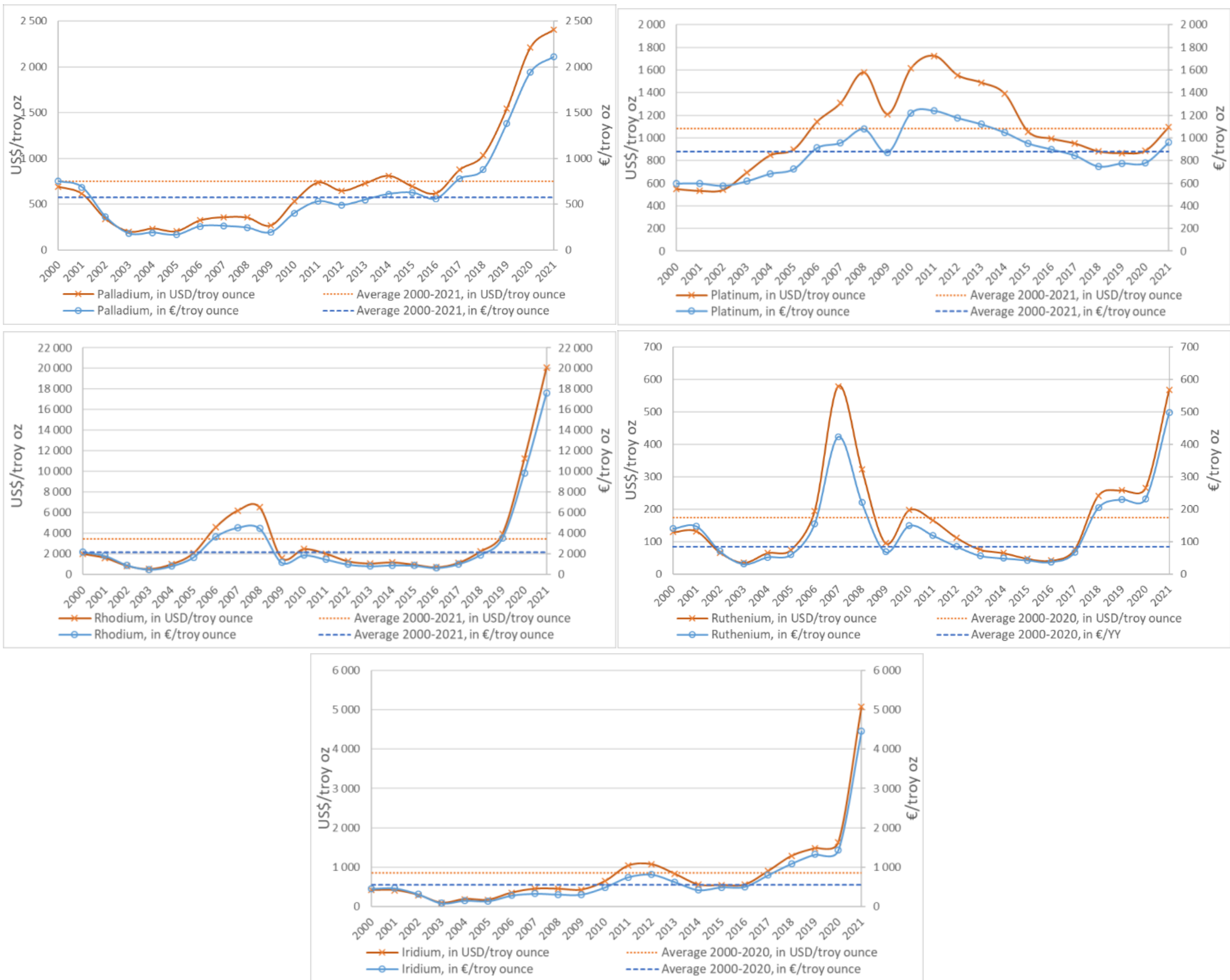

Figure 1. Annual average price of PGM between 2000 and 2020 (USGS, 2021)[1].

Primary supply: 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.

Secondary supply: The PGMs are highly recyclable in technical terms due to their noble characteristics and durability in use, and 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

[1] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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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 very small amounts (UNEP, 2011).

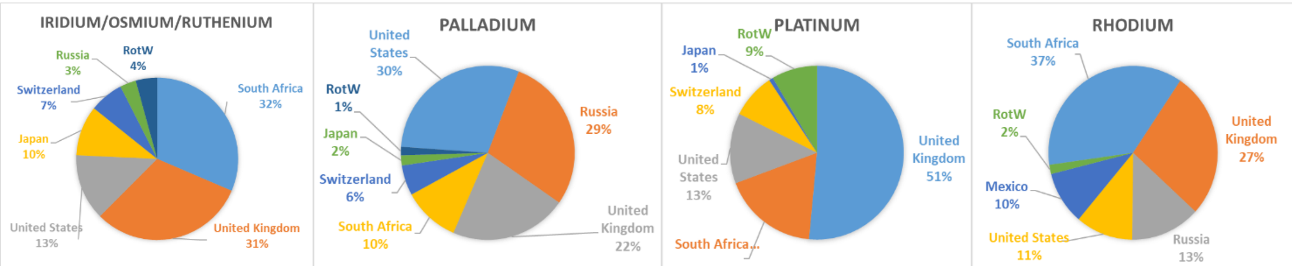

Figure 2. EU sourcing of PGM, average 2016-2020 (Eurostat 2022)

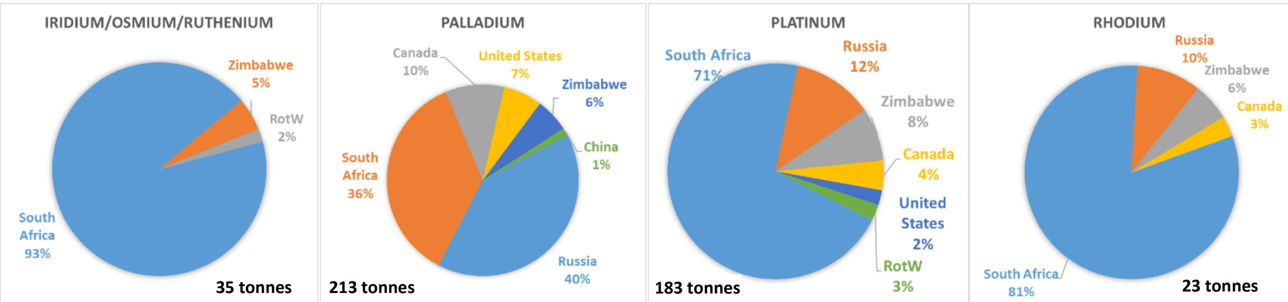

Figure 3. Global mine production of PGM, average 2016-2020, (WMD 2022)

Uses: Because of their unique properties, PGMs are fundamental components in a broad range of modern technologies. All 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.

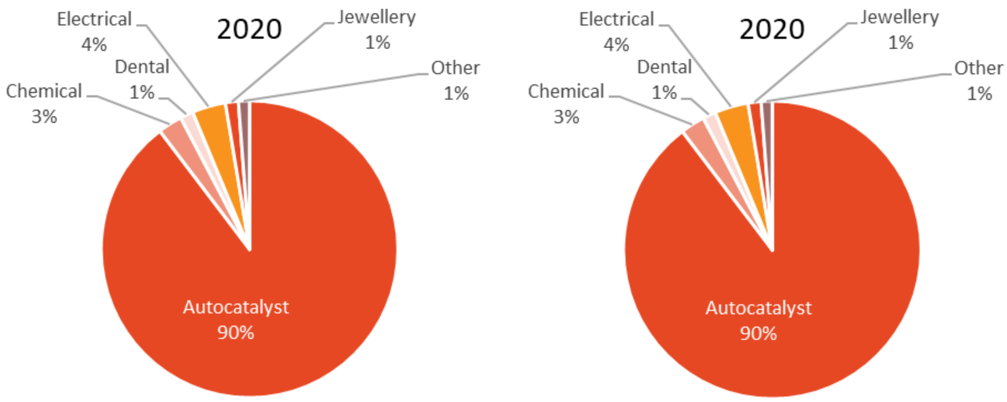

Figure 4: EU uses of palladium (left) and platinum (right) in 2020 (Johnson Matthey 2022)

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Substitution: Available substitutes are often 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.

Table 2. Overview of substitutes of PGMs in general. Substitution of one PGM for another is not covered in this table but is described within the following section. Percentage of application bases on data by Johnson Matthey (2022) for the year 2020.

Use	% use	Substitute	Comment on substitute
Autocatalysts	60 %	Material: Transition metals Technology: EVs	Only for partial substitution; overall poor substitutability of PGM in autocatalysts. EVs do not need autocatalysts.
Jewellery	9 %	Silver, titan, tungsten, nickel	Depending on cultural attitudes and historical factors. Coatings and alloying elements are partially substitutable.
Chemical	9 %	Material: Nickel, cobalt, molybdenum, magnetite Technology: Alkaline or solid oxide electrolysers	Highly depending on application.
Electronics	7 %	Nickel, copper, gold, molybdenum, tungsten	Highly depending on application.
Investment	4 %	Gold, silver	Depending on prices.
Medical/dental	2 %	Nickel-based metal alloys	
Petroleum	2 %		
Glass	2 %		
Electrochemical	1 %	Tin	Highly depending on application.
Other	4 %	Other precious metals	

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. PGM supply and demand in metric tonnes, 2016-2020 average

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Data and data quality varies quite strongly among the different PGMs. The markets for platinum (Pt), palladium (Pd) and rhodium (Rh) are globally the most important and largest in both quantity and value. Iridium, ruthenium and osmium markets are much smaller with very special applications and market data is quite scarce.

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. In 2021 South Africa was the leading producer of PGMs with a market share of 73% for Pt and 39% for Pd (Johnson Matthey, 2021). Russia produced about 10% of global primary Pt and 38% of Pd. Both countries together supplied 83% of global primary Pt and 77% of Pd. In total, global PGM production from primary sources for the year 2021 was approx. 463.2t, with 86% allocated to Pt and Pd.

Secondary supply has been and is of utmost importance to the PGM market. In 2021, about 24% of total Pt supply was from secondary source, and 35% for Pd. Secondary Rh accounted for about 34% of the total supply. The value of PGM supply (incl. secondary) at average annual prices of 2021 was € 45 billion, of which € 7.7 billion for Pt, € 21.8 billion for Pd, € 13.8 billion for Rh, and € € 0.4 billion for ruthenium and € 1.2 billion for iridium (Johnson Matthey, 2022).

The global mine production of PGMs is dominated by few companies. The top four PGM producers are Anglo American Platinum, Norilsk Nickel, Impala Platinum, and Sibanye Stillwater. They accounted for approximately

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90% of primary Pt production and 79% of primary Pd production in 2020 (S&P Global, 2022). The largest Pt producer is Sibanye Stillwater with a market share of approx. 40%. The largest Pd producer is Norilsk Nickel with a market share of 42%. These producers maintain considerable processing assets that supply the market with refined PGMs and by-products of the PGM production. 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. The company is currently expanding into the lithium business. Sibanye-Stillwater currently controls 25% of the world's Pt/Pd primary production and has become the world's largest PGM producer (S&P Global 2022).

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's operations (now Sibanye-Stillwater) are integrated through to refined metal, while the remainder is refined and sold by other companies.

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. Non-integrated miners (Ndlovu, 2015) carried out about 25% of the processing of the extracted ores.

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. 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.

Table 4. Relevant Eurostat CN trade codes for PGMs

Processing/refining	
CN trade code	**Title**
711041	Iridium, osmium and ruthenium, unwrought or in powder form
711049	Iridium, osmium and ruthenium, in semi-manufactured forms
711021	Palladium, unwrought or in powder form
711029	Palladium in semi-manufactured forms
711011	Platinum, unwrought or in powder form
711019	Platinum, in semi-manufactured forms
711292	Waste and scrap of platinum, incl. metal clad with platinum, and other waste and scrap containing platinum or platinum compounds, of a kind used principally for the recovery of precious metal (excl. ash containing platinum or platinum compounds, waste and scrap of platinum melted down into unworked blocks, ingots, or similar forms, and sweepings and ash containing precious metals)
711510	Catalysts in the form of wire cloth or grill, of platinum
711031	Rhodium, unwrought or in powder form
711039	Rhodium in semi-manufactured forms

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Almost all PGMs derived from primary source materials (i.e. mine production) are traded in the form of refined metal produced from integrated mining/metallurgical operations. As refinement mainly takes place in the countries of mining these are also the main exporting countries. South Africa is the largest net-exporting country for Pt (DERA, 2021). Russia is the main net-exporting country for Pd. There is only minimal international trade in PGM ores and concentrates. There is currently no primary PGM production in Europe. However, there is a well-established recycling industry. Especially in the chemical and automotive sector. EOL-Recycling rates vary among applications.

Price development of PGMs has been very volatile in the past years. Average global prices are as follows: Pt = 1,096 $US, Pd = 2.414 $US, Rh = 20.089 $US, Ru = 567 $US, Ir = 5.710 $US (Johnson Matthey 2022). This implies a Pd/Pt premium of 2.2.

EU TRADE

The relevant PGM commodities that are considered in this factsheet are listed in Table 4. The trade flow figures in this factsheet were derived from Eurostat database. The reported figures must be treated with caution since it might not represent the full picture of the reality of the trade flows.

IRIDIUM, OSMIUM, AND RUTHENIUM

The trade codes considered for this assessment are CN 711041 Iridium, osmium and ruthenium, unwrought or in powder form and CN 711049 Iridium, osmium and ruthenium, in semi-manufactured forms. The trade figures of ruthenium and iridium are estimated from the same two datasets. The trade flows for both materials therefore follow the same trend. The relative market size of iridium and ruthenium is proportional to their average yearly world demand in 2017-2022 accounting for 82% of ruthenium and 18% of iridium based on calculated figures reported in Johnson Matthey, 2022. There is no traditional trade through investors for raw osmium, also referred to as osmium sponge. Raw osmium is toxic and therefore not sold to private individuals or investors (Osmium World Council, 2022). The global annual production of osmium since 2019 is about 1000 kg (Osmium World Council, 2022). A significant amount of osmium is used for crystallization and the remaining amount in compounds form is used internationally in industry and academic research (Osmium world council, 2022). The trade flows for osmium were therefore estimated to be negligibly small and, therefore, set to zero.

EU TRADE OF IRIDIUM AND RUTHENIUM

Figure 5 shows that from 2000 to 2004 the EU was a net importer of iridium in unwrought and powder form. This tendency changed from 2005 to 2021 where the EU export exceeded its import. The average yearly EU import of iridium for the year 2017-2020 was 1 tonne/year while the export was 1.86 tonnes/year. The average yearly EU import for ruthenium was 4.69 tonnes/year and the export was 9.06 tonnes/year in the same period. During the first four months of 2021, all the PGM except platinum traded significantly above historical levels, as constrained supplies and an improvement in demand created acute liquidity squeezes and unusual price volatility (Johnson Matthey, 2022).

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Ruthenium price reached a fourteen-year high while iridium price reached the all-time highest price (Johnson Matthey, 2022). In the EU, in 2021 the export for iridium and ruthenium jumped six times than the average while the import remained relatively stable. However, it is not possible to determine how much of this metal was derived from primary or secondary sources.

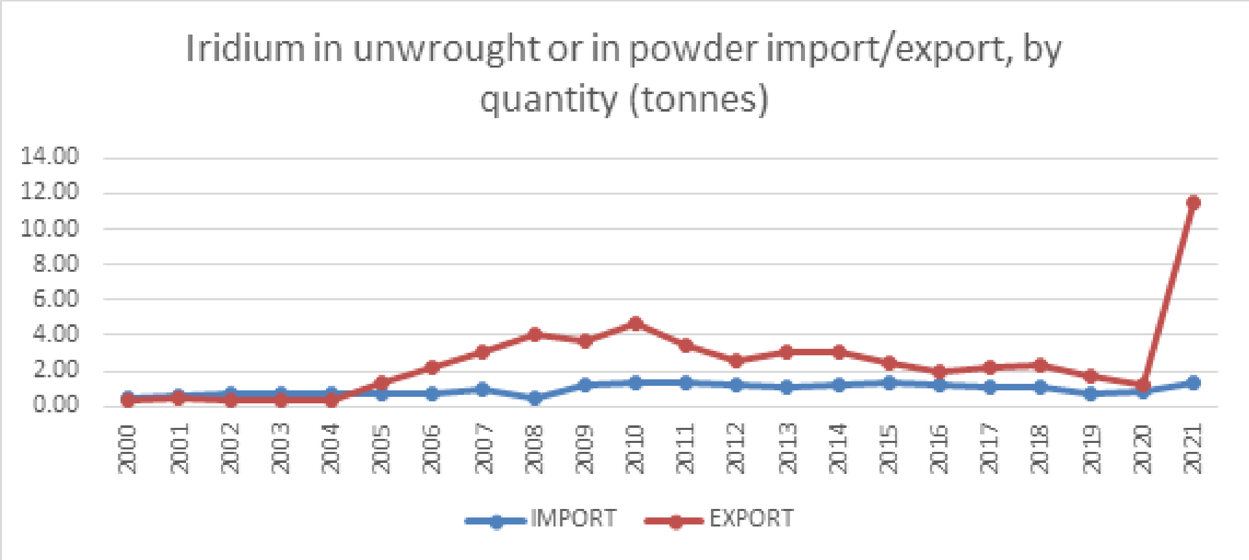

Figure 5. Estimated EU trade flows for iridium in unwrought or powder forms (Eurostat, 2022)

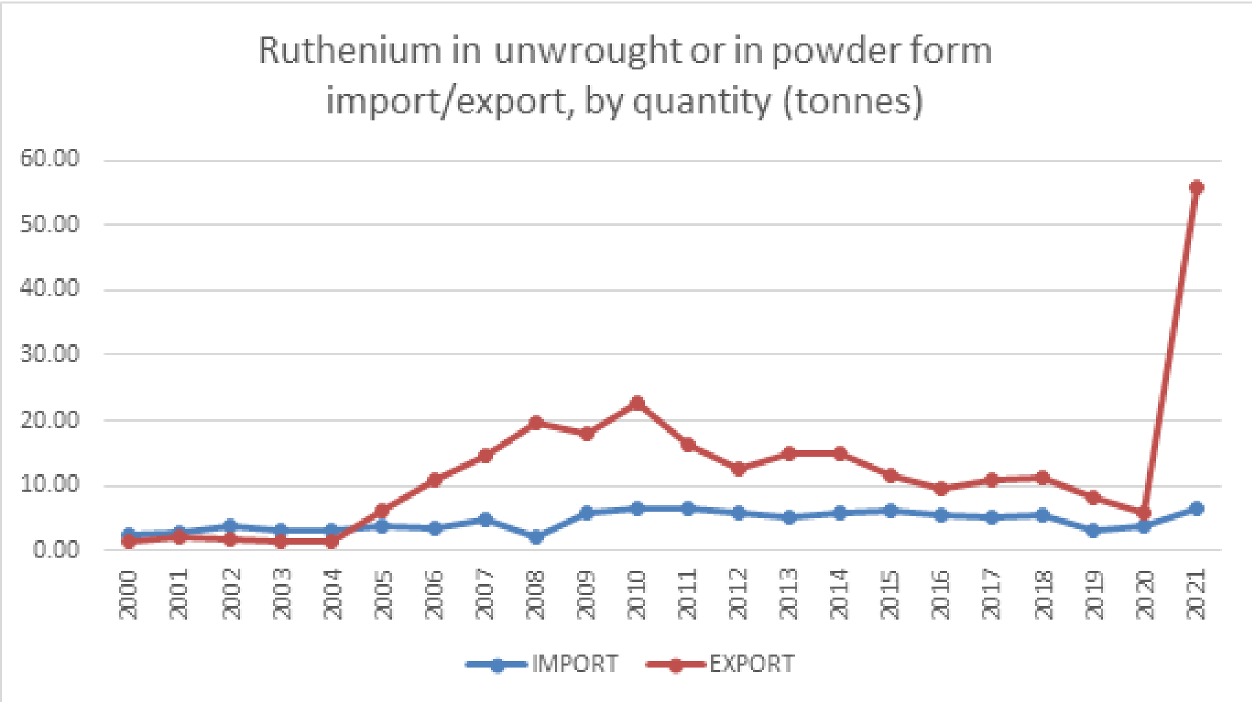

Figure 6. Estimated EU trade flows for ruthenium in unwrought or powder forms (Eurostat, 2022)

Figure 7 presents the average EU imports of iridium and ruthenium in unwrought or in powder form by suppliers for the period 2000-2021.

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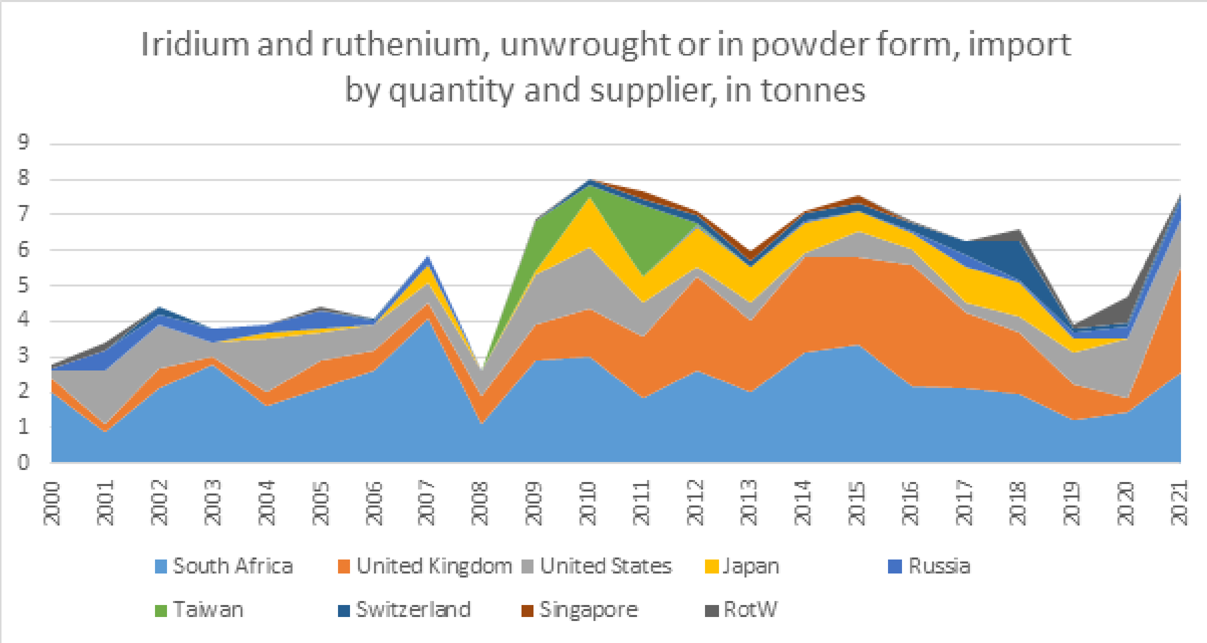

Figure 7. EU imports of iridium and ruthenium in unwrought or powder forms by supplying country between 2000-2021 (Eurostat, 2022)

As shown in Figure 8, the EU has been both net importer and net exporter of iridium and ruthenium in semi-manufactured forms during the year 2000-2021. The biggest change happened in 2005-2006 when the EU turned from a net importer into a net exporter. The annual average EU imports of semi-manufactured forms were approximately 0.18 tonnes for iridium and 0.9 tonnes for ruthenium in 2017-2020 while the export was slightly higher, at 0.23 tonnes and 1.16 tonnes, subsequently. The major suppliers of the EU over the year 2000-2021 were the United States and United Kingdom, corresponding to 72% and 15% of EU's imports in the period (Figure 10).

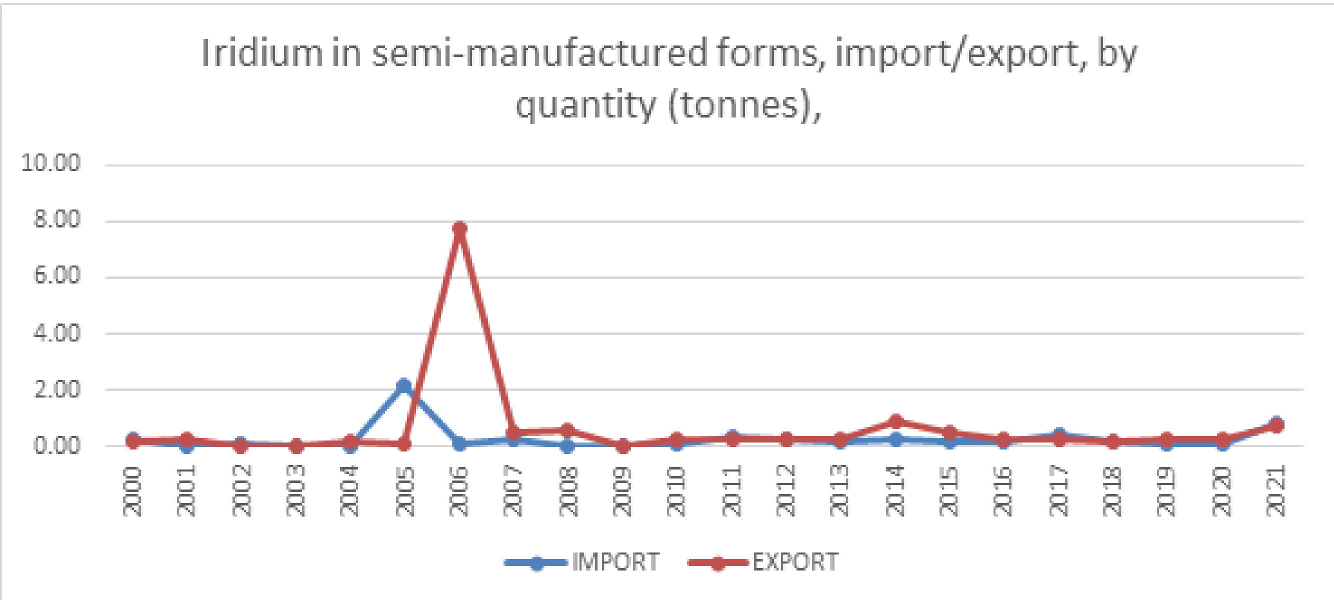

Figure 8. Estimated EU trade flows for iridium in semi-manufactured forms (Eurostat, 2022)

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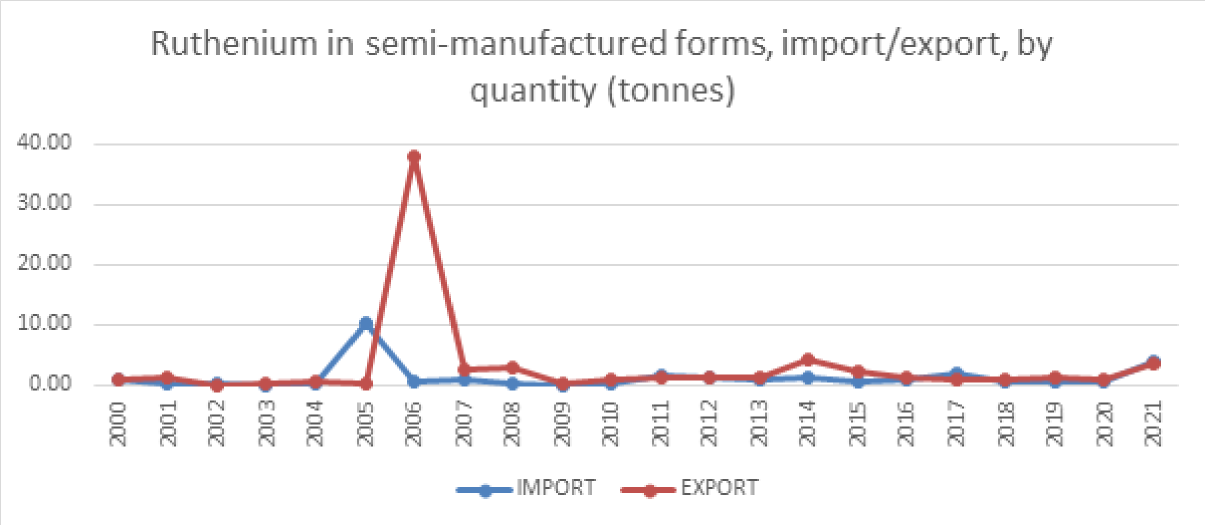

Figure 9. Estimated EU trade flows for ruthenium in semi-manufactured forms (Eurostat, 2022)

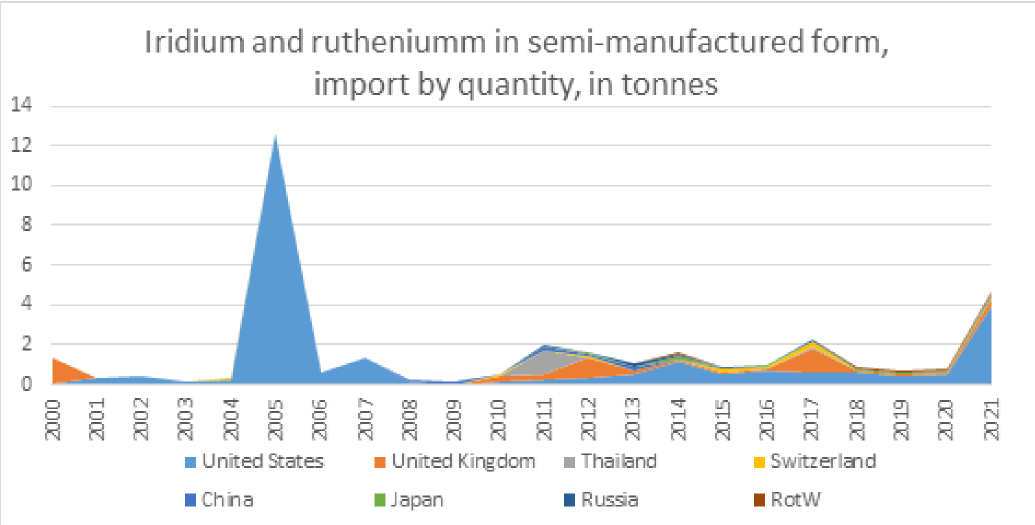

Figure 10. EU imports of iridium and ruthenium in semi-manufactured forms by supplying country between 2000-2021 (Eurostat, 2022)

PALLADIUM

The trade figures for palladium are available for palladium metal in unwrought or in powder form (HS code 711021) and in semi-manufactured forms (HS code 711029). Figure 11 shows that for most of the years in 2000-2021 period, the EU has been a net importer of palladium in unwrought or powder forms. The yearly average EU import was 56.8 tonnes/year. Exception occurred in 2009, 2011, 2013, 2014, and 2020 when the EU became a net exporter. There was an increasing trend of EU import quantity of Palladium from the year 2013 to 2018. The main suppliers of unwrought palladium to the EU were Russia (28% of share), United Kingdom (21%), United States (20%), South Africa (15%) and Switzerland (10%) over the period 2000-2021 (Figure 8).

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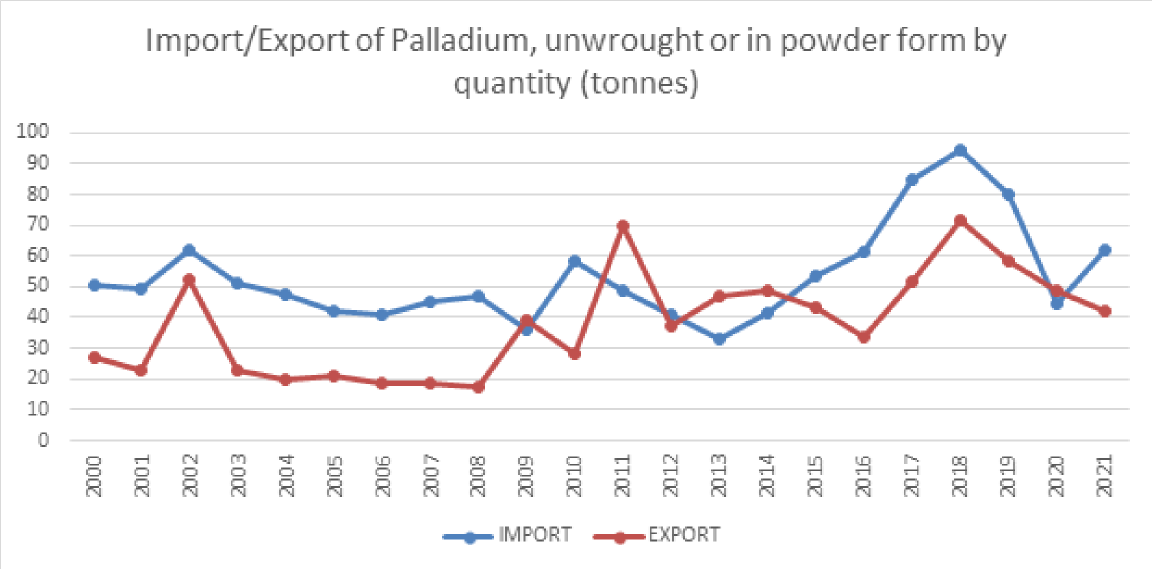

Figure 11. Estimated EU trade flows for palladium in unwrought or powder forms (Eurostat, 2022)

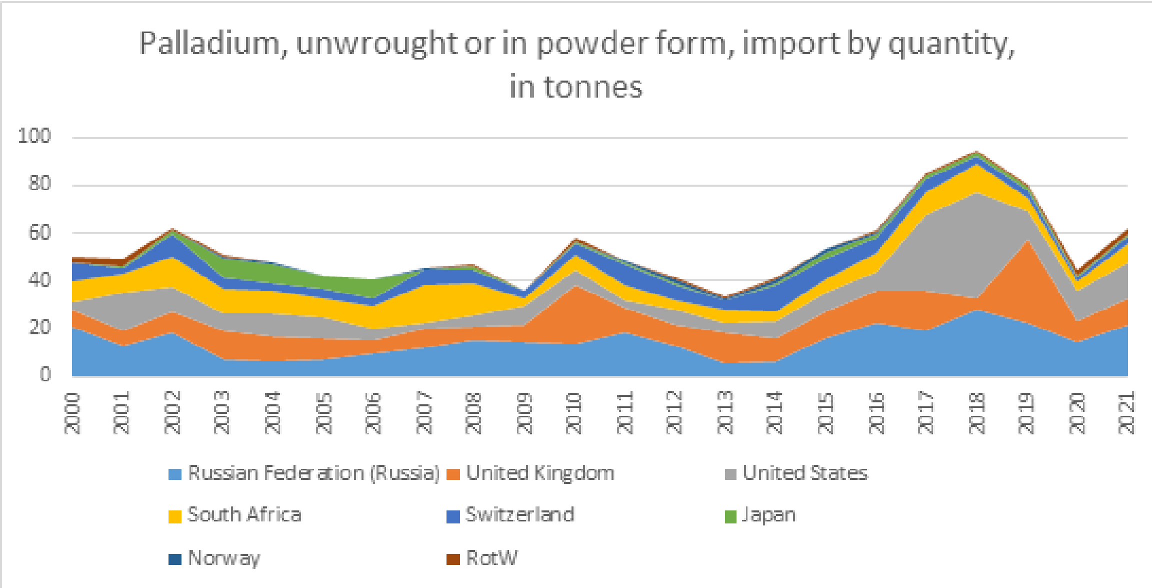

Figure 12. Estimated EU trade flows for palladium in unwrought or powder forms by quantity and supplier (Eurostat, 2022)

The observed trend was different for palladium in semi-manufactured forms. From 2000-2005, the EU was a net exporter of palladium with average yearly export quantity of 9.19 tonnes/year. From 2006, the EU import quantity began to exceed its export, reaching its peaks with 28.72 tonnes in 2011 and 39.58 tonnes in 2014. After 2014, the EU import dropped to the average level of 6.89 tonnes/year, close to its export. United States, Switzerland, United Kingdom, and Russia were the main suppliers of semi-manufactured forms of Palladium over the year 2000-2021, each with 28%, 26%, 26%, and 14% of share. The import/export of palladium in semi-manufactured form by quantity and by suppliers in 2000-2021 is shown in Figure 13.

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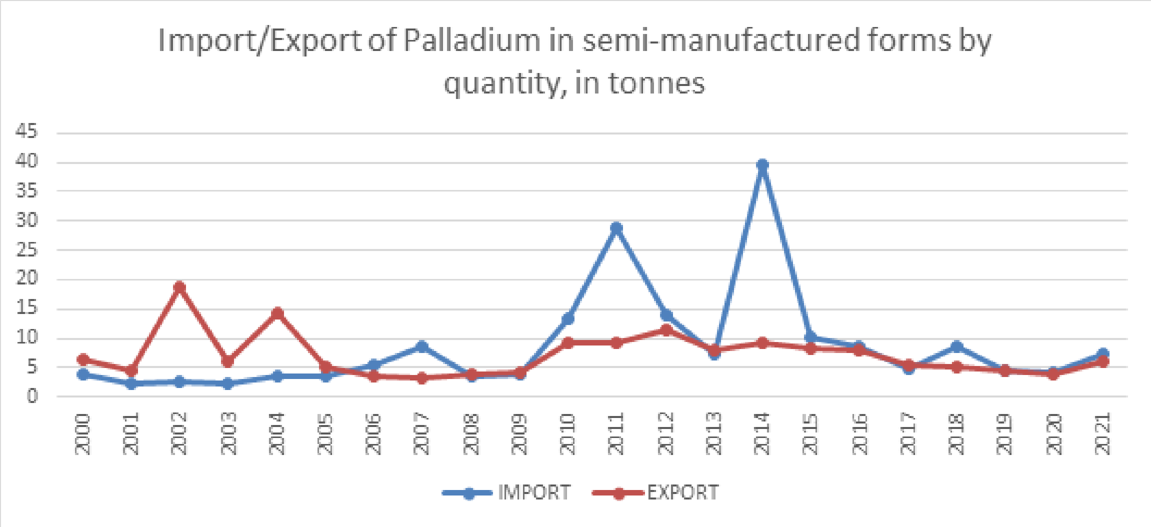

Figure 13. Estimated EU trade flows for palladium in semi-manufactured forms (Eurostat, 2022)

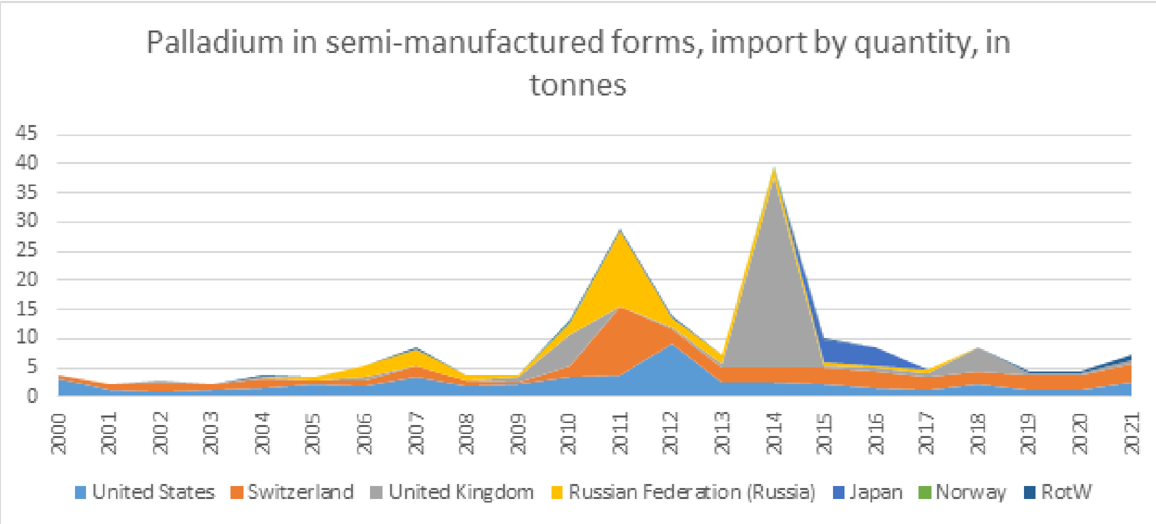

Figure 14. Estimated EU trade flows for palladium in semi-manufactured forms by quantity and supplier (Eurostat, 2022)

PLATINUM

The EU import of unwrought or powder form of platinum (HS 711011) has been fluctuating since 2000. The import from 2000 to 2009 was relatively stable at 39.3 tonnes/year while the export was 34.4 tonnes/year. During this time, the EU was most of the time a net importer, except in 2003. In 2010 the import quantity skyrocketed at 132 tonnes, almost three times the average 2000-2009 while the export stayed at 21.8 tonnes. The following year, in 2011, the EU became a net exporter with export quantity 90 tonnes. From 2012 until 2014, the EU import dropped at the level of 2000-2009 period. The EU import gradually raised from 2015 to 2019 and dropped again in 2020, when the global pandemic started. Figure 15 shows that in 2021 the EU import continued to be lower in quantity at 35.6 tonnes/year. Meanwhile, still in 2021, the EU turned into a next exporter once again

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with export quantity amounting to 101.8 tonnes, almost three times its import level. Figure 16 shows that supply from Turkey was significantly high in 2010. The figure also shows an increasing import from the United Kingdom. The main suppliers for the EU were South Africa (38% share), United Kingdom (27%), United States (15%), Russia (6%), Turkey (6%), and Switzerland (5%).

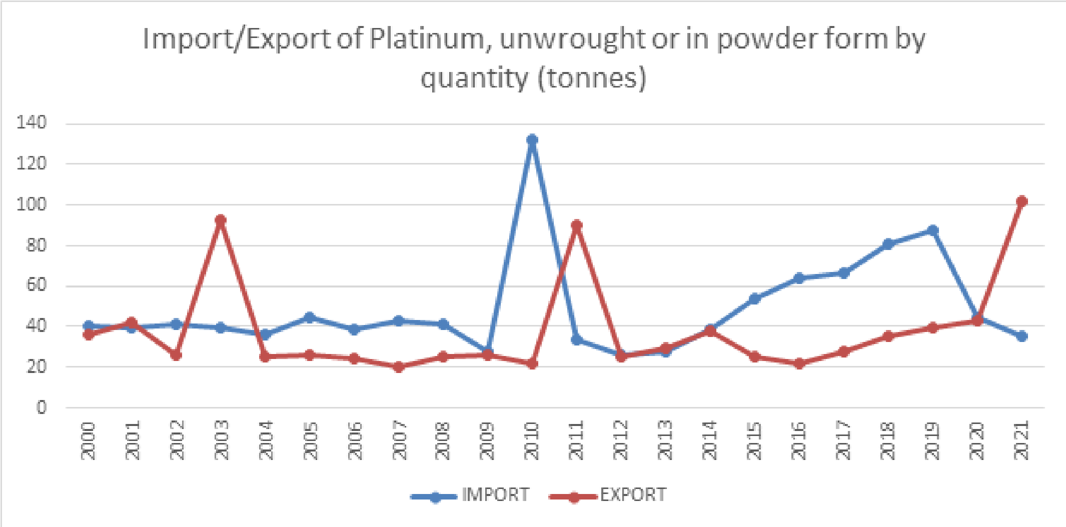

Figure 15. Estimated EU trade flows for platinum in unwrought or powder forms (Eurostat, 2022)

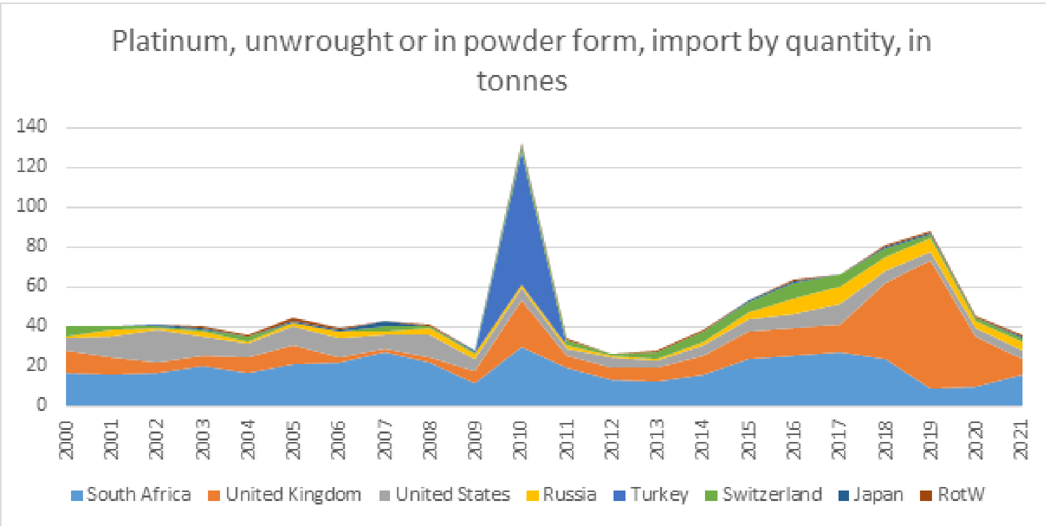

Figure 16. EU imports of platinum, unwrought or in powder form by country between 2000-2021 (Eurostat, 2022)

A great variation also occurred in the EU trade flow of semi-manufactured forms of platinum (HS 711019). The data from Eurostat shows that the EU has been both a net exporter and net importer in the period 2000-2021. In 2002 and 2003 the EU export reached the highest quantity with 165.5 tonnes and 100.4 tonnes consecutively. In 2007, the EU export fell significantly to one twenty-fifth of the quantity in 2004. The EU export recovered again in 2009 but decreased continuously until 2016. Meanwhile, the EU import began to increase from 2007. During the year 2010-2016, the EU import of semi-manufactured forms of platinum exceeded its export and the EU turned from a net exporter

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to a net importer. In 2017, EU the import and export stayed almost at the same level. In 2019 and in 2020, the EU became a net importer. In 2021, both EU import and export increased. The EU export was almost double than the import and the EU was once again an exporter of semi-manufactured of platinum. Half of the platinum in semi-manufactured forms imported to the EU originated from the United Kingdom (52%), followed by United States (19%), Switzerland (13%), Turkey (7%), and Russia (6%).

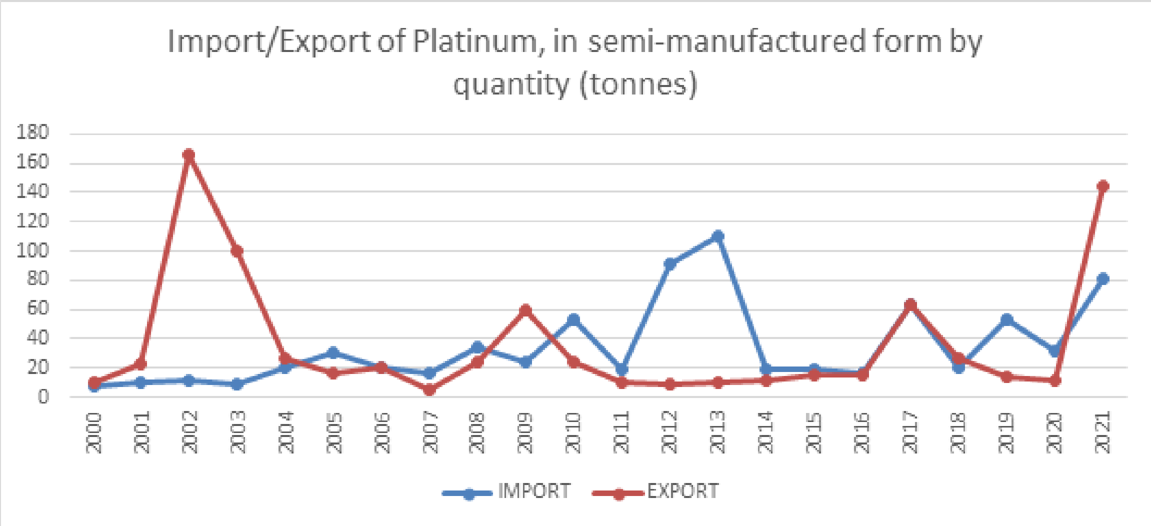

Figure 17. Estimated EU trade flows for platinum in semi-manufactured forms

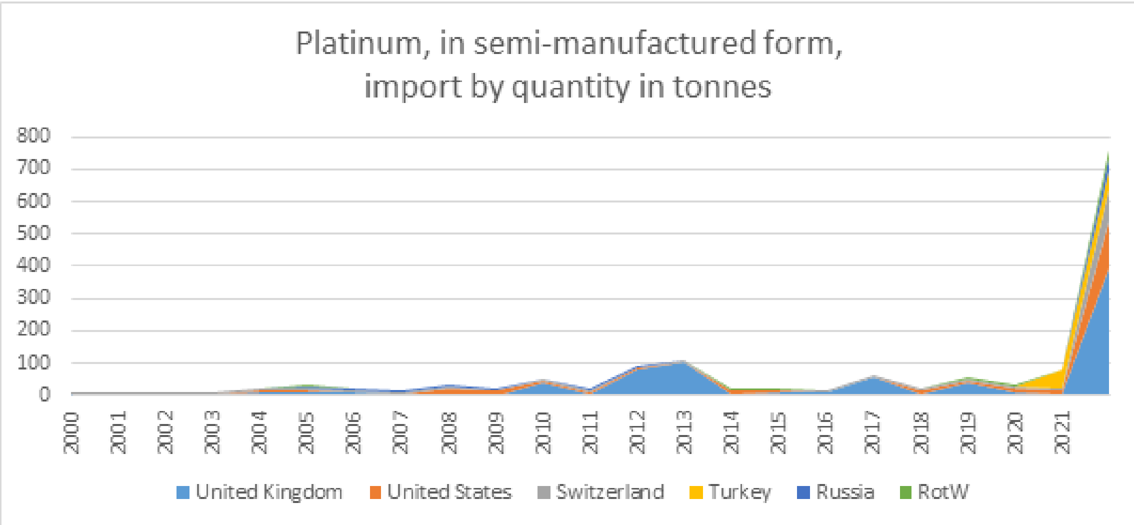

Figure 18. Estimated EU trade flows for platinum in semi-manufactured forms by quantity and supplier

Platinum is also traded in various intermediate products and wastes (HS 711292[1]). The EU import of waste and scrap of platinum began to rise from 2,693 tonnes in 2002 to 8,653 tonnes in 2007. During this time, the EU export was less than the import, making the EU as a net importer of waste and scrap of platinum. From 2008 until 2015 the EU export surpassed its declining import. During this time, the EU major export destinations were the United States (61%) and United Kingdom (29%). The EU import of waste and scrap of platinum experienced a considerable leap during the year 2018-2021, reaching

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approximately five times its import level at a rate of 26,954 tonnes/year, leaving the EU as a net importer waste and scrap of platinum. The main countries of origin of EU import were South Africa (38%), United States (14%), United Kingdom (12%), Nigeria and Switzerland (4% each). The breakdown by country was only available from 2002-2021.

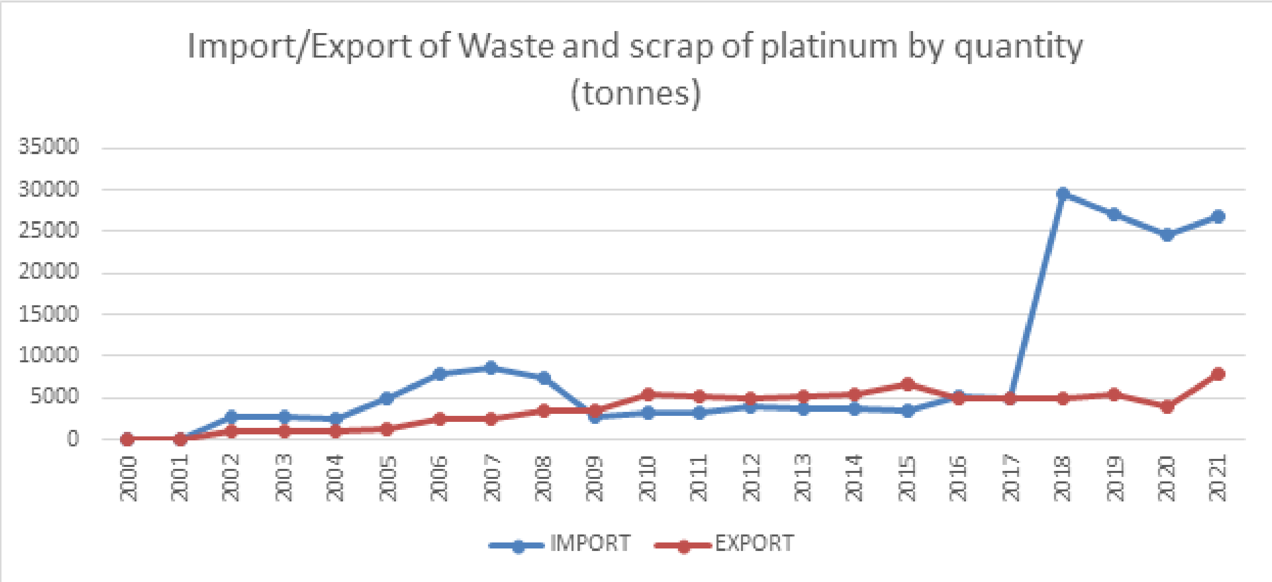

Figure 19. Estimated EU trade flows for waste and scrap of platinum by quantity (Eurostat, 2022)

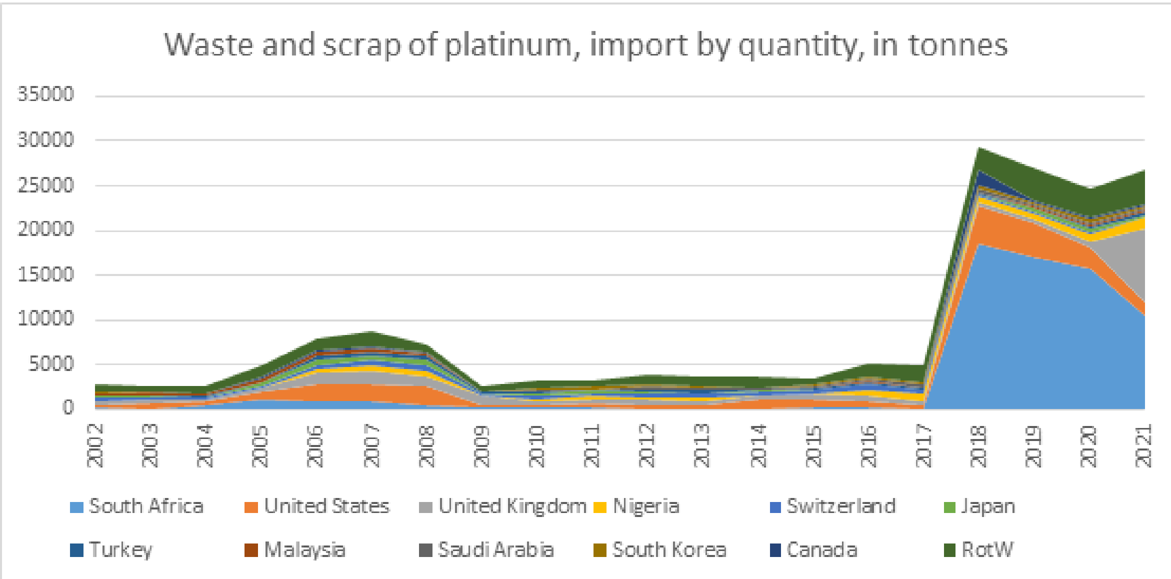

Figure 20. Estimated EU trade flows for waste and scrap of platinum by quantity by quantity and supplier (Eurostat, 2022)

Platinum in the EU is mostly used to produce autocatalyst. The import and export of platinum-based catalyst from 2000-2021 is presented in Figure 21. Since 2012, the quantity of EU export of platinum catalyst has been exceeding its import.

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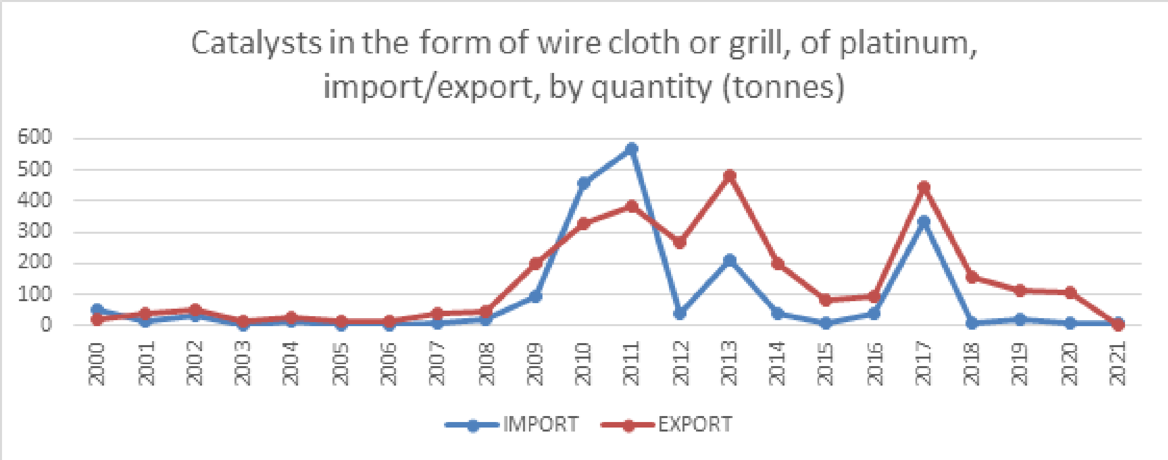

Figure 21. Estimated EU trade flows for Catalysts in the form of wire cloth or grill, of platinum quantity (Eurostat, 2022)

RHODIUM

Trade flow information for rhodium is available for unwrought or in powder form (HS code 711031) and rhodium in semi-manufactured forms (HS code 711039). Figure 22 shows the trade dynamics of rhodium in unwrought or powder form from the year 2000-2021. The EU was a net importer of rhodium in unwrought or powder form in 2000-2006. Since 2007, the EU export quantity has started to be greater than the import. In 2010, both the EU import and export began to climb, with export quantity higher than import. The EU has been a net exporter since 2007 until 2021. The average yearly EU export during the period 2010-2021 was 6.74 tonnes/year while the import was 4.87 tonnes/year. Figure 23 shows that the main suppliers of rhodium in unwrought or in powder form to the from 2000-2021 EU were South Africa (35%), United Kingdom (28%), United States (16%), and Russia (14%). In 2021, the price of rhodium was the most severely affected among the PGMs. The high price was said to reflect shortages of availability following outages at Anglo American Platinum's converter plant (ACP) during 2020 (Johnson Matthey, 2022).

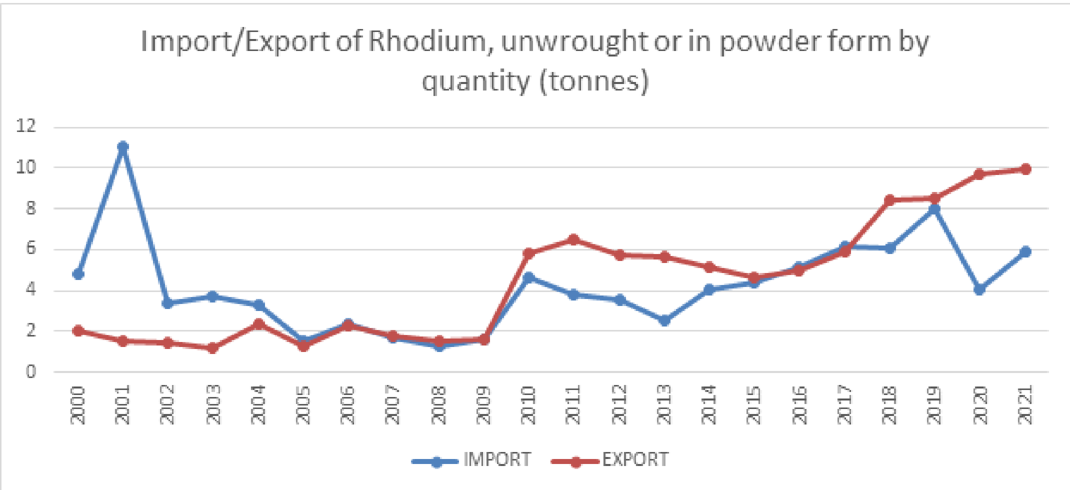

Figure 22. Estimated EU trade flows for rhodium in unwrought or powder forms (Eurostat, 2022)

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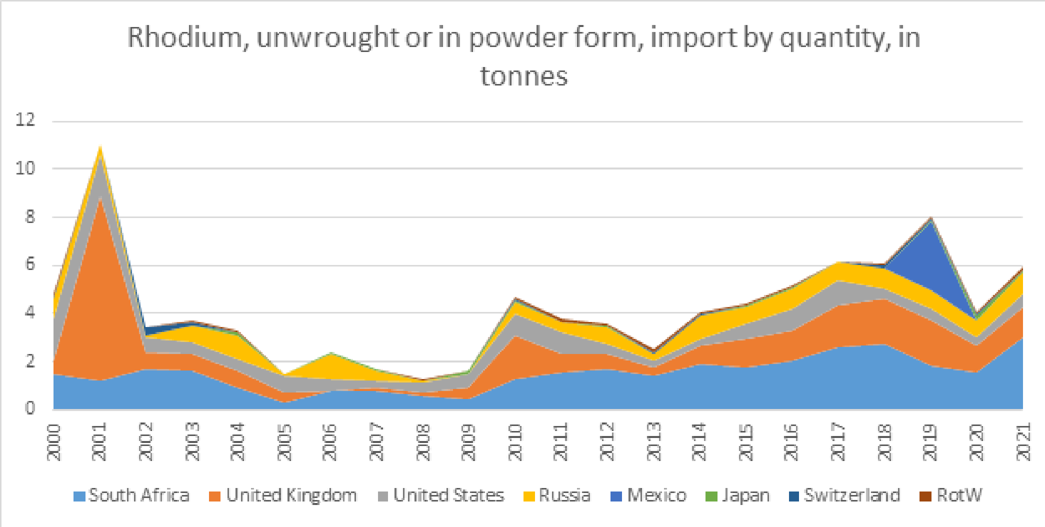

Figure 23. Estimated EU trade flows for Rhodium, unwrought or in powder form by quantity and supplier (Eurostat, 2022)

The average EU import of rhodium in semi-manufactured forms was 0.06 tonnes/year and the export was 0.31 tonnes/year in 2000-2008. The following three years the EU became a net importer with import quantity at 1.92 tonnes/year, doubling its import. Figure 24 shows that in 2012, the EU trade flow was in balance. In 2013 and 2014 the EU became a net exporter once again, but in 2015 the import quantity was higher than the export. Since 2016-2021, the EU has constantly become an exporter with average yearly export of 4.11 tonnes/ year. The average yearly EU import in the same period was 0.45 tonnes/year. United Kingdom, with 34% of share in the EU supply was the main exporter to the EU, followed by Viet Nam (26%), Thailand (15%), China (8%), United States (7%), and Switzerland (4%) (Figure 25).

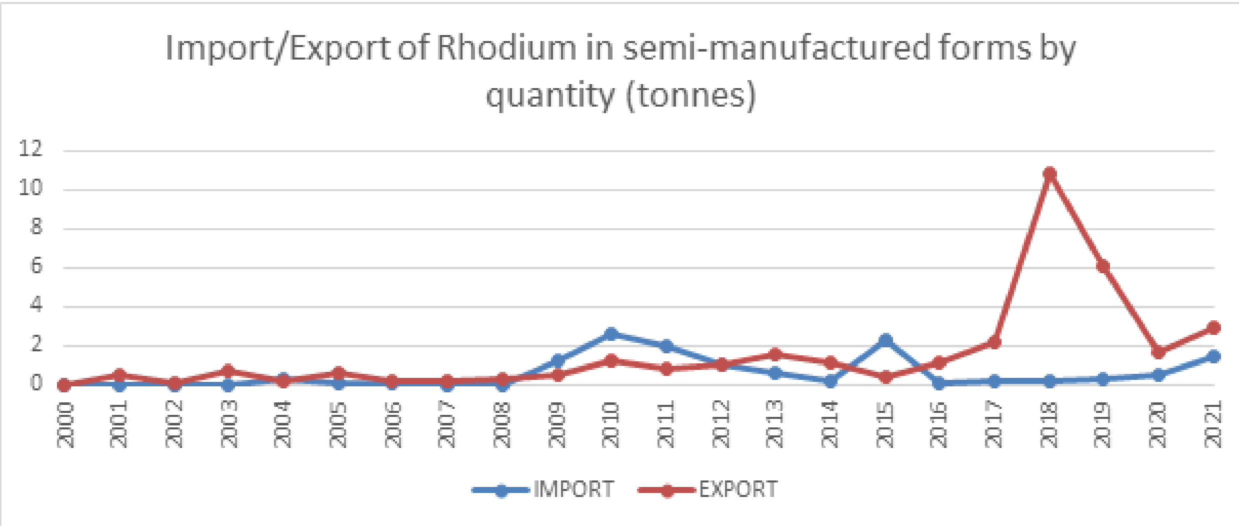

Figure 24. Estimated EU trade flows for rhodium in semi-manufactured forms (Eurostat, 2022)

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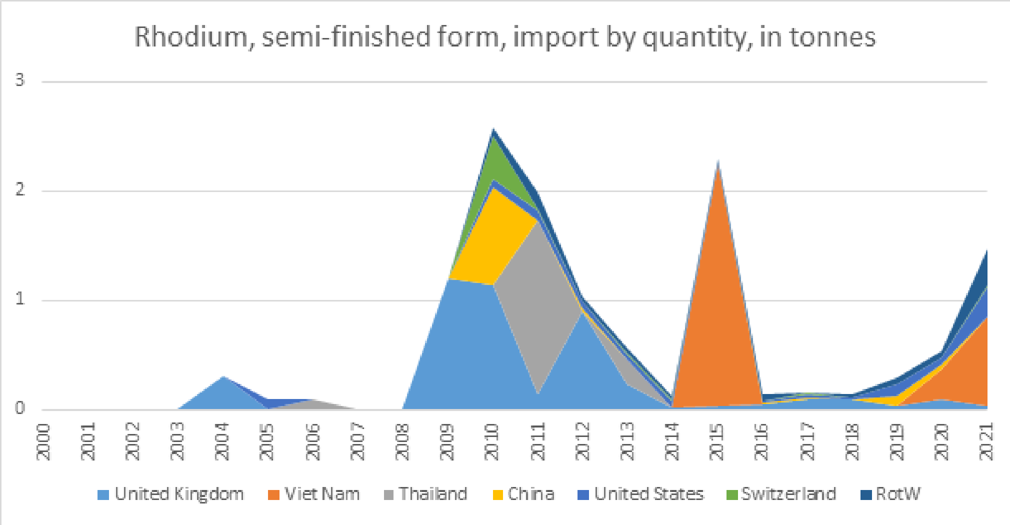

Figure 25. Estimated EU trade flows for Rhodium, semi-finished form by quantity and supplier (Eurostat, 2022)

PRICES

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). 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). In recent years, the major disruption to global supply was caused by lockdowns during the COVID-19 pandemic in addition to increased labour costs, increased costs for electricity, unreliable supply of electricity, and challenges related to deep-level mining (USGS, 2021).

PLATINUM

Platinum's price demonstrated an upward trend in the years after 2000, peaking at a record high in early 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 in late 2008. With the recovery of the global economy, the price of platinum increased because of increased demand, supply shortages and speculation by investors (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. The diesel crisis and the resulting trend toward gasoline vehicles, as well as the partial substitution of platinum by palladium in diesel catalysts, affected the increased demand for palladium in comparison to platinum (DERA, 2017). Production disruptions in South Africa and the Covid 19 pandemic tightened supply and resulted in a subsequent increase in price in the 2020-2021 period (Johnson Matthey, 2022).

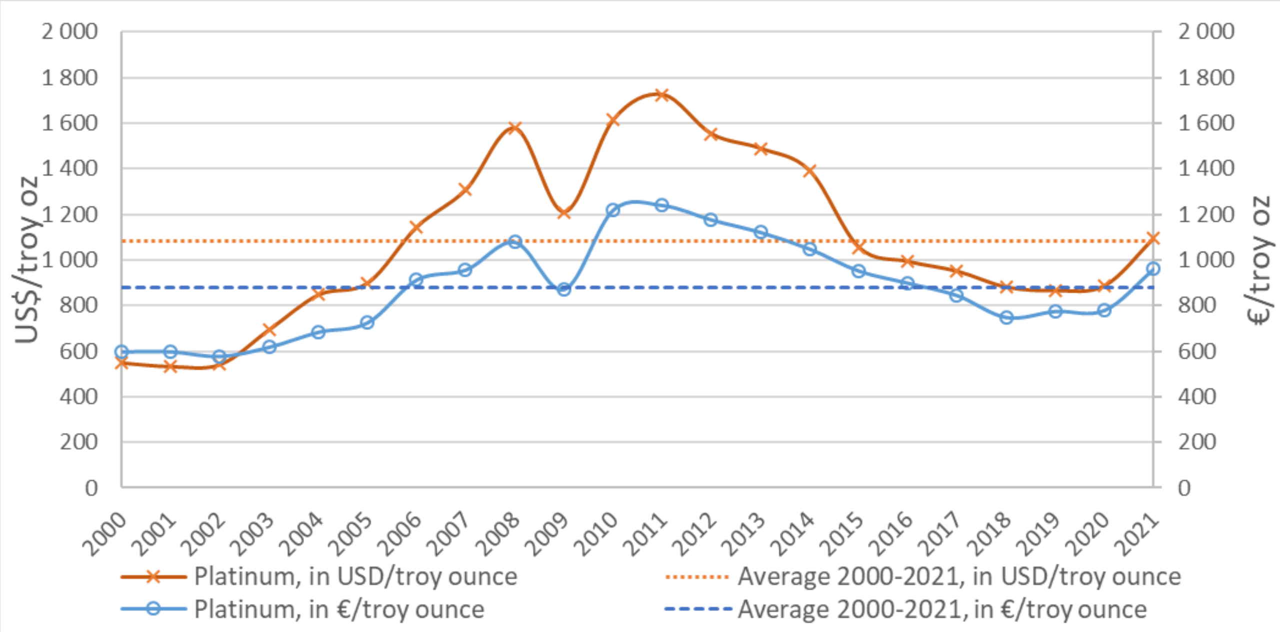

Figure 26. Annual average price of platinum between 2000 and 2021, in US$/kg and €/kg (Johnson Matthey, 2022). Dash lines indicates average price for 2000-2021.

PALLADIUM

A strong demand and supply disruption caused prices to rise sharply until 2001. 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. 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. The diesel emissions scandal in Europe is considered a factor that resulted in an increasing trend toward 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). The steep price increase continued in 2019 when the autocatalyst demand in Europe rose due to new emission legislation in China causing a bigger consumer demand than predicted (Johnson Matthey, 2020). The temporary mine closures triggered by the Covid 19 pandemic caused a 12% decrease in supply and resulted in the highest prices ever seen for palladium in 2021 (Johnson Matthey, 2022).

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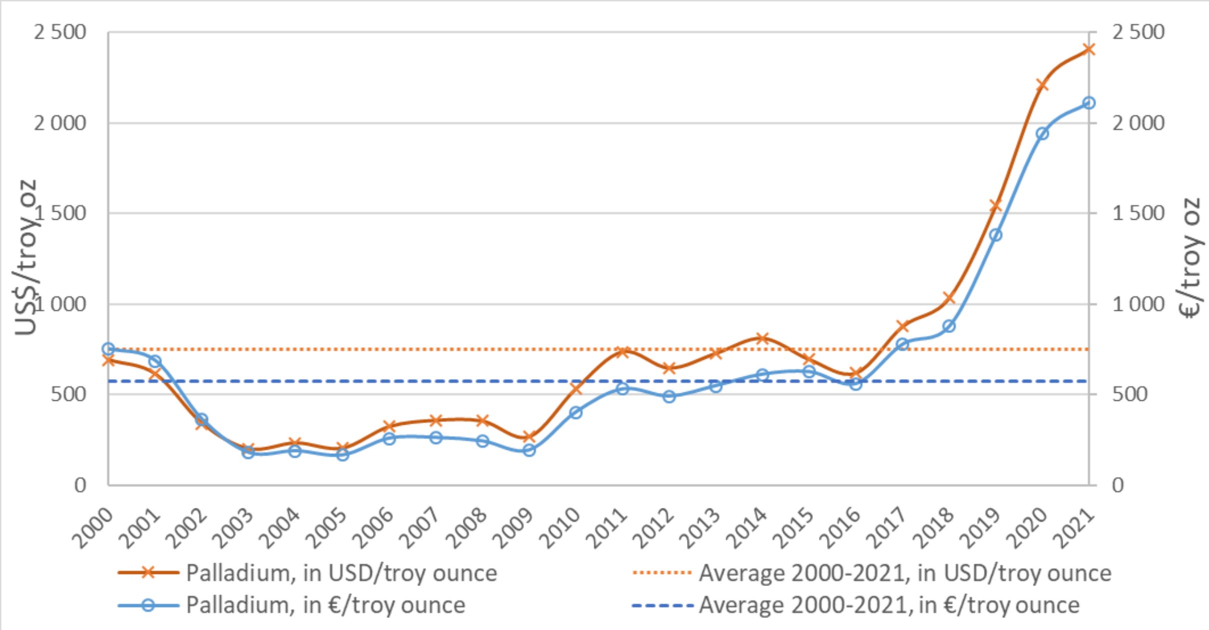

Figure 27. Annual average price of palladium between 2000 and 2021, in US$/kg and €/kg (Johnson Matthey, 2022). Dash lines indicate average prices for 2000-2021.

RHODIUM

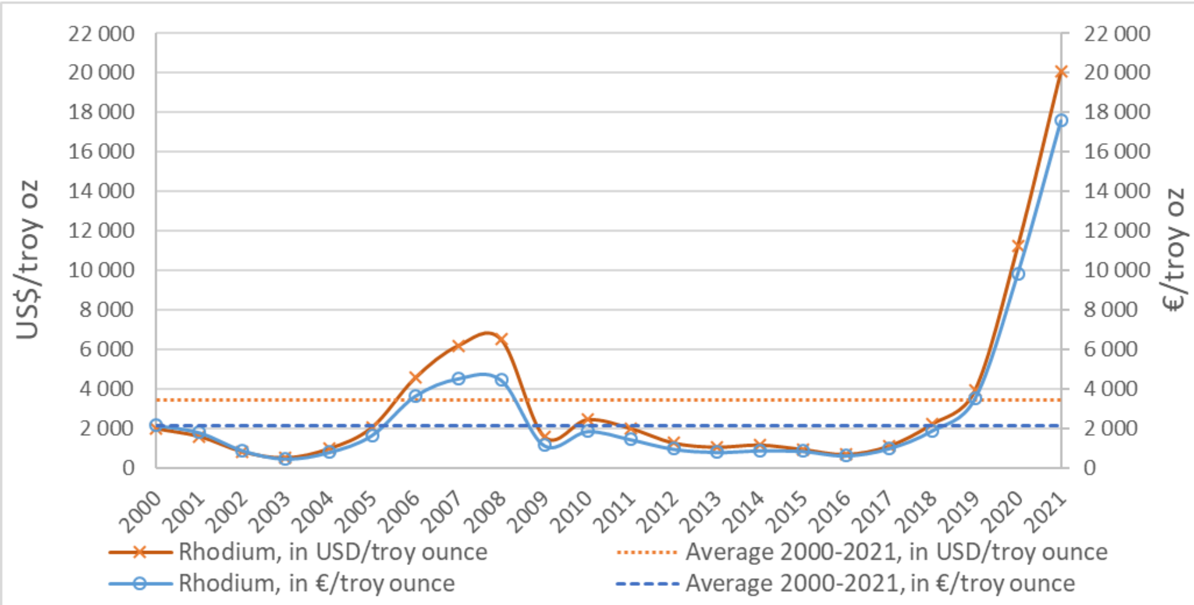

Figure 28. Annual average price of rhodium between 2000 and 2021, in US$/kg and €/ kg (Johnson Matthey, 2022). Dash lines indicate average prices for 2000-2021.

In response to the rapidly growing demand for autocatalysts, especially in Asian markets (Zientek et al., 2017), the price rose steadily from 2004 onward. Due to the global economic recession in 2008, it fell sharply by 90% . Between 2013 and 2017, rhodium's price fluctuated between US$640 per troy ounce and US$1260 per troy ounce, as a result of weak industrial demand (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)

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(Hagelüken, 2019). Since mid-2017, the rhodium price has been rising which according to Johnson Matthey, is mainly due to speculative and strategic purchasing of rhodium, especially in Asia, which had a significant impact in metal availability (Johnson Matthey, 2018). In the last two years, the price has risen sharply and to all-time high levels. In 2020, there were major disruptions to primary rhodium shipments following outages at Anglo American Platinum's converter plant (ACP) in South Africa. Demand surpassed supply in 2021 due to the recovery of vehicle production after the Covid 19 pandemic (Johnson Matthey, 2021); (Johnson Matthey, 2022). This steepgrowth in rhodium price is due to increasing demand for autocatalysts due to tighter emissions legislation and more stringent testing.

IRIDIUM

Over the first decade of the 2000s, the price varied between about 100 and 400 USD per troy oz. Due to a rapid and significant expansion of demand for iridium crucibles by the electrical sector, the price peaked in 2011 at xx. (European Commission, 2017). However, the high level of demand was not sustained in combination with reduced demand from the chlor-alkali industry in China resulting in the price falling back sharply to about 400 USD per troy oz in late 2013 (European Commission, 2017). Since 2016, the iridium price has risen gradually due to supply fluctuations of refined metal, increased industrial demand for crucibles from the electrical sector and for the coating of anodes in the electrochemical sector,and due to strategic purchasing in Asia (Johnson Matthey, 2018); (Johnson Matthey, 2019). In late 2020, the price rose to record-high levels due to tight supply caused by processing outages in South Africa which coincided with the recovery of iridium demand after the Covid 19 pandemic. Investors have taken a particular interest in iridium due to its potential application in the production of green hydrogen. Speculative buying might also have contributed to these high prices. (Johnson Matthey, 2021).

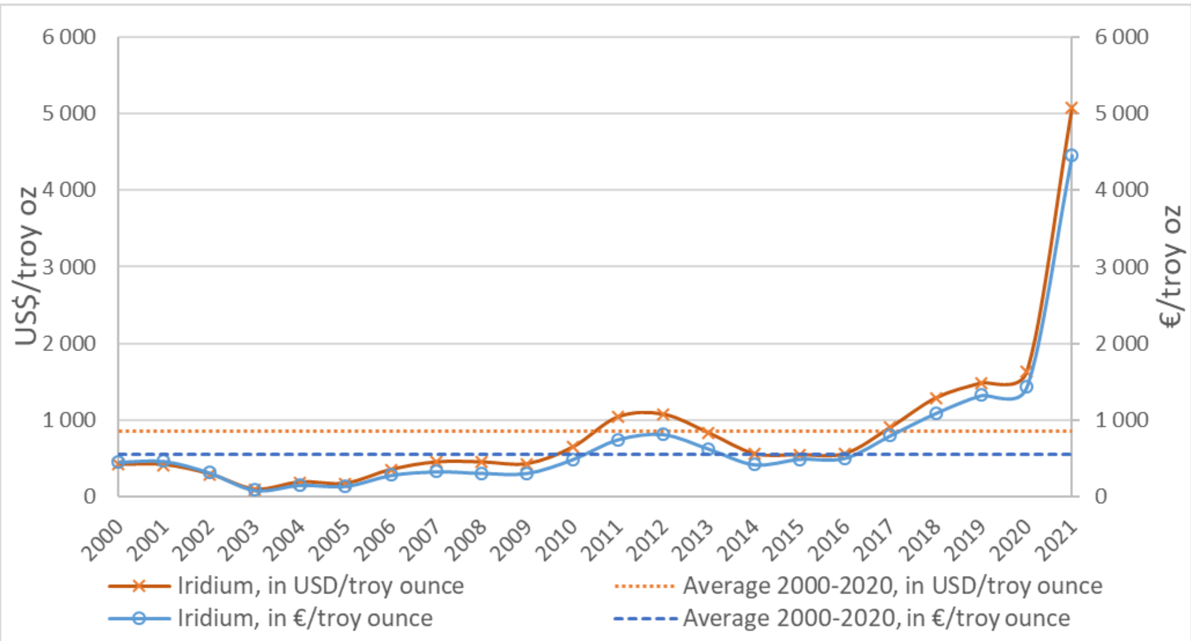

Figure 29. Annual average price of iridium between 2000 and 2021, in US$/kg and €/ kg (Johnson Matthey, 2022). Dash lines indicate average prices for 2000-2021.

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RUTHENIUM

Increased ruthenium usage in electronics, especially in computer hard disk drives resulted in peak ruthenium prices in 2007 (Zientek et al., 2017). With the onset of the global economic recession, the price fell (with a brief recovery in 2010) and continued to decline until early 2017. The rise of ruthenium prices in the latter part of 2017 and 2018 is attributed to steady industrial demand and strategic purchasing in Asia as well as fluctuations in supply from primary and secondary refiners (Johnson Matthey, 2018); (Johnson Matthey, 2019). From mid-2018, ruthenium prices stabilized 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, 2019). The price rose to a thirteen-year high of 430 USD per troy oz in late April 2021. This is likely due to higher ruthenium consumption in electronics in combination with disruptions to South African supply following processing outages and the Covid 19 pandemic (Johnson Matthey, 2021).

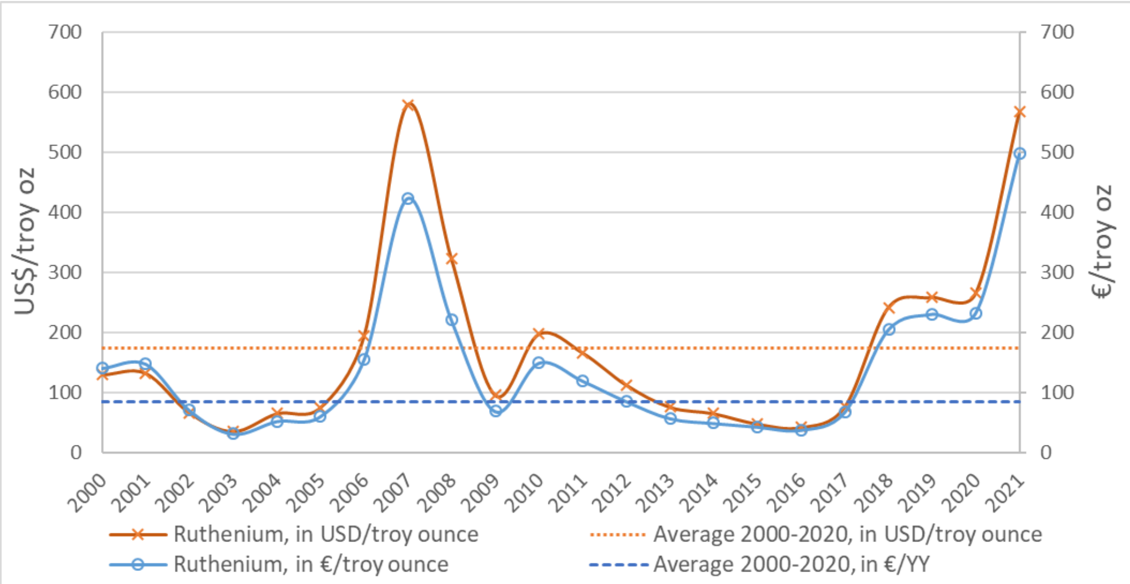

Figure 30. Annual average price of ruthenium between 2000 and 2021, in US$/kg and €/kg (Johnson Matthey, 2022). Dash lines indicate average prices for 2000-2021.

OUTLOOK FOR SUPPLY AND DEMAND

In general, PGMs are always produced together. Pt and Pd are the prime metals and the other PGMs being by-products. In South Africa PGMs are mined as main commodities, whereas in Russia PGMs are produced as by-products of the nickel industry. The product basket (ratio of produced PGMs) varies from country to country and company to company. The future supply situation with South Africa and Russia being the prime sources will not change in the mid to long term, as these countries hold the largest known resources (96.5% of global resources). South Africa alone holds 90% of global resources (USGS 2022). Sanctions against Russia may have a profound effect on supplies of Pd and to a lesser extent Pt. Covid-19 induced short term production outages from South Africa. Other socioeconomic problems such as power restrictions etc. may also have an effect of PGM output in South Africa.

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Pt demand is still strong for catalytic component in diesel ICE. Despite efforts to go fully electric this will still be the major demand driver, at least in the mid-term. In addition, higher PGM loadings in catalytic converters may offset an overall decline in ICE. Industrial demand (catalytic applications) and the glass industry will also remain strong. There may also be a growing future demand from fuel cells for Pt. The market has been in deficit in recent years, which has always been buffered by the financial sector (physically backed ETFs).

As for Pd, the automotive sector will be the major driver, especially in petrol ICE and petrol PHEV as diesel ICE are on the decline. Stricter emission standards may push PGM loadings to higher levels. Industrial Pd demand (chemical) will increase. Therefore, the Pd market will remain in deficit (Johnson Matthey, 2021). The deficit in the Pd market has been much more profound in the last years compared to Pt and will remain so in the future. It is not possible to increase Pd output from South Africa to counterbalance this due to the Pt/Pd ratio of the deposits.

Rh is also used in catalytic converters demand is expected to rise. The same is true for Ru even though with lower growth rates as this metal is not used in the automotive sector (catalytic converters). There may be a dramatically growing demand for Ir in the future from electrolysis of water to produce “green hydrogen”. This market is set to growth by a factor of 4 – 6 from current levels. As Ir is a by-product these demand scenarios will be hard to match as production cannot be ramped up to this extent.

Johnson Matthey forecasts that the PGM market in 2022 is highly uncertain. Since Russia is the world’s largest primary palladium supplierand a major producer of platinum and rhodium, the war in Ukraine has created significant risks to supply. The crisis is expected to exacerbate existing difficulties in supply chains, augment inflation, and depress economic growth. An added challenge is that South African supplies will fall in 2022, as plant maintenance and operational challenges hit output. Furthermore, investor interest in PGMs appears to be limited even with the evident supply risks. Covid still continues to create major disruptions for PGM demand, especially in China where major cities are experiencing lockdowns due to the spread of the Omicron variant (Johnson Matthey, 2022). Over the long term, platinum demand is expected to rise as the hydrogen economy gains momentum although the metal may experience some reduced demand for diesel engine catalytic converters as traditional ICEs lose market share. The demand for palladium and rhodium is forecast to remain firm until around 2025, when EVs are expected to start gaining significant market share over ICEs and prices for these two metals will start to fall. Iridium and ruthenium prices are also anticipated to remain strong as hydrogen production increases (Edison, 2021).

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Platinum group metals extraction stage global demand is presented by global gross demand of platinum, palladium, rhodium, iridium and ruthenium. Consumption data is extracted from Johnson Matthey (2008-2021).

Gross demand data of platinum and palladium for Europe is available from Johnson Matthey (2008-2021).

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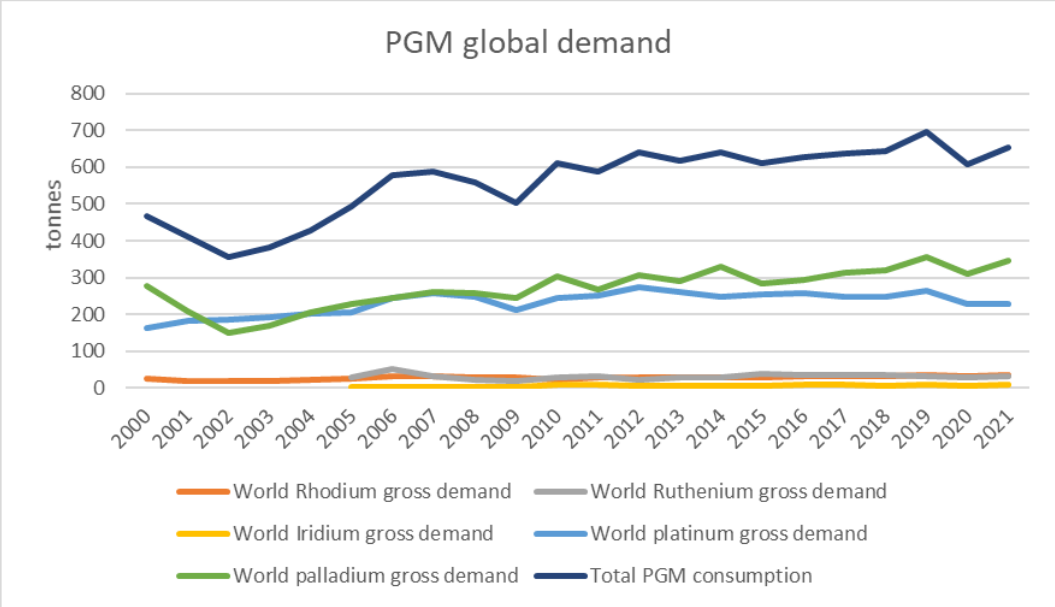

Figure 31. Total PGM global gross demand. Demand data is extracted from Johnson Matthey (2008-2021). Data for ruthenium and iridium demand is available for 2005-2021. Gross demand = sum of manufacturer demand for metal in that application and any changes in unrefined metal stocks.

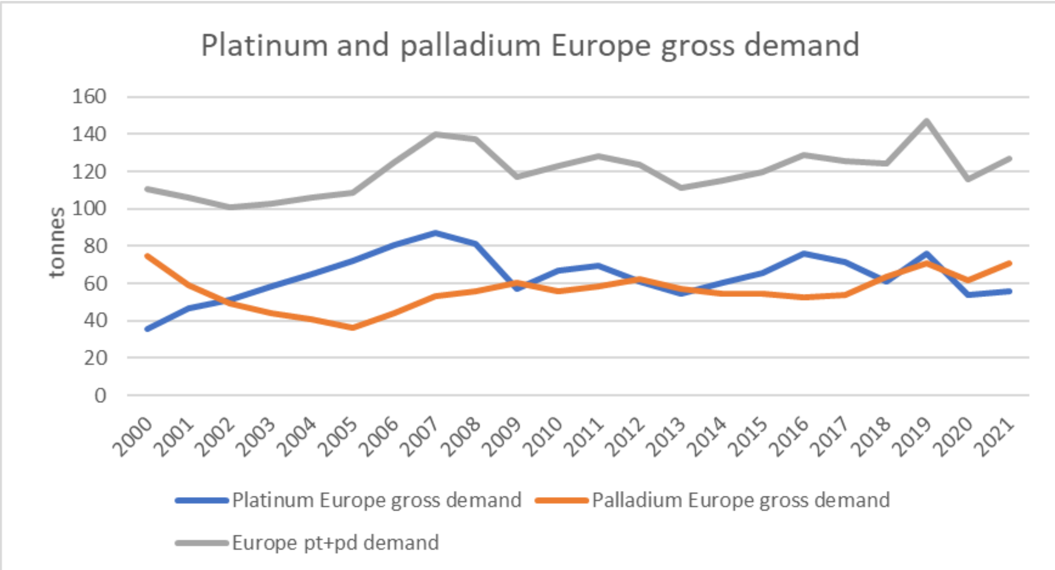

Figure 32. Gross demand data of platinum and palladium for Europe (Johnson Matthey 2008-2021). Gross demand = sum of manufacturer demand for metal in that application and any changes in unrefined metal stocks.

EU DEMAND AND CONSUMPTION OF IRIDIUM, OSMIUM AND RUTHENIUM

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.

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Gross global demand for iridium in 2021 was 8.3 tonnes (Johnson Matthey, 2022). 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)).

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 2021 was 32 tonnes (Johnson Matthey, 2022). 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)).

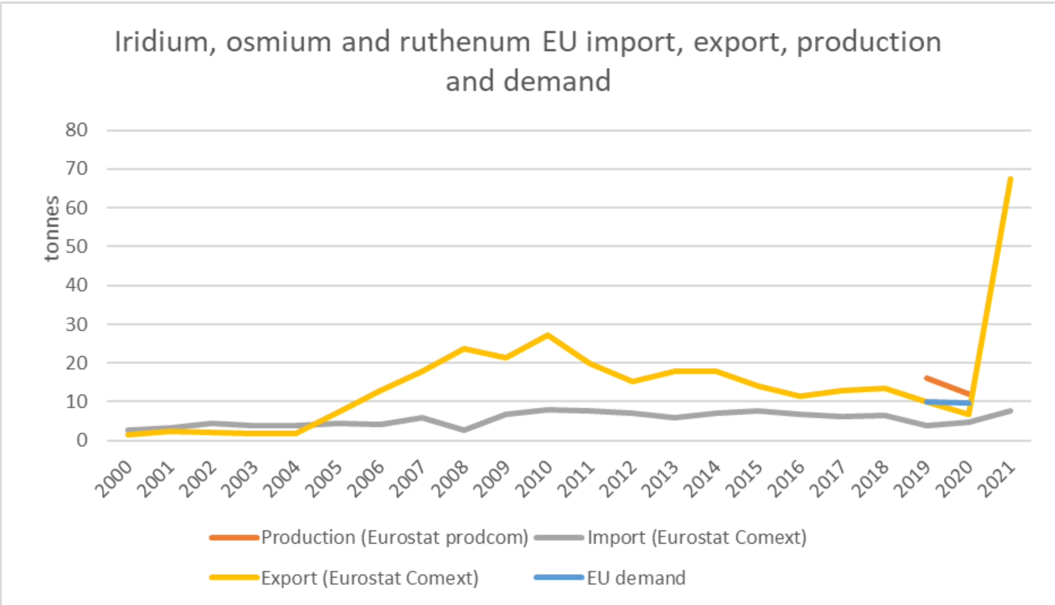

Figure 33. Iridium, osmium and ruthenium (CN 711041 Iridium, osmium & ruthenium, unwrought or in powder form) processing stage apparent EU consumption. Production data through Eurostat Prodcom is only available for 2019-2020. Consumption is calculated EU production+import-export.

Iridium, osmium and ruthenium processing stage apparent EU consumption is presented by HS code CN 711041 Iridium, osmium & ruthenium, unwrought or in powder form. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24413025 Iridium, osmium and ruthenium. Unwrought or in powder form.

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of iridium, osmium and ruthenium at extraction stage is -40.9 % for 2019-2020.

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

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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 and in rhodium in semi-manufactured forms.

Gross global demand for rhodium in 2021 was 36.1 tonnes (Johnson Matthey, 2022). 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)).

Rhodium processing stage apparent EU consumption is presented by HS code CN 711031 Rhodium, unwrought or in powder form. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24413020 Rhodium. Unwrought or in powder form.

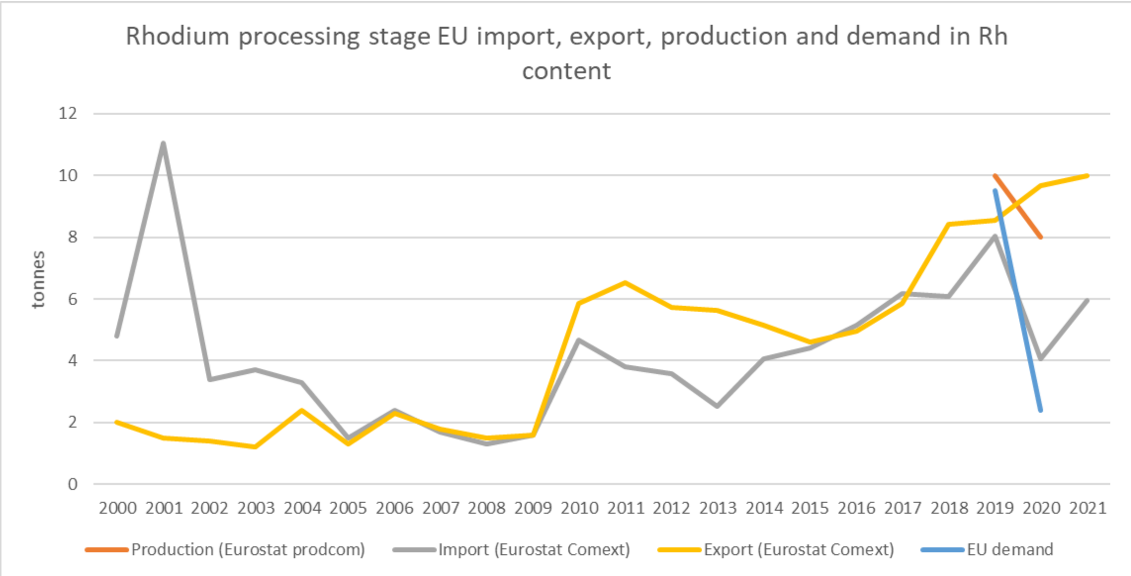

Figure 34. Rhodium (CN 711031 Rhodium, unwrought or in powder form) processing stage apparent EU consumption. Production data through Eurostat Prodcom is only available for 2019-2020. Consumption is calculated in rhodium content (EU production+import-export).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of rhodium at processing stage is -119.6 % for 2019-2020.

EU DEMAND AND 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 Johnson Matthey (Johnson Matthey, 2022), the average annual European demand for palladium, for all uses except investment, was 64 tonnes in the period 2017-2021. In the last five years (2017-2021), the

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European demand for palladium represents a share of between 17% and 21% of the global demand (Johnson Matthey, 2022).

Palladium processing stage apparent EU consumption is presented by HS code CN 711021 Palladium, unwrought or in powder form. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24413015 Palladium. Unwrought or in powder form.

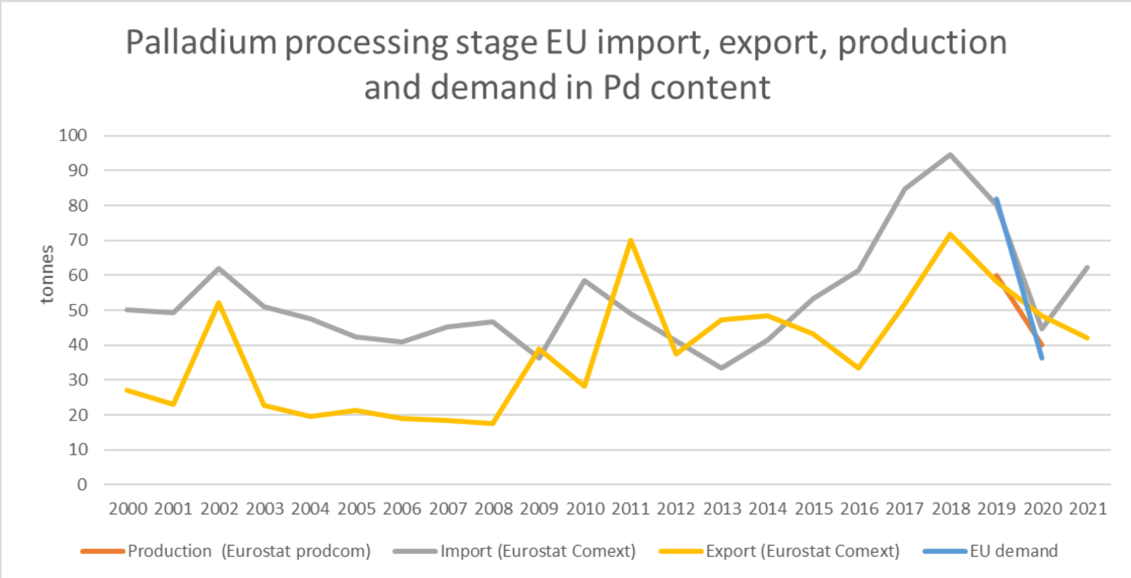

Figure 35. Palladium (CN 711021 Palladium, unwrought or in powder form) processing stage apparent EU consumption. Production data through Eurostat Prodcom is only available for 2019-2020. Consumption is calculated in palladium content (EU production+import-export).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of palladium at processing stage is 8.2 % for 2019-2020.

EU DEMAND AND 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 platinum 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 Johnson Matthey (Johnson Matthey, 2022), the average annual European demand for platinum, for all uses except investment, was 63.7 tonnes in the period 2017-2021. In 2021, platinum demand in Europe amounted to 55.8 tonnes. In the last five years (2017-2021), the European demand for platinum represents a share of between 24 % and 29 % of the total global demand.

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Platinum processing stage apparent EU consumption is presented by HS code CN 711011 Platinum, unwrought or in powder form. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24413010 Platinum. Unwrought or in powder form.

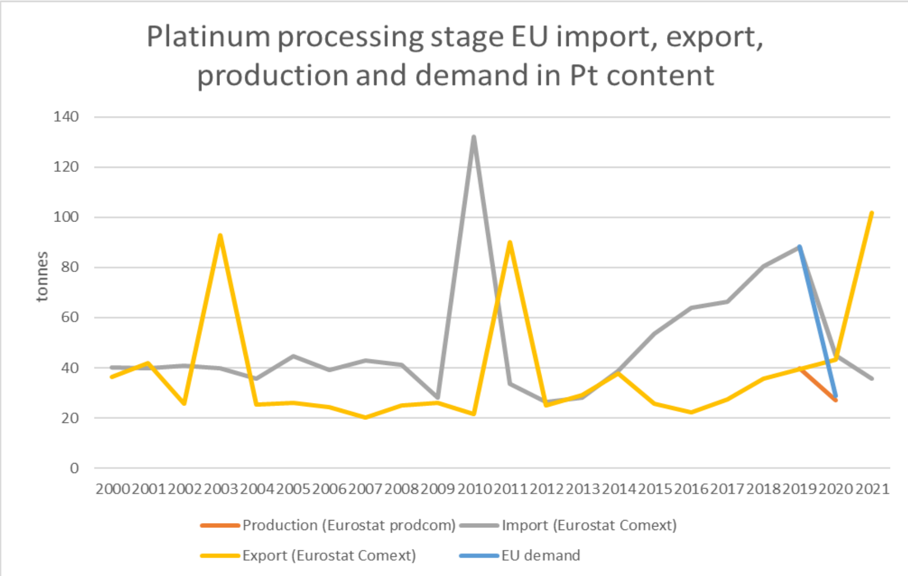

Figure 36. Platinum (CN 711011 Platinum, unwrought or in powder form) processing stage apparent EU consumption. Production data through Eurostat Prodcom is only available for 2019-2020. Consumption is calculated in platinum content (EU production+import-export).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of platinum at processing stage is 30.3 % for 2019-2020.

GLOBAL AND EU USES AND END-USES OF PGM

GENERAL APPLICATIONS

Because of their unique properties, PGMs are fundamental components in a broad range of modern technologies.

All 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 is automotive catalysts for emissions control.

Other important uses (accounting for smaller proportions) are jewellery, catalysts for chemical processes, and electronic/electrical applications.

PGMs are used in very small quantities. 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, 2015b).

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An overview of PGM demand by end-use sector is given in **Erreur ! Source du renvoi introuvable.** for 2012 and 2020.

Within this time, the use of PGMs for autocatalysts and chemicals gained in importance, while the share of the other applications declined in relative market share.

Beside these technical applications, PGMs are stocked as investment goods due to their high value.

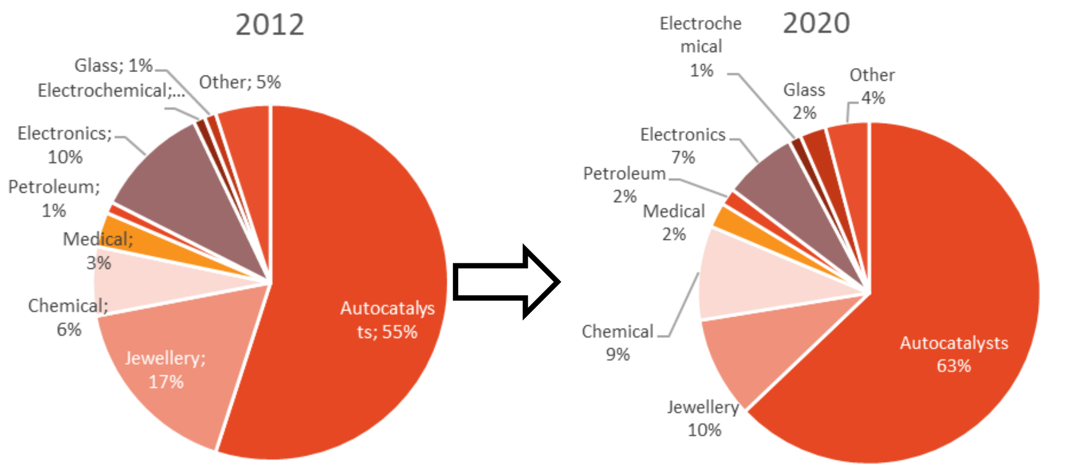

Figure 37. Global gross demand for PGMs (aggregate of platinum, palladium, rhodium, ruthenium and iridium) by end use sector for 2012 (Johnson Matthey, 2012) and 2020 (Johnson Matthey, 2021).

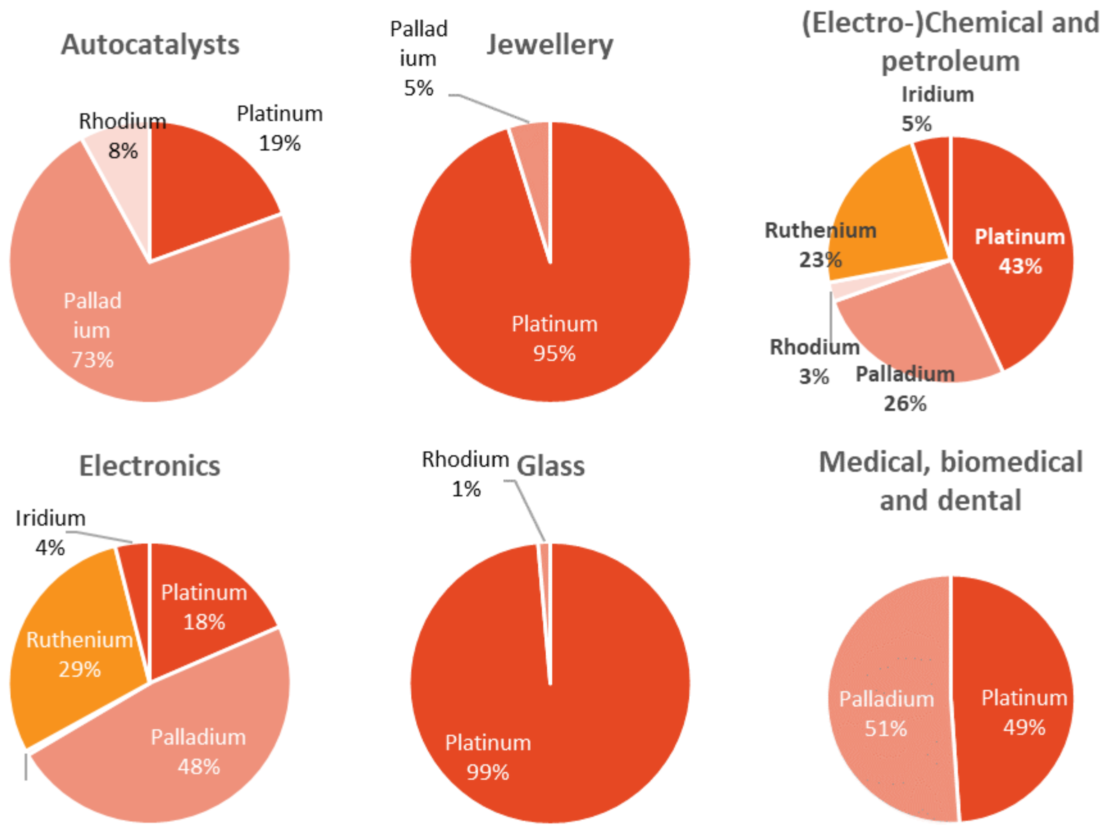

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Figure 38. PGM global demand by sector and material in 2020. Background data from (Johnson Matthey, 2021)

Given the different properties of each PGM, many applications are specific to individual PGMs.

Erreur ! Source du renvoi introuvable. 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.

APPLICATIONS

The following is a summary of PGM applications (European Commission, 2014; European Commission, 2017; European Commission, 2020), with further information provided in the specific PGM factsheets.

AUTOCATALYSTS

Autocatalysts are by far the most important application of PGM (cf. Figure 4.1.1).

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 (NOx), 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 73% of the global PGM gross demand in autocatalysts, and platinum and rhodium for 19% and 8%, respectively.

JEWELLERY

The value and physical properties of PGMs means they are suitable and desirable for high-value jewellery, which accounts for 10% of their consumption (cf. **Erreur ! Source du renvoi introuvable.**).

Platinum is by far the most used PGM in jewellery, followed by palladium (cf. **Erreur ! Source du renvoi introuvable.**).

CATALYSTS IN CHEMICAL, ELECTROCHEMICAL, PETROCHEMICAL AND HYDROGEN 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.

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All PGMs are employed as catalysts on an industrial scale (cf. **Erreur ! Source du renvoi introuvable.**).

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, and with iridium in electrochemical processes.

PGMs are expected to play a major role in future hydrogen technologies (CRM experts, 2022) – as an electrolyser to produce hydrogen with electrical power and in fuel cells to generate electrical power from hydrogen. Proton-proton exchange membrane (PME) technology uses a combination of platinum and iridium as catalysts (World Platinum Investment Council, 2021). This application is currently very small for PGMs, but could increase significantly in future as hydrogen could become one enabler of the energy transition in both stationary applications (e.g. energy storage) and mobile applications (e.g. fuel cell electric vehicles).

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 miniaturization 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.

Mainly platinum, but also rhodium, is employed in the production of glass fibre, LCD manufacture and some other types of glass.

Glasses with lower quality requirements like bottle glass are not produced using PGMs.

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. Platinum is used for medical implants and cardiac pacemakers.

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).

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4.1.2.2 GLOBAL AND EU USES AND END USES OF INDIVIDUAL PGM

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. The share of electrochemical applications on the overall global iridium demand increased from 22 % in 2016 to 37% in 2020, becoming the most important application. In 2020, electrical applications accounted for 22% (38% in 2010), and chemical applications for 11% (9% in 2010) of the global gross demand (cf. **Erreur ! Source du renvoi introuvable.**). The remaining global gross demand came from a range of other minor uses, including spark plugs and medical implants. There is no specific data for the applications of iridium in Europe.

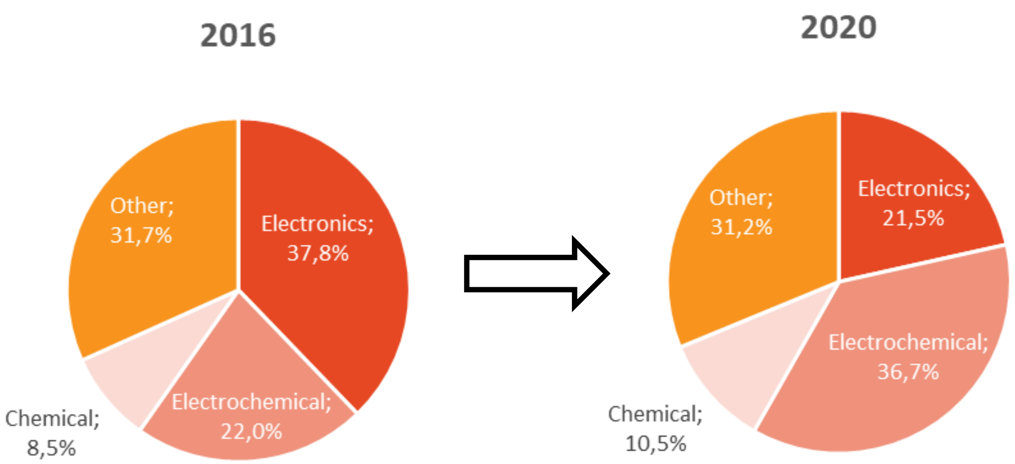

Figure 39. Global end uses of iridium in 2016 and 2020 (Johnson Matthey, 2021).

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in **Erreur ! Source du renvoi introuvable.**.

Table 5. Iridium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2019 (* for 2014) (Eurostat, 2022).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Electronics	C26 - Manufacture of computer, electronic and optical products	84,074*	C2611 - Manufacture of electronic components
Chemical	C20 - Manufacture of chemicals and chemical products	117,150*	C2014 - Manufacture of other organic basic chemicals
Electrochemical	C20 - Manufacture of chemicals and chemical products	117,150*	C2013 - Manufacture of other inorganic basic chemicals

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Other	C29 - Manufacture of motor vehicles, trailers and semi-trailers	234,398	C2931 - Manufacture of electrical and electronic equipment for motor vehicles

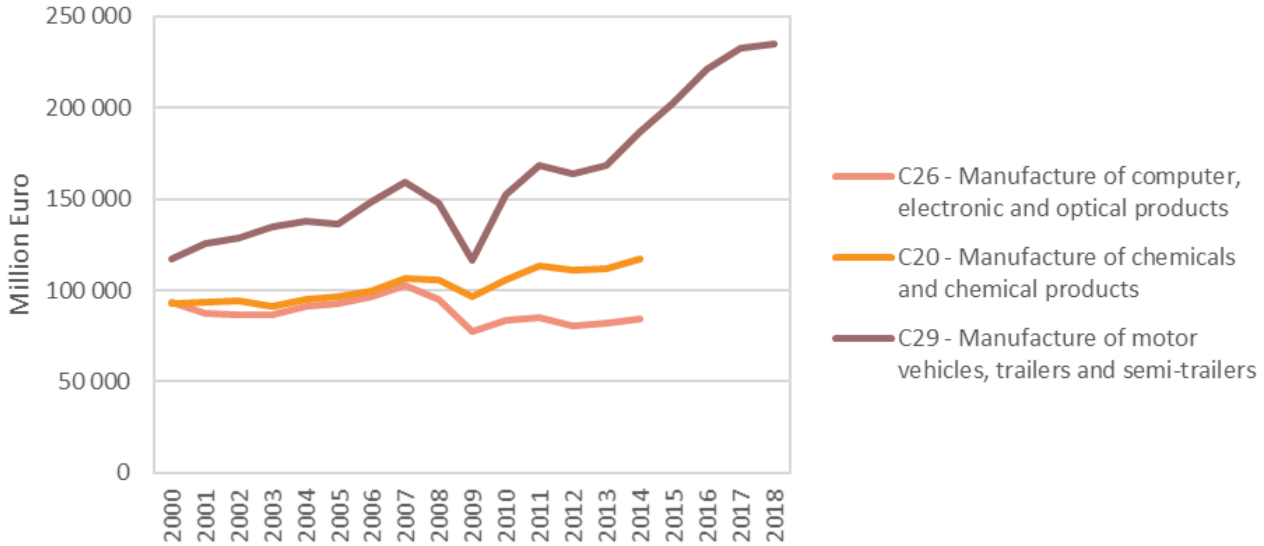

Figure 40. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS

The specific applications of iridium are described below.

ELECTRONIC AND ELECTRICAL

Because 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 include:

- Yttrium Aluminium Garnet (YAG) crystals for lasers
- LSO and GSO crystals for medical scanners and X-ray scanners for baggage and container screening,
- Sapphire that provides as a substrate in the production of gallium nitride which is used for light-emitting diodes (LEDs), as increasingly utilised in flat-screen displays and portable electronic equipment (European Commission, 2017),
- 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.

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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, platinum-iridium alloys can be used in electrodes for medical implants such as heart pacemakers, aura and retinal implants, neuromodulation and neurostimulation devices.

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.

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)- due to its unique corrosion resistance and hardness.

Iridium is used, together with platinum, as a catalyst for hydrogen generation for fuel cells.

USES AND END-USES OF PALLADIUM

The distribution of palladium applications on overall demand is shown for 2010 and 2020 in **Erreur ! Source du renvoi introuvable.** for the whole world and in **Erreur ! Source du renvoi introuvable.** for Europe. The development of global palladium use is mostly similar to the European use structure.

European palladium demand is strongly dominated by its use in catalytic converters for vehicles.

In 2020, autocatalysts represented a share of 90% of the total consumption of about 56 tonnes. The other applications contributed with 4% for electronics, 3% for chemicals, each 1% for dental and jewellery (Johnson Matthey, 2022).

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The predominant global use was in autocatalysts, which accounted for 84% of the total demand. The remainder was used mainly in electrical/electronics, chemical, dental and jewellery applications.

Both globally and in Europe, autocatalysts was the increasing application of palladium between 2010 and 2020.

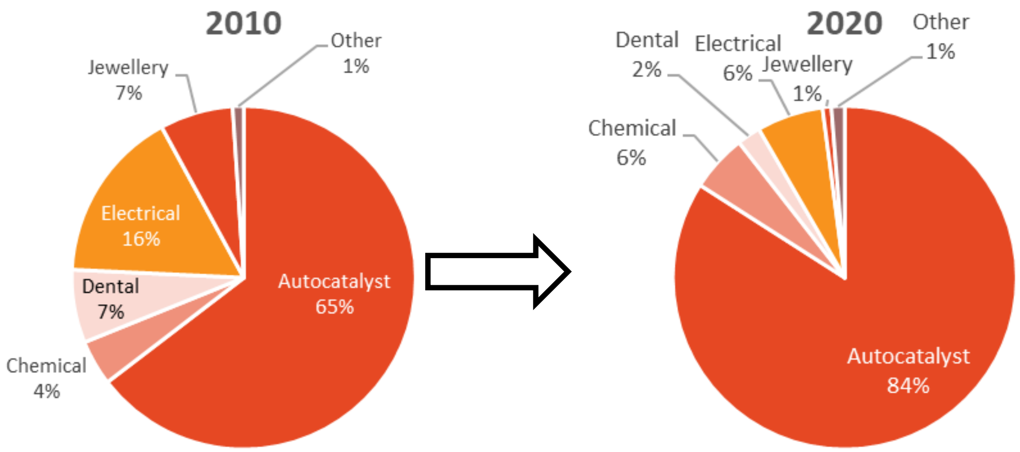

Figure 41. Global end uses of palladium 2010 and 2020 (Johnson Matthey, 2022).

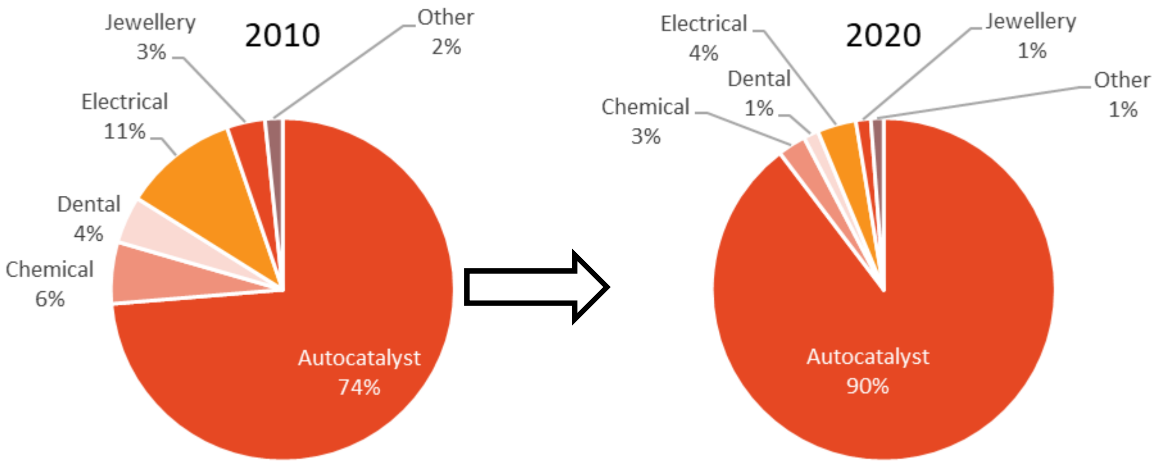

Figure 42. End uses of palladium in Europe in 2010 and 2020 (Johnson Matthey, 2022).

The above figures for demand do not include investment, as the demand for palladium investment items has been negative in 2020 (within this year, 5.3 tonnes globally and in Europe 0.5 tonnes of palladium became available from destocking investments). The trend of selling palladium investment items in the global market is prevailing since 2015, while 2021 a trend reversal is apparent (Johnson Matthey, 2022).

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in **Erreur ! Source du renvoi introuvable.**.

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Table 6. Palladium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2019 (* for 2014) (Eurostat, 2022).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	234,398	C2932 - Manufacture of other parts and accessories for motor vehicles
Electronics	C26 - Manufacture of computer, electronic and optical products	84,074*	C2611 - Manufacture of electronic components
Chemical	C20 - Manufacture of chemicals and chemical products	117,150*	C2015 - Manufacture of fertilisers and nitrogen compounds
Dental	C32 - Other manufacturing	64,377* (C31 & C32)	C3250 - Manufacture of medical and dental instruments and supplies
Jewellery	C32 - Other manufacturing	64,377* (C31 & C32)	C3212 - Manufacture of jewellery and related articles
Investment	There is no NACE code associated with investment and therefore no related value-added		

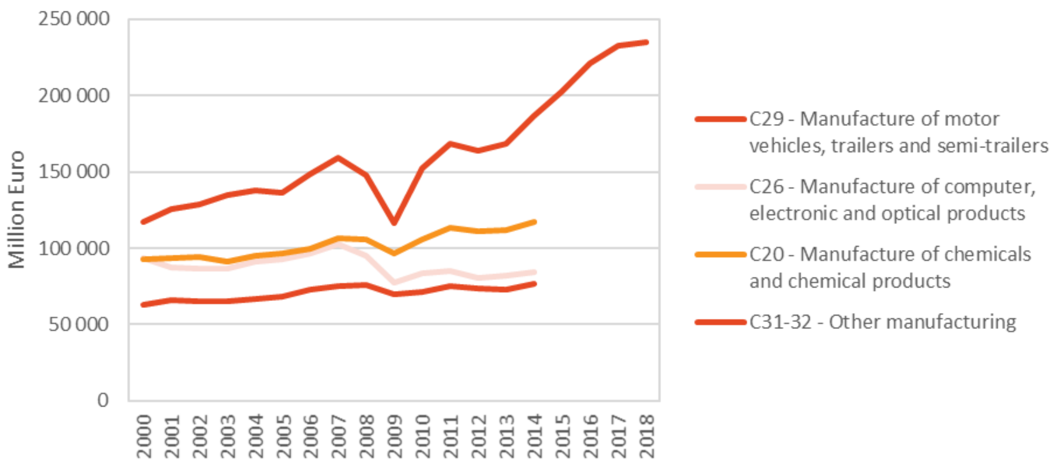

Figure 43. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS

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 nitrogen oxides from gasoline-powered vehicles.

Autocatalysts can eliminate 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.

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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 with 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.

The 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 (silver / palladium) tracks of hybrid integrated circuits (HIC) used primarily in 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 (tin/lead) solder.

Palladium-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 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.

Palladium is used by the petrochemical industry to catalyse the hydrocracking process.

JEWELLERY

Palladium is commonly used either as an alloying addition to platinum and gold (white gold), or as palladium jewellery itself.

DENTAL

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Palladium is an essential component of alloys used for dental restorations such as inlays, bridges and crowns, providing 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 palladium-containing alloys varies widely from country to country depending on customer preferences.

INVESTMENT

Palladium, like platinum and rhodium, (and gold and silver), is also used for investment in the form of physical assets (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 (palladium/silver) membranes.

USES AND END-USES OF PLATINUM

The use of platinum for all its applications is shown for 2010 and 2020 globally (**Erreur ! Source du renvoi introuvable.**) and for the EU (**Erreur ! Source du renvoi introuvable.**)

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

In Europe, autocatalysts account for around half of the overall platinum demand, reflecting the dominance of diesel-powered vehicles in the European fleet compared with the rest of the world. The share of autocatalysis on the European platinum demand decreased significantly from a maximum of 80% in 2006 to 52% in 2020 (Johnson Matthey, 2022).

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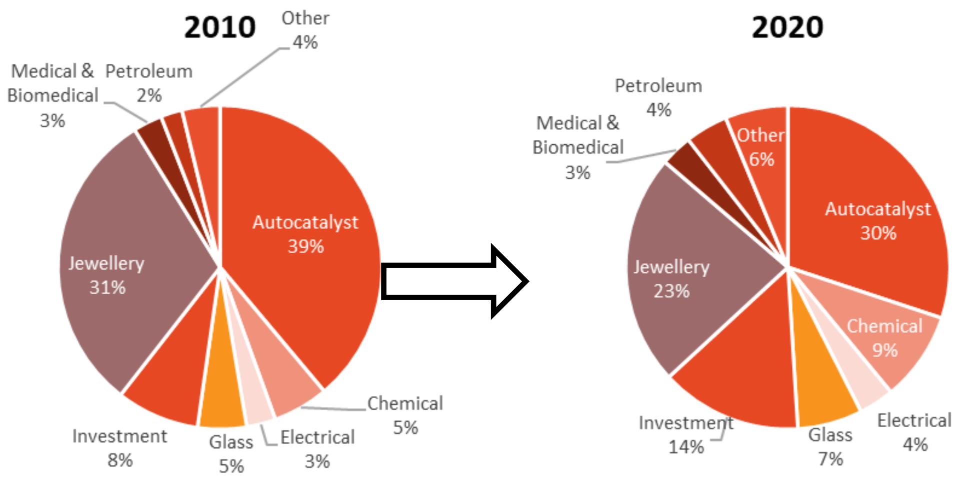

Figure 44. Global end uses of platinum in 2010 and 2020 (Johnson Matthey, 2022).

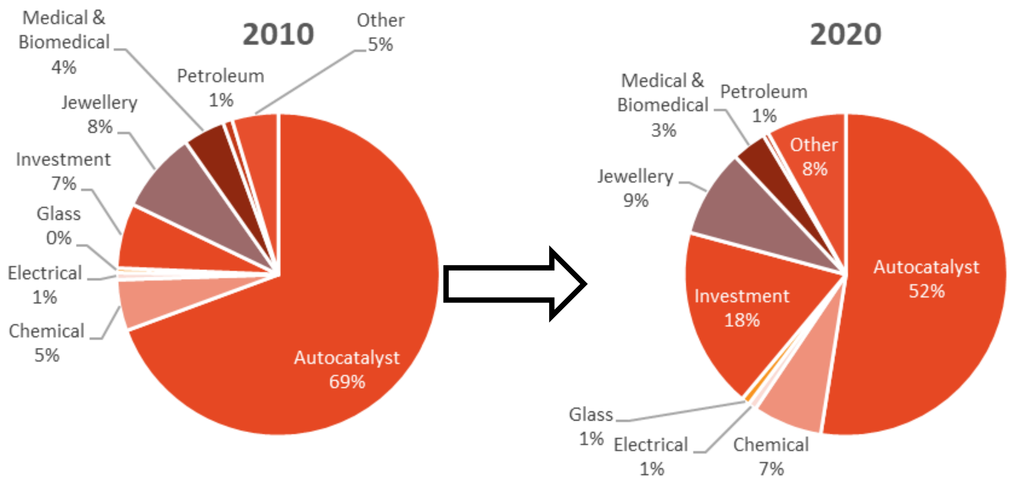

Figure 45. End uses of platinum in Europe in 2010 and 2020 (Johnson Matthey, 2022).

Table 7. Platinum applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2019 (* for 2014) (Eurostat, 2022).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	234,398	C2932 - manufacture of other parts and accessories for motor vehicles
Jewellery	C32 - Other manufacturing	64,377* (C31-32)	C3212 - manufacture of jewellery and related articles
Chemical	C20 - Manufacture of chemicals and chemical products	117,150*	C2013 - manufacture of other inorganic basic chemicals; C2014 - manufacture of other organic basic chemicals; C2015 - manufacture of fertilisers and nitrogen compounds

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Medical	C32 - Other manufacturing	64,377* (C31-32)	C3250 - manufacture of medical and dental instruments and supplies
Petroleum	C19 - Manufacture of coke and refined petroleum products	24,896	C1920 - manufacture of refined petroleum products
Electronics	C26 - Manufacture of computer, electronic and optical products	84,074*	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	72,396	C2311 – manufacture of flat glass
Investment	There is no NACE code associated with investment and therefore, no related value-added.		

The share of autocatalysts in world demand of platinum is much lower (30% in 2020). 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 23% of world platinum demand in 2020, compared with 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 7% share of platinum demand in Europe and 9% globally in 2020.

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 2010 and 2020 but remained positive. In 2020, 18% of the European and 14% of the global platinum demand came from investment (Johnson Matthey, 2022).

The relevant industry sectors and their 2- and 4-digit NACE codes are summarized in **Erreur ! Source du renvoi introuvable.**.

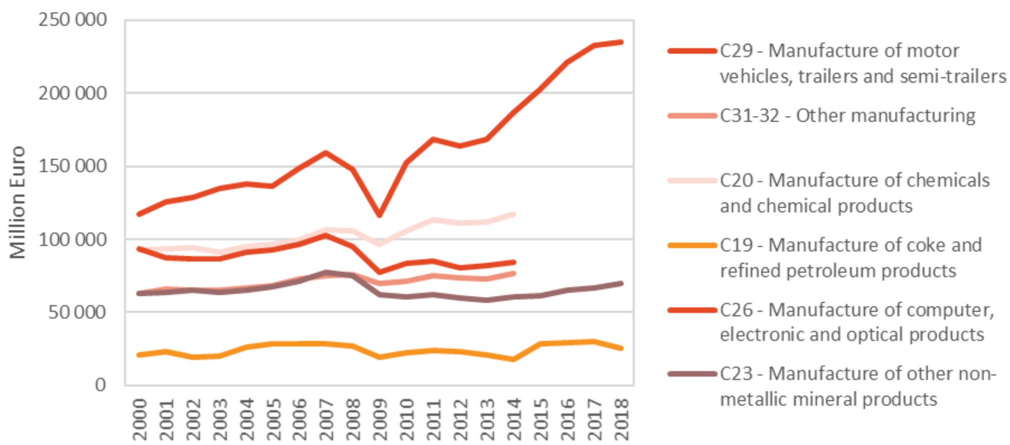

Figure 46. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS

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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 "General applications", are described below (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, and because of the higher sulphur tolerance of platinum.

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. Platinum 96% / Copper 4%; Platinum 95% / Palladium 5%) are widely used to make fine jewellery.

CHEMICAL INDUSTRY

Many chemical processes employ platinum-based catalysts in 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, 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 employed in the production of paraxylene (PX) which is an intermediate in the production of PET used for plastics and polyester textiles.

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.

Platinum is an active ingredient in anti-cancer drugs, as certain compounds (cisplatin, carboplatin and oxaliplatin) are effective in the treatment of a range of cancers by inhibiting cell division. Due to platinum's excellent biocompatibility, outstanding resistance to oxidation, durability and electrical conductivity combined

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with its radio-opacity, it 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).

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.

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 platinum solutions, with the platinum content of the catalyst usually less than 0.6% by weight.

ELECTRICAL AND 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) - although to a lesser extent than palladium.

GLASS

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).

Platinum's high melting point and resistance to corrosion by molten glass means that 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 (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 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

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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 are the predominant application of rhodium, accounting for 93% of total gross demand in 2020. Besides autocatalysts, rhodium is used in the chemical sector, which accounted for 6 % of the total gross demand.

The glass sectors demand for rhodium decreased significantly from a historic maximum of 2.9 tonnes in 2018 to only 0.1 tonnes in 2020.

Erreur ! Source du renvoi introuvable. shows the global use sectors of rhodium in 2010 - European numbers do not appear to be available.

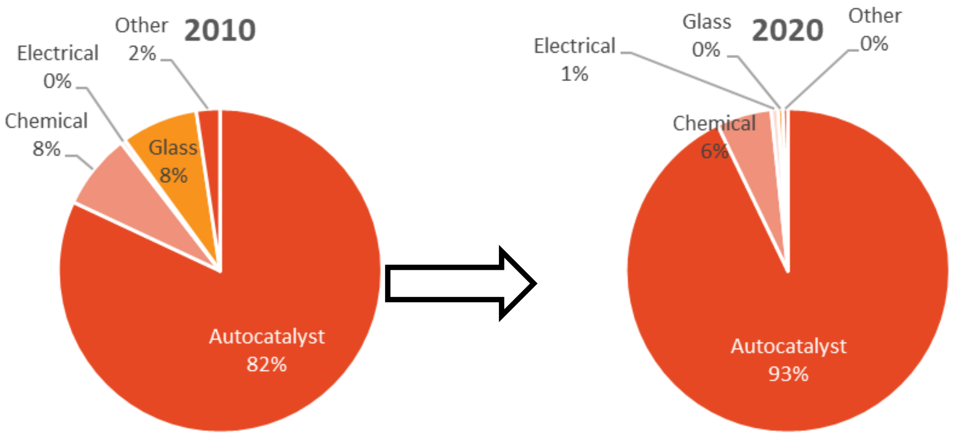

Figure 47. Global end uses of rhodium in 2010 and 2020 (Johnson Matthey, 2022).

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in **Erreur ! Source du renvoi introuvable.**.

Table 8. Rhodium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2018 (* for 2014) (Eurostat, 2021).

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Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Autocatalysts	C29 - Manufacture of motor vehicles, trailers and semi-trailers	234,398	C2932 - Manufacture of other parts and accessories for motor vehicles
Glass	C23 - Manufacture of other non-metallic mineral products	72,396	C2311 - Manufacture of flat glass
Chemical	C20 - Manufacture of chemicals and chemical products	117,150*	C2015 - Manufacture of fertilisers and nitrogen compounds
Electronics	C27 - Manufacture of electrical equipment	97,292	C2712 - Manufacture of electricity distribution and control apparatus

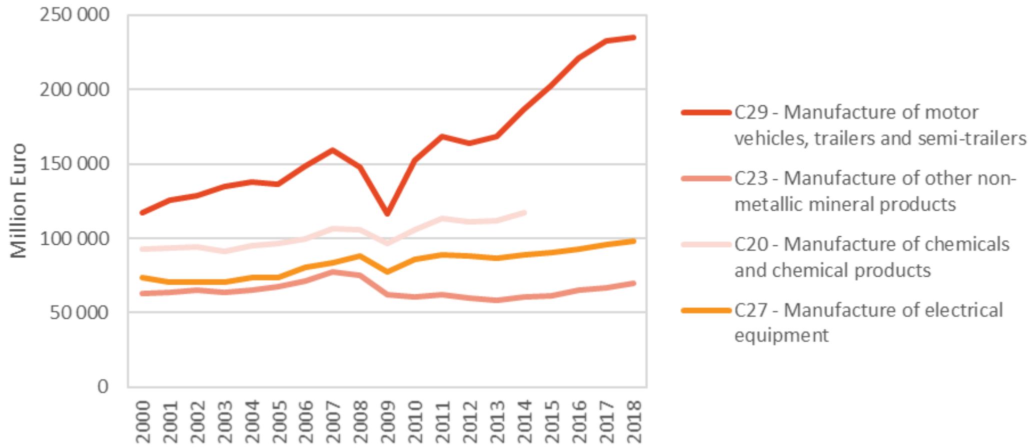

Figure 48. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS

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 (NOx) 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.

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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 been developed for use as catalysts in the production of various organic chemicals such as aldehydes, acetic acid production and hydrogenation reactions.

GLASS

Due to 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).

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 and spark plug tips.

USES AND END-USES OF RUTHENIUM

Ruthenium is used in electronic components and products, such as hard disk drives and contacts for thermostats and relays, which accounted for 39% of global gross demand in 2020 (**Erreur ! Source du renvoi introuvable.**). The remainder was used in chemical process catalysts (37%) and electrochemical applications (14%).

A range of other minor uses accounted for 10% 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 **Erreur ! Source du renvoi introuvable.**.

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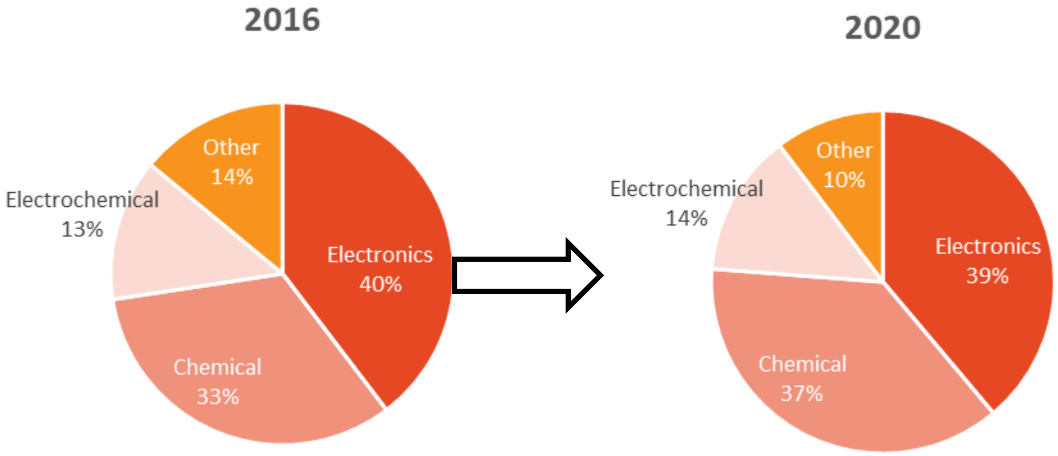

Figure 49. Global end uses of ruthenium in 2016 and 2020 (Johnson Matthey, 2021).

Table 9. Ruthenium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2019 (Eurostat, 2022).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Electronics	C26 - Manufacture of computer, electronic and optical products	84,074	C2620 - Manufacture of computers and peripheral equipment
Chemical	C20 - Manufacture of chemicals and chemical products	117,150	C2014 - Manufacture of other organic basic chemicals C2013 - Manufacture of other inorganic basic chemicals
Electrochemical	C20 - Manufacture of chemicals and chemical products	117,150	C2013 - Manufacture of other inorganic basic chemicals

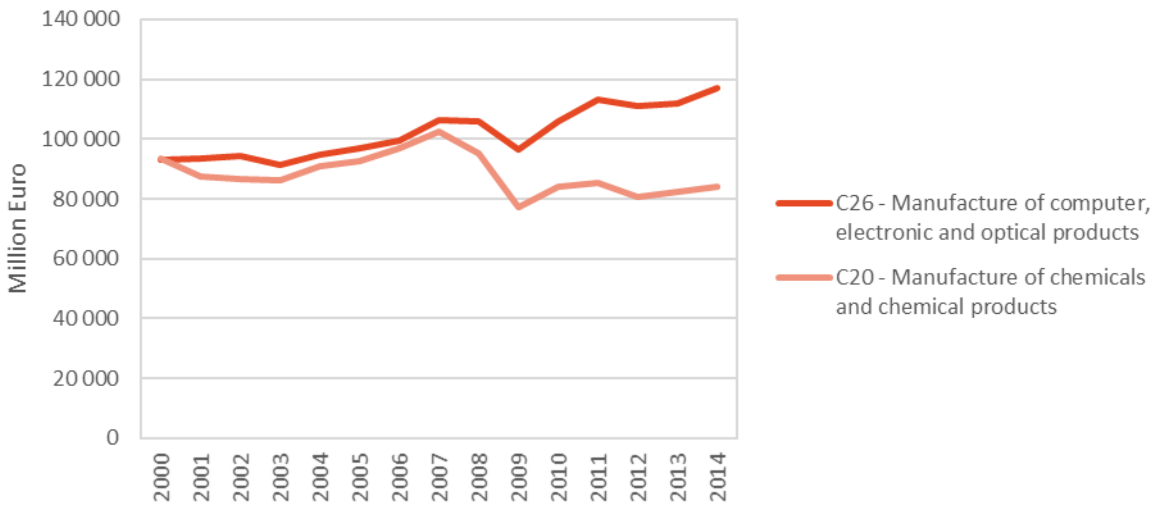

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Figure 50. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS

The applications of ruthenium are described below.

ELECTRICAL

A platinum-ruthenium alloy plays an important role in hard disk drives which apply the perpendicular magnetic recording (PMR) technology to increase the data storage capacity per unit area.

Ruthenium is 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.

CHEMICAL INDUSTRY

Ruthenium catalysts are employed in the production of a variety of speciality chemicals and 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 (nylon) production (process applied in China) (Johnson Matthey, 2019a).

The production of nylon is expected to increase in future leading to a higher ruthenium demand of this sector (SCRREEN CRM experts, 2022).

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.

SUBSTITUTION

SUBSTITUTION OF PGM IN GENERAL

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Nassar (2015) presented a detailed review of the potential for PGM substitution in the major commercial applications of the PGMs, concluding 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.

Substitution among PGM may occur when the price differential is large enough, as it had happened in 2000/2001 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, 2017).

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, 2017).

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, 2017). 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).

A shift from internal combustion engine vehicles to electric vehicles makes autocatalysts, which are needed to clean the exhaust gas, obsolete. This technology-by-technology substitution can lower the demand for PGMs without directly corresponding substitution materials (SCRREEN CRM experts, 2022).

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Table 10. Overview of substitutes of PGMs in general. Substitution of one PGM for another is not covered this table, but is described within the following section. Percentage of application bases on data by Johnson Matthey (2022) for the year 2020.

Use	% Application use	Substitute	Comment on substitute
Autocatalysts	60 %	Material: Transition metals Technology: EVs	Only for partial substitution; overall poor substitutability of PGM in autocatalysts. EVs do not need autocatalysts.
Jewellery	9 %	Silver, titan, tungsten, nickel	Depending on cultural attitudes and historical factors. Coatings and alloying elements are partially substitutable.
Chemical	9 %	Material: Nickel, cobalt, molybdenum, magnetite Technology: Alkaline or solid oxide electrolysers	Highly depending on application.
Electronics	7 %	Nickel, copper, gold, molybdenum, tungsten	Highly depending on application.
Investment	4 %	Gold, silver	Depending on prices.
Medical/dental	2 %	Nickel-based metal alloys	
Petroleum	2 %		
Glass	2 %		
Electrochemical	1 %	Tin	Highly depending on application.
Other	4 %	Other precious metals	

Platinum and iridium containing PEM electrolysers and fuel cells could be substituted by by alternative hydrogen technologies. Alkaline or solid oxide electrolysers, both usually not applying PGMs, could substitute PEM electrolysers. For the substitution of fuel cell technology, the applications need to be distinguished between stationary and mobile applications. In stationary use cases, solid oxide fuel cells can be a PGM-free alternative to PEM fuel cells. For mobile applications, the platinum and iridium containing PEM fuel cells are preferred due to their high power density (CRM experts, 2022). Hydrogen technologies itself can be replaced by e.g. battery electric vehicles instead of fuel cell electric vehicles, which would also decrease the demand for electrolysers.

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

SUBSTITUTION OF INDIVIDUAL PGMS

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

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ELECTRICAL

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.

ELECTROCHEMICAL

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).

CHEMICAL

For 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).

ALLOYING

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).

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

AUTOCATALYSTS

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

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applications (USGS, 2019). A shift from internal combustion engine vehicles to electric vehicles makes autocatalysts, which are needed to clean the exhaust gas, obsolete. This technology-by-technology substitution can lower the demand for palladium without directly corresponding substitution materials (CRM experts, 2022).

ELECTRONICS

In electronics, nickel-based multilayer ceramic capacitors can be used in place of those based on palladium with good performance (Graedel et al., 2015a).

JEWELLERY

In jewellery palladium could be substituted by nickel in some applications. In further applications, other base metals or special metals can be a substitute. In pure silver jewellery, palladium can be substituted by titanium and tungsten (CRM experts, 2022).

DENTAL

In dental restorations, alloys with palladium as an alloying agent can be replaced by nickel-based metal alloys (Graedel et al., 2015a).

PROCESS CATALYSTS

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).

INVESTMENT

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).

OTHER

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).

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. 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

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the event of a supply disruption of platinum, the ability to substitute it with palladium is likely to be limited. On a scale of 0 to 100, platinum's substitution index has been assessed as 66 by Graedel et al. (2015a). For particular applications of platinum, the potential substitutes are listed below.

AUTOCATALYSTS

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 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). A shift from internal combustion engine vehicles to electric vehicles makes autocatalysts, which are needed to clean the exhaust gas, obsolete. This technology-by-technology substitution can lower the demand for platinum without directly corresponding substitution materials (CRM experts, 2022).

JEWELLERY

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).

INVESTMENT

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).

PROCESS CATALYSTS

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).

GLASS

For glass manufacturing equipment, rhodium is a possible substitute and the other way round (CRM experts, 2022).

ALLOYS

Palladium-based alloys as alternatives to platinum-based alloys in dental and biomedical applications with adequate performance (Graedel et al., 2015b).

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ELECTRICALS

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).

OTHER

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).

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

AUTOCATALYSTS

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. A shift from internal combustion engine vehicles to electric vehicles makes autocatalysts, which are needed to clean the exhaust gas, obsolete. This technology-by-technology substitution can lower the demand for rhodium without directly corresponding substitution materials (CRM experts, 2022).

CHEMICAL INDUSTRY

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).

GLASS

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.

ELECTRICALS

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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.

OTHER

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.

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

ELECTRICAL

In some of ruthenium`s electrical applications, 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).

CHEMICAL INDUSTRY

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 most 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).

ELECTROCHEMICAL

Generally, the substitution of ruthenium in electrochemical application is difficult (CRM experts, 2022). In the chlor-alkali industry iridium-based coatings of dimensionally stable anodes are an alternative to ruthenium-

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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).

OTHER

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).

SUPPLY

EU SUPPLY CHAIN

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). **Erreur ! Source du renvoi introuvable.**presents the total PGM production in the EU for both primary and secondary sources.

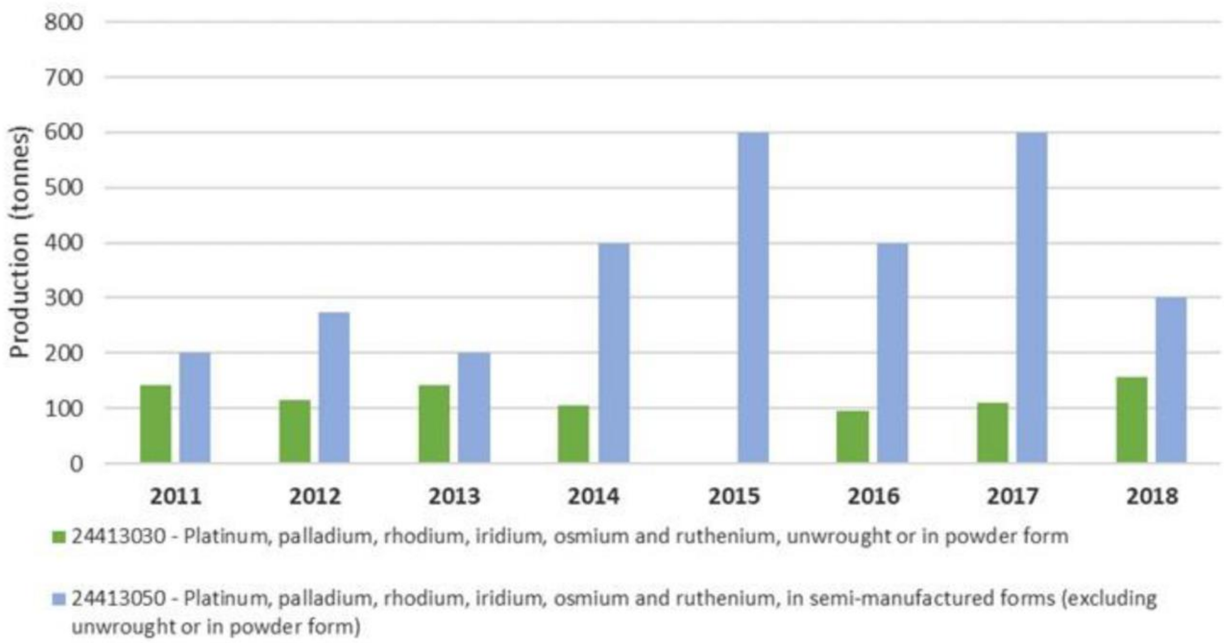

Figure 51: Production sold of PGM in various forms in EU. Data202 from Eurostat Prodcom (Eurostat, 2019b).

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

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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 or by the automotive. 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 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 copper mining. The annual average head grade of the ore ranges from 0.29 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 kilograms 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

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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).

EU SUPPLY CHAIN OF PGMS BY INDIVIDUAL METAL

IRIDIUM

There is no Ir production in EU by primary resources. About 3.9 and 5 tonnes of Iridium were imported in EU in 2019 and 2020. About 9.8 and 6.8 tonnes of Ir were exported by EU in these years contained in final or intermediate products. United Kingdom, South Africa and United Stated are the major importers at the processing stage. There are no data concerning the specific recycling rate of Ir in EU. The end-of-life recycling input rate globally is estimated at 14% (Eurostat, 2020).

PALLADIUM

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. The palladium flows through the EU economy (2012 data) are illustrated in Figure 5. A small quantity of palladium by primary resources is taking place in Finland (700 kg and 850 kg in 2019 and 2020). Few kgs are produced annually in Poland. Russia, United States and United Kingdom were the main importers at the processing stage. Around 80 and 45 tonnes were imported in 2019 and 2020. The exports in the same period were 57 and 48 tonnes. The Pd EoL RIR in EU is estimated at 10%, significantly lower in comparison to the recycling rate globally (27%) (Eurostat, 2020).

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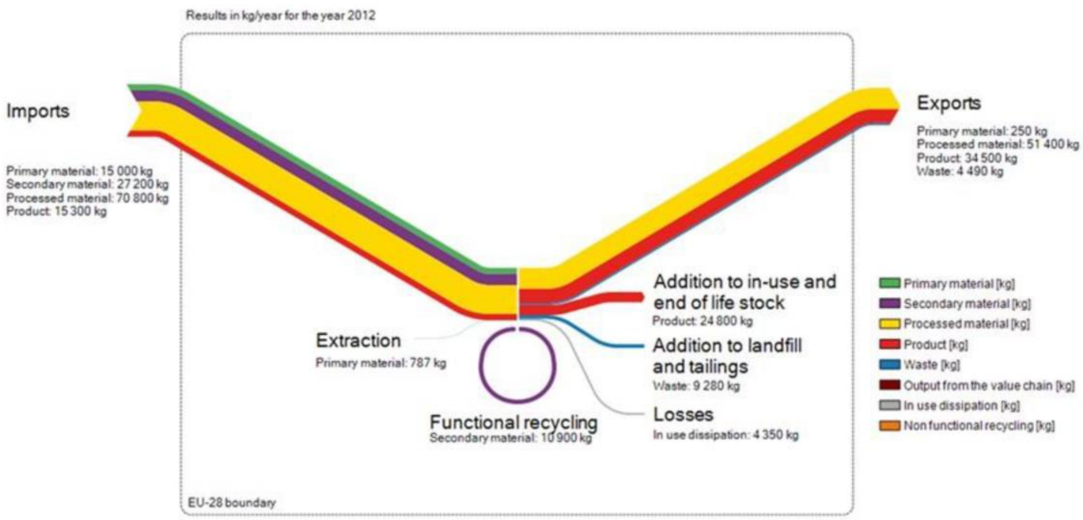

Figure 52: Simplified MSA of palladium flows in the EU for 2012. (BIO Intelligence Service, 2015a).

PLATINUM

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. The platinum flows through the EU economy (2012 data) are illustrated in Figure 53. A minor platinum production by primary resources is performed in Finland. The produced amount was about 950 kg in 2019 and 1300 kg in 2020. A very small production (few kgs) is reported in Poland. Platinum imports were 53.5 and 31.5 tonnes in 2019 and 2020. The respective exported amounts were about 40 and 43 tonnes. United Kingdom, South Africa and United States are the main importers at the processing stage. The Pt EoL RIR in EU is estimated at 11%, significantly lower in comparison to the recycling rate globally (27%) (Eurostat, 2020).

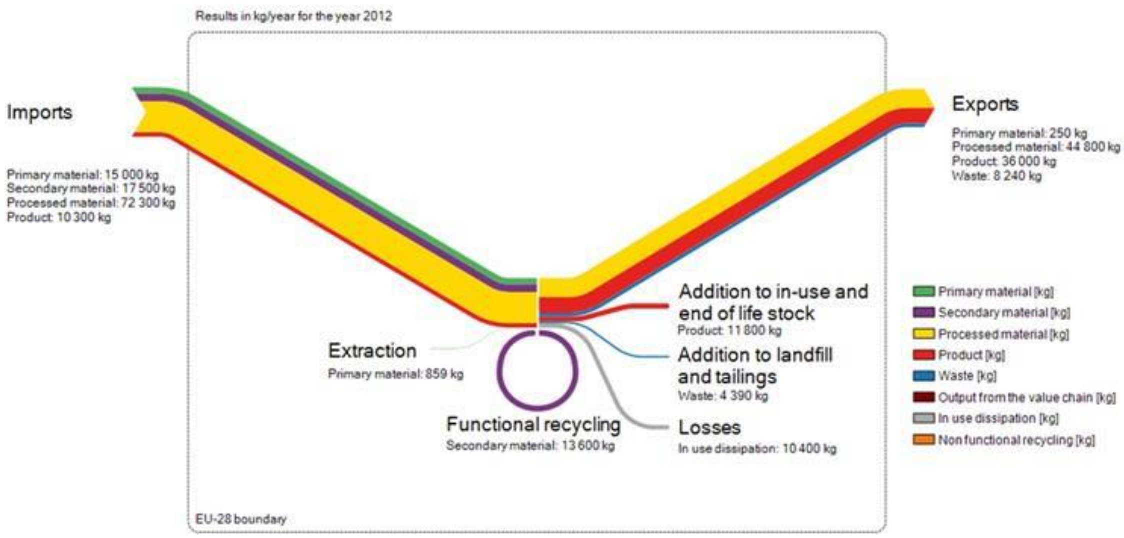

Figure 53: Simplified MSA of platinum flows in the EU for 2012. (BIO Intelligence Service, 2015a).

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RHODIUM

Figure 8 shows the rhodium flows through the EU economy (2012 data). There is no Rh production in EU by primary resources. About 5.6 and 4 tonnes of Ruthenium were imported in EU in 2019 and 2020. About 8.5 and 9 tonnes of Rh were exported by EU in these years contained in final or intermediate products. United Kingdom, Russia and United Stated are the main producers at the processing stage. The EoL RIR of Rh in EU is estimated at 24 %, while the respective recycling rate globally is 28% (Eurostat, 2020).

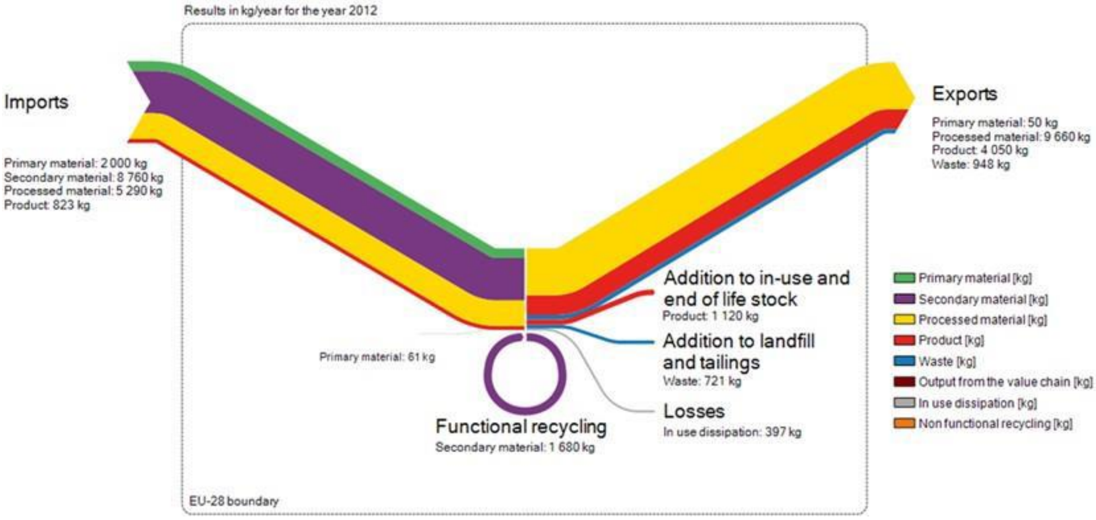

Figure 54: Simplified MSA of rhodium flows in the EU for 2012. (BIO Intelligence Service, 2015a).

RUTHENIUM

There is no Ru production in EU by primary resources. About 3.9 and 4.5 tonnes of Ruthenium were imported in EU in 2019 and 2020. About 9.8 and 6.5 tonnes of Ru were exported by EU in these years contained in final or intermediate products. United Kingdom, South Africa and United Stated are the major importers at the processing stage. There are no data concerning the specific recycling rate of Ru in EU. The EoL RIR globally is estimated at 14% (Eurostat, 2020).

SUPPLY FROM PRIMARY MATERIALS

Palladium and platinum are overwhelmingly produced as the dominant companion metals in PGM ores and in smaller but not insignificant amounts as by-products from nickel-copper ores. The Russian PGM production is almost exclusively by-product from nickel mining. Very minor amounts of palladium, and even less platinum, are recovered from other types of copper ores. Other PGMs are almost exclusively recovered as by-products from palladium and platinum ores; minor volumes of iridium, rhodium, and ruthenium may be recovered from nickel ores with platinum and palladium, but exact information as how much is missing.

GEOLOGY, RESOURCES AND RESERVES OF PGMS

GEOLOGY

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211

The PGMs are among the rarest elements on Earth. Their abundance in the Earth's upper continental crust ranges from 0.022 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. The 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).

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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 several 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+palladium containing 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.

IRIDIUM

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. The most common Ir minerals are irarsite (IrAsS), laurite ($(Ru,Ir)S_2$) and erlichmanite ($(Os,Ir)S_2$).

PALLADIUM

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). Among the common palladium-rich minerals are kotulskite (PdTe), merenskyite ($PdTe_2$), michenerite (PdTeBi), vysotskite (PdS), palladoarsenite ($Pd_2(As,Sb)$), and braggite ((Pt,Pd)S).

PLATINUM

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). The most common Pt minerals are sperrylite (PtAs2), moncheite (PtTe2), braggite (Pt,Pd)S), and cooperite (PtS). In addition, metallic platinum and platinum-palladium alloys occur in placer deposits; in weathered parts of PGM deposits, also platinum–palladium±gold±copper±iron alloys may be present in volumes that make an occurrence an economic ore. Note, however, that both the placers and weathered parts of the deposits are of very minor significance for the global PGM supply, and typically are significant only as an income for the local artisanal miners.

RHODIUM

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. The most common Rh minerals are hollingwortite (RhAsS), and laurite ($(Ru,Ir)S_2$).

RUTHENIUM

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

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significantly lower than that of platinum and palladium. The most common Ru minerals are laurite ($(Ru,Ir)S_2$), and cuprorhodsite $CuRh_2S_4$.

GLOBAL RESOURCES AND RESERVES:

According to USGS (2022) the world identified resources of PGMs is about 100 million kilograms and reserves at 70 million kilograms (USGS 2022). Mudd et al. (2018) estimated that 68 % of all PGM resources are in South Africa, 17 % in Russia and 9 % in Zimbabwe; but the global reserves only at 17,000 tons, similarly distributed as the resources. Additional resources and reserves have been defined since the Mudd et al. (2018) work, but the dominant host and producing countries are the same; also, the aggregated global resources and reserves are of the same size (USGS 2018, 2022). More than 90 % of the PGM reserves and resources are formed by palladium and platinum.

It is practically impossible to get reliable information on iridium, rhodium, and ruthenium reserves and resources. This is due to not reporting them at all even from most PGM-only deposits or reporting them calculated together in various ways, such as total PGM content, total PGM+gold, or as palladium+platinum+rhodium. In a few exceptions, the rhodium content is given, but not that of iridium or ruthenium.

Main minerals wherefrom PGMs are extracted include braggite, cuprorhodsite, erlichmanite, hollingwortite, irarsite, kotulskite, laurite, merenskyite, michenerite, moncheite, palladoarsenite, sperrylite, and vysotskite.

Depending on the source of information (Mudd et al. 2018, USGS 2022), 65–90 % of the global PGM reserves are in South Africa, 6–23 % in Russia, and the rest is other countries, as shown in **Erreur ! Source du renvoi introuvable.**.

Table 11. PGM reserves by country, in tons and by percentage of global total.

	USGS (2022)		Mudd et al. (2018)	
Country	*Tonnes*	*%*	*Tonnes*	*%*
South Africa	63,000	90	10,790	64
Russia	4,500	6.4	3,932	23
Zimbabwe	1,200	1.7	747	5
USA	900	1.3	727	4
Canada	310	0.4	504	3
Finland	41[1]	<0.1	41[1]	0.4
Total	70,000[2]		16,840	

1 Figures from Boliden (2022), indicate end-2021 situation.
2 Rounded

EU RESOURCES AND RESERVES

The most significant EU PGM resources occur in Finland and Sweden into Ni–Cu sulphides ores at concentrations in the range of few ppm to few dozens of ppm. Most platinum-group minerals occur as single, minute grains included in silicates (57%) or attached to the grain boundaries of sulphides (Gervilla and Kojonen, 2022). The largest platinum-group metal (PGM) resource in Europe is located at the Suhanko Arctic Platinum mine project in Finland (www.suhanko.com/english), comprising two contact-type deposits 3 km apart, and containing 226.5 tons Pd and 52.4 tons Pt in a NI43-101 compliant resource. Other significant deposits in Finland, by tonnes of contained PGM, include the Kevitsa mine, Sakatti mine project, and Siika-Kämä Reef and Sompujärvi Reef deposits (Mineral Deposit Database of Finland 2022). More detailed listing of the largest deposits in Finland is given in Tables 12 and 13. At the end of 2021, aggregated PGM reserves in Finland were 41 tons, CRIRSCO-compliant resources (in addition to reserves) 584 tons, and CRIRSCO-noncompliant resources of 217 tons (Mineral Deposit Database of Finland 2022). In addition, there a median estimate of 'undiscovered' resources gives 17,600 tons for the whole country – these are assumed resources which cannot be indicated to any known deposit but are estimated for PGM-potential domains of Finland (Rasilainen et al. 2016). More than 90 % of the Finnish PGM reserves and resources are in PGM-dominated deposits hosted by layered intrusions; the rest is in nickel deposits in other types of ultramafic intrusions (Rasilainen et al. 2010). In addition, there might be several tens of tons palladium and platinum in the ore of the black-shale-hosted Terrafame Ni-Cu-Co-Zn mine, possibly at grades 0.015–0.03 ppm. However, we have no information if any of the PGMs in the Terrafame mine is recovered.

In Sweden, the total reported resources amount to about 0.485 tons of PGM, shared between two nickel deposits (Eilu et al. 2021a, 2021b). Similar to Sweden, there is a PGM resource potential in nickel deposits in Cyprus, Portugal, and Spain but with no reported PGM in resource tonnage (Lauri et al. 2018).

During the past 25 years, Poland has reported production of 5–100 kg PGMs per year (WMD 2022). These are extracted from the Kupferschiefer-type deposits in southern part of the country. Kucha (1982) and Piestrzynski et al. (2002) have reported from Lubin, of a few cm to 22 cm thick unit rich in PGMs and gold. In detail, Piestrzynski et al. (2002) report the unit containing, in average 2.25 ppm gold, 0.138 ppm platinum, 0.082 ppm palladium. Shepherd et al. (2005) mentions from Lubin a 0.5–1.5 m thick blanket extending for 120 km^2, and having metal grades at 0.5 ppm gold, 0.2 ppm platinum, and 0.1 ppm palladium. Including this unit into the copper ores mined at Lubin would explain the PGM production of Poland. On the other hand, the Polish national deposit database does not report any PGM reserves nor resources (PGI 2022). Similar deposits also occur in Germany, has been described within the Mansfeld–Sangerhausen district, but also from there no resource data including the PGMs seem to exist.

Porphyry copper deposits may also contain recoverable PGMs. Within the EU, the Elatsite deposit in Bulgaria is known to contain 6.7 t of platinum+palladium (Pt+Pd), and in Greece, the Skouries 2 porphyry copper deposit is reported to have an average grade of 0.047 ppm Pt+Pd; the Skouries deposit is, hence, assumed to contain about 23 tons PGMs (John & Taylor 2016). Similar PGM potential is present also elsewhere in the Balkans (McFall et al. 2018).

Little is known of PGM contents in laterite nickel deposits in the Balkans. These relate to ultramafic intrusions and, hence, one would expect them to have also the PGMs, as is indicated by, e.g., Proenza et al. (2008) and Ma et al. (2022). In any case, laterite nickel deposits are not known to have produced much, if any, PGMs,

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anywhere, indirectly suggesting issues related to ore processing, whereas placer deposits were a major source of platinum and palladium prior to the discovery of the Bushveld deposits in early 1920s.

Table 12. Platinum-group metal resources data in the EU. Note that a number of deposits in Finland is not included, each of which containing 0.2 to 10 t PGM, the estimates of which mostly non-compliant with the CRIRSCO reporting codes (i.e., equal to UNFC categories 331 to 343).

Country	Classification	Quantity (Mt of ore)	Grade (ppm)	Reporting code	Reporting date	Deposit, Source
Finland	Measured	50.0	0.11 Pd 0.17 Pt	PERC	12/2021	Kevitsa mine (Boliden 2022)
	Indicated	88.0	0.07 Pd 0.11 Pt		12/2021	
	Inferred	0.2	0.02 Pd 0.03 Pt		12/2021	
	Indicated	3.5	1.18 Pd 0.98 Pt	NI43-101	2017	Sakatti mine project (Anglo American 2017)
	Inferred	40.9	0.43 Pd 0.61 Pt			
	Measured	38.197	0.707 Pd 0.141 Pt	NI 43-101	2017	Ahmavaara mine project (Mineral Deposit Database of Finland 2022)
	Indicated	114.816	0.851 Pd 0.175 Pt			
	Inferred	34.757	0.867 Pd 0.187 Pt			
	Measured	26.031	1.064 Pd 0.307 Pt	NI 43-101	2017	Konttijärvi mine project (Mineral Deposit Database of Finland 2022)
	Indicated	37.571	0.902 Pd 0.255 Pt			
	Inferred	11.638	0.867 Pd 0.241 Pt			
	Indicated	6.1	2.72 Pd 0.77 Pt	JORC	06/2004	Siika-Kämä Reef deposit (Mineral Deposit Database of Finland 2022)
	Inferred	43.3	2.41 Pd 0.65 Pt			
	Inferred	6.7	5.36 Pd 3.08 Pt 0.38 Rh	Historic	1990	Sompujärvi Reef deposit (Mineral Deposit Database of Finland 2022)
	Indicated	38.2	0.61 Pd 0.22 Pt	NI43-101	04/2022	Kaukua deposit (Mineral Deposit Database of Finland 2022)
	Inferred	10.875	0.52 Pd 0.2 Pt			
	Indicated	32.7	0.25 Pd 0.1 Pt	NI43-101	04/2022	Haukiaho deposit (Mineral Deposit Database of Finland 2022)
	Inferred	13.2	0.64 Pd			

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			0.2 Pt			
	Inferred	29.8	1.12 Pd 0.18 Pt	Historic	2000	Yli-Portimojärvi deposit (Mineral Deposit Database of Finland 2022)
	Inferred	5.0	2.48 Pd 4.04 Pt 0.08 Rh	Historic	1990	Paasivaara deposit (Mineral Deposit Database of Finland 2022)
	Indicated + Inferred	32.0	0.68 Pd 0.25 Pt	NI43-101	2011	Vaaralampi deposit (Mineral Deposit Database of Finland 2022)
Sweden	Inferred	0.2	0.4 Pd	Historic	2019	Storsjö kapell deposit (Eilu et al. 2021b)
	Inferred	0.46	0.68 Pd 0.2 Pt	JORC	2018	Lainijaur deposit (Eilu et al. 2021b)

Table 13. Platinum-group metal reserves data in the EU.

Country	Classification	Quantity (Mt of ore)	Grade (ppm)	Metal content (t)	Reporting code	Reporting date	Source
Finland	Proven	72.0	0.11 Pd	7.29	PERC	12/2021	Kevitsa mine (Boliden 2022)
		72.0	0.18 Pt	12.96			
	Probable	52.0	0.15 Pd	7.8	PERC	12/2021	
		52.0	0.23 Pt	11.96			

GLOBAL AND EU MINE PRODUCTION

Global annual mine production of PGMs during the past 20 years (excluding the slump in 2014 for platinum in South Africa) has been 185–225 tons, of platinum 165–205 tons, and that of rhodium 19–28 tons (**Erreur ! Source du renvoi introuvable.**-59 (USGS 2022, WMD 2022). No global production data exists for iridium and ruthenium, but from demand data (Johnson Matthey 2022) one may deduce mine production for iridium at 6–8 tons and for ruthenium about 30–35 tons per year. In the same time period within the EU, 12–162 tons of palladium and 23–1584 tons of platinum have been extracted from mines. Of the EU PGM production, 95–100 % has come from mines in Finland since 1984 except for 2008–2011 when no PGMs were extracted from the Finnish mines (Tukes 2022, WMD 2022). The rest of the EU PGMs has been produced from Poland, at 0.015–0.08 tons per year since 1998.The dominant global PGM producer, except for palladium, is South Africa with the shares of >90 % for iridium and ruthenium, 33 % for palladium, 68 % for platinum, and 81 % for ruthenium, in 2020 (Johnson Matthey 2022, USGS 2022, WMD 2022). Russia is the largest global palladium miner (41 %) and the second for the other PGMs (13 % of platinum, 8.6 % of rhodium). During the past four decades, the South African and Russian shares of the global PGM mining have been very much the same (WMD

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2022). Zimbabwe, Canada, and USA have constantly formed the ranks three to five in the global data. The EU share of the global mined PGMs was 0.6 % in 2020; this figure has varied from zero to about the current value during the past four decades. Only palladium and platinum are extracted from the EU mines (WMD 2022).

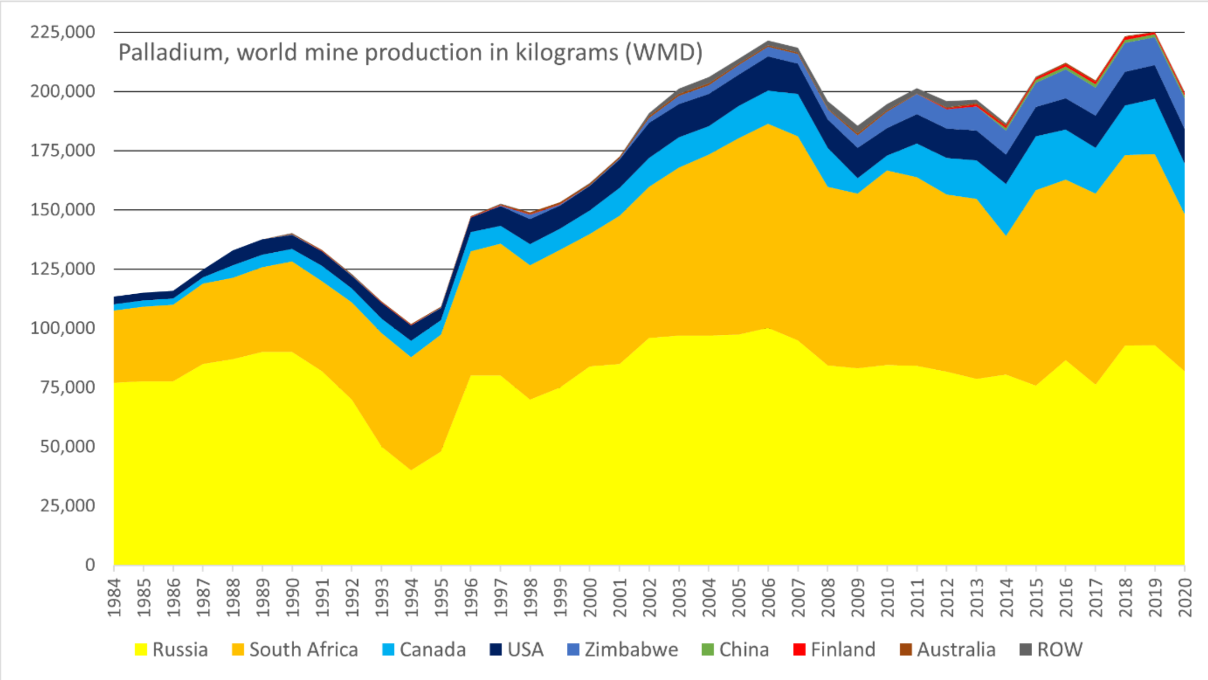

Figure 55. Global mine production of palladium (WMD 2022). The largest producers (as of 2020) shown individually, in decreasing order. ROW = rest of the world.

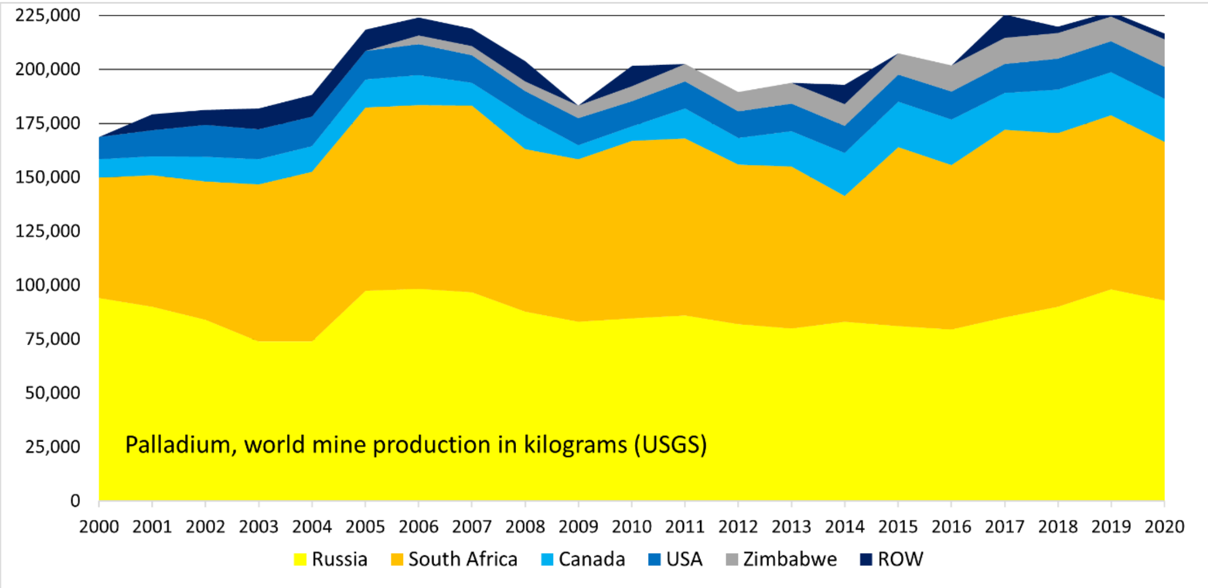

Figure 56. Global mine production of palladium (USGS 2022). The largest producers (as of 2020) shown individually, in decreasing order. ROW = rest of the world.

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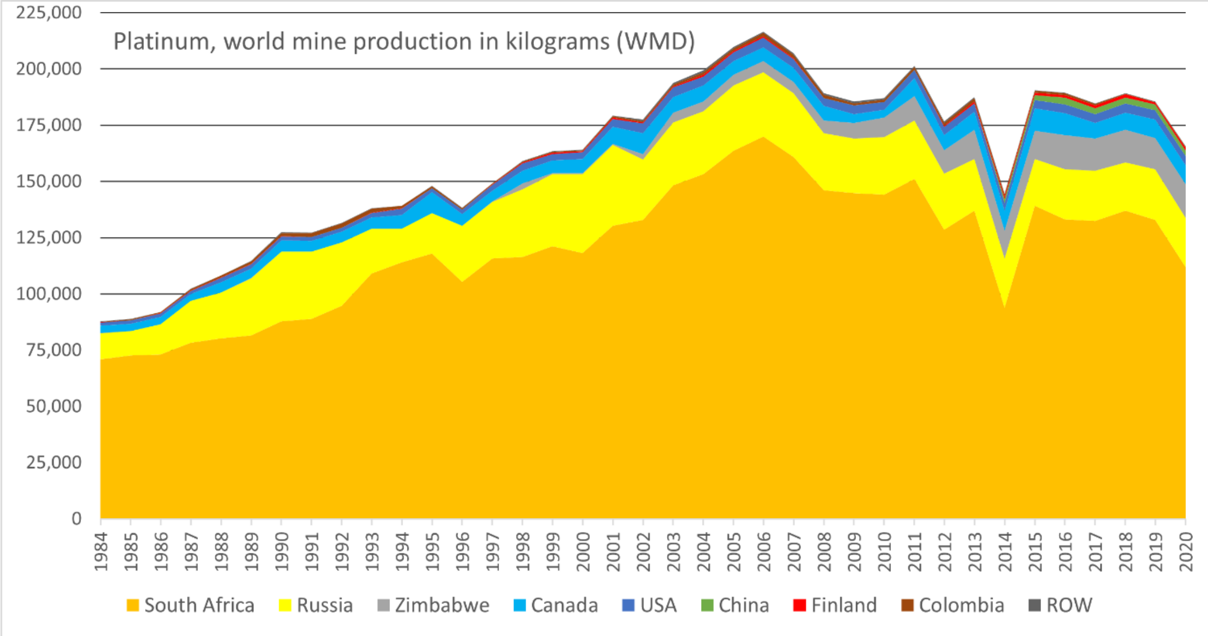

Figure 57. Global mine production of platinum (WMD 2022). The largest producers (as of 2020) shown individually, in decreasing order. ROW = rest of the world.

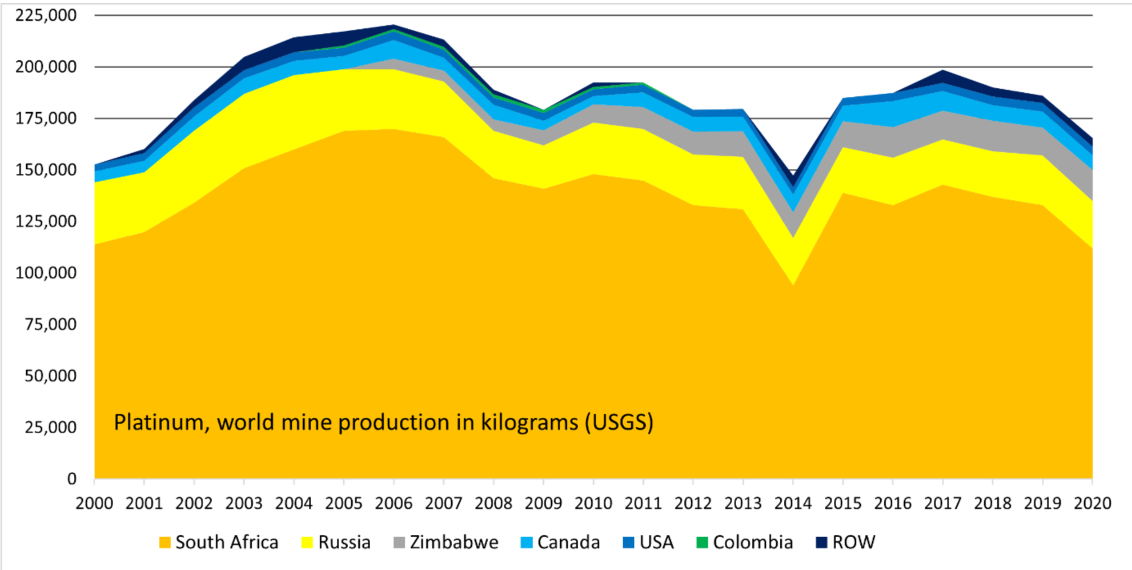

Figure 58. Global mine production of platinum (USGS 2022). The largest producers (as of 2020) shown individually, in decreasing order. ROW = rest of the world.

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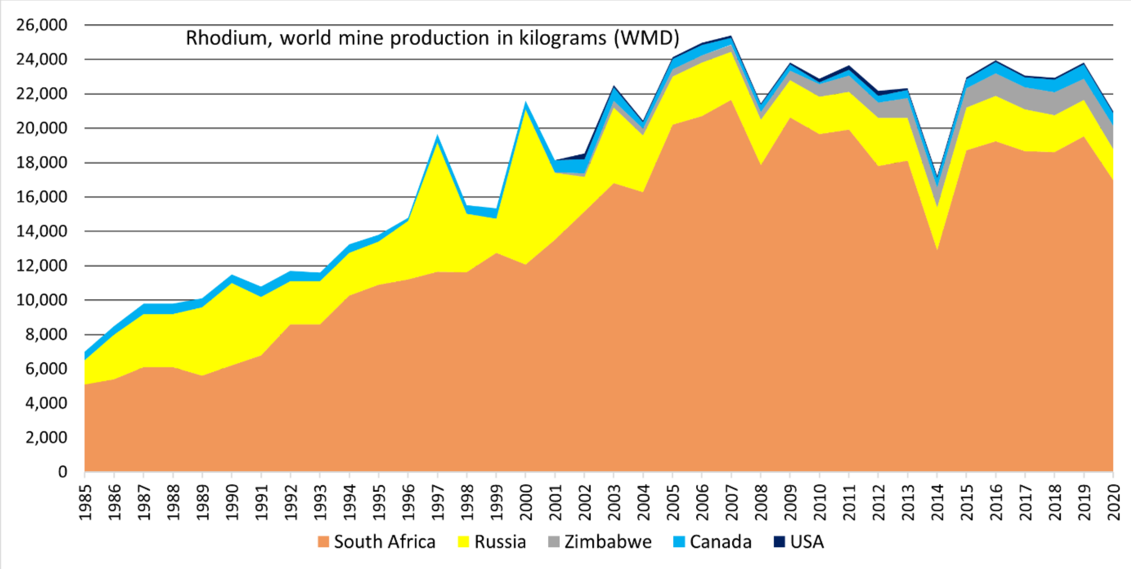

Figure 59. Global mine production of rhodium, in kilogram (WMD 2022). All known producers (as of 2020) shown individually, in decreasing order.

OUTLOOK FOR SUPPLY

Most probably, Russia and South Africa will continue to be the leading global suppliers of the platinum-group metals. However, the war in Ukraine and related sanctions against Russia may cause severe disruptions in palladium availability especially in the EU, USA, Japan and South Korea. This issue with Russia is not as severe with other PGEs, as South Africa is the dominant producer than for palladium. Other possible PGM supply risks include energy availability in South Africa and social unrest in both Zimbabwe and South Africa, and reliance of just one processing plant in a dominant producing country. Unless the supply risks realise, it is assumed that Zimbabwe, Canada, and USA will remain the next largest PGE producers, jointly comprising 15–25 % of the global PGE mining.

On supply issues related to Russia, Johnson Matthey (2022) reports: "... the removal of Russian refineries from the LPPM [London Platinum and Palladium Market] 'Good Delivery' list on 8th April will affect deliveries of metal to Western customers going forward. It is difficult to anticipate the size of the impact..." and "The LPPM decision means that ingot and sponge produced by Russian refineries after 8th April will no longer be accepted for 'Good Delivery' into the London and Zurich bullion market."

An example of supply issues resulting from a commodity production heavily relying on just one processing plant realised in South Africa in 2020–2021 and was reflected by metal prices. The Anglo American Platinum's converter plants (ACP) were severely broken down. On this, Johnson Matthey (2022) reports: "Rhodium was the most severely affected: the price surged repeatedly to highs of around $30,000 [per ounce], reflecting extreme shortages of availability following outages at Anglo American's ACP plant during 2020, which created a backlog containing around one million ounces of PGM. Iridium also experienced extreme price pressure, climbing to a peak of $6,300 in April – by far the highest price ever seen for this metal – while ruthenium reached a fourteen-year high of $800 during May."

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A few PGM and PGM-nickel-copper mines projects are under development globally, in xxx, xxx, xxx. Of PGM mine projects there also are two Finland: Sakatti and Arctic Platinum. The latter focusses on the Ahmavaara and Konttijärvi deposits. In both cases, work is ongoing towards a full feasibility, but the opening of the mines is not expected to take place in short nor medium term.

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

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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).

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

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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.

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".

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

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, and 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

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economically attractiveas 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).

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 14) 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.

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 regarding 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).

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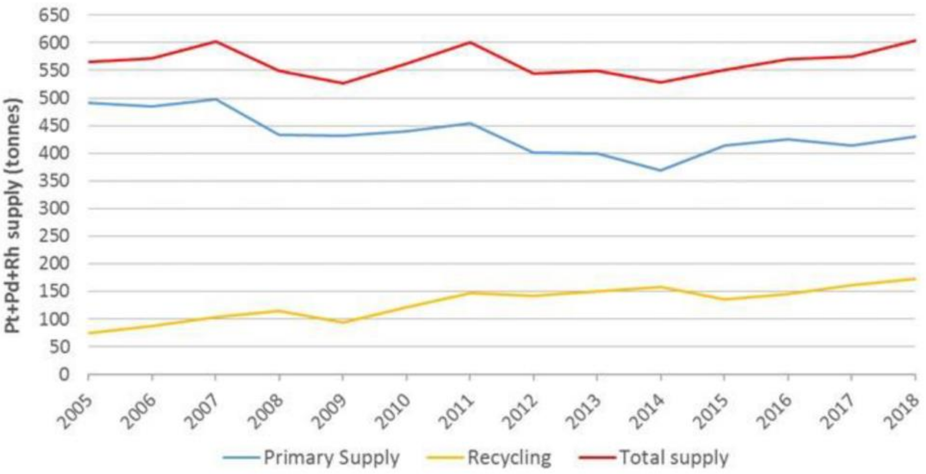

Figure 60: Global supply of PGM (Pt+Pd+Rh) from mine production and recycling (2005–2018). Background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, and (Johnson Matthey, 2014) for 2005-2012.

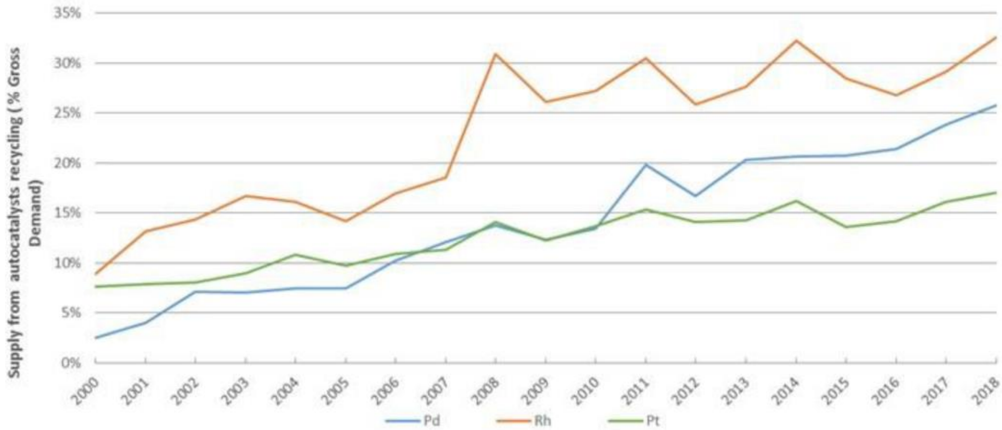

Figure 61: Contribution of autocatalysts recycling to platinum group metals world market balance (2000-2018). Background data from (Johnson Matthey, 2019a) for 2014-2018, (Johnson Matthey, 2018) for 2013, and (Johnson Matthey, 2014) for 2005-2012.

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%.

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

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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.

SUPPLY OF INDIVIDUAL PGMS FROM SECONDARY MATERIALS

SUPPLY OF IRIDIUM FROM SECONDARY MATERIALS

Recycling makes an important and growing contribution to global PGM supply

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

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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%. **Erreur ! Source du renvoi introuvable.** provides an overview of the recycling rates by end-use sectors.

Table 14: 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 **Erreur ! Source du renvoi introuvable.** .

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Table 15: Global end-of-life recycling rates (%) for palladium by end-use sector (Hagelüken, 2014; UNEP, 2011).

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

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application (European Commission, 2017). An overview of the recycling rates by end-use sectors is provided in **Erreur ! Source du renvoi introuvable.**.

Table 16: 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 9), 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 **Erreur ! Source du renvoi introuvable.**), 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 17: Global end-of-life recycling rates for rhodium by end-use sector (UNEP, 2011; Hagelüken, 2014).

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,

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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 **Erreur ! Source du renvoi introuvable.**). 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 18: 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

OTHER CONSIDERATIONS

IRIDIUM

HEALTH AND SAFETY ISSUES RELATED TO THE RM OR SPECIFIC/RELEVANT COMPOUDS AT ANY STAGE OF THE LIFE CYCLE

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Iridium192, a radioactive isotope of iridium (Ir), is used as an ionizing source in industrial radiography to detect flaws in metal components. A 10-year medical follow-up (kicked off in 2002) of 70 Chinese workers exposed to low-dose Ir192 radiation showed that exposure to persistent low-dose Ir192 radiation caused various degrees of immune dysfunction, blood cells and bone marrow abnormalities, chromosome aberrations, and changes in the telomerase activity of bone marrow mononuclear cells. Furthermore, according to the findings, the recovery from immune dysfunction and abnormalities in blood cells and bone marrow took 1-3 years, the recovery from chromosome aberration took between 5 and 10 years, and the recovery of normal telomerase activity of bone mononuclear cells took more than 10 years (Hongbo, Li et al., 2016). (Wiseman, C., 2014) reviewed bioaccessibility and toxic potential of platinum group metals (PGMs), a group of metals which includes iridium, platinum, palladium, rhodium, ruthenium, and osmium. The author reported that the most relevant route of exposure to PGMs is airborne particulate matter (PM), emitted to the atmosphere by vehicle catalytic converters. There is evidence that PGMs are bioaccessible and even though their toxicity needs further analysis, their widespread presence in the organism suggests that they are a human health concern.

ENVIRONMENTAL ISSUES

No recent information found

NORMATIVE REQUIREMENTS RELATED TO MINING/IRIDIUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

(ASTM International 2022) developed a set of voluntary standard specification for refined iridium. The scope of this specification covers refined iridium as sponge and powder in two grades as follows: Grade 99.80 (UNS PO6100)—Iridium having a purity of 99.80 % ; Grade 99.90—Iridium having a purity of 99.90 %. This standard specification was developed in accordance with the guiding principles of the World Trade Organization (WTO).

(MMTA 2022) provides optional guidance for sampling and assaying iridium for shipments, regarding inspection schedule, sampling schedule and sampling preparation. Other issues such as Standard documentation, Weighing & Sampling when shipping iridium follow the MMTA Consolidated Regulations (MMTA 2022b).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF IRIDIUM FOR EXPORTING COUNTRIES

Table 20 lists the countries for which the economic value of exports of iridium, osmium and ruthenium represents more than 0.1 % of the total value of their exports.

Table 19: Countries with the highest economic shares of iridium, osmium, and ruthenium exports in their total exports.

Country	Export value (USD)	Share in total exports (%)
South Africa	1,191,984,881	1.0

Source: COMTRADE (2022), based on data for 2021.

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SOCIAL AND ETHICAL ASPECTS

In 2014 the platinum mining industry, of which iridium is a by-product, was subject to the longest workers' strike in South African history. Seventy thousand workers of the three biggest companies of the country (Impala Platinum, Lonmin, and Anglo-American Platinum) went on strike from January to June, requesting a 150 % wage increase. However, the companies did not meet their demands and offered an increment of 10 %, which triggered a prolonged strike, clashes, intimidations, and violence, leading to the death of 9 workers. On June 24th the Association of Mineworkers and Construction Union signed a deal with the platinum companies to end the strike, with the promise of an 18 % wage increase (Buratovic, E., et al., 2017; UK Foreign & Commonwealth Office, 2014). More recent sources (Stoddard, E., 2018) show that South Africa's platinum belt, where platinum group metals are extracted, was still afflicted by miner protests as of March 2018. Between 2016 and 2018 the road infrastructure was frequently afflicted by either roadblock, wildcat strikes, marches, or acts of vandalism. The reason of the protests was the high unemployment rates, poverty, and unsafe working conditions at the mine.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Iridium application in hydrogen production

Iridium is the primary material used in catalysts for water splitting in hydrogen production, given its high corrosion resistance, high conductivity, wide pH window, and catalytic properties (Dhawan H. et al., 2021). According to Chen Z. et al. (2020), Iridium is used in the two semi-reactions involved in the process: hydrogen evolution reaction (HER), where H_2 molecules are created, and oxygen evolution reaction (OER), where water is split to generate H^+ protons and O_2. Iridium can be used in different forms, even though the authors claim that the best option is metallic Ir-based catalysts for the HER process, considering that some strategies to enhance catalytic performance are morphology control and alloying. As for the OER process, the best Iridium forms are Ir oxides. The most efficient method to improve their catalytic properties are doping, component regulation and hybridisation with other electroactive nanomaterials

- Iridium light-emitting electrochemical cells

According to Ma D. et al. (2020), Iridium and other ionic transition metal complexes are currently being studied to be applied as active layer materials in light-emitting electrochemical cells (LEC), which are a young and promising lighting technology. They are characterised by low-cost, easy large-scale manufacturing thanks to their simple architecture. They are composed of a light emissive layer sandwiched between a reflective cathode and a transparent anode. Nonetheless, LEC hasn't yet reached the efficiency and lifetimes needed to be launched in the market, and researchers are making significant efforts to improve their features.

Namanga J. et al. (2020) have applied cationic iridium (III) complexes as active layers in an LEC structure, reporting a luminance value of 2267 cd/m^2, a power efficiency value of 25.8 lm/W and a 757-hour lifetime. Thus, results show that, even though still far away from efficiencies of light emitting diodes, this technology

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progresses towards its use at the industrial scale, achieving high luminance, current and power efficiency, long service time and fast turn-on time.

- HEMCAT2: Towards Non-Iridium High Entropy Material ElectroCATalysts for Oxygen Evolution Reaction in Acidic Media - (EU 2021-2023)

This EU-funded project aims at finding alternatives to Iridium for the oxygen evolution reaction because of its scarcity in the Earth's crust and production difficulty leading to high prices. The goal is to use high-entropy materials (HEM) to substitute the metal as an electrocatalyst. The HEM will be prepared to start from a high-entropy alloy which will be oxidised to obtain a high-entropy oxide, which will be converted to the final HEM by applying different treatments. The material was characterised by stability, structure, and morphology. Its electrocatalytic properties are tested in the oxygen evolution reaction to evaluate its potential as a substitute for iridium.

- AdIrCAT[3]: Atomically Dispersed IRidium CATalyst for efficient and durable proton exchange membrane water electrolysis, (EU 2021 – 2023)

The increased interest in green hydrogen – produced by water electrolysis using renewable energy as source of power – is increasing the need for proton exchange membrane (PEM) water electrolysis. In this context, the EU-funded AdIrCAT project will develop the emerging atomically dispersed metal iridium (Ir) catalysts, which will maximise the utilisation of Ir and significantly improve the mass activity of Ir catalysts. A method will also be developed that potentially allows for upscale production of atomically dispersed Ir catalysts. The success of this project will benefit the widespread deployment of PEM electrolysers and make electrolysed hydrogen fuel economically competitive.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- CATKERB[4] project: Total Syntheses of Catharanthine and Keramaphidin B by an Iridium-Catalyzed Reductive Cyclization Cascade (2022-2022, EU)

The CATKERB project planned to design a reductive cyclization cascade for dihydropyridinones, which consists of an iridium-catalyzed reduction to the corresponding electron-rich dienes and subsequent [4+2] cycloaddition (Diels-Alder reaction). The project's activities are organised around finding suitable Lewis acids and better solvents, and optimising the reaction times and temperature. This reaction cascade provides a potential route to the late-stage synthesis of catharanthine. Catharanthine is a precursor of the anti-tumour drugs vinblastine and vincristine, formed by the dimerisation of catharanthine with vindoline. Vinblastine and vincristine are valuable agents in cancer treatment due to their ability to inhibit microtubule formation.

[2] https://cordis.europa.eu/project/id/101025516
[3] https://cordis.europa.eu/project/id/101038048
[4] https://cordis.europa.eu/project/id/892540

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211

- Luminescent “Chugaev-type” cyclometalated iridium(III) complexes synthesized by nucleophilic addition of hydrazine (Chenggang et al, 2022)

A series of six neutral Chugaev-type chelating dicarbene iridium complexes with different cyclometalating ligands is described. The effects of different cyclometalating ligands on the emission properties of dicarbene iridium complexes are evaluated. The triazole- and NHC-derived cyclometalating ligands combine with the strong σ–donating Chugaev-type dicarbene ligand, resulting in phosphorescence that is blue-shifted compared to previously described analogues. Electrochemical properties of the compounds were evaluated by cyclic voltammetry analysis, which provides evidence that the *highest* and *lowest unoccupied molecular orbital* energies are dependent on the cyclometalating ligands employed. All the Chugaev-type iridium complexes exhibit blue to blue-green phosphorescence in solution at 77 K and all but one in poly(methyl methacrylate) (PMMA) thin films at room temperature. Although the quantum yields for all the complexes are modest, we succeeded in blue-shifting the emission wavelength of these dicarbene-type iridium complexes.

PALLADIUM

HEALTH AND SAFETY ISSUES RELATED TO THE PALLADIUM OR SPECIFIC/RELEVANT COMPOUDS AT ANY STAGE OF THE LIFE CYCLE

According to the International Labour Organization (ILO) in its Encyclopaedia of Occupational Health and Safety, “studies indicate cases of allergy and contact dermatitis caused by palladium in dental alloys and fine jewellery. […] Palladium chloride produces dermatitis and allergic skin sensitization in workers exposed daily. In addition, it should be regarded as an eye irritant” (ILO, 2011). Moreover, regarding safety and health measures, the ILO specifies that “correct exhaust ventilation is necessary when working with palladium and its compounds.” (ILO, 2011).

Regarding palladium, according to the notifications provided by companies to ECHA in REACH registrations no hazards have been classified (ECHA, 2022).

ENVIRONMENTAL ISSUES

Palladium extraction is associated with potential for Acid Mine Drainage, in a context of “extraction from nickel-magnetic gravel deposits and thus closely associated with the heavy metal nickel” (German Environment Agency, 2020).
The International Platinum Group Metals Association (IPA) carried out in 2013 the first-ever industry-wide Life Cycle Assessment (LCA) study (Bossi and Gediga, 2017). The study quantifies the environmental impacts of both primary and secondary production of platinum, palladium and rhodium for a variety of impact categories. The production of one gram of palladium is calculated to induce 25 kg CO_2-eq, and to require 304 MJ of primary energy demand. Nuss and Eckelman (2014) further observe that, when considering five impact categories in a life cycle perspective (global warming, cumulative energy demand, terrestrial acidification, freshwater eutrophication, and human toxicity – cancer and non-cancer), the impact intensity of palladium (i.e. impact per kg produced) is among the largest in comparison with other metals.

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NORMATIVE REQUIREMENTS RELATED TO MINING/PALLADIUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

In 2016, a group of researchers issued a palladium acetate user's guide for the chemistry community, in which they identified an optimum synthesis of the material, explained how to verify its purity, and demonstrate the impact of palladium acetate and its impurities on catalyst performance (Carole et al. 2016).

The German company BASF issued the platinum/palladium sourcing policy, specifying key elements of BASF's sourcing of Platinum/Palladium materials for BASF catalyst recycling business. It contributes to the company vision of a circular economy and reflects specific requirements related to the OECD Due Diligence Guidance for Responsible Supply Chains of Minerals in Conflict Affected and High-Risk Areas (OECD Guidance) and is subject to the requirements of applicable laws or regulations (BASF 2021).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF THE PALLADIUM FOR EXPORTING COUNTRIES

Table 20 lists the countries for which the economic value of exports of Palladium represents more than 0.1 % in the total value of their exports.

Table 20: Countries with highest economic shares of palladium exports in their total exports

Country	Export value (USD)	Share in total exports (%)
South Africa	3594057857	4.2171 %
Russian Federation	6449233241	1.9131 %
United Kingdom	5427741233	1.3717 %
Norway	492954720	0.5963 %
Belgium	1684669319	0.5689 %
Italy	2104066599	0.4242 %
Switzerland	1201058508	0.3770 %
USA	5365968382	0.3752 %
Germany	2051565162	0.1480 %
Finland	84869557	0.1294 %
China, Hong Kong SAR	674892654	0.1224 %
Canada	450793589	0.1161 %
Japan	708316593	0.1105 %

Source: COMTRADE (2022), based on data for 2020

For South Africa (4.2 %), Russian Federation (1.9 %) and United Kingdom (1.3 %), the value of their Palladium exports represent more than 1 % of the total value of their exports. Norway (0.59 %), Belgium (0.56 %) and Italy (0.42 %) export palladium whose value is around 0.5 % of their total exports. For countries such as Switzerland and USA export share account for 0.3 % of their total exports. For other exporting countries such as Germany, Finland, China, Canada and Japan this share is around 0.1 %.

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SOCIAL AND ETHICAL ASPECTS

The extraction and refining of platinum-group-metals (PGMs) is hard on the local environment. The ore is floated and dried, which are highly water consuming processes. On average 400 m^3 of water are needed per kg PGM. Smelting and refining contribute to air pollution, by emitting dust and SO_2. SO_2 have negative effects on the respiratory functions in the body and may worsen existing problems with the cardiovascular system [Eugene Cairncross, 2014]. These issues - together with large volumes of solid waste - are of course apparent wherever the PGMs are mined but may be an especially delicate issue in South Africa, a country with limited water resources. The renewable water resource is 1,048 m^3 per person and year, meaning that South Africa qualifies as water stressed, on the border to water scarce [Esmeralda Louise Haggard, 2017].

RHODIUM

HEALTH AND SAFETY ISSUES RELATED TO RHODIUM OR SPECIFIC/RELEVANT COMPOUDS AT ANY STAGE OF THE LIFE CYCLE

According to the notifications provided by companies no hazards have been classified under REACH and regarding CLP the substance is identified as a flammable solid (ECHA 2023).

Up to now, human exposure to rhodium has been considered too low to present a health risk. However, reported increases in environmental levels and more information on concentrations in the finest fractions of particulate matter have inspired a growing interest concerning the potential impact of this metal on human health (Iavicoli 2022, Rentschler 2018, Das 2020, Khan 2018, Rinkovec 2019, Tenea 2018).

ENVIRONMENTAL ISSUES

It has been estimated that in Europe, mean soil concentrations have been more than doubled for gold, rhenium and rhodium (Bengtsson 2019). The tightening of vehicle standards for air quality implied a widespread use of exhaust reduction technologies, many based on the use of PGMs. The positive reduction of NO_x and PM (particulate matter) in ambient air had, in reverse, the negative consequence of the increase of rhodium levels (Das 2020, Orecchio 2019).

Life cycle assessment (LCA) results show the lower environmental impact of secondary platinum group metals incl. rhodium in all aspects of the assessment. Thus, recycling plays an important role in lowering the environmental footprint of global PGM production (IPA 2022).

Table 21: LCA of average production of 1 g of rhodium

	Primary Production	Secondary Production
Global Warming Potential (kg CO_2 eq/g)	34.9	0.819
Primary Energy Demand (MJ/g)	459	12.4

Source: IPA 2022

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NORMATIVE REQUIREMENTS RELATED TO MINING/RHODIUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

The International Platinum Group Metals Association (IPA) provides to its members a set of indications on policy and regulations related to Conflict Minerals and Emissions Control. On conflict minerals, due diligence schemes have been set up to ensure responsible supply chains of minerals (including rhodium) from conflict-affected and high- risk areas (IPA 2022).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF RHODIUM FOR EXPORTING COUNTRIES

According to COMTRADE (2022), the shares of exports of rhenium remain below 0.1 % for each of the exporting countries.

SOCIAL AND ETHICAL ASPECTS

South Africa, the top rhodium supplier in the world, has a low governance level for the “political stability and absence of violence/terrorism” component of governance, falling even lower compared to previous years assessments. The average of the six worldwide governance indicators (WGI) is on a medium level. The mining industry in South Africa faces issues as 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. (World Bank, 2021)

The governance of Russia, another major producer of rhodium, has also been assessed as low for the governance components “political stability and absence of violence/terrorism”, “rule of law”, “voice and accountability” and “control of corruption”. (World Bank, 2021) Zimbabwe, which accounts for 5% of the global rhodium primary supply, has an even more critical situation, as its governance indicators are very low (World Bank, 2021). Similarly, Zimbabwe ranks related to high corruption perceptions (157th of 180 countries) and high state fragility (Transparency International, 2022; The Fund for Peace, 2022).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

No data available for Rhodium applied in emerging LCGT. But some relevant research trends for Rhodium applied in existing LCGT.

- Production of green hydrogen

For production of green hydrogen, the use of rhodium in proton exchange membrane (PEM) electrolisers was tested to catalyse the hydrogen evolution reaction (HER) and to carry out the oxygen evolution reaction (OER) [I. Golvano-Escobal et al. 2016]. Rhodium appears as an excellent electrocatalyst in a wide PH range and with promising applications in hydrogen generation and hydrogen reactions because it increases the catalytic activity for the HER in comparison to platinum alone, in particular if a Rh-based organometallic complex is

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immobilized on a carbon black powder to catalyse the HER in a PEM electrolyser [G. Perez et al. 2022]. Thus, the results of this research make a step forward in the substitution of conventional cathodes for the electrolytic HER by new materials with very low metal loadings.

- Hydrogen storage

Metallic alloys are materials that have a unique ability to store hydrogen compactly and safely as stable hydrides. Recently, it was found that also rhodium nanoparticles with diameters < 10 nm exhibit hydrogen-storage capability even though bulk rhodium does not absorb hydrogen. The nanosized-induced hydrogen storage capacity of rhodium nanoparticles increases with decreasing particle size [C. Song et al. 2018, H. Kobayashi et al. 2011]. This finding opens a new scenario for the application of rhodium in the field of hydrogen storage.

- Perovskite solar cells

The incorporation of a tiny amount of rhodium ions Rh^{3+} in perovskite films can help the nucleation of perovskite grains, passivate the grain boundaries' defects and improve the overall properties of perovskite-based solar cells. With the incorporation of 1 % rhodium into perovskite film, the solar cell achieves an efficiency of 20.71 % without photocurrent hysteresis [W. Liu et al. 2020]. The advantages of rhodium incorporation in the perovskite solar cells promote future industrial applications of rhodium into the field of solar cells.

- SPIN-PORICS[5]: Merging Nanoporous Materials with Energy-Efficient Spintronics - (EU, 2015-2020)

This Project aimed to integrate engineered nanoporous materials into novel energy-efficient spintronic applications. The Project developed of a new type of nanocomposite material, comprising an electrically conducting or semiconducting nanoporous layer filled with a suitable dielectric material. The magnetic properties of the metal/semiconductor are largely tuned at room temperature (RT) by simply applying a voltage, via electric charge accumulation. The porous layer will consist of specific alloys (Cu-Ni or Fe-Rh) or oxide diluted magnetic semiconductors, where surface magnetic properties have been recently reported to be sensitive to electric field at RT. Based on these new materials, three technological applications are envisaged: electrically-assisted magnetic recording, voltage-driven switching of magnetic random-access memories and spin field-effect transistors. Moreover, the project also includes the development of sizeable and tunable Fe-Rh nanoparticles and their activity toward hydrogen evolution reaction.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- PEACOC - Pre-commercial pilot for the efficient recovery of Precious Metals from European end of life resources with novel low-cost technologies (2021 – 20125, EU)[6]

[5] CORDIS EU research results: https://cordis.europa.eu/project/id/648454
[6] https://cordis.europa.eu/project/id/958302

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The recovery of Rhodium and other PGMs from spent autocatalyst is the focus of the PEACOC project. The project concept is based on previously developed recovery and refining technologies to TRL5 in the frame of another H2020-funded research and innovation project, PLATIRUS.

From Platinum Group Metals to gold and silver, precious metals are irreplaceable industrial goods. Used in a broad range of sectors, they are critical for the EU economy. Hence, the recycling of precious metals is important. Under the EU-funded project PEACOC, a consortium of 19 partners from 8 European countries and Turkey will work together to develop a first-of-a-kind economically and environmentally viable pre-commercial metallurgical system for recovering precious metals. The project will reduce the supply risk of precious metals in the EU and enable new business opportunities for SMEs who recycle end-of-life products. Its concept is based on the recovery and refining technologies previously developed in the frame of the H2020-funded PLATIRUS project (i.e. microwave-assisted leaching, gas-diffusion electrocrystrallisation, and deep eutectic solvents).

- PLATIRUS - PLATInum group metals Recovery Using Secondary raw materials (2016 – 2021, EU)[7]

The PLATIRUS project aimed at reducing the European deficit of Platinum Group Metals (PGMs), by upscaling to industrial relevant levels a novel cost-efficient and miniaturised PGMs recovery and raw material production process. The targeted secondary raw materials were autocatalysts, electronic waste (WEEE) and tailings and slags from nickel and copper smelters, opening-up an important range of alternative sources of these critical raw materials, with the potential to substitute a large amount of primary raw materials which are becoming more and more scarce in Europe.

- Advanced strategies for hydrogen generation by rhodium metal catalysts coated by the electrodeposition method (Devendra et al, 2022)

The theory and kinetics of the hydrogen evolution reaction (HER) on electrodeposited rhodium in acidic media (0.5 M H2SO4 solution) were investigated. An electrodeposition approach using direct current (DC) and pulse current (PC) was used to deposit rhodium on a stainless steel 304 (SS304) substrate. Several parameters, including rhodium concentrations, current densities, temperature, pH, and coating duration, were used to optimise the rhodium bath. Scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy-dispersive X-ray (EDX) analyses were used to assess the change in surface shape and chemical composition.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- OXLEET[8] project: Oxidation via low-energy electron transfer - (EU, 2010-2015)

Development of green oxidation methodology via a biomimetic approach. Oxidation reactions are of fundamental importance in Nature and are key transformation in organic synthesis.

[7] https://cordis.europa.eu/project/id/730224
[8] https://cordis.europa.eu/project/id/247014

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There is currently a need from society to replace waste-producing expensive oxidants by environmentally benign oxidants in industrial oxidation reactions. The aim with the proposed research is to develop novel green oxidation methodology that also involves hydrogen transfer reactions. In the oxidation reactions the goal is to use molecular oxygen (air) or hydrogen peroxide as the oxidants. In the present project new catalytic oxidations via low-energy electron transfer will be developed. The catalytic reactions obtained can be used for racemization of alcohols and amines and for oxygen- and hydrogen peroxide-driven oxidations of various substrates. Examples of some reactions that will be studied are oxidative palladium-catalyzed C-C bond formation and metal-catalyzed C-H oxidation including dehydrogenation reactions with iron and ruthenium. Coupled catalytic systems where electron transfer mediators (ETMs) facilitate electron transfer from the reduced catalyst to molecular oxygen (hydrogen peroxide) will be studied. Highly efficient reoxidation systems will be designed by covalently linking two electron transfer mediators (ETMs). The intramolecular electron transfer in these hybrid ETM catalysts will significantly increase the rate of oxidation reactions. The research will lead to development of more efficient reoxidation systems based on molecular oxygen and hydrogen peroxide, as well as more versatile racemization catalysts for alcohols and amines.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- Prospects for the Use of Palladium from NPP Spent Nuclear Fuel and Ways to Design the Technology of its Recovery at a Radiochemical Enterprise (Pokhitonov et al. 2022)

The removal of kilograms per tonne of platinoids (Pd, Rh, and Ru) from irradiated fuel is is a complex problem due to a number of technological and economic reasons. The paper proposes ways of a phased approach to the introduction of technology for the recovery of platinum-group metals (PGM) at one of the radiochemical enterprises. Information is presented on the dynamics of production volume and prices of PGMs in the world over the past decades and on the possibility of using reactor platinoids in various fields. According to the authors, it is of interest to consider the problem of isolating and using reactor palladium in hydrogen power engineering and in the processing of waste from radiochemical enterprises.

- ChemoBOOM Development of Palladium-Labile Prodrugs for Bioorthogonally-Activated Chemotherapy (2016 – 2018, EU)[9]

The heterogeneity and capacity to evolve in response to treatment of the most aggressive forms of cancer make the selective inhibition of molecular targets an insufficient strategy to reach complete neoplastic remission. In this context, the unspecificity of classic chemotherapeutic agents becomes an advantage for treatment. Nonetheless, due to dose-limiting adverse effects, chemotherapeutic drugs become ineffective against some late-stage primary tumours, which are typically responsible for the death of the patient. To tackle those difficult to treat cancers, improved chemotherapeutic strategies far beyond the one-pill paradigm are mandatory. One of those novel concepts is based on the use of palladium to activate drug precursors by heterogeneous bioorthogonal organometallic (BOOM) catalysis.

[9] https://cordis.europa.eu/project/id/658833

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- LATESTAGE Palladium catalyzed C(sp3)–H late-stage diversification of biologically active molecules (2016-2018, EU)[10]

Aliphatic amines are central to the function of many biologically active molecules as evidenced by their prevalence in a large number of pharmaceutical agents. The groups appended to these nitrogen atoms are crucial in determining the physical properties of the amine and are linked to how well it interacts with a biological target. The first objective of this proposal aims to directly apply the transformations developed by Gaunt, e.g. carbonylation, aziridination and acetoxylation reactions, to a precise class of drugs that contain the secondary amine motif as central function, i.e. β-adrenergic drugs. The use of the oxidative Pd(II)/(IV) catalytic cycle will then allow the development of a novel fluorination. The second objective relies on a new methodological concept, which seeks to merge palladium catalysis with radical chemistry, opening a route to develop novel perfluoroalkylation, amination and methylation reactions via a new Pd (II)/(III)/(IV) catalytic cycle. Finally, the third aim will be to apply all the methods developed to four important anticancer drugs, in collaboration with the new AstraZeneca oncology unit in Cambridge, to prepare novel analogues for biological testing.

RUTHENIUM

HEALTH AND SAFETY ISSUES RELATED TO THE RUTHENIUM OR SPECIFIC/RELEVANT COMPOUDS AT ANY STAGE OF THE LIFE CYCLE

According to the CLP notifications the substance is identified as a flammable solid and may cause long lasting harmful effects to aquatic life. Bismuth lead ruthenium oxide may damage the unborn child, suspected of damaging fertility, is very toxic to aquatic life, is very toxic to aquatic life with long lasting effects, is harmful if swallowed, is harmful if inhaled and may cause damage to organs through prolonged or repeated exposure. Some uses of bismuth lead ruthenium oxide substance are restricted under REACH Annex XVII. (ECHA 2023)

ENVIRONMENTAL ISSUES

No information available

NORMATIVE REQUIREMENTS RELATED TO MINING/RUTHENIUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

The International Platinum Group Metals Association (IPA) provides to its members a set of indications on policy and regulations related to Conflict Minerals and Emissions Control. On conflict minerals, due diligence schemes have been set up to ensure responsible supply chains of minerals (including ruthenium) from conflict-affected and high- risk areas (IPA 2022).

[10] https://cordis.europa.eu/project/id/702462

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The tightening of vehicle standards helps to reduce the amount of NO_x and particulate matter in ambient air and is enabled by improved exhaust reduction technologies of which many are based on the use of PGMs including ruthenium. (IPA 2022)

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF THE RUTHENIUM FOR EXPORTING COUNTRIES

Ruthenium is part of the minor PGM (Platinum group metals) along with Iridium (Ir) and Osmium (Os). 73 % of all ruthenium deposits have iridium and 53 % of all ruthenium deposits have osmium. Hence they are analysed as a single commercial commodity. (Mindat.org, 2023)

Table 22lists the countries for which the economic value of exports of Ruthenium (Ir,Os,Ru) represent more than 0.1 % in the total value of their exports.

Table 22: Countries with highest economic shares of palladium exports in their total exports

	total exports in US$	Ruthenium (Ir,Os,Ru) exports in US$	Share
South Africa	85.2 bn	474,429,113	0.56 %

Source: COMTRADE (2022), based on data for 2020

South Africa's share of exports of ruthenium (Ir,Os,Ru) is 0.5% of its total exports. For other countries such as Belgium and the United Kingdom, the export share remains well below 0.1 %.

SOCIAL AND ETHICAL ASPECTS

Swedwatch's case study of the PGM industry in South Africa shows that risks for adverse human rights impacts are severe. Problems are the result of a lack of capacity by the State, including dysfunctional legislation. The traditional councils also play an important role where they have a responsibility for local communities living in their jurisdiction. It is important to point out that the South African state has been criticized in several cases for high-ranking members of the ruling party owning considerable stock or holding board positions in the mining companies. This leads to conflicts of interest. There are failures in communication between the mining companies and the local communities, underpinning to a large extent the local communities' frustration with their situation. (International Platinum Group Metal Association, 2020)

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

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- Ruthenium nano-based supercapacitor application in energy storage

A ruthenium nano-based supercapacitor supported on reduced graphene oxide (RGO) was successfully prepared with a fast and green synthesis method. The proposed supercapacitor has a stable potential window up to 1.1 V with excellent cycling stability over 5,000 cycles at 24 A/g (Hassan et al., 2017).

Multi-walled carbon nanotube (MWCNT)/ruthenium hydroxide aerogel has been synthesized and utilized as an electrode active material for a symmetrical supercapacitor. A MWCNT/ruthenium hydroxide aerogel-based supercapacitor cell has offered a superior energy density of 36.6 Wh/kg even at a high power density of 8.36 kW/kg (Korkmaz et al., 2022).

A nickel-deposited ruthenium/ruthenium-oxide symmetric supercapacitor exhibiting particularly fast scan rates and high power density of 88/kW/cm^3 was developed, promising applicability in alternating current (AC) line filtering and power conditioning (Morag et al., 2019).

- Ruthenium nanoparticles employment for the emerging hydrogen economy

The reactivity of ruthenium nanoparticles generated from an organometallic precursor, is tuned to achieve a high rate of hydrogen gas production from methanol at low temperature. The outstanding long term stability of the studied catalyst may encourage the search for an efficient industrially viable process for the transformation of methanol into hydrogen gas (Awasthi et al., 2021).

Ruthenium modifications can improve the hydrogen evolution reaction/hydrogen oxidation reaction (HER/HOR) performance of platinum more significantly than other transition metals (Zhu et al. 2021; McCrum et al. 2020; Liu et al. 2019). A rutile-structured ruthenium–manganese solid solution oxide with oxygen vacancies was developed by using an electron-feeding modulation strategy to stabilize the catalyst structure and accelerate the OER for sustaining green hydrogen generation (Wang et al., 2022). Ruthenium and nitrogen cooped carbon nanowires are effective hydrogen evolution catalysts. Results can be exploited for the rational design and engineering of ruthenium-based single atom catalysts for HER in alkaline media (Lu et al., 2019).

For the emerging hydrogen economy, the development of ruthenium and nickel-based catalysts for decomposition process of ammonia as a source of hydrogen has recently concerned their high catalytic performance at low temperatures and the innovation of manufacturing methods (Le et al., 2021).

Ruthenium oxide (RuO_2)/tungsten oxide (WO_3) composite nanofibers based photoanode was developed for the photoelectrochemical splitting of water molecules via biophotovoltaic cells (Karthikeyan et al., 2019). A multi-walled carbon nanotube catalyst with ruthenium nanoparticles (Ru@MWCNT) produces an efficient and stable hydrogen evolution reaction (HER) catalyst for acidic and alkaline media. Ru@MWCNT has a strong potential for mass production at low-cost, for use in practical applications (Kweon et al., 2020).

- Ruthenium as a new opportunity for achieving high efficiencies in solar cells

Ruthenium can be used as an absorbent material in solar cell applications being capable of absorbing light in a range of visible light wavelengths (Hardani et al., 2021; Hardani et al 2022).

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- Supramolecular Architectures for Ruthenium Water Oxidation Catalysis – SUPRAWOC (EU, 2018-2024)[11,12]

New types of Ru-based supramolecular metal assemblies are developed. Ruthenium complexes with 2,2'-bipyridine-6,6'-dicarboxylate (bda) as equatorial ligand and pyridines as axial ligands are among the most promising molecular water oxidation catalysts (WOC) to achieve practical artificial photosynthesis. The goal is therefore to develop new catalytic systems with outstanding performance in solar-driven water splitting. The results obtained so far concern the synthesis and characterization of Ru-WOC systems of different sizes and geometries. The catalytic activity of these WOCs in the chemical, photochemical and electrochemical oxidation of water was also studied. Ru-based WOCs have been implemented as active components in porous crystalline polymers and all studied systems have been evaluated regarding the catalytic activity.

- Magnetism and optic for nanoparticle catalyst – MONACAT (EU, 2016-2021)[13, 14]

MONACAT proposes a novel approach for intermittent energy storage. Specifically, the purpose is to conceive and synthesize novel complex nano-objects displaying both physical and chemical properties enabling catalytic transformations with a fast and optimum energy conversion. Both magnetic and plasmonic nanoparticles (will be studied for this purpose. In all cases, deposition of additional materials as islands or thin layers will improve the NPs catalytic activity. A similar approach will be used for direct light conversion using as first proofs of concept Au or Ag nanoparticless coated with ruthenium. As regards the industrial part, this has led to collaborations and contracts with 4 large industrial companies and two small and medium-sized enterprises.

- In-situ fabricated hydrogen evolution catalysts for alkaline water electrolysis – HYCAT project (EU, 2020-2022)[15]

The yydrogen evolution reaction (HER) electrocatalysts, such as platinum (Pt), are the most active but costly, and they are non-resistant over time due to the accumulation of metal nanoparticles on the support. The HyCat project proposes solutions to reduce the quantity of Pt in order to secure catalyst stability by impeding aggregation. The solution will be based on a highly active and stable HER catalyst composed of a nanostructured Cu-Pt porous layer, directly grown onto a titanium current collector. In addition, the production of Cu-Pt (Cu: copper) and Cu-Ru catalysts will be upscaled in this project. Their HER activity will be tested under industrially relevant conditions.

The results obtained showed that the expensive platinum could be replaced by much cheaper ruthenium at about a third of the cost. The average amount of Ru on the electrode was only 53 µg/cm^2, ten times less than the platinum used in other state-of-the-art electrolysers. When implemented in a 1 MW hydrogen plant, the system produces at costs of approximately USD 2.26/kg of hydrogen, in line with the European Commission's 2030 green hydrogen target cost of less than USD 2.50 USD/kg. The next step is to further expand the electrode

[11] https://cordis.europa.eu/project/id/787937
[12] https://cordis.europa.eu/project/id/787937/reporting
[13] https://cordis.europa.eu/project/id/694159
[14] https://cordis.europa.eu/project/id/694159/reporting
[15] https://cordis.europa.eu/project/id/899412

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to a practical size of approximately 100 cm^2. Around this scale, the electrolyser will become practically useful for producing hydrogen for on-site use, reaching kilowatt-scale power generation. With a 2.5 kW electrolyser, for example, it is possible to produce about 1 kg of hydrogen per day, enough to power a house.

- New Directions in Sustainable Catalysis by Metal Complexes – SUSCAT (EU, 2016 - 2022)[16]

The project aims to discover and develop novel, sustainable and environmentally benign catalytic reactions. Such reactions are useful for 'green' organic synthesis methodology which generates no waste and uses sustainable substrates, as well as the development of liquid organic hydrogen carrier (LOHC) systems. The catalyst development method used by SUSCAT is based on a mechanistic approach, employing both experimental and computational methods. Particularly significant for its work has been the use of pincer complexes as catalysts. SUSCAT has used these pincer complexes to pioneer several green and sustainable catalytic reactions useful for organic synthesis that can feasibly replace currently used polluting processes. An environmentally significant example of a reaction accomplished by SUSCAT using ruthenium is the unprecedented hydrogenative depolymerisation of widely used, robust nylons to form amino alcohols, efficiently catalysed by a ruthenium pincer complex. The amino alcohols can be polymerised back to Nylons of similar molecular weight, thus providing a green and sustainable closed loop cycle for recycling Nylon waste. Another example of SUSCAT's successes in green catalytic reactions includes a waste-free, one-step direct synthesis of valuable hydrogen gas.

- Ru–Zn Heterobimetallic Complexes - RuZn (EU, 2018 - 2020)[17]

The RuZn project deals with heterobimetallic late transition metal – Lewis acidic metal complexes. Having similar properties with other Pt-group metals, Ru is more than order of magnitude cheaper. The cooperativity between Ru and Lewis acidic metal (Zn) can enhance the stability, selectivity and reactivity of the catalytic system and lead to new catalytic applications of ruthenium complexes, making them more appealing for both academia and industry. The RuZn project develops new synthetic approaches to Ru-Zn complexes, a systematic study of their chemical properties and reactivity and tests of their potential applications as catalysts for the synthesis of organic compounds. The results obtained over the course of the project represent a significant advancement of knowledge. In particular, understanding of cooperativity between Ru with Zn was improved, and developed simple synthetic routes to unconventional Ru-Zn systems. This is expected to eventually contribute to the field to catalysis and become appealing for industrial application to facilitate access to materials, drugs and agrochemicals.

- Dual catalysis for meta functionalisation under mild conditions - DC Meta (EU, 2019 - 2021)[18]

The project aims to integrate visible light photoredox catalysis with metal catalysed C-H functionalisation processes, with an emphasis on meta functionalisation under ruthenium (Ru) catalysis. By using photoredox catalysis to control the electron transfer events governing the metal catalytic cycle, it is hoped to establish new reactivity under mild conditions, that can be widely exploited in chemical synthesis. From the beginning

[16] https://cordis.europa.eu/project/id/692775
[17] https://cordis.europa.eu/project/id/792674
[18] https://cordis.europa.eu/project/id/798926

of the project a large number of reaction systems based around Ru was investigated. In particular, Ru-ortho arylation of arenes was successful obtained.

- 3D micro - supercapacitors for embedded electronics – 3D-CAP (EU, 2018 - 2023)[19]

The 3D-CAP project was proposing a 3D paradigm shift of micro-supercapacitor design to ensure increased energy storage capacities. Hydrous ruthenium dioxide (RuO_2) is a pseudocapacitive material for supercapacitor electrode well-known for its high capacitance. A thin-film of ruthenium oxide will be conformally deposited onto a high-surface-area 3D current collector. These electrodes will be combined with an innovative electrolyte in solid form able to operate over an extended cell voltage. In a parallel investigation, it will develop a fundamental understanding of electrochemical reactions occurring in pseudocapacitive RuO_2 electrodes. From the beginning of the project highly porous metallic current collectors have been obtained as well as 3D micro supercapacitor electrodes with high capacitance. Prototypes with different design will be produced.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- SUPRAWOC[20] project: Supramolecular Architectures for Ruthenium Water Oxidation Catalysis, (2018-2024, EU)

Ruthenium complexes with 2,2'-bipyridine-6,6'-dicarboxylate (bda) as equatorial ligand and pyridines as axial ligands are currently the most favoured class of efficient water oxidation catalysts (WOCs) and thus a great hope for achieving practical artificial photosynthesis. Based on the outstanding WOC performance of our recently reported macrocycles bearing three [Ru(bda)] units, the project aims to explore a wider variety of multinuclear metallosupramolecular architectures including more diverse polygons, polyhedra and coordination polymers. Precise control of structure and size will be achieved through a directional bonding approach with suitable vertices and edges, e.g. for cubic, tetrahedral, or dodecahedral architectures, and new ring-opening living supramolecular polymerization protocols with specially-tailored [Ru(bda)] precursors and multitopic azaaromatic initiators towards unprecedented polymer topologies.

- RuZn[21] project: Ru–Zn Heterobimetallic Complexes (2018-2020, EU)

The RuZn proposal aims not only at developing a new range of ruthenium catalysts, but will also work on the cutting edge of science, as well as improve his skills in leadership, teaching, mentoring and grant-management. As an interdisciplinary part of the program, knowledge in computational chemistry while be acquired while studying the Ru–Zn bonding and reactivity.

- Ru4EYE[22] project: Ruthenium-based photoactivated chemotherapy against eye cancer (2020-2022, EU)

Uveal melanoma (UM) is a rare malignancy of the eye. Current treatment options do not always preserve vision or the eye and often result in patient death from metastasis to the liver. Photoactivated chemotherapy (PACT) is an innovative therapeutic solution that involves photosensitive compounds that can kill cancer cells

[19] https://cordis.europa.eu/project/id/771793
[20] https://cordis.europa.eu/project/id/750686
[21] https://cordis.europa.eu/project/id/792674
[22] https://cordis.europa.eu/project/id/875709

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selectively under the action of light. The EU-funded Ru4EYE project aims to develop a pre-clinical proof of concept that ruthenium (Ru)-based PACT compounds can be used to treat uveal melanoma. The success of the project will not only provide pre-clinical proof-of-concept that PACT may become an effective treatment option for uveal melanoma patients, but also accelerate the adoption of Ru-based PACT in the treatment of other diseases as well.

- CylcoRu4PACT[23] project: Cyclometallated ruthenium complexes for photo-activated chemotherapy (2018-2020, EU)

Chemotherapy is efficient in curing cancer, but most treatments are very hard to stand for the patient, and side effects limit treatment efficacy. Phototherapy is a promising alternative, where the toxicity of a light-sensitive chemotherapeutic compound is locally released upon visible light irradiation of the compound-containing tumour. Photodynamic therapy is already available in the clinic for oxygen-rich tumours; however, it fails when the oxygen concentration at the place of irradiation is too low. This project proposes to synthesize new ruthenium-based photochemotherapeutic compounds containing cyclometallated ligand, and to test them in an in vitro model of hypoxic cancer.

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