

Review

Platinum Group Elements in Geosphere and Anthroposphere: Interplay among the Global Reserves, Urban Ores, Markets and Circular Economy

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Abstract: Industrial and strategic significance of platinum group elements (PGEs)—Os, Ir, Ru, Rh, Pd, Pt—makes them irreplaceable; furthermore, some PGEs are used by investors as “safe heaven” assets traded in the commodity markets. This review analyzes PGEs from various aspects: their place in the geosphere, destiny in the anthroposphere, and opportunity in the economy considering interactions among the exploration, recycling of urban ores, trade markets, speculative rhetoric, and changes required for successful technological progress towards the implementation of sustainability. The global market of PGEs is driven by several concerns: costs for extraction/recycling; logistics; the demand of industries; policies of waste management. Diversity of application and specific chemical properties, as well as improper waste management, make the recycling of PGEs complicated. The processing

approach depends on composition and the amount of available waste material, and so therefore urban ores are a significant source of PGEs, especially when the supply of elements is limited by geopolitical or market tensions. Recycling potential of urban ores is particularly important in a long-term view disregarding short-term economic fluctuations, and it should influence investment flows in the advancement of innovation.

Keywords: circular economy; commodity markets; critical elements; limitation of resources; mining; platinum group metals; recycling; supply and demand; sustainability

1. Introduction

Patterns of sustainability and circular economy have gained broad recognition not only from industry but also from society and media. Currently, it is understood that planetary resources are limited, and changes in consumption must be implemented globally notwithstanding the economic demands and personal reluctance. Among the various resources, platinum group elements (PGEs), namely Os, Ir, Ru, Rh, Pd, and Pt, are critical elements of strategic, industrial, and market significance [1–5]. To provide a reasonable description of the interactions among the global reserves, urban ores, markets, and circular economy, this review is divided into several parts reflecting the viewpoints from various disciplines of natural, environmental, and economic sciences. The first part of the review is addressed to PGEs from the planetary and geological perspectives, drawing up the main outlines why the scarcity concerns arise and why it is vital to move towards recycling of urban ores and maintain the targets of the circular economy. The second part defines the main industrial uses of PGEs as this aspect is important for efficient recycling achieved by effective planning and use of appropriate technologies. The experience gained from the exploration of primary resources provides tips for recycling/recovery of the secondary materials which urban ores are. The third part of the review covers the outlook on the global market with its efficiencies and inefficiencies; historical prices of PGEs are analyzed in conjunction with geopolitical, economic, and socio-environmental turning points. Concluding chapters discuss the questions related to global sustainability indicating leading macro-trends in the mining business for the future. As PGEs usually are a byproduct of the larger exploration industry, the aspects of the circular economy, such as waste management, logistics of supply chains, and recycling potential of urban ores, must be taken into consideration. At the end of the article, the outlook in the future of exploration and markets of PGEs is provided, and the conclusions are drawn on the main influencing factors.

In general, this paper aims to provide a literature review from an interdisciplinary perspective and analyze the primary interconnections among the geological resources, industry, markets, and sustainability aspects related to PGEs, highlighting the existing problems.

2. Complementarity of Geology, Industry, and Environment

PGEs are mostly found in minerals and rocks as trace accessory elements; usually, they occur in native metal state or bond with sulfur or other ligands of groups VA and VIA. Initially, it is a stellar material, fully purified and recognized with unique properties; only in the late 18th century, PGEs were considered as valuables due to their physical-chemical properties, such as high melting point, chemical inertness, ability to catalyze chemical reactions [1,6]. PGEs are concentrated in the Earth's core and mantle, however, their natural abundance in the continental crust is low ranging from 0.02 ng/g (ppb) for Ir to 0.5 ng/g for Pt and Pd, representing less than 0.01% of the Earth's minerals budget [7–9]. Despite the low abundance of PGEs in crustal rocks, Pt, for instance, has served as a commodity for means of value storage surpassing the monetary value of gold for a long time. Later, greater amounts of Pt and other PGEs were demanded by the industry. Growth of demand for

PGEs is dominantly in the production of catalytic converters for chemical industry and low emission automobiles [6,10–13].

Nowadays, various industry sectors require Pt, Pd, and Rh primarily, and these elements are most often found at the unique Bushveld Complex in South Africa, followed by Norilsk deposits in Russia and Stillwater in the USA [1,6,13,14] as highlighted in Figure 1. Mineralogy and genetic aspects of similar related podiform chromitites in the East Sayan ophiolite massif are described recently [15,16]. The concentration of all PGEs is at least 10,000 times higher in sulfide melts of magmas than elsewhere [17,18], meaning that specific geological areas determine the geographical location of mining and extraction. Another class of large magmatic deposits consists of Ni sulfides in ultramafic komatiites which also often contain PGEs [19–22]. For example, numerous intrusions containing the deposits of PGEs together with Cu and Ni are located in Russia at the Norilsk ore region [23–26]. Implications of ore-forming processes as well as magmatic evolution aspects are given in the literature [27,28].

The deposits of PGEs mostly are concentrated in the areas of old Archaean-Proterozoic cratons as well as in the regions where massive magmatic outputs have created intrusions with ultramafic-mafic complexes and bearing deposits of Cu and Ni sulfides (Figure 1). This geographical aspect is critical as it dictates the situation of global geopolitics and the market.

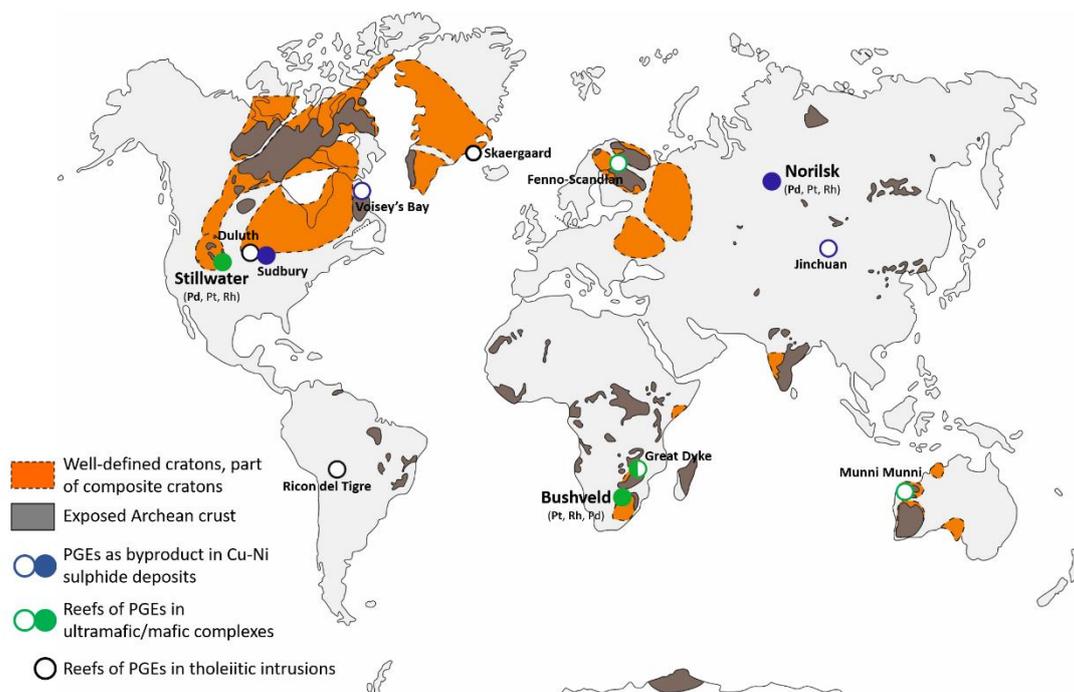


Figure 1. Worldwide deposits of PGEs; geological linkage to cratons and the types of deposits, indicating the main locations with corresponding PGEs [1,17,20,29,30].

The cycling of PGEs in the surface environment is minimal, and it was not seriously considered until some economic or environmental problems were globally recognized. Worldwide production of PGEs has steadily increased since the 1970s; importance to assess the potential impacts of emissions, accumulation, and dispersion of elements have attracted broad audience of international researchers [11,12,31–38]. Newly appearing uses of PGEs may also result in additional emissions [3,39]. Producers of catalytic converters and fuel cells, manufacturers of consumer electronics, as well as jewelry industry are not the only demanding sectors. Other industries like producers of fertilizers, petroleum, electrical appliances, glass, and medical equipment are onboard as well [30,40–43]. Environmental studies on PGEs regarding animal and human health effects induced by low exposure

concentrations of elements are sparse [6,44], yet could become extended in the future due to wider uses of PGEs.

Geological situation hand in hand with the factors of geopolitics, industries, and global finances are the leading influencers of PGEs exploration and recycling, their market, and technological progress in the frames of sustainability and circular economy. These interactions are analyzed further in the article.

3. Scarcity and Recovery from Urban Ores

The critical strategic importance of PGEs is evaluated on possible risk for restrictions in the supply of PGEs as their production is led only by the countries where the principal reserves are found: South Africa, Russia, Zimbabwe, the USA and Canada (Figure 2a). South Africa is the dominant producer of Pt, followed by Russia, while the production of Pd is very similar in South Africa and Russia (Figure 2b); South Africa dominates in the market of Rh by 80%. Altogether this oligopoly in the production of PGEs creates associated challenges and periodical global shocks regarding supply and demand at the world market [2,4,44–51]

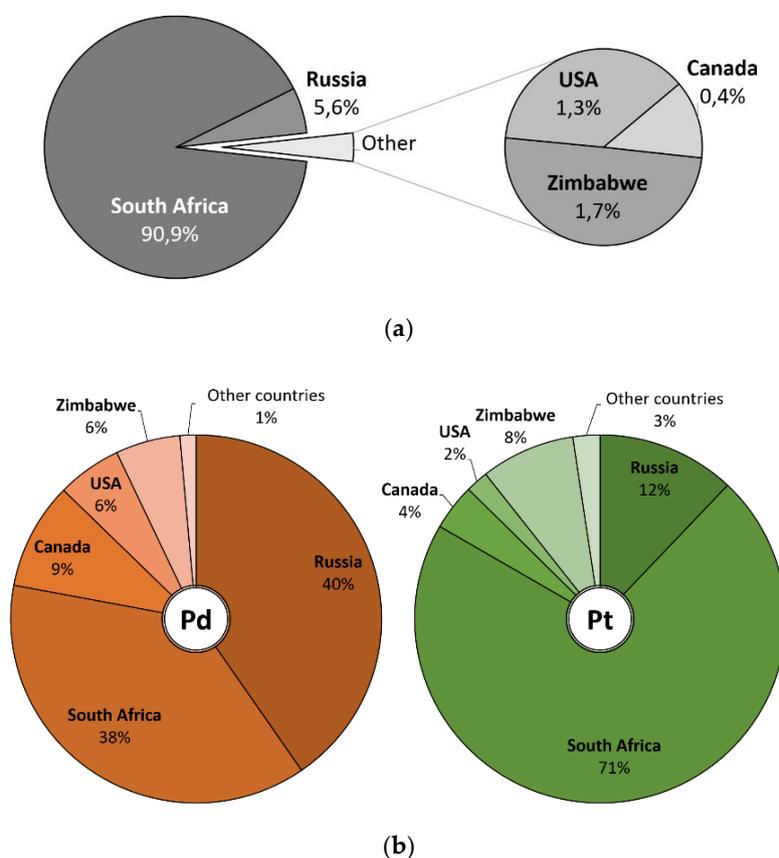


Figure 2. Global management of PGEs (indicating relative percentage) [52,53]: (a) Amount of global PGEs reserves in 2019; (b) Production of Pd and Pt in 2019.

PGEs are costly and scarce, but their physical-chemical properties (such as high stability, etc.) determine the options for their application in various fields of industry (Figure 3a).

High recovery costs and low concentrations in virgin ores are the main factors that encourage the recycling of PGEs; however, diversity of their application and chemical properties are the factors making recycling complicated. Pt, Pd, and to a lesser extent also Rh and Ir, are used in jewelry, and, typically, they remain as jewelry for 40 to 60 years before being returned to material cycle [54]. Growing sectors demanding PGEs include the production of catalytic converters for the chemical

industry (used in the synthesis of nitric acid, as reforming and isomerization catalysts in oil processing, catalytic converters for hydrogenation, and for Fischer-Tropsch process, etc.) and for the reduction of toxic exhaust gasses in the automotive industry. Further fields of PGEs application include electronic industry, i.e., production of electrical appliances and electronic equipment used for broad purposes from home to professional medical and laboratory scale [55]. The lifetime of catalytic converters in an application is limited due to fouling, thermal degradation, or sintering of catalytically active compounds [56,57]. Recovery of PGEs from spent catalytic converters is the major challenge for recycling; and different pyro- and hydro-metallurgical processes are developed supporting effective extraction and separation of PGEs from other elements, such as Fe, Ni, Zn, Cu, commonly used in industrial catalytic converters. The lifecycle of PGEs can be sectioned into the primary and secondary processes (Figure 4). The selection of the approach suitable for recycling depends entirely on the composition of PGEs-containing waste material and the amounts of the waste to be processed, while the process is similar to the primary production just skipping the step of mining and concentration [5,42,58].

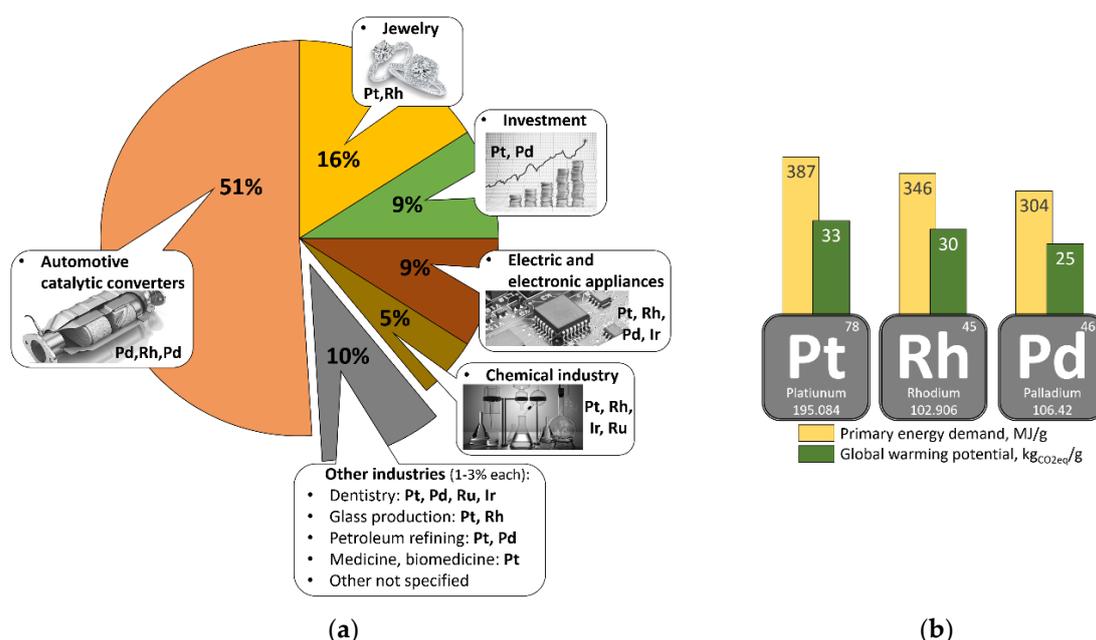


Figure 3. PGEs in use: (a) The main industrial applications of PGEs [5,40]; (b) Primary energy demand and global warming potential for Pt, Rh, and Pd [40].

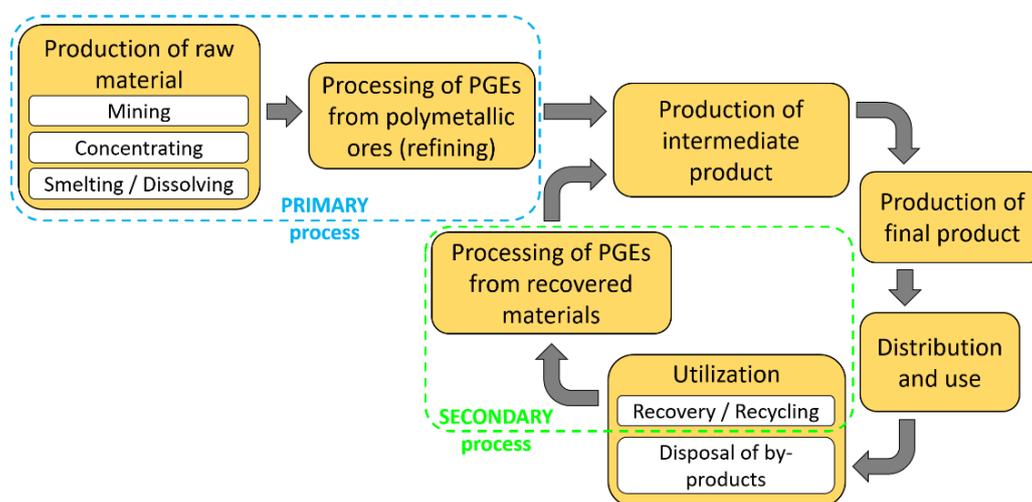


Figure 4. Lifecycle of PGEs: the primary and secondary processing [5,30,40,42,58].

Thermal pre-treatment of PGEs-containing waste is the first step to the recovery of metal. Thermal pre-treatment is particularly necessary for the decomposition of organometallic catalytic converters derived from the petrochemical industry as the common problem of catalyst fouling is a deposition of coke onto the surface of a catalytic converter. The process includes waste heating at temperatures up to 800 °C in air or atmosphere of hydrogen, oxygen, nitrogen to obtain PGEs-containing ashes [58]. Smelting process or incineration of low-grade scrap from the electronics industry also can be applied [59,60]. Limitations of thermal pre-treatment processes are related to high energy consumption and the appearance of toxic gases as well as a need to use further chemical leaching to obtain metallic PGEs.

Recovery of PGEs is most widely provided by hydro-metallurgical processing [55,61–63], inducing metal leaching by acidic or alkaline solutions in presence of strong oxidants (O_2 , halogens/halide salt ions, H_2O_2 , etc.). Considering significant differences in the chemical properties of PGEs, industrial recovery technologies are mostly developed to regain Pt and Pd [10]. During the hydro-metallurgical processing, strong acids (sulfuric acid, hydrochloric acid, nitric acid) or complex-forming substances, such as sodium cyanide, chloride, or iodide solutions, are used to form stable chlorine-containing complexes. Due to the high chemical stability of PGEs, harsh reaction conditions have to be provided, and presently significant efforts are directed for seeking less aggressive reaction conditions, at first considering complex-forming agents, lower acid concentrations, lower temperatures. Pre-treatment using acid/alkali reagents followed by processing in nitric acid can be a better option. Another approach involves reactions in the presence of chloride ions using chloride-containing salts ($AlCl_3$, $NaCl$, $CaCl_2$, etc.). The substitution of HCl with $AlCl_3$ as well as the reduction of nitric acid concentration does not much affect the yields of Pt dissolution, but significantly reduces the consumption of chemicals [61]. Another opportunity is a reaction with HCl in the presence of a strong oxidizing agent as H_2O_2 [64]. This approach allows dissolving Pt from spent catalytic converters as well as other PGEs from various waste [65]. Oxidative fluorination is applied for the recovery of Ir, which is used as a hardening agent in thermo-resistive alloys, and for the reduction of NO emissions in oil refineries and catalytic processes [66]. For the recovery of Os chemo-entrapment strategy in catalytic olefin cleavage reaction is applied [67]. The final stage of PGEs recovery includes precipitation of metals, reduction of their complexes, and metal isolation in a form of powder applying electrochemical reactions and other approaches [68].

A relatively new method is plasma arc smelting technique applicable for extremely selective separation and recovery of individual PGEs directly from the solution of HCl/ Cl_2 , developed by IBC Advanced Technologies, Inc.; the process is known as a molecular recognition technology (MRT). The importance of MRT was emphasized in 1987 by the Nobel Prize in Chemistry that was awarded to three developers of the technology [69–72]. Highly selective metal separation is achieved by employing pre-designed metal-selective ligands to solid supports as silica gel or polymer substrates, therefore, column-based solid-phase extraction becomes possible. The product is named SuperLig[®] and it works without any organic solvent [70–72]. This green chemistry approach requires fewer inventories, creates minimal waste, no hazardous waste, and the rates of recovery are close to 100%. This system is applied in such refineries of PGEs as Tanaka Kikinzoku Kogyo, Ltd. (Japan), Impala Platinum, Ltd. (South Africa), SepraMet, Ltd. (USA), Sino-Platinum, Ltd. (China), etc. [73]. Provident refining companies of precious metals as Umicore N.V. (Belgium) promote efficient recovery of intermediates from the primary and secondary processing of PGEs, meaning that recycling is technically efficient from any type of waste. Investing in recycling is a far better solution for the industry players as more independence is achieved from the market cartel prices and geopolitics. Localized and very extensive recycling provides resources for the automotive industry in the USA, Japan, and Europe. It is a specific product flow, largely unquantified for the competitive advantages, yet adds only some amounts to the actual supply of PGEs. Thus, the cost per kg of recycled PGEs is lower than for mined PGEs, and it makes huge downward pressure on global prices. Three essential PGEs are Pt, Pd, and Rh, and their two main uses are automotive catalytic converters and chemical catalytic converters in the petroleum

business, as well as jewelry, but storage of the value is limited due to the difficulties of production and illiquidity in markets, emphasizing that recycling is significant price driver [54,73]. In 2017–2019, almost a half of Pt and Pd was exploited for the production of automotive catalytic converters [3].

As described above, several approaches for PGEs' recovery from urban ores (mostly waste) are beneficial, and recycling technologies are functioning and developing. However, the known rate of PGEs recycling (ratio between the total supply minus supply by mining, divided by the total supply) indicates that significant amounts of PGEs are lost: the recycling rates of PGEs in Europe vary from 40% to 60% and in the rest of the world from 10% to 30% [54]. The recycling efficiency problem is not as much in the technology because the process of recycling at existing facilities is working with 96–99% recovery [54], but rather in the management of urban ores containing PGEs.

4. Peculiarities of the Global Market

4.1. The Price Action of PGEs

The demand for PGEs, as well as their price is growing continuously due to their increased use in catalytic converters keeping up with stricter requirements for emissions (in particular regarding Pt and Pd). Inevitable speculations are attributed to the development of electric and hydrogen-engine cars: when and to what extent they will take a part of the market share and/or substitute PGEs-containing catalytic converters. The question is if the price trend will reverse and diminish the demand for PGEs knowing that PGEs serve as a buffer pillow against the economic downturns during the market declines. Although the market collapse at the beginning of 2020 did not much suppress growing of Pt and Pd (neither Au) prices (Figure 5), a slight decline was observed in all commodities' assets. It usually occurs in the panic moments at the market when the approach of 'cash is the king' starts to dominate intensively. Also throughout the health crisis at the beginning of 2020, all kinds of financial and commodities assets were of brutal sell-off. This crisis had a short time effect. However, the future is not apparent yet as the economic consequences will be felt in the coming years. The reason for price collapse for Pt and Pd was a negative industrial-economic future accompanied by a fear of recession as well as raising of cash by investors to cover the losses of financial assets in leveraged positions.

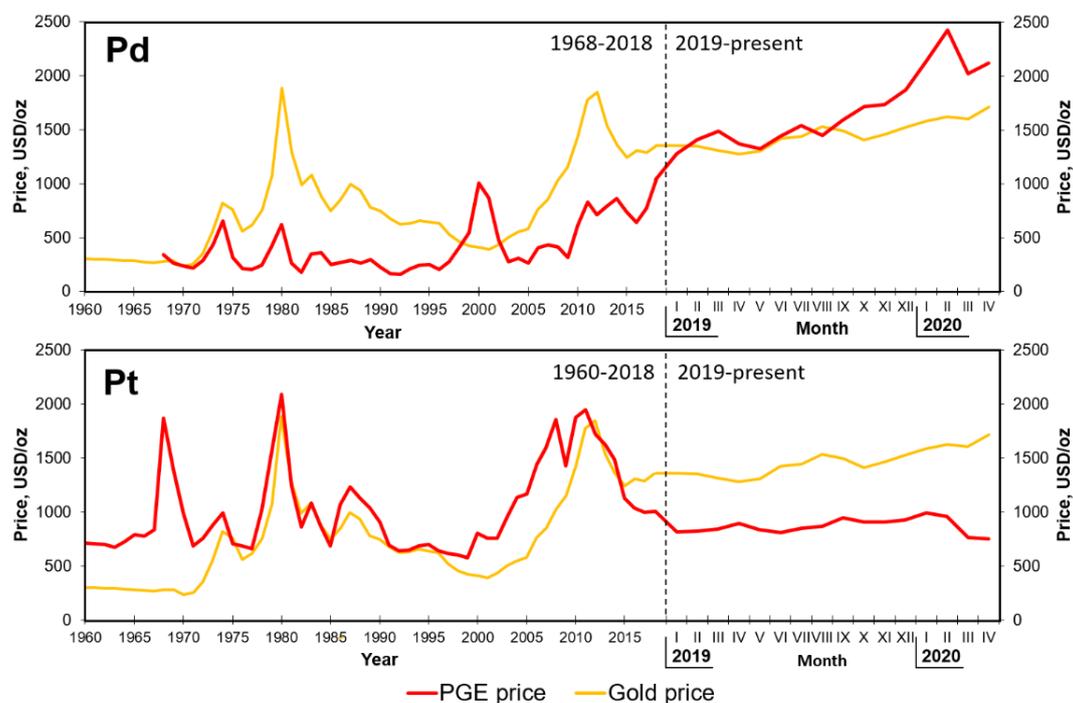


Figure 5. Historical and current price trends for Pd and Pt versus the gold price (up to April 15, 2020; inflation-adjusted prices indicated) [74,75].

The long-term negative growth of Pt demand during previous years was triggered by the ‘diesel scandal’ in the automotive industry, in the 2013–2015 period, which largely shadowed the price of Pt [76], and in 2017 the price of Pt was surpassed by the price of Pd. However, currently, it is unknown which will be the right fundamentals in the macro-economics and geopolitics scenes that will drive the markets in the nearest short- and mid-term periods. From one side it can be gradual removal of diesel and other fossil combustion engines, from another—the growth of population and economies with almost a linear trend and simultaneous production of more cars in general. Moreover, the rising interest and changing patterns of consumer behavior in the co-driving market may lead to phasing out the production of too many vehicles as the millennium and later generations might shift to lower affection for ownership of things than was prevailing before. The demand for Pt at the beginning of the 21st century was continually growing. The demand for automobiles was expected to grow with the improvement of the Japanese market. However, it remains a question for the future with high economic uncertainty. Meanwhile, the supply of Pt was decreasing as South Africa and Russia trimmed the mining outputs. Secondary supply also decreased due to stagnation in scrap metal cycling and Pt prices. The price of Pd have beaten the price of Pt with increasing demand after the ‘diesel scandal’ when catalytic converters for diesel cars became less demanded. Also, ‘criminal recycling’ increased when thieves damage vehicles and remove catalytic converters for the sale in black market [77].

For other PGEs the prices are even more volatile as the market becomes smaller than for Pt and Pd. Price curves for the rest of PGEs are given in comparison with the gold price indicating both, yearly average prices and inflation-adjusted (real) prices, to reveal the more decent picture (Figure 6). For example, some of the major peaks for the price of Rh have appeared due to increased demand and the lack of supply in 2008 as well as recently in 2019. In 2017, also a violent price volatility appeared by 375%. Changes in the price of Ru often are linked to the volatility spikes of the price of Rh. Mainly, these fluctuations of the prices are just partially linked to the supply/demand ratios; they are exaggerated as the markets are very specific, thus allowing speculative flash-crashes.

Historically the prices of PGEs have fluctuated mainly due to the social and/or political reasons. Significant and imminent role of the PGEs supplies is attributed to the mining circumstances at the Bushveld Complex in South Africa, for example, the miners’ social unrests in South Africa skyrocketed the prices in 2012 [78]. The reason was that at Anglo American Platinum, Ltd., which had difficulties of financial character, the workers demanded higher salaries, but the production struggled due to the unrest. The market price of Pt raised from 1430 USD/oz to 1600 USD/oz. Closing of few mines in South Africa inevitably diminishes supplies of PGEs, and, without ensuring labor and political stability, the price volatility grows (Figures 5 and 6).

Another example can be presented: in January 2001, the price of Pt reached its highest level in 14 years at around 645 USD/oz; however, it crashed to fall back just over 400 USD/oz in October, the same year, before rallying up for the remaining year. This case represents a clear linkage with the global economic crisis because of the technological market crash (so called ‘dot com bubble’). Volatile fluctuations of the Pt price proceeded with a speculative record of 1544 USD/oz in December 2007. The next crisis in 2007–2008 lead the price to the bubble conditions again, and it peaked at 2276 USD/oz in March 2008, falling sharply to 900 USD/oz at the end of 2008, a level not seen since 2005. 2009 came with bullish sequences, and the price of 1500 USD/oz was the point in December 2009 [79]. As it was already mentioned, the price of Pt steadily lost steam after the ‘diesel scandal’ (in 2017) when the divergence with the price of Pd occurred. At the beginning of 2020, the price of Pt felt down to less than 600 USD/oz (Figure 5), and now is slightly recovering from the overselling conditions. Pd was highly appreciated through the second part of the 1990s reaching the record price amount of 1094 USD/oz at the beginning of 2000. It decreased to 315 USD/oz later that year before beginning to grow again. Nevertheless, it remained relatively weak until 2002. In contrast to the Pt price, it traded more in a trendless (sideways) way until it outperformed in 2006 and was keeping pace in the first half of 2007. Mortgage debt of the financial crisis in 2008 lead the Pd price to a volatile pace from 370 USD/oz, that is in line with the prices of gold and Pt, and it climbed to 588 USD/oz in

March 2008, its highest point since 2001, similar to the Pt price, falling back by double digits percentage. The price of Pd was more volatile than the Pt price, and it was going through doubling, retreating, and regaining value over the following years. In 2019, the price of Pd was far exceeding the price of Pt and in October 2019, passed a mark of 2500 USD/oz, while the price of Pt was at range 800–950 USD/oz. The market crash at the beginning of 2020 significantly affected both the prices of Pd and Pt, decreasing them to 1500 USD/oz and 600 USD/oz, respectively, but recovering later in April 2020, to >2000 USD/oz and >700 USD/oz, respectively.

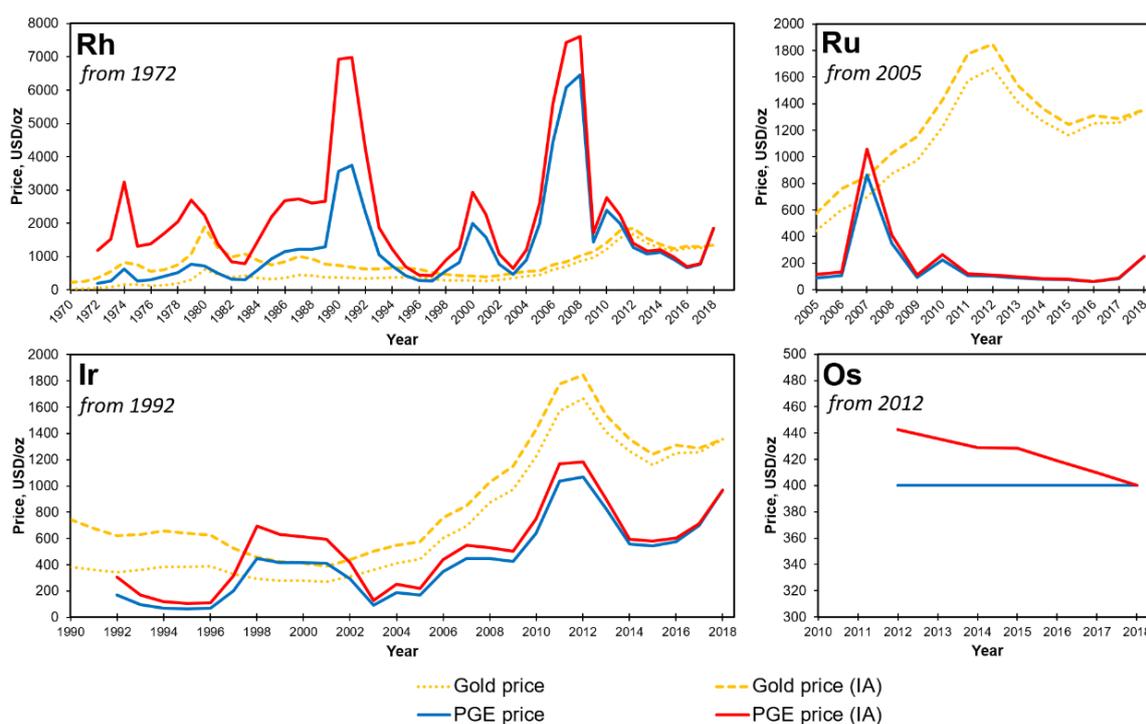


Figure 6. The price of Rh, Ir, Ru, and Os versus the gold price and inflation (IA—inflation-adjusted) [74,75].

Some studies [80–82] have described the models of price fluctuations for Pt and Pd by adapting the modeling tools on the price behavior of the leading precious metals before, during, and after the financial crisis of 2007–2008. Explosive/multiple bubble technology developed by Phillips et al. [83] describes significant, short periods of mildly explosive behavior in the spot and futures prices of all four precious metals (Au, Ag, Pt, Pd). This study pinpoints that, apart from other PGEs, Pt and Pd are viewed as the objects of investment category. Hereby, dual opposite reasons for the price rise like for “safe heaven metals” and economic slowdowns that might downgrade the demand have to be taken into account. Furthermore, the ups and downs of the US dollar’s value play a significant role that must be equalized if the price change is taken as a leading comparative measure for the market analysis.

A few remarks should be devoted to the markets of Os and Ir. Both elements are scarce, and their demands are limited and very specific. The markets of Os and Ir are non-liquid and dominated by a small number of global market makers ruling the prices (Figure 6). Use of Os is limited to less than 10 companies worldwide, virtually making the floating market non-existent.

4.2. Indicators and Drivers of the Global Market

The markets of PGEs are digitalized to great extent, and reliable information on the prices becomes more viable. In theory, there should be one common price for a commodity at a single point of time [84], meaning that the markets of PGEs, if following this rule, should also be integrated from the regional to the global scale. The markets of PGEs are consolidated mainly, and they are easily standardizable

apart from other specific goods, however, if transaction costs and trade barriers exist, these markets will hardly be integrable in the future.

It is stated that violation of the law-of-one-price (LOP) occurs when significant differences are expected due to the transactional costs and exchange rates [85]. The future markets of Pt and Pd will mostly be affected by the New York Mercantile Exchange (NYMEX) and the Tokyo Commodity Exchange (TOCOM), as two biggest market players, thus determining the price relationships among the price series before and after the break periods [86–90]. The trading platforms at the London Metal Exchange and smaller companies like Johnson Matthey, PLC, are working as derivatives of the future market of PGEs, and the prices may differ significantly because of various aspects, such as contract expiration dates, transaction costs, opening times, spreads, etc.

The issues concerning the sustainability of mining, use, and recycling are an additional large driver of the discussion, markets and price action apart from geopolitics, and are managed by international treaties and governmental policies in various countries. Creating an effective policy to distribute and use PGEs according to the sustainable emission standards leads to a large impact on supply/demand and is acting as a long-term break-even point. In large trends, the commodity prices acting in a simultaneous macro-way [91,92]. The dispute on climate change is significant not only because the PGEs-containing catalytic converters diminish the exhausts of vehicles. It is important to remember that the mining and production of PGEs itself creates a huge amount of greenhouse gas emissions as estimated for Pd, Pt, and Rh (Figure 3b). Therefore, it is important to increase the recycling potential from urban ores and to reduce the use of virgin material. First of all, it is necessary to postpone the depletion of the planetary resources in general, and, secondly, to develop efficient exploitation of secondary resources derived from urban ores. The estimates for 2019 have revealed that recycled material for Pt compiles 27% (2,261,000 oz) of total gross demand (8,484,000 oz), for Pd –30% (3,416,000 oz of 11,502,000 oz) and for Rh –32% (372,000 oz of 1,144,000 oz) [3]. A general upward trend of the prices has influenced the rate of recycling and the activity of circular use of PGEs. Already in 1990s, the demand for PGEs by carmakers in the USA resulted in a tremendous shift from Pt to Pd, decreasing the price of Pt and increasing the price of Pd. It was a result of the reverse situation occurring in Europe, when the European carmakers reported increased production of diesel cars due to sentiment of being more environmentally friendly at that time, thus switching back increase of the price and the demand for Pt. It means that in longer time scale the most important drivers of the demand for PGEs would be the following: the legislation regulating emissions, production of automotive catalytic converters, the proportion of diesel engines (Pt) in the car industry versus petrol engine (mainly Pd) vehicles.

South Africa and Russia are the dominant countries in the global production of PGEs: any significant changes or disruption in governmental policies and behavior determine structural changes and volatility of prices. The rapid increase of recycling and ideology of circular economy presses on recycling initiatives that affect the price, primarily through the improvements of technologies and diminishment for the self-cost of production (PGEs usually are mined and produced simultaneously with other significant metals). As previously mentioned, one of the supply threats from South Africa are labor unrests (one of the biggest in 1987) that might cut supply and push up prices. In the case of geopolitics in Russia, international sanctions and even oligarchy of mining companies can lead the price directions [93]. Other threats may include natural hazards, production accidents, power cuts, local price, and energy policies [93,94]. Smelter closures, geological risks, safety issues, and complicated industrial relations can generate social unrest and strikes that significantly influence the output [78]. Although the Republic of South Africa largely dominates in the PGEs industry, it needs to earn and, therefore, produces a large amount of PGEs despite the price decline. An additional problem of another “PGEs whale”, the Russia Federation, is that there is no clear and transparent accounting on the amount of produced and stored stockpiles, thus leaving an opportunity for illicit manipulations of price (similar to the behavior of China in the market of rare earth elements). It is estimated that the deposits of Norilsk enterprise will be rich in the reserves of Pd and Pt until 2102 or even beyond, and within the technology advances the extraction of less rich ores becomes economically attractive [95].

The extraction of PGEs is almost always linked to the mining of other dominant metallic ores, and so therefore the cycles in Ni and Cu mining influence the extraction of PGEs [96]. In 2019, total estimated reserves were 69,000 t of PGEs [60]. Nevertheless, historically the government of Russia has never tried to change its policies regarding PGEs, not even in the time of the former USSR, as a need for cash flows of foreign currency usually existed [94]. However, other risks, such as mining accidents, political instabilities, or international sanctions, have already influenced stock prices of MMC Norilsk Nickel, PJSC in the markets in, e.g., 2018. In future such accidents cannot be excluded.

The prices of PGEs experience large volatility swings owing to the currency rates, e.g., the exchange rate for USD/AUD leads to ideal market conditions for Australian producers when AUD value is low and the price of PGEs (in USD) is high. However, the Forex rates have significant deviations from the industrial cycles and general trends in macro-economics. Therefore, it is hard to predict these cycles as they are linked to policies of the Central Bank, media rhetoric, traders' sentiment, and algorithmic trading rhymes.

5. The Global Sustainability Question

In the 1970s, the authors of the book "Limits to Growth" generated acknowledgement, as well as criticism of pessimistic global future scenarios [97]. Understandably, the exponential growth of consumption *versus* limited resources means collapsing of the system at a certain point. Critiques argued that not enough innovation was considered. Nevertheless, as shown in related studies [98], many of the projections anticipated by Meadows et al. [97] were accurate enough. Pollution and resource consumption are growing problems and the capital should be diverted to sustainable production even if it is not economically profitable [99]. It is possible by implementing the ideas of the circular economy in practice. In the case of PGEs, the discussion is still open on waste management, efficient logistics, and recycling technologies.

The extraction of mineral resources by definition cannot be sustainable, and the largest high-grade deposits will be exhausted due to growing demand [100]. Ongoing debates on the geopolitical scene have highlighted the impact of crises and the narrowness of supplies. However, the picture becomes a bit brighter as the Earth's resources are not so finite as it was thought initially. Technologies are developing, and new alternatives become accessible. Nevertheless, overall industrial development and the need for 'clean energy' will require greater amounts of metals, and until 2050, the demand for metals will be greater than in the entire previous century [101–103].

Unlike unrenovable and unrecyclable hydrocarbons, metals can be recycled. The circular economy policies discuss secondary raw materials and the three pillars of sustainability: economy, environment, and social equity. General principles of sustainable development, such as the ISO 26000 requirements on social responsibility [104] and certification standards for the mining industry, increase the confidence of financial investors as well [105].

Mineral resources are unevenly distributed both, geologically politically. For example, during 2015, 70% of the world's Pt was produced in South Africa [53] and almost exclusively at the Bushveld Complex [1]. Considering that PGEs are crucial as precious metals for investment and critical components for catalytic converters, the strategic importance of South Africa is immense as it holds 80–90% of the world's PGEs reserves [106]. Likewise, 50% of the world's production of rare earth elements comes from the Bayan Obo mine in Mongolia [107]. Regional geological history and endemic concentration of specific resources due to natural processes have become an aspect that influences the social and economic sides of the story [108].

6. Substitution *versus* Recycling

The mining of PGEs has colossal capital and operating expenses (Opex). Besides, mining and separation itself is a toxic process. The modern demand for PGEs appeared in the 1970s when catalytic 'cats' for the conversion of CO and unburned fuel to CO₂ and water was considered safer for the environment. Later the acidic rain problem caused by N oxides and S oxides lead to an approach of

adding synthetic cordierite ceramic honeycomb where Rh was added. In 1989, General Motors, Ltd. established a PGEs recycling operation for self-supply needs. New ventures as Impala Platinum, Ltd. in South Africa appeared, smelting and refining giant Umicore, Ltd. (previously known as Union Minière du Haut Katanga) in Belgium, soon followed by other mining and smelting companies. In the last 25 years, the recycling systems of the plasma arc technology allowed to ‘simply’ throw the entire catalytic converter into a furnace and extracting PGEs with HCl (releasing chlorine gas), the most popular technology exploited at dominant countries, such as Russia and South Africa [73].

The model described by Zhang et al. [109] pinpoints that automotive demand for PGEs is likely to grow, especially the demand for Pd will grow strongly by 2030. Already from 2014 to 2019, the demand for Pt increased from 7,967,000 oz to 8,484,000 oz (+6.5%), while supply increased from 5,154,000 oz to 6,020,000 oz (+16.8%), as well as recycling—from 2,045,000 oz to 2,261,000 oz (+10.5%). The difference between the supply and demand indicates a shortage of resources, i.e., in 2014 it was minus 777,000 oz, but in 2019—minus 203,000 oz [3]. Still, today we can observe prices falling for Pt due to the ‘diesel scandal’ and rhetoric on diesel ban. The model described by Zhang et al. [109] forecasted and increase of the Pt price by approximately 5%, while the use of Pd was estimated to increase by approximately 45%. Potential of the substitution rates and technological changes should not be underestimated when modeling the future outlooks of the industry and markets of PGEs.

Decision-makers in industries and governmental institutions need to analyze and plan the supply chains for critical materials, including PGEs [110,111]. Malthusian (revolutionary demand) metrics, analyzes the scarcity of commodities and the rates of their use, thus considering the risks of resource exhaustion in the future [112]. Substitution is the way how the industry solves the problems. For example, automotive applications of PGEs with catalytic properties provide substitution for other PGEs which are mainly mined alongside Pt. However, these are not reliable substitutes as the industry has to change the production lines and methodology, and the production of other PGEs usually is concentrated in the hands of the same mining actors. The price diagrams of Rh, Pd, and Pt are obvious witnesses for that.

Ricardian metrics analyzes ore grade and energy costs of extraction. The low concentration (e.g., 0.5–3.0 g/metric ton for Pt) means that the price rises exponentially if the regulations or extraction costs increase [54]. In the case of Pt, primary supply is concentrated in South Africa (75% of the production, 88% of the reserve base). Five companies (Lonmin, Inc., Anglo Platinum, Ltd., Impala Platinum, Ltd., Aquarius Platinum, Ltd., and MMC Norilsk Nickel, PJSC) control most of the primary supply [42]. This leads to the consequences of large price fluctuations and inefficiencies if any disruptions of the supply chains, legislation, or social processes proceed. Regarding the secondary sources from recycling the scene differs. Recycling is a prerogative of highly industrialized developed countries which are the consumers of PGEs themselves. Therefore, the recycled amount depends on the use of PGEs by the industry and the consequent waste management efforts [54,113]. The problem of recycling is the need for specific infrastructure not readily available at all locations [42]. To improve Malthusian metrics, pre-treatment of PGEs-containing waste (urban ores) and efficient logistics are crucial.

A model of the use of PGEs and environmental pressure has been developed for Europe. It reveals that reducing SO₂ emissions from, e.g., MMC Norilsk Nickel, PJSC located in Russia would cut the cumulative emissions by 35%, generating cleaner electricity in South Africa—by another 9%. Increased recycling efficiency up to 70% would reduce the SO₂ emissions by 25% [114]. As PGEs often are emissions-reduction-items themselves, the cumulative effects (if substituting Pt by Pd) of price increase should also be considered. The role of substitution, recycling, and demand patterns of the end consumers influence the use of PGEs, while excessive use of Pd may lead to increased specific environmental impacts. Besides technological improvement, the basic design of the vehicles and mobility aspects *per se* are essential. Here, the conclusion is that the choice of consumer is the decider.

7. Future Trends of Exploration and Markets

Several principal outcomes from this review are attributed to the global and macro-economic factors that may impact the exploitation of resources, price pivots, and macro-trends for the price formation, if the daily volatility noise of the prices would be reduced. This review suggests that projects involving PGEs are sensitive to the following factors: (a) the prices of metals; (b) the Forex exchange rates; and (c) the large requirements for the capital expenditure against the small size of PGEs-only deposits. When high prices of PGEs are the reality, the exploration and mining flourishes [115], still, the reality is that South Africa, Russia, and Canada own approximately 98% of the known global PGEs reserves [52,53].

Mining of PGEs and rare earth elements from the seafloor sulfide ores is questionable because of international legislation gaps and unbearable costs [116], at least for the nearest future. More encouraging outlooks are discussed concerning the space exploration and extra-terrestrial resources [6], however, it is a challenge for the coming centuries. New paradigms on tectonics and metallo-genesis might widen exploration potential for the primary mining in the mid-term future [117]. It is vital to increase optimization of PGEs' recovery in the mining processes of the primary concentrates of Cu and Ni [1,17–19]. Thereof, the improvement of metallurgical approaches is crucial, moreover, these methodologies are efficient for the recycling of secondary raw material, such as urban ores. Sulfide mineralogy is a problem for the development of Cu-Ni and PGEs resources in the Duluth complex in the USA [118] that can be solved by future technologies.

The economic cycles significantly affect the mining and metal production industries. Mines have to be operated continuously as stopping the work and reopening is too expensive. Initially, the price of PGEs-containing ores is induced by investment in infrastructure, followed by falling prices due to economic reasons or overproduction.

The major changes in global commodity markets expected to commence after successful implementation of the sustainability goals and the Green Deal. If fuel engines would be accepted worldwide as indicated by the European policy, and additional strategies supporting the circular economy for promoting recycling would be implemented, they will determine the PGEs prices.

Mining operations require substantial community approval which is an integral part of Corporate Social Responsibility (CSR). Mining should incorporate the needs of local people, manage their expectations, and provide actual and long-lasting benefits [119,120]. The technologies developed for the processing of complex ores from virgin resources will drive the improvement of recycling technologies towards cheaper and environmentally friendlier production of PGEs. CSR has to be an essential driver as the problem related to recycling from urban ores is waste management not a technology issue. Greater attention has to be paid to recycled urban ore as a better solution over a natural ore. While the globalization or de-globalization will be considered in the national economies for a short or medium term, the questions on critical commodities will require global and sustainable solutions.

8. Conclusions

PGEs (Os, Ir, Ru, Rh, Pd, Pt) are of critical industrial demand, and they are a strategic commodity traded in the global market. Exploration of new mines depends on global demand of metal commodities and the price action, as PGEs are always a byproduct at other major element extraction. In addition, the classical rules of supply and demand are often overridden by irrational and speculative aspects in commodities' markets, revealed by the historical price charts.

The increase in demand for PGEs is mainly due to fuel production and engine emission control. Hence, the 'diesel scandal' caused the price divergence between Pt and Pd, significantly improving the latter's price. Thus, stricter requirements for transport emissions increase the demand for PGEs, and development of electric car production is expected to re-form the market share.

Although, high costs and limited availability of PGEs drive the recycling technologies of urban ores, the diversity of PGEs' application and their specific chemical properties highlights the complexity of recycling management. It can be concluded that apart from geopolitical and fiscal

factors, production cycles and the long-term supply of metals through geological extraction and recycling are the most important fundamental drivers.

In the PGEs' price formation, social and/or political issues are equally important as there are only a few countries (Russia and South Africa) among the largest producers that may induce global "supply shocks." Pt and Pd nowadays have become investment grade objects, known as "safe heaven" metals. Thus, contradicting the economic slowdowns of the industrial demand, Pt and Pd provide a mixed valuation bias (less demand by industry influences price in a downward direction more than investment opportunity would drive it up). As US dollar usually is dominant in the trades, the currency markets play significant role in the valuation of PGEs.

Finally, analysis of scientific studies, as well as the market analysis, led to the conclusion that exploration and recycling projects involving PGEs apart from classic ratios of supply and demand are mainly sensitive to (a) the prices of PGEs, (b) the Forex rates, (c) the sentiment of general markets and (d) the large Capex requirements for new mining initiatives. Yet, in the future, the role of PGEs as critical elements for the industry will facilitate the need for sustainable exploration, mining, and dominance of recycling in the frame of the circular economy.

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