Platinum Group Metal Catalysts

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

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About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgments

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Nomenclature or List of Acronyms

AMO	Advanced Manufacturing Office
CSG	Corporate Sustainability Governance
DOE	Department of Energy
EO 14017	Executive Order on America's Supply Chains
ESIB	Energy Sector Industrial Base
FCC	fluidized catalytic cracking
FCEV	fuel cell electric vehicle
GDP	gross domestic product
GHG	greenhouse gas
GM	General Motors
HDI	Human Development Index
HF	hydrogen fluoride
HFTO	Hydrogen and Fuel Cell Technologies Office
HHI	Herfindahl-Hirschman Index
ICE	internal combustion engine
ICP-OES	inductively coupled plasma optical emission spectroscopy
IEA	International Energy Agency
Ir	iridium
MW	megawatt
NGL	natural gas liquids
NMIC	National Minerals Information Center
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OER	oxygen evolution reaction
Os	osmium

Pd	palladium
PDH	propane dehydrogenation
PEM	polymer electrolyte membrane
PGM	platinum group metal
Pt	platinum
RDD&D	research, development, demonstration and deployment
Rh	rhodium
RON	research octane number
Ru	ruthenium
RVP	Reid vapor pressure
SMR	steam methane reforming
TBD	to be determined
TRL	technology readiness level
UK	United Kingdom
U.S.	United States
USA	United States of America
USGS	United States Geological Survey
XRF	X-ray fluorescence

Executive Summary

In February 2021, President Biden signed the "Executive Order on America's Supply Chains" (EO 14017), directing seven executive agencies to evaluate the resilience and security of the nation's critical supply chains and to craft strategies for six industrial bases that underpin America's economic and national security. As part of the one-year response to EO 14017, the U.S. Department of Energy (DOE), through the DOE national laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base (ESIB), with a particular focus on technologies required to decarbonize the U.S. energy industrial base by 2050.

This report focuses on the supply chain for catalysts, specifically platinum group metal (PGM) catalysts, used for decarbonizing energy technologies. Catalysts are substances that increase the rate, conversion, and selectivity of chemical reactions and are used in a variety of applications such as chemical manufacturing, petroleum refining, and catalytic converters. Catalysts containing PGMs ("PGM catalysts") are particularly useful in widespread industrial applications, including the production of high-volume chemicals such as ammonia, acetic acid, nitric acid, and the refining of crude oil into petroleum products. The PGM metals possess extraordinary properties such as being active oxidation and hydrogenation catalysts; excellent electrical conductors and electrodes; and outstanding adsorbers of oxygen and hydrogen. Within the energy industrial base, PGM catalysts improve the energy and materials efficiency of petroleum refining and chemical industry processes and reduce energy consumption in manufacturing. In addition to their use in catalytic converters, PGM catalysts are important to maximizing the efficiency of emerging decarbonization technologies, specifically in proton exchange membrane (PEM) electrolyzers for green hydrogen production from water and PEM fuel cells for transportation and stationary energy storage. Green hydrogen is expected to play a significant role in decarbonization scenarios.

PGMs, designated as critical materials by the U.S. Government, [1] represent a class of co-product metals that include platinum, palladium, rhodium, ruthenium, and iridium as well as osmium (which is not currently designated as a critical material). PGMs are among the least abundant elements on earth and occur in only a few countries worldwide, with the majority of production and reserves in South Africa and Russia. Two PGM mines operate in the United States, although both are owned by a South African company and produce less than 7% of world supply. In addition to catalysts, PGMs are used in a variety of applications, including electronics, jewelry, and glass. Currently, the catalytic converter market consumes the most PGM, specifically platinum, palladium, and rhodium.

Under aggressive decarbonization scenarios, such as those striving toward net zero carbon emissions by 2050, demand for PGM catalysts is expected to grow rapidly, both domestically and globally. The availability of PGMs for decarbonization technologies may be further challenged by two coproduction issues, specifically misalignment of future demands with those of 1) base metals, such as cobalt and nickel, that support mine operations and new mine developments; and 2) PGMs (i.e., platinum and palladium) present in higher concentrations in ores than those that are present in lower concentrations (i.e., rhodium, ruthenium, iridium, and osmium). As major constituents, platinum and palladium support operations and capital investment for PGM refining. This coproduction increases the vulnerability of the other PGMs, and particularly iridium, whose anticipated supply will be inadequate to meet aspirational demand from green hydrogen production given today's water electrolyzer technologies. Research and development of substitute technologies are essential to reduce iridium content by an order of magnitude or more. Figure ES1 shows the relative global mine production of PGMs, where iridium accounts for the smallest share among the coproducts (data for osmium is not available).

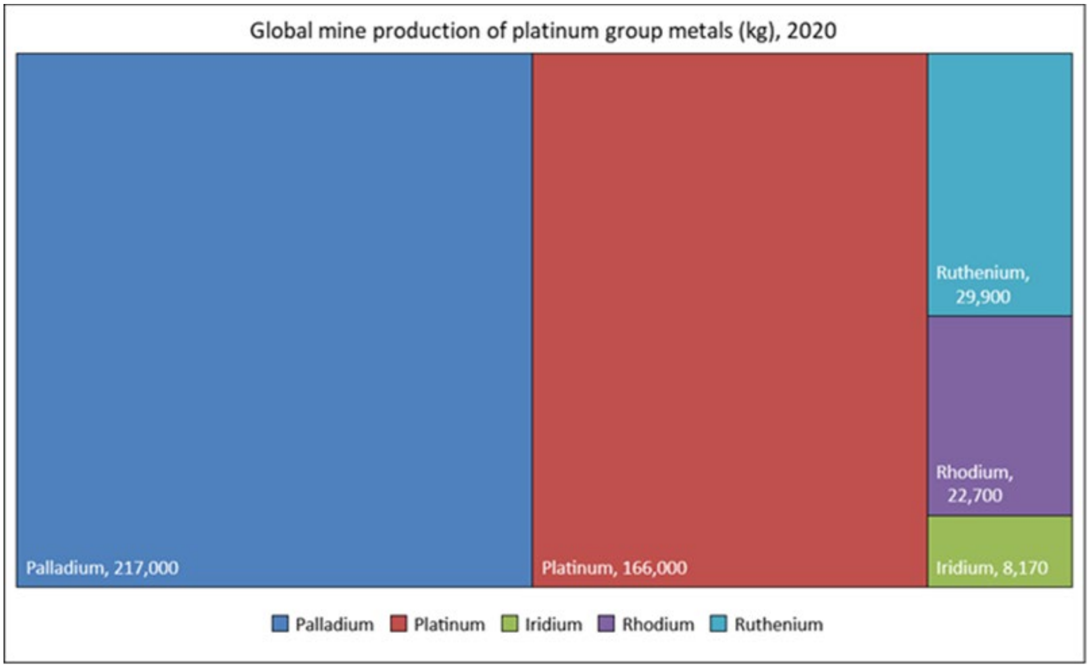

Figure ES1. Relative global mine production of PGMs, 2020 [2]

The main supply chain segments for PGM catalysts, including downstream segments as well as the recycling of PGMs, are 1) PGM production, which includes the mining and processing of PGM-bearing ore as well as the separation of PGMs into individual metals; 2) PGM catalyst manufacturing for components of finished products and associated final uses; and 3) end-of-life product recovery.

This report provides information on PGM mining and refining, catalyst manufacturing, and secondary recovery technologies, with a focus on the PGM catalysts important for transitioning to the production and use of green hydrogen. The study points to the need to establish a domestic strategy dedicated to assuring sustainable supply chains for the manufacture of PGM catalysts to support both decarbonization goals and the chemical industry in the United States.

Vulnerabilities potentially hindering U.S. efforts to decarbonize the ESIB include:

- Limited publicly available data for characterizing and assessing PGM catalyst supply chains and their applications to support decarbonization goals.
- Current technology for energy-efficient PEM water electrolysis that depends on iridium supply, one of the rarest minerals in the world for which the United States relies 100% on imports.
- Reliance on PGMs, both scarce and byproduct materials, from mines and refineries that are energy-, water-, carbon-, and capital-intensive, cause damage to the environment, and have adverse effects on workers and communities.
- Potential decline in PGM available from recycled catalytic converters as internal combustion engine vehicles are replaced by electric vehicles.
- Immature technologies for the recovery and recycling of PGM from water electrolyzers and fuel cells.
- Lack of PGM refining in the United States.

These vulnerabilities lead to opportunities for the United States to position itself to:

- Take a leadership role in innovation and adoption of decarbonization technologies, including PEM water electrolyzers and fuel cells.
- Provide support to PGM catalyst industries to enable decarbonization.
- Develop substitutes to reduce reliance on iridium-based anode catalysts in PEM water electrolyzers.
- Develop and commercialize technologies for recovering PGM from end-of-life PEM fuel cells and water electrolyzers.
- Expand PGM mining and refining in the United States.

To realize these opportunities, a number of challenges need to be overcome:

- Information gap in PGM catalyst manufacturing processes and data.
- Dependence of PEM water electrolysis on iridium-based catalysts.
- Lack of infrastructure to recycle PGMs from emerging PEM electrolyzer and fuel cell technologies.
- Potential disruption from changing demands in the PGM catalyst industries.
- Environmental, energy, and societal burdens of PGM mining and refining.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Introduction

The U.S. and global economies will require radical transformations to decarbonize by 2050, including transitioning to renewable energy generation from carbon-neutral sources combined with carbon-neutral transportation and decarbonized industrial processes. While efficient technologies are available to help achieve these goals, some currently rely on raw materials characterized by volatile global markets often concentrated in geopolitically sensitive areas. Furthermore, several midstream stages of supply chains, such as material processing and the manufacturing of components, are also concentrated in foreign countries with potentially complicated geopolitical relationships with the United States. This report focuses on the supply chain for platinum group metal (PGM) catalysts, which are used for decarbonizing energy technologies.

Catalysts are substances that increase the rate, conversion, and selectivity of chemical reactions and are used in a variety of applications such as chemical manufacturing, petroleum refining, and automotive catalytic converters. While catalysts are not consumed in the chemical reactions, some losses may occur in use. A wide variety of catalysts are marketed, many of which are important for reducing energy consumption and carbon emissions in manufacturing and during the use of energy technologies. In the United States, 18 chemicals account for 80% of energy demand in the chemical industry and 75% of greenhouse gas (GHG) emission from that sector. Advanced catalysts and related process improvements could reduce energy intensity for these chemicals 20% to 40% as a whole by 2050 [3].

PGM catalysts have many useful and unique properties that make them well-suited for use in widespread industrial applications, including the production of high-volume chemicals such as ammonia, acetic acid, and nitric acid and the refining of crude oil into petroleum products. PGMs are particularly well-suited to catalysts used in high-temperature applications due to their high melting point [4]. Other major (non-catalyst) uses of PGMs include electrical and electronics applications (hard disk drives), glass manufacturing, and jewelry applications [5]. This analysis focuses on PGM catalysts because of their use in decarbonization technologies and processes, their potential for growth as we transition to more decarbonized economies, and because of the scarcity of PGM raw materials.

Within the Energy Sector Industrial Base (ESIB) sector, PGM catalysts are critical components of many decarbonization technologies and energy technologies, including catalytic converters used to reduce pollutants from internal combustion engines, natural gas fuel cells, fuel cells for energy storage (electricity), fuel cell electric vehicles, thermal catalytic reactors with advanced catalysts, electrochemical reactors for chemical productions, and electrolyzers to produce green hydrogen using the polymer electrolyte membrane (PEM) water electrolysis process. Green hydrogen has widespread potential for decarbonizing industrial processes, including chemical manufacturing (in particular, green ammonia production, which has many downstream uses), petroleum refining, low carbon emissions steel manufacturing, and biofuels (including renewable diesel and sustainable aviation fuels).

This report summarizes information on PGM catalysts, including providing a mapping and discussion of the PGM catalyst supply chain, from the extraction of raw materials to the production and recycling of PGM catalysts. Also evaluated are the risks and resilience, as well as current U.S. competitiveness and potential opportunities of the PGM catalyst supply chain. The study revealed vulnerabilities (and their causes) in the PGM catalyst supply chains that are important to decarbonizing the ESIB.

1.1 Background and Key Assumptions

PGMs include platinum (Pt), palladium (Pd), rhodium (Rh), iridium (Ir), ruthenium (Ru), and osmium (Os), which occur in common deposits and have similar properties that make them efficient catalysts. Current consumption of PGMs (especially Pt, Pd, and Rh) is driven by use in catalytic converters in internal combustion engine (ICE) vehicles. Use of PGMs by sector (including non-catalyst uses) in tonnes for 2020 are shown in Table 1.

Table 1. Use of PGMs (tonnes) by sector in 2020 [6]. (Note: data not available to separate PGM use in catalysts for PEM water electrolyzers and fuel cells from their use in other catalysts. More detail on PGM consumption is provided in the Appendix Table A1.)

Use	Platinum	Palladium	Rhodium	Ruthenium	Iridium
Catalytic Converters	71.2	266.0	29.4	-	-
Catalysts (chemical, petroleum, electrochemical)	29.3	18.0	1.7	15.5	3.5
Electronics	7.5	19.5	0.2	11.8	1.6
Glass	14.1	-	0.2	-	-
Investment	31.8	-5.9	-	-	-
Jewelry	53.1	2.7	-	-	-
Other	21.0	11.0	0.2	3.2	2.3
Total	**228.0**	**311.3**	**31.7**	**30.5**	**7.4**

Substantial and aggressive decarbonization of all economy sectors will be needed to meet 2050 climate goals. Replacing fossil fuels with hydrogen is a focal point for the United States to reach 2050 net-zero GHG emissions, given hydrogen has zero carbon dioxide (CO2) emissions during application. However, current production of hydrogen is not carbon-free as it is produced by steam methane reforming (SMR). To meet net-zero carbon goals, hydrogen production needs to transition to green hydrogen produced by electrolysis of water and powered by renewable energy. With applications in both industrial and transportation sectors, which are the two leading CO2 emitters in the United States (29% and 36%, respectively), green hydrogen can contribute to decarbonization in several ways:

- Replacing grey hydrogen produced from carbon intensive SMR process. Currently, SMR hydrogen is broadly used, incurring a large amount of CO2 emissions. Each year about 10 million tonnes of hydrogen is produced in the United States of which 95% is from SMR. [7] About 9 million tonnes of CO2 is emitted per million tonnes of hydrogen production, accounting for about 2% of the U.S. total annual CO2 emissions. [8] Replacing grey with green hydrogen in such applications can reduce the direct CO2 by 86 million tonnes. However, this substitution is not considered to be a near-term opportunity for two reasons: 1) currently, green hydrogen is substantially more expensive compared to grey hydrogen; and 2) significant capital is invested in SMR plants, making companies less likely to retire their assets, instead equipping them with carbon capture technologies.
- For the industrial sector, green hydrogen can contribute to decarbonization by replacing carbon-intensive reducing agents (e.g., replacing coal use in steel plants) and/or replacing fossil fuels (e.g., natural gas) as energy sources to supply heat, steam, or electricity.

- For the transportation sector, green hydrogen can contribute to decarbonization by powering fuel cells for electric vehicle propulsion and to power electric systems and propulsion in spacecraft and aircraft.

Emerging energy-efficient technologies supporting these applications, specifically PEM water electrolyzers and fuel cells, require PGM catalysts. Figure 1 shows global and U.S. projections of annual capacity additions of these two technologies for 2020–2050 according to the companion report prepared by the National Renewable Energy Laboratory (NREL) with funding from the Hydrogen Fuels Technology Office (HFTO). [9]

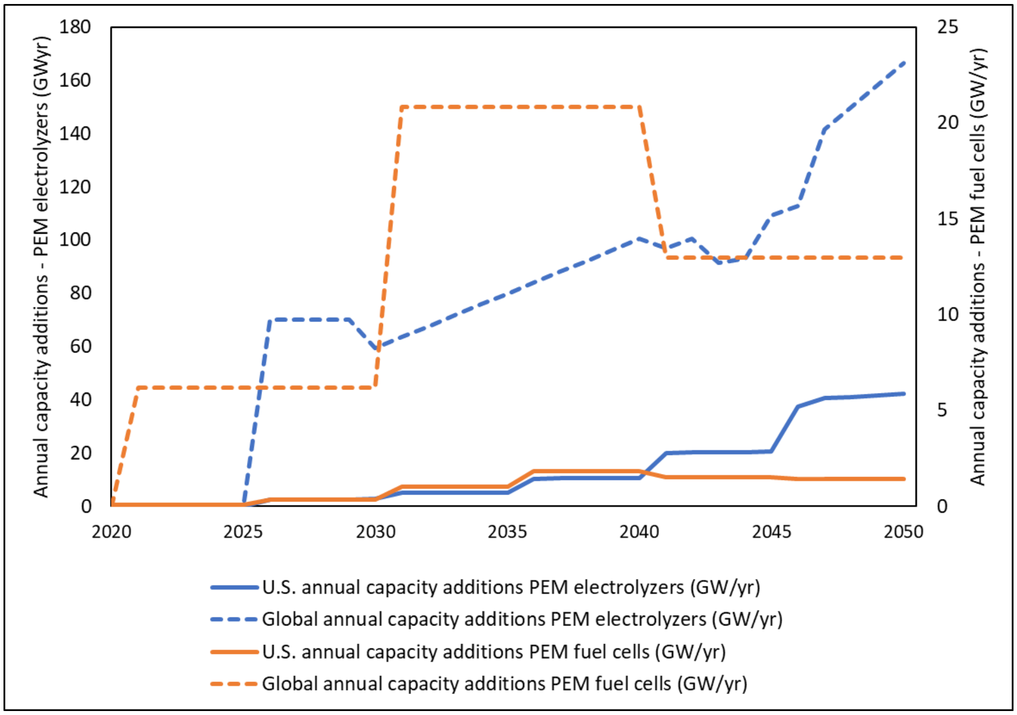


Figure 1. Annual global and U.S. capacity additions for PEM water electrolyzers and fuel cells

For decarbonization, this analysis focuses on growth in PGM catalyst demand for green hydrogen and fuel cells. It also discusses the use of PGM catalysts in the production of petroleum products and chemicals. It does not, however, include an analysis of supply chains for catalyst support materials (e.g., zeolites, activated carbon, alumina, and silica) or other non-catalyst elements of end use products such as PEM fuel cells and PEM water electrolyzers. It also does not include an analysis of the downstream uses of green hydrogen, as those issues are covered by the companion supply chain review performed by NREL for HFTO. [9]

Shifts in demand for specific end uses, including PEM water electrolyzers for green hydrogen production and fuel cells for transportation and energy storage, will influence markets for PGMs. Table 2 shows a summary of assumptions and uncertainties about future PGM demand across the various sectors. With the exception of catalytic converter applications, this analysis assumes that demand across the existing major use sectors will continue to grow in tandem with global economic growth and not due to the adoption of new technology. This analysis also assumes that the global demand for catalytic converters will initially increase as countries, including China, enact stricter vehicle emission laws, and then decrease as battery and fuel cell electric vehicles replace ICE vehicles. The assumptions for PEM water electrolyzers and fuel cells demand in this report are aligned with the hydrogen supply chain analysis effort funded by HFTO. [9]

While PGM catalysts account for a subset of catalysts used in industry, they are among the most expensive and rare catalytic agents [10]. Additional study is needed to analyze the supply chains for all catalysts (including non-PGM catalysts) important to decarbonizing the petroleum, chemical, and other industries.

Table 2. Summary of assumptions and questions about future PGM demand in catalyst and non-catalyst uses across sectors

End Use	Use as catalyst?	Global growth of sectors by 2030 independent of decarbonization scenarios	Domestic growth of sectors by 2030 independent of decarbonization scenarios	Change in PGM per unit product to achieve decarbonization scenarios	Assumptions
Catalytic converter	Yes	Grow	Decline	Constant	As more EVs are brought into market, less catalytic converters are needed
Catalysts (chemical, petroleum, electrochemical)	Yes	Grow	Grow	Constant	Advanced catalytic processes deployed to reduce energy intensity
Electronics	No	Grow	Grow	Constant	PGM use in electronics are not tied to energy input
Glass	No	Grow	Grow	Constant	PGMs use in glass is not tied to energy input but used in the protection of mfg. equipment.
Investment, jewelry, other	No	Grow	Grow	Constant	PGM use in electronics are not tied to energy input (not catalysts).
Fuel cell electric vehicles	Yes	Grow slightly	Grow	Decline	Use of fuel cell electric vehicles will be primarily in the transportation sector for medium and heavy- duty vehicles
Green hydrogen for decarbonization	Yes	Grow slightly	Grow	Decline	Green hydrogen produced via PEM electrolysis will be broadly utilized in various sectors.

Vulnerabilities potentially hindering U.S. efforts to decarbonize the ESIB include:

- Limited publicly available data for characterizing and assessing PGM catalyst supply chains and their applications in chemical manufacturing.
- Current technology for energy-efficient PEM water electrolysis that depends on iridium supply, one of the rarest minerals in the world for which the United States relies 100% on imports.
- Reliance on PGMs, both scarce and byproduct materials, produced and imported from mines and refineries that are energy-, water-, carbon-, and capital-intensive, cause damage to the environment, and have adverse effects on workers and communities.
- Potential decline in PGM available from recycled catalytic converters as internal combustion engine vehicles are replaced by electric vehicles.
- Immature technologies and insufficient prioritization of RDD&D to enable the recovery and recycling of PGM from water electrolyzers and fuel cells.

These vulnerabilities lead to opportunities for the United States to position itself to:

- Provide informational support to private and public stakeholders supporting the PGM catalyst industries important to attaining global decarbonization goals.
- Take a leadership role in innovation and adoption of decarbonization technologies, including PEM water electrolyzers and fuel cells.
- Develop substitutes to reduce reliance on Ir supply to support decarbonization transitions, including the manufacturing and adoption of PEM water electrolyzers
- Develop and commercialize technologies for recovering PGM from end-of-life PEM fuel cells and water electrolyzers.

To realize these opportunities, a number of challenges need to be overcome:

- Information gap in PGM catalyst manufacturing processes and data.
- Dependence of PEM water electrolysis on Ir-based catalysts.
- Lack of infrastructure to recover PGMs from emerging PEM electrolyzer and fuel cell technologies.
- Potential disruptions from changing demands in the PGM catalyst industries.
- Environmental, energy, and societal burdens of PGM mining and refining.

1.2 Bottlenecks in the PGM Catalyst Supply Chain

A number of existing bottlenecks and challenges in the PGM catalyst supply chain may inhibit U.S. decarbonization goals. PGMs are among the least abundant elements on earth and occur in only a few countries worldwide, with most of the production and reserves located in South Africa and Russia. A small percentage of PGMs are mined and smelted in the United States; however, the refined PGMs are currently separated in South Africa.

PGMs are critical materials for many catalyst applications in petroleum refining and chemical manufacturing. They are byproducts of base metal mining, which can increase instability in the supply chain and lead to volatile pricing. [11] The lease or purchase of PGM is a major contributor to the costs of PGM catalysts. Consequently, PGM prices and price volatility, which has occurred in response to supply or demand issues and uncertainties, can affect the profitability of catalyst manufacturers. PGM are difficult to substitute in catalytic applications, however, and thus demand is relatively non-responsive to price fluctuations.

Currently, the largest demand for PGM, specifically Pt, Pd, and Rh, is for the manufacture of catalytic converters for ICE vehicles. As ICE vehicles are phased-out to meet decarbonization goals, the subsequent reduction in demand for these PGM (particularly Pt and Pd, which occur at the highest concentrations in mined ores) could affect the profitability of PGM mines. Important decarbonization technologies, specifically PEM electrolyzers and fuel cells, rely on Pt catalysts, possibly mitigating the co-production issue. One significant bottleneck for PEM water electrolyzers, however, is the current technology reliance on Ir-based anode catalysts. Adoption of this technology will be highly constrained by available supply of Ir, for which the United States has 100% import reliance. This bottleneck has the potential to be worsened if PGM mine production declines in response to reduced sales of catalytic converters as the transportation sector is decarbonized.

2 Supply Chain Mapping

This section discusses the supply chain for producing PGM catalysts and the various production and manufacturing steps required. It also discusses their use in components and final products within the ESIB (i.e., PEM water electrolyzers and fuel cells) and various approaches to recycling PGMs from end-of-life products.

2.1 Supply Chain Overview

PGM catalysts are an intermediate product used in the production of chemicals and end-use products such as catalytic converters, PEM water electrolyzers, and PEM fuel cells. Accordingly, the supply chain for PGM catalysts includes segments both upstream of catalyst manufacturing, such as raw materials production, and downstream, such as the production of catalytic converters and their recycling. Materials used in PGM catalysts include the PGMs (Pt, Pd, Ir, Ru, and Rh) as well as a wide variety of other elements used in combination with PGMs to manufacture precursors. This report focuses on PGM supply chains for two reasons: 1) PGM inputs typically make up a significant portion of material costs for these catalysts; and 2) these inputs are more likely to be subject to supply disruptions than other material inputs to PGM catalyst production.

The main supply chain segments for PGM catalysts, including downstream segments as well as the recycling of PGMs, are 1) PGM production, which includes the mining and refining of PGM-bearing ore as well as the separation of PGMs into individual metals; 2) PGM catalyst manufacturing for catalyzing chemical processes and for components of finished products; and 3) end-of-life product recovery. Because catalyst composition, form, and manufacturing processes are highly dependent on end use, catalyst manufacturing is discussed in the context of end uses. Figure 2 illustrates the production steps associated with each of these supply chain stages. The following sub-sections describe PGM production, PGM catalyst production, and PGM catalyst recycling.

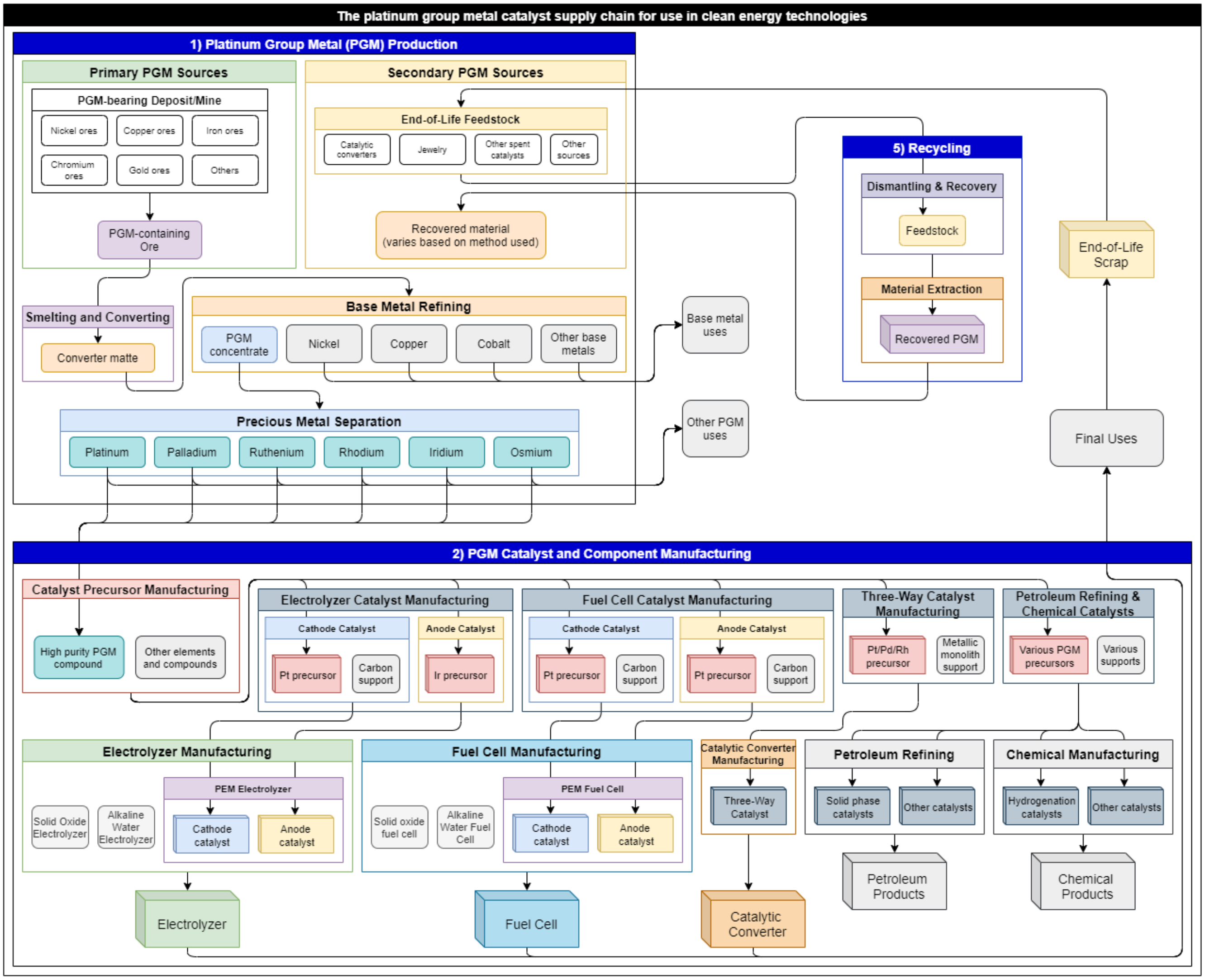


Figure 2. PGM catalyst supply chain

2.2 Supply Chain Segments

2.2.1 PGM Production

<u>Key Takeaways:</u> This section discusses the primary mining, processing, and separation of PGMs. The majority of PGM production for Pt, Rh, Ru, Ir, and Os takes place in South Africa; the majority of Pd production takes place in Russia. While South African-owned PGM mines exist in the United States, PGMs are exported for separation into individual metals. As such, the United States is highly dependent on imports and secondary recovery of PGMs (primarily Pt and Pd) from recycled catalysts and products. Furthermore, major companies and stakeholders that mine, process, and separate PGMs are largely vertically integrated, and PGMs are often mined as a byproduct of nickel, iron, copper, chromium, and gold , leading to potential opportunities for instability in the PGM production market. Figure 3 shows the general steps for producing PGM raw materials.

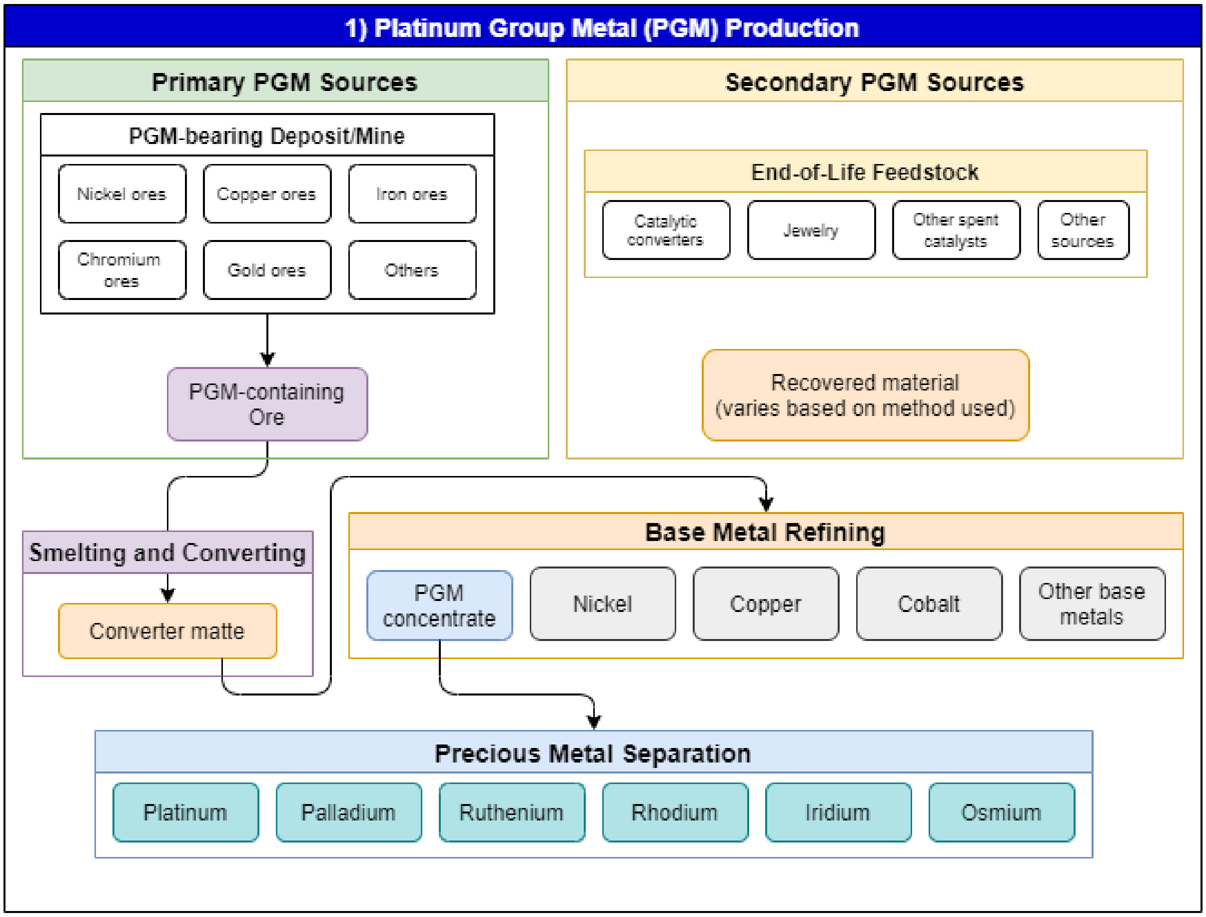


Figure 3. Schematic for Stage 1, PGM production

According to the USGS, PGM resources totaling 104,000 tonnes have been reported by exploration and mining companies.[12] Figure 4 shows the geographic locations of these resources. Table 3 provides estimated PGM reserves accounting for 97% of global total and contents for the individual PGMs in these reserves. The largest global PGM reserves are in stratiform chromite deposits in South Africa as are reserves in the Stillwater Complex.

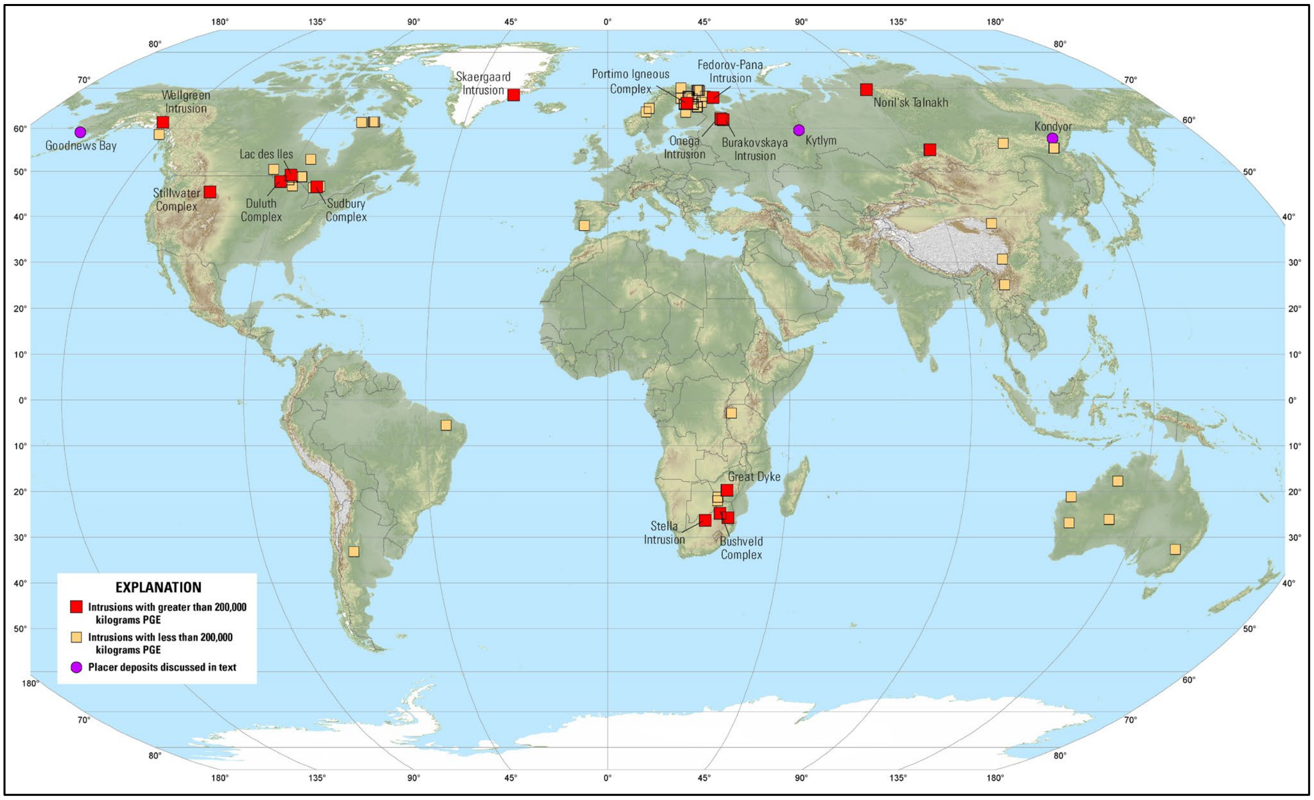


Figure 4. Map of significant global PGM resources [12]

Table 3. Approximate PGM ore concentrations and reserves [12, 13]

Ore Body	Pt g/t	Pd g/t	Rh g/t	Ru g/t	IR g/t	Os g/t	PGM Reserves (USGS) tonnes
South Africa							**75,410**
Merensky Reef	2.7	1.4	0.16	0.33	0.05	0.04	75,200
-East Bushveld (M)	2.32	1.22	0.13	0.23	0.04	-	
-West Bushveld (M)	3.6	1.6	0.28	0.63	0.14	-	
Platreef	1.9	1.9	0.12	0.14	0.04	0.03	
-North Bushveld (M)	0.32	1.1	0.08	-	-	-	
UG2	2	1.3	0.34	0.45	0.13	0.05	
-East Bushveld (M)	2.42	2.06	0.45	0.76	0.18	-	
-West Bushveld (M)	2.89	1.48	0.54	0.93	0.22	-	
Stella							210
Russia							12,362
Noril'sk	2.5	7	0.24	-	-	-	10,100
Onega	-	-	-	-	-	-	837
Fedorov-pana	-	-	-	-	-	-	780
Burakovskaya	-	-	-	-	-	-	645
Zimbabwe							8,190
Great Dyke	2.6	1.8	0.21	-	-	-	8,190
USA							3,630
Stillwater Complex	3.3	11	0.6	0.36	0.21	-	2,240
Duluth Complex, MN	-	-	-	-	-	-	1,390
Canada							447
Sudbury Complex	0.3	0.4	0.03	0.04	0.01	0.01	240
Lac-des Iles	0.2	2.3	-	-	-	-	207

The geographic distribution of global PGM mine production in 2020 is illustrated in Figure 5. Sibanye Stillwater, a South African company, owns the only operating PGM mines in the United States, namely the Stillwater and East Boulder mines near Nye, Montana. By the company's account, the Stillwater mine has resources to operate through 2045 and the East Boulder mine through 2059. The PGMs mined in the United States, however, are refined and separated in South Africa. Secondary production of PGM overshadows mined PGM in the United States. According to the USGS, U.S. mine output totaled 14.6 tonnes of Pd and 4.2 tonnes of Pt in 2020, while 63 tonnes of Pd and 32.6 tonnes of Pt were recovered from recycling. [2] All United States demand for individual PGMs is met by foreign suppliers.

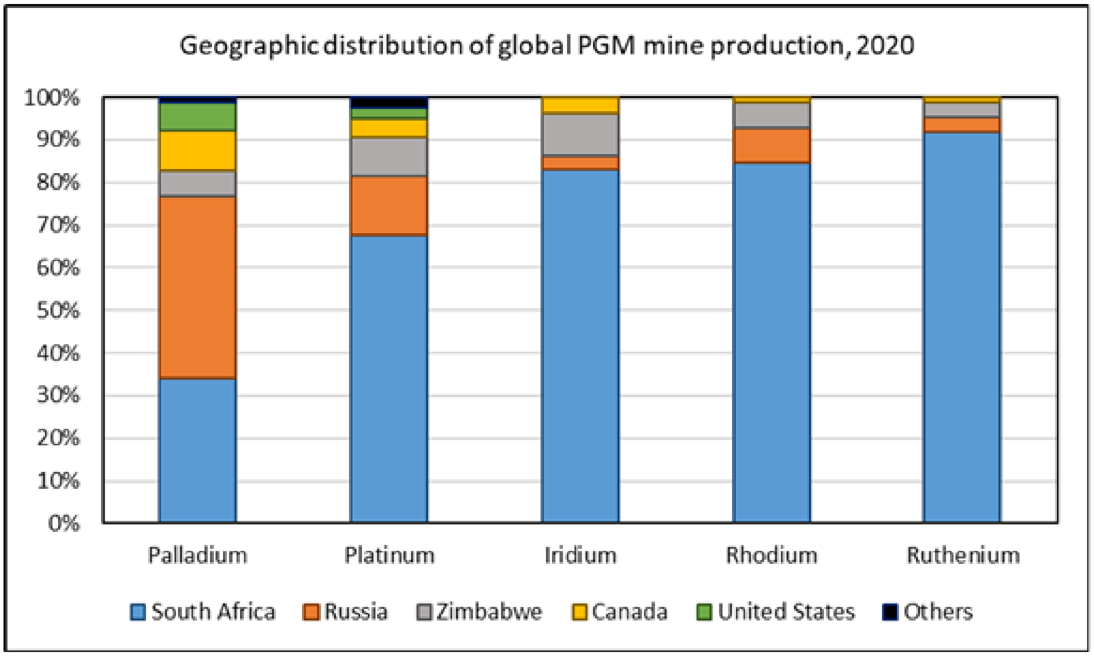


Figure 5. Geographic Distribution of PGM Mining in 2020 [2] (Data provided in the Appendix, Table A2)

U.S. imports and exports of individual PGM in various metal forms are tracked by the United States International Trade Commission. From these data, the USGS estimates PGM imports and exports, which for 2020 are provided in Appendix A, Table A1. In 2020, South Africa, Russia (Pd), Italy, Germany, and Canada were the top suppliers of PGM metals to the United States, as shown in Figure 6. Most of these imports are supplied by allied nations.

PGM content in ores mined for their recovery is typically 5 to 15 ppm. PGMs are present in different mineral forms that contain other metals, such as nickel, iron, copper, chromium, and gold [14]. At the mine site, PGM ores are crushed, milled, and separated by gravity and water flotation to produce a PGM concentrate. Different types of ores, however, require different processing to recover PGM, including different smelting conditions and post-smelting process. For example, PGM from low-grade ores such as those produced in the Minnesota Duluth Complex use a chloride-assisted pressure leaching process (PLATSOL™) to recover PGMs. [15]

The concentrate is transported to a refinery for recovery of purified PGM. Major PGM mining companies own and operate refineries for the production of PGM. In the refinery, the PGM concentrate is dried and smelted at high temperature (>1500 ^{o}C) in electric arc furnaces to separate waste silicate and oxide slags, yielding a PGM-rich matte. The matte is further processed in air-blown converters and by leach processing to remove iron, sulfur, and base metals (e.g., copper and nickel). Finally, the PGM are separated through several stages of solvent extraction, precipitation, and dissolution and then refined to produce ingots, grains, or sponge (fine powder) of high purity PGM.

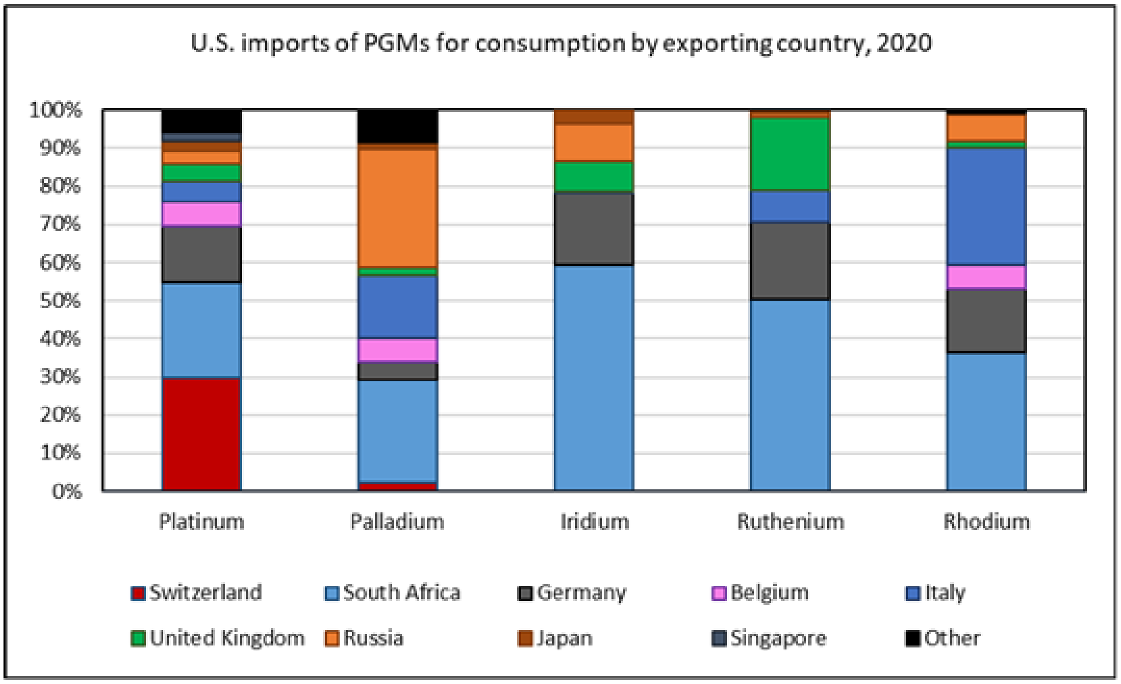


Figure 6. U.S. imports by trade partner of PGMs for consumption, 2020 [2] (Data provided in the Appendix, Table A3a, b, and c)

Given the process-intensive capabilities needed to mine and refine PGMs, capital costs can total over a billion dollars, where these costs depend on mine depth, ore type, planned base metal production, and location. Location factors include labor costs, taxes, land rents, and the availability of existing or need to build new energy, water, and transportation infrastructure. According to AngloAmerican Platinum, mining accounts for 60% of operating costs, concentration 20%, smelting 8%, production of base metals 3%, and refining to produce individual PGM 2%. [16] Large PGM mines are publicly owned, where shareholders provide a critical source of funds for the capital investments essential to construction, start-up, and upgrades. Table 4 provides information on five of the major PGM-producing companies, which accounted for ~83% of global PGM supply in 2020.

Table 4. Information on PGM mining companies published in 2020 corporate reports, in order of decreasing PGM reserves (Note: 2020 mine production was low due to COVID-19 shutdowns.)

Company	Country Incorporated	Mine locations and amount owned & operated in 2020	PGM refined in 2020 (tonnes)	PGM unit costs ($/g)	Employees (including contractors)
Anglo American Platinum [17]	South Africa	South Africa, Zimbabwe (5)	84	$25	25,796
Implats [18]	South Africa	South Africa, Zimbabwe, Canada (6)	87	$27	50,744
Norilsk Nickel [19]	Russia	Russia, Finland (7)	110	N.A.	~72,800
Sibanye-Stillwater [20]	South Africa	South Africa, Zimbabwe, USA (6)	68 (19 in USA)	$28 (U.S. mine costs)	84,775
Northam Platinum [21]	South Africa	South Africa (4)	18	$22-67	15,953

2.2.2 PGM Catalyst Manufacturing and Major Uses

Key Takeaways: *The manufacturing of catalysts requires significant post-processing from pure elements to final catalyst. Their manufacture, including mapping of PGM source to end use, is complex and highly sector dependent. Additionally, the compositional makeup of PGMs needed for catalysts is closely tied to their end uses, while catalyst precursor, support, and form differ widely. Currently, PGM catalyst manufacturing in the United States is heavily skewed toward catalytic converters, which consume Pt, Pd, and Rh. However, emerging technology, especially in fuel cells, PEM electrolyzers, and the chemical sector, have the potential to drastically alter the makeup of the U.S. PGM portfolio, particularly with respect to Ir. In light of the complexity of PGM usage and changing landscape of PGM-containing technology in the United States, further analysis is required to map, identify, and address United States vulnerabilities for manufacturing of PGM catalysts. Figure 7 shows the stylized supply chain steps for producing PGM catalysts for different end uses within the ESIB.*

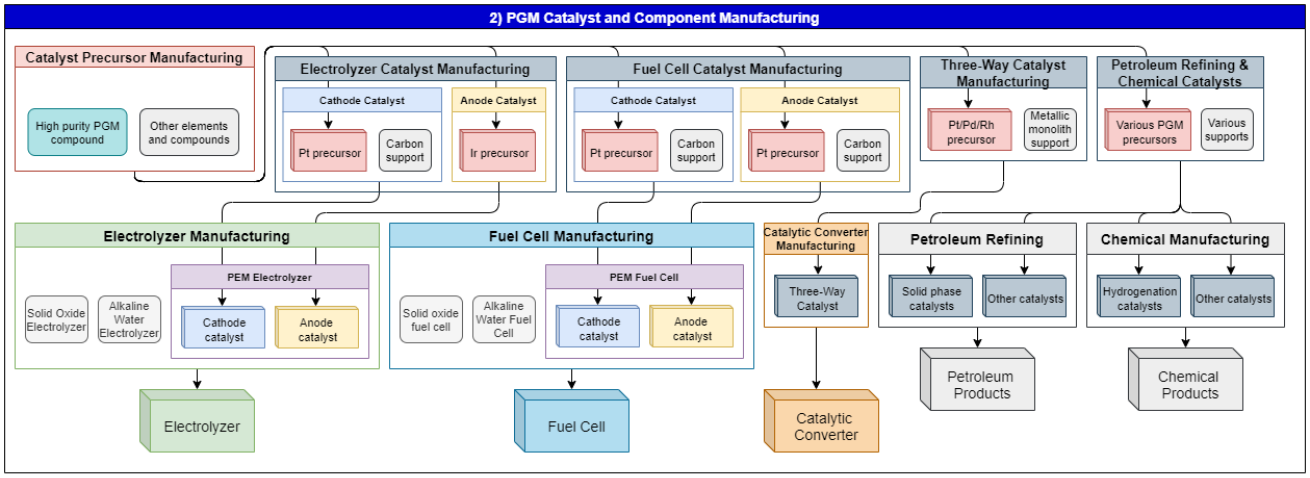


Figure 7. Schematic for Stage 2, PGM catalyst and component manufacturing

To meet purity requirements, PGM catalyst manufacturing usually starts from precursors fabricated from metal sponges produced at the PGM refinery. Then, the PGMs in their elemental forms are converted into different organometallic or inorganic compounds depending on industrial applications. Such compounds are often called "catalyst precursors" because they serve as feedstock for making the catalysts through additional processing. Catalyst precursor makeups (elemental composition of PGMs) vary widely depending on end use of the catalyst. The conversion of raw PGMs to catalyst precursors usually happens at the site of the catalyst manufacturers, although some PGM producers also produce and sell the catalyst precursors. PGM catalyst manufacturers include Johnson Matthey, BASF, UOP Honeywell, Umicore, Clarient, Heraeus, and others.

PGM catalysts have been applied extensively in emissions control, petroleum refining, and commodity and fine chemicals production. They are also under intensive development and are expected to play critical roles in emerging energy efficiency and renewable energy applications such as PEM fuel cells and electrolyzers. Technologies under study (such as electrocatalytic conversions of carbon dioxide to chemicals/fuels and nitrogen to ammonia) may also need significant amounts of PGMs to promote production efficiency.

Table 5 shows various PGM catalyst applications, along with their support systems and PGM constituents. Across these technologies, Pt is by far the most important for catalyst applications. Pd represents another major PGM with wide application in catalytic converters and industrial catalysis. The table also shows PGM catalyst applications and their respective catalyst structure for existing (yellow), emerging (green), and nascent (blue) technologies. For each of these applications, PGM catalysts require different structures, can be co-loaded with other catalytic agents, and vary in manufacturing and loading onto support materials. Thus, PGM catalyst manufacturing is highly dependent on their application and industrial sector. This section describes major applications of PGM catalysts. Further information on the technological needs for these applications can be found in Appendix B.

Table 5. PGM Catalyst Applications.

Application	Process/Product	Catalyst Supports	PGMs	Life (yr)
Existing PGM Catalyst Applications [22]				
Oil-Refining	Reforming	Al_2O_3	Pt; Pt/Re, Pt/Ir	1-12
	Isomerization	Al_2O_3, zeolites	Pt; Pt/Pd	
	Hydrocracking	SiO_2, zeolites	Pd; Pt	
	Gas to liquid	Al_2O_3, SiO_2, TiO_2	Co + (Pt; Pd; Ru; Re)	
Chemicals	Nitric acid	Gauzes	Pd	0.5
	Hydrogen peroxide	Powder (black)	Pd	1
	Hydrogen cyanide	Al_2O_3 and gauzes	Pt; Pt/Rh	0.2-1
	Purified terephthalic acid	Carbon granules	Pd	0.5-1
	Vinyl acetate monomer	Al_2O_3, SiO_2	Pd/Au	4
	Ammonia*	Activated carbon	Ru	
	Oxo alcohol	None - homogeneous	Rh	1-5
	Acetic acid		Rh; Ir/Ru	
Other Processes	Hydrogenation, oxidation, debenzylation	Activated carbon	Pd; Pd/Pt Ru; Rh; Ir	0.1-0.5
Automotive	Catalytic converters	Cordierite monolith ceramic pellets; Metallic monolith	Pt/Rh; Pt-Pd-Rh; Pt	>10
	Diesel particulate filters	SiC or cordierite	Pt/Pd	
Emerging PGM Catalyst Applications				
Light-duty vehicle PEM fuel cells	Green hydrogen fueling	carbon	Pt	8 ~ 10
Heavy-duty vehicle PEM fuel cells	Green hydrogen fueling	carbon	Pt	10 ~ 15
PEM water electrolyzers	Green hydrogen production	carbon/support free	Pt / Ir	7 ~ 10
Nascent PGM Catalyst Applications				
CO_2 reduction reaction	CO_2 electrolyzer for chemical	carbon	Ir or Pt	TBD
Nitrogen reduction reaction	N_2 electrolyzer for ammonia synthesis	carbon	Ir or Pt	TBD

2.2.2.1 Catalytic Converters: Three-way Catalysts

Catalytic converters for automotive emission control convert toxic gases and pollutants in exhaust gas from an internal combustion engine into less-toxic pollutants by catalyzing a redox reaction. They are commonly known as three-way catalysts because they perform three functions of pollutant mitigation simultaneously, i.e., 1) oxidizing carbon monoxide to carbon dioxide, 2) oxidizing unburned hydrocarbons to carbon dioxide and water, and 3) reducing the nitric oxide and nitrogen dioxide generated during high-temperature combustion to nitrogen. Three-way catalysts are essential for mitigating the emissions from internal combustion engines in passenger automobiles, diesel trucks, buses, and other vehicles. Catalytic converters, which house the emission control catalysts, are regulated devices to ensure air quality.

Three-way catalysts contain Pt, Pd, and Rh in varying concentrations. Their production consumes the majority of Pd and Rh global demand as well as about 30% of Pt. PGM-containing catalyst slurries are “washcoated” over high-temperature ceramic honeycomb to form a thin layer on the surface. Following drying and calcination in a furnace, the catalytic converter is assembled. PGM consumption for catalytic converters is expected to eventually wane in the 2030’s as zero emission vehicles such as fuel cell and battery-powered electric vehicles gain traction in the market. The United States currently has a diverse catalyst converter manufacturing base. According to IBIS world (2021), 177 companies, none with more than 5% market share, participate in this $8 billion business in the United States. [23]

2.2.2.2 Fuel Cells

Fuel cells are used to generate electricity from electrochemical reactions using hydrogen as fuel. Their applications include transportation (fuel cell electric vehicles), energy storage (regenerative fuel cell systems), and power generators (including fast charging stations (GM 2022)). [24] For transportation, fuel cells may be preferentially adopted for medium- and heavy-duty vehicles in the future, as battery-powered vehicles compete in the light-duty vehicle markets [25]. They consist of two electrodes (an anode and a cathode) separated by a membrane electrolyte. At the anode, hydrogen is oxidized through the hydrogen oxidation reaction. The electrons produced from this reaction pass through an external circuit to the cathode where oxygen is reduced to water through an oxygen-reduction reaction. The electric current thus generated drives the external load to deliver power.

Three types of fuel cells are currently under development, specifically: PEM fuel cells, alkaline electrolyte membrane fuel cells, and solid-oxide fuel cells. Among the three, PEM fuel cells (which rely on PGM catalysts) have been the development focus for transportation applications due to the technology’s higher current/power density, low stack weight, operational flexibility, and fast response. However, currently they are less mature, more costly, and have shorter lifetimes than non-hydrogen fueled technologies. [26] At present, however, the market has a number of commercial PEM fuel cell vehicles, including the Toyota Mirai, Honda Clarity, and Hyundai Nexo. As of 2020, the IEA estimated the total global stock of fuel cell vehicles to be 35,000, of which 75% were passenger light duty, 16% buses, and the remainder trucks and light commercial vehicles. [27]

PEM fuel cells use Pt catalysts for both the anode and cathode. Pt loadings are assumed on the cathode to be 0.12 kg/MW and on the anode to be 0.06 kg/MW, as detailed in the companion report Electrolyzer and Fuel Cell Supply Chain. [9] The cathode requires more Pt than that used in the anode due to more sluggish kinetics of the oxide reduction reaction. According to the companion HFTO report on Electrolyzers and Fuel Cell Supply Chains, existing technologies for alkaline electrolyte and solid oxide fuel cells do not require PGM catalysts. [9]

The manufacturing processes of individual PEM fuel cell catalyst producers are proprietary. However, they generally involve batch production by mixing a PGM precursor solution with the amorphous carbon support followed by separation, drying, and reduction under the reducing environment. Fuel cell supply chains are covered in detail by the companion report, "Supply Chain Review – Water Electrolyzers and Fuel Cells." [9]

A major R&D objective for PEM fuel cells is reducing or replacing Pt. DOE's Hydrogen and Fuel Cell Technology Office set a technology goal of Pt usage in light duty vehicles with 5,000 hours operating life as 0.125 g/kWe. At this loading, an 80 kW PEM fuel cell vehicle will need approximately 10 g of Pt. This number is approaching the Pt loading in a three-way catalyst for an internal combustion engine vehicle (3 to 7 g/vehicle). Therefore, it is perceived that the transition from internal combustion engine vehicles to PEM fuel cell vehicles can be achieved without major Pt supply chain stress if DOE's target can be achieved. The PEM fuel cell catalysts are made of PGMs, mainly Pt, supported over the high surface area conductive carbon materials. While the focus in the United States is now on mid- and heavy-duty fuel cell vehicles [25], light-duty PEM fuel cell vehicles are still being developed in other parts of the world and will have an impact on Pt demand.

As stated above, fuel cells for vehicular application have shifted to clean technologies for buses, trucks, trains, ships, aircraft, as well as for stationary energy storage. [25] For mid- and heavy-duty buses and trucks, the demand for the fuel cell lifespan increases substantially to 25,000 hours or more (30,000 hours being the ultimate target). Correspondingly, the target for Pt loading is also raised to accommodate the increase of operating life. Such an increase is acceptable given that it accounts only for a small fraction of the total vehicle cost. At present, the DOE Hydrogen and Fuel Cell Technologies Office has set the target of Pt usage as 2.5 kW/g_{Pt}, or 0.40 kgPt/MW for mid- and heavy-duty vehicles. [28] For this study, estimates for the PGM content in PEM fuel cells are aligned with those of the companion report on Electrolyzer and Fuel Cell Supply Chains, specifically a cathode catalyst loading of 0.12 kg Pt/MW and an anode catalyst loading of 0.06 kg Pt/MW. [9]

Most major PEM fuel cell catalyst manufacturers are located outside the United States, including Johnson Matthey, Umicore, Heraeus, Tanaka Precious Metals, and others. Domestic manufacturers include 3M and a few small business companies.

2.2.2.3 Electrolyzers

Three types of water electrolyzers for hydrogen production are under development, specifically: PEM water electrolyzers (TRL 9), alkaline water electrolyzers (TRL 9), and solid-oxide electrolyzers (TRL7). [29] PEM water electrolyzers use Pt at the cathode and Ir at the anode as electrocatalysts to facilitate the electrochemical reactions. Traditional alkaline water electrolyzers do not use PGM catalyst although some emergent membrane technologies use Pt as the cathodic catalyst for faster electrolytic process. Solid oxide electrolyzers do not rely on PGM catalysis, though they are at an earlier stage of development and have not yet reached commercial scale. Among the three, PEM water electrolyzers are considered most promising due to their ability to produce high purity hydrogen, robust operation, small footprint, and fast response time – properties particularly suitable for coupling with intermittent electricity supply from renewable energy such as wind and solar.

In PEM water electrolyzers, carbon-supported Pt catalyzes the hydrogen formation at the cathode, and Ir promotes the water oxidation at the anode. The water oxidation is kinetically more sluggish than hydrogen formation, and the Ir anode catalyst loading is typically significantly higher than the cathode Pt loading. Furthermore, carbon cannot be used as the catalyst support at the anode due to oxidative corrosion under high potential. Therefore, typical supports that minimize PGM usage via better dispersion cannot be applied to

Ir-based anode technology. Instead, Ir or Ir oxide are applied directly to the electrode. Such limitations impede efforts to reduce Ir metal usage.

A key challenge for PEM water electrolyzers is to reduce the currently high usage of PGMs, particularly Ir. Current commercial PEM water electrolyzers are estimated to have Ir loadings as high as 0.67 kg Ir/MW.[30] For this study, estimates for PGM content in PEM water electrolzyers are aligned with those of the companion report on electrolyzer and fuel cell supply chains, specifically a cathode catalyst loading of 0.26 kg Pt/MW and an anode catalyst loading of 0.45 kg Ir/MW. [9]

The companies producing Ir catalysts for PEM electrolysis applications include DeNora, an Italian company with operations in Texas, Tanaka Precious Metals, and others.

2.2.2.4 Liquid Organic Hydrogen Carriers (LOHCs)

Liquid organic hydrogen carriers (LOHCs) are being evaluated as an alternative for transport and delivery of hydrogen. A few examples of LOHCs are toluene/methylcyclohexane, benzene/cyclohexane, naphthalene/decalin, and dibenzylltoluene/perhydro-dibenzyltoluene. Their storage mechanism relies on the transfer of hydrogen ions from one chemical to another. Hence, these carriers require hydrogenation and dehydrogenation catalysts, for which Pt, Pd, and Rh based catalysts are being evaluated. [31] Non-PGM catalysts are also being evaluated for LOHCs.

2.2.2.5 Other Current and Nascent Electrocatalytic Technologies

PGM catalysts are used in electrochemical processes. In 2020, about 36% of Ir was supplied for these processes [6]. For example, Ir-Ru catalysts are used in chlor-alkali plants for the production of caustic soda and chlorine. The chlor-alkali process is driven by electrocatalysis in the aqueous solution of salt (NaCl). The chloride ions are oxidized to chlorine (Cl_2) at the anode and hydrogen is generated at the cathode leaving behind concentrated sodium hydroxide solution. Among many electrocatalyst options, Ir-based catalysts offer low overpotential, better energy efficiency, and long operating time. [6]

Electrocatalytic production of chemicals offers potential paths to electrify the chemical industry using renewable energy. At present, nascent electrocatalytic technologies are gaining traction. Two examples include the electrocatalytic CO2 reduction reaction to convert carbon dioxide to fuels/chemicals and the electrocatalytic N2 reduction reaction to convert nitrogen to ammonia. These applications require Ir at the anode of the electrolyzer. Consequently, adoption of these nascent technologies will further stress Ir supply. New catalyst materials and technologies to reduce or replace PGMs, particularly Ir, in these industrial electrochemical processes should be a key technology development focus to enable the chemical industry's transition to electrification.

2.2.2.6 Petroleum Refining

Oil refining processes extensively involve catalytic processes, many of which require PGM-based catalysts. These catalytic processes generally use heterogeneous catalysis.

Reforming: This process is prevalent in the U.S. refinery industry, with a charge capacity of 3.8 million barrels per day in 2019. [32] The catalytic reforming process often uses Pt-Rh catalyst supported on chlorinated alumina to catalyze multiple reactions: dehydrogenation, dehydrocyclization, isomerization, hydrocracking, and others. [33] Along with the formation of aromatics, hydrogen is also co-produced in many of these reactions and serves as an important hydrogen supply source for other refinery units, such as hydrotreating.

Isomerization: This process converts low-octane petroleum mixtures to a high-octane gasoline blending stream. The isomerization reaction is catalyzed by a Pt catalyst on various supports, e.g., alumina, zeolite, or metal oxide.

2.2.2.7 Chemical Production

Hydrogenation and dehydrogenation: In petrochemical processes, hydrogenation is used to convert olefins and aromatics to saturated paraffins and cycloalkanes by saturating double bonds or aromatic rings. The hydrogenation catalysts often consist of Ni, Co, Fe, and can also contain PGM (e.g., Pt, Pd, Ir, Ru). [34] Pt is also used to catalyze dehydrogenation reactions.

Nitric acid and acetic acid productions: Two of the major chemicals, nitric acid and acetic acid, have been produced at vast industrial processes using PGM-based catalysts. Nitric acid has broad applications in fertilizer, chemicals, polymer production, and other products. High purity nitric acid is produced through the oxidation of ammonia by oxygen over PGM catalysts. A majority of the world's supply of acetic acid is produced through carboxylation of methanol promoted by Rh- and Ir-based PGMs.

2.2.3 End-of-Life Product Recovery

<u>*Key Takeaways:*</u> *Secondary production of PGMs represents a significant share of total global annual production. Within the United States, a robust recycling ecosystem for catalytic converters exists. However, given the current PGM content of most catalytic converters (Pt, Pd, Rh), secondary PGMs from converters may be unable to address Ir demand for emerging technologies such as PEM water electrolyzers. Furthermore, the recovery of PGMs for these emerging technologies at the end-of-life require specific processing that can be incompatible with catalytic converter recycling. Processing and recycling of emerging technologies are less understood from a scientific and engineering standpoint and do not have an active domestic industry to support their development. Figure 8 shows the stylized supply chain steps for end-of-life recovery and recycling.*

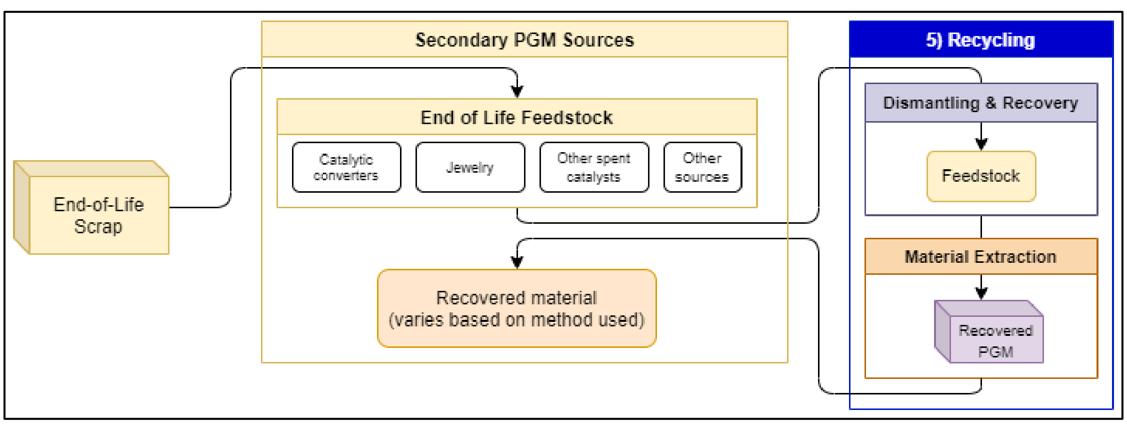


Figure 8. Schematic for Stage 3, Recycling

For some PGM catalyst applications, such as catalytic converters (and likely PEM fuel cells and electrolyzers), the PGMs are "owned" by the purchasers of the product, are typically present in low content, and are widely dispersed – complicating their secondary recovery. For petroleum and chemical industry catalysts, however, the PGM are often "leased" from pool accounts managed by catalyst manufacturers who retain ownership and management of the PGM. In addition to leasing fees, the catalyst manufacturer sets the catalyst price based on non-PGM materials costs, the costs and profit for the catalyst manufacturing, and expected PGM losses during use. [35] While these catalyst manufacturing companies may report on their pool accounts, more specific information on their PGM recycling is not readily available.

PGM's from scrap catalytic converters, electrolyzers, and fuel cells contain a mixture of precious and base metals. Spent catalytic converters account for about 60% of PGM use and, as such, are the dominant secondary sources with comparatively high PGM content and relatively few impurities. [22] The PGMs used and recycled in catalytic converters are Pt, Pd, and Rh.

In future scrap of PEM fuel cells and electrolyzers, common materials will include Pt (electrolyzer cathode, fuel cell cathode and anode), titanium (bipolar plate and anode), strontium (anode), Ir (electrolyzer anode), graphite (bipolar plate) and cobalt (substitute for Pt), aluminum (base plate), and copper and nickel (anode catalyst, bipolar plates). [36, 37] The recovery of PGMs from this spent scrap will depend on the composition of the scrap material, the PGM content, and the types of binders or additives present in the parent material.

Compared to fuel cells and electrolyzers, the recycling of catalytic converters is a well-established domestic and global industry that ultimately creates high-purity individual PGMs for use in multiple sectors. Actual recovery of the PGM materials generally occurs in two primary steps: pre-processing or pre-treatment, and material recovery via pyro-metallurgical, hydro-metallurgical, or bio-metallurgical routes. Of the three recovery routes, pyro- and hydro-metallurgical routes are more developed, while bioleaching is still in the earlier stages of development. Figure 9 illustrates these overall secondary recovery pathways, and process flows.

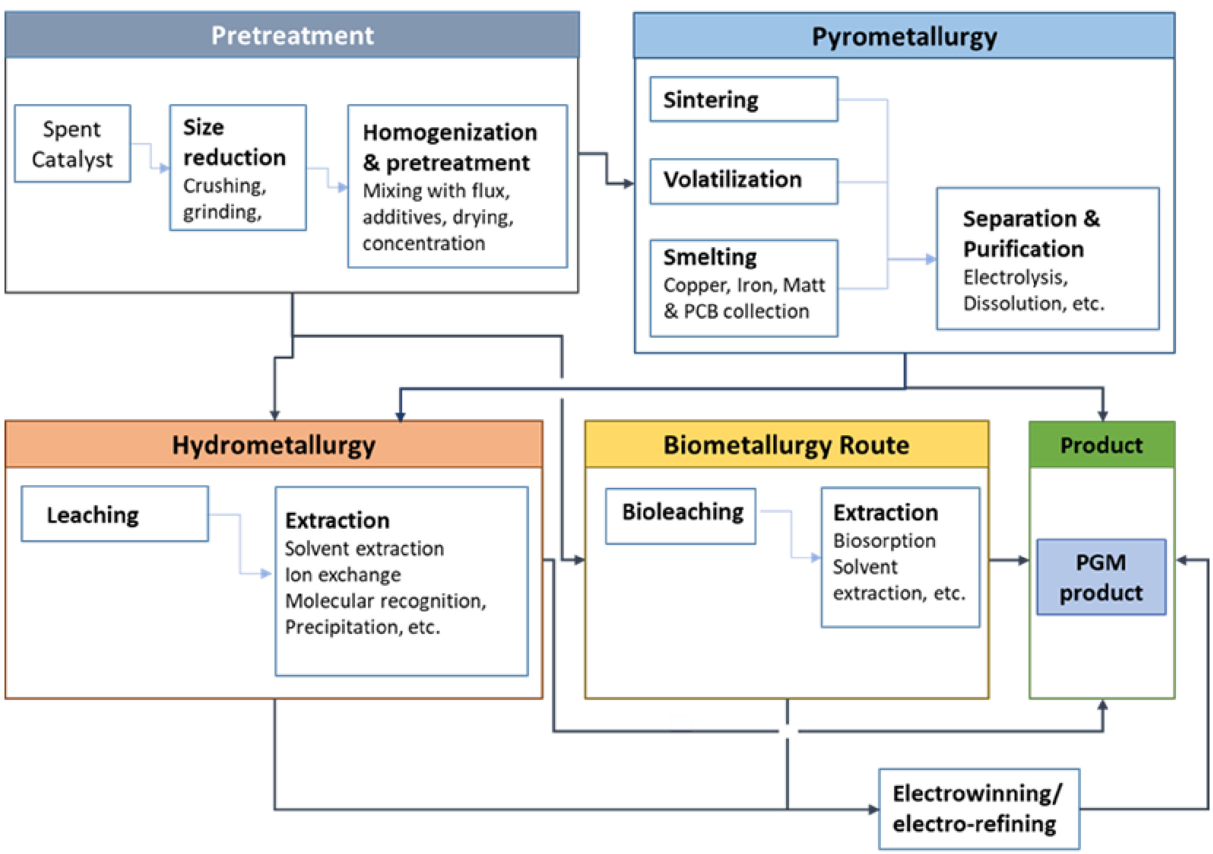


Figure 9. Pathways for PGM catalyst recovery

2.2.3.1 Collection and Pre-treatment

The collection pipeline for catalytic converters is well developed, with intermediary companies that collect spent converters to sell them to processing facilities, or resell them to aggregators who de-can (separating the catalyst from its metal container) to extract the honeycomb ceramic modules before selling to the processors. [38, 39] The collectors are usually paid per spent converter or according to PGM content after an assay of the composition is completed. [38] In recent years, recycling volumes at the collection stage have been affected by vehicle demand (including effects due to COVID), the black-market economy for catalytic converters, and stability of primary sourcing, compounded by a lack of effective policy enforcing or incentivizing PGM recycling. [38-40] Once the processor company purchases the feedstock, it proceeds to the pretreatment step, which generally involves size reduction via grinding, crushing, or milling; roasting, reduction, pressure leaching, and homogenization. The purpose of pretreatment is to eliminate organic substances, surface coatings (e.g., deposited carbon from catalyst use), passivation layers, as well as impurities which could reduce the efficiency of the downstream separation process and create a stream with physical and chemical properties suited to the downstream separation route. [22, 41-43]

2.2.3.2 Pyro-metallurgical Recovery

Pyrometallurgy is a core pathway for primary PGM processing and is the most developed for secondary PGM material recovery. A number of process routes exist under this category but can be broadly grouped into three: sintering, volatilization, and smelting. These techniques rely on the principle that minerals and metals have varying physical and chemical responses to heat. In pyrometallurgy PGM recovery, thermal treatments allow manufacturers to separate PGM and PGM-containing alloys from base materials for further refining. A detailed discussion of the three major pyrometallurgical techniques can be found in Appendix B.

2.2.3.3 Hydro-metallurgical Route

Hydrometallurgy offers a versatile and well-developed process for secondary recovery of PGM materials and is often used downstream of pyro-metallurgical routes such as chlorination. Compared to pyro-metallurgical recovery, hydrometallurgy can lead to higher purification yields, operates at milder process temperatures, consumes less energy, and is easier to scale. [44] It is also a two-stage process, with the first focused on base metal recovery and the second on precious metal recovery. The main challenges with hydrometallurgy include heavy use of toxic and expensive reagents, and hazardous waste management.

2.2.3.4 Bio-metallurgical Route

The bio-metallurgical process is similar to the hydro-metallurgical process, with the primary difference being the use of bio-based interactions to achieve the same end. Processes like bio-leaching and bio-sorption may replace the standard leaching and extraction steps from hydrometallurgy, and the key is to find microorganisms (mostly bacteria) that naturally – or can be engineered to – selectively sequester PGM ions from dilute mineral or cyanide solutions. [45-47] This approach is still nascent, with modest to high recovery yields of individual PGMs. Das et al. reported yields of 63%, 38%, and 99% for Pt, Pd, and Rh, respectively, using Chromobacterium violaceum in glycine to recover PGM from automotive catalytic converters. [48]

2.2.3.5 Recycling PGM from Fuel Cells and Electrolyzers

For PEM fuel cells and water electrolyzers, the recycling pipeline is still nascent. Once collected, the initial step involves disassembly of the stack into individual components and the separation of the major components – electrode assembly comprising the anode, cathode, electrolyte, and the bipolar interconnecting plates. [37, 49] The membrane materials are processed by shredding and delamination to separate the laminate layers. [37, 49] Subsequent processing, refining, and separation may follow similar (and possibly tailored) downstream pyro-metallurgical or hydro-metallurgical processing routes as with catalytic converters. Few well-developed, scalable, tailor-made recovery system exist for electrode assemblies, which are the PGM-containing portions of fuel cells. [50, 51] Many techno-economic and life cycle analysis of PEM fuel cell and water electrolyzer recycling technologies rely on estimates from lab-scale demonstrations. [52] But once established, there may be significant overlap with the current PGM recycling ecosystem, enabling it to leverage existing infrastructure.

2.2.3.6 Closing the Recycling Loop

The recovered PGM is sold back to original equipment manufacturers for reuse. The overall process can take several months from the pre-treatment to the recovery of high purity PGM catalyst materials for sale to manufacturers, including Johnson-Matthey and others. [42, 53] A number of companies also provide dedicated pre-treatment services – mixing, size reduction, smelting, etc. – for processors that do not have those facilities in-house, producing PGM-rich powders or ingots from smelts. These secondary streams supply 20% to 40% of PGM demand, with differences between metals – e.g., Pt, Pd, and Rh – and across industries. [6] However, the effective demand from secondary sources depends on a number of factors, such as market volatility, primary supply levels, and vehicle scrappage rate. In 2020, global secondary demand fell by about 12%, largely because of pandemic-induced reduction in vehicle scrappage rates and car plant closures. [6] The situation is different for PGM from PEM fuel cell and electrolyzers, which must still overcome key technology barriers for reprocessing, and to grow sufficiently to have a developed recycling pipeline.

Information in Box 1 describes the markets for end-of-life recovery of PGM from catalytic converters and the potential applicability of for recovering PGM from PEM water electrolyzers and fuel cells.

Box 1. Collection, recycling, and PGM recovery from end-of-life catalytic converters

Collection	
Strategy	Companies collect spent converters. They either sell them still in can or "de-can" and sell the honeycomb catalyst content
Pay structure	Buyers and sellers transact either spent converters or de-canned catalyst modules. Sellers are either paid per converter or based on assay/catalyst content
Number of players	There are many players here, including individual collectors and aggregators in both the formal and black markets
Factors affecting this sector	Depends on number of vehicles scrapped each year (lower in 2020 due to COVID pandemic); black markets for catalytic converters that siphon off some recycling supply; policy directing end-of-life vehicle recycling; stability of primary sourcing.
Considerations for PEM fuel cells and electrolyzers	The reverse logistics infrastructure for these products is yet to be developed, but could leverage existing collector networks, though different expertise will be required to disassemble components prior to selling to processors
Mixing /pulverization	
Strategy	Spent converters are pulverized and thoroughly mixed in a closed system. Samples may be analyzed via x-ray fluorescence (XRF) or inductively coupled plasma optical emission spectroscopy (ICP-OES) to inform pricing as well as downstream recovery
Pay structure	Mixers produce and sell powders or ingots (if they smelt in-house). The price is determined at point of sale and depends on PGM content and market prices.

Number of players	While many mixers/pulverizers exist, few have in-house laboratories, so contract out testing. Often, this is integrated with the homogenization and smelting steps in the same facility.
Factors affecting this sector	Pricing and revenue depend on market volatility of PGMs. Shipping samples can also add several weeks to overall processing time.
Considerations for PEM fuel cells and water electrolyzers	PEM fuel cells and water electrolyzers require a different process given the product complexity, and face technology barriers with efficient delamination, preservation of other valuable components such as membranes and carbon supports, and concerns with toxic off-gassing. Most reported processes to overcome these hurdles have been demonstrated at lab-scale, but have potential to overlap with current PGM recycling ecosystem.
Base Metal Refining	
Strategy	Ingots are refined either via pyrometallurgy or hydrometallurgy to separate out the collector metals from precious metals. The same facility may also carry out precious metal refining
Pay structure	Base metal refiners buy ingots from smelters, and produce PGM cakes, whose concentrations and compositions may vary depending on the refining process and feedstock composition
Major players	A number of major companies that refine the PGM, including Johnson-Matthey, Heraeus, BASF, and UMICORE, British Petroleum, among others
Factors affecting this sector	Pricing and revenue depend on market volatility of PGMs. Facilities require significant investment, but can leverage processes developed for primary metal refining
Considerations for PEM fuel cells and electrolyzers	The technology for base metal refining of end-of-life PEM fuel cells and electrolyzers has not been demonstrated at scale. Most reported processes have been lab-scale but have potential to overlap with current PGM recycling ecosystem. A key opportunity relates to understanding gaps that need to be bridged to leverage existing infrastructure, or novel, tailor-made process-intensified recycling solutions.
Precious Metal Refining	
Strategy	Use specialized electrochemical processes to purify and precipitate out each individual PGM. These processes can take up to months to produce 99%+ purity PGMS.
Pay structure	Facilities purchase a mixture of PGMs plus base metals. After refining, they can sell >99% purity individual PGMs.
Major players	A subset of the players engaged in PGM refining
Factors affecting this sector	Pricing and revenue will depend on market volatility of PGMs. While PGM refining facilities require significant investment, can leverage processes developed for PGM production.
Considerations for PEM fuel cells and electrolyzers	Once the PGM and base metals have been recovered from end-of-life PEM fuel cells and electrolyzers, existing technologies and infrastructure for recovering PGM could be deployed. An exception may be if the base metals are significantly different from those managed in PGM refining.

3 Supply Chain Risk Assessment

3.1 Risk/Resilience Factors

Supply chain risk is one of the key components of material criticality [54]. While focusing primarily on the riskiness of raw materials supply chains, these metrics can also be extended to downstream stages of supply chains. Common measures (described in Box 2) cited by material criticality in assessments of supply risk include [55-57]:

- Market and geographical concentration of production
- Geopolitical sensitivity of supply
- Net import reliance
- Price/market volatility
- Substitutability of materials and technologies
- Environmental and workplace safety compliance/conditions

Box 2. Material criticality risk factors

Market concentration: the extent to which an industry or supply chain is controlled by a small number of firms or countries. Highly concentrated industries are those where a single or few actor(s) affect market outcomes, such as by restricting supply to raise prices, or by oversupplying the market to lower prices below a profitable level for competitors.

Geopolitical sensitivity: the strength of a producing nations' relationships with the United States, covering issues including political stability, strength of institutions, labor rights issues, political rivalry, acrimonious relationship, and stability of supply coming from a given country.

Net import reliance: the dependence of a country on imports to meet domestic consumption, measured by the share of total apparent consumption that is provided by imports. [58, 59]

Price and market volatility describes fluctuations in the price and supply/demand balance of a commodity. High volatility increases the cost and riskiness of doing business, as low prices may disincentivize new investments or make production unprofitable for producers, while high prices may make producers operating on the margin unprofitable. Price volatility is typically higher for by- and co-product metals. [60]

Substitutability is the ability of firms/supply chains to alter their material, product, manufacturing, or consumption patterns in response to price changes or other market shocks. [61]

Environmental compliance and workplace safety conditions indicate potential environmental damage and occupational safety and health practices that could result in unsteady supply. Producers that have a poor record of adherence to environmental policies have a greater likelihood of being shut down or penalized with fees (increasing costs), and those with poor safety records may face labor shortages or boycotts.

3.2 Current United States Resilience

3.2.1 Assessment of Risk Factors for PGM

The supply of PGM from primary and secondary sources currently meets society's demand. Further, identified mineral resources, with the possible exception of Ir, appear to be adequate to meet U.S. decarbonization goals. The concentrated location of most of the resources, however, makes their supply susceptible to disruption.

The PGM market is considered to be illiquid, so their prices (Figure 10a) are indicators of relative differentials in supply and demand, with the added effect of risk hedging investments. Further, the price volatility (Figure 10b) of such byproduct metals as PGM have been found, on average, to be 50% greater than for primary metal products. [60] Coproduction among the PGM elements also affects volatility, as seen most prominently in the Rh prices.

Past market conditions that affected PGM prices include:

- 2019 price increases: automotive demand for Pt, Pd and Rh steeply increased when stricter emission control legislation in China were implemented.
- March 2020 price fall: demand reductions caused by COVID-19 pandemic shutdowns.
- April 2020 – May 2020 price increases: supply deficit caused by an unexpected 90-day shutdown of a South African converter operated by Anglo American Platinum and reductions in recovery from catalytic converters, mitigated by higher glassmaking, chemical production, and financial investments. [62]
- November 2020 – May 2021 price increases: reduction in Anglo American Platinum's PGM production caused by closure of converter due to water leaks, coupled with higher relative demands amongst PGM. Rh – autocatalyst demand growth for NOx reduction and strong industrial demands; Ir - 5G technology growth, specifically for the manufacture of crucibles for growing lithium tantalate crystals. [63]
- February 2021 price increases: Norilsk Nickel (Nornickel) shutdown of two PGM mines due to structural problems.
- May 2021 PGM price declines: Investor actions and the slowdown in vehicle production (caused by shortage in electronic chip production), and hence in demand of PGM for catalytic converters.

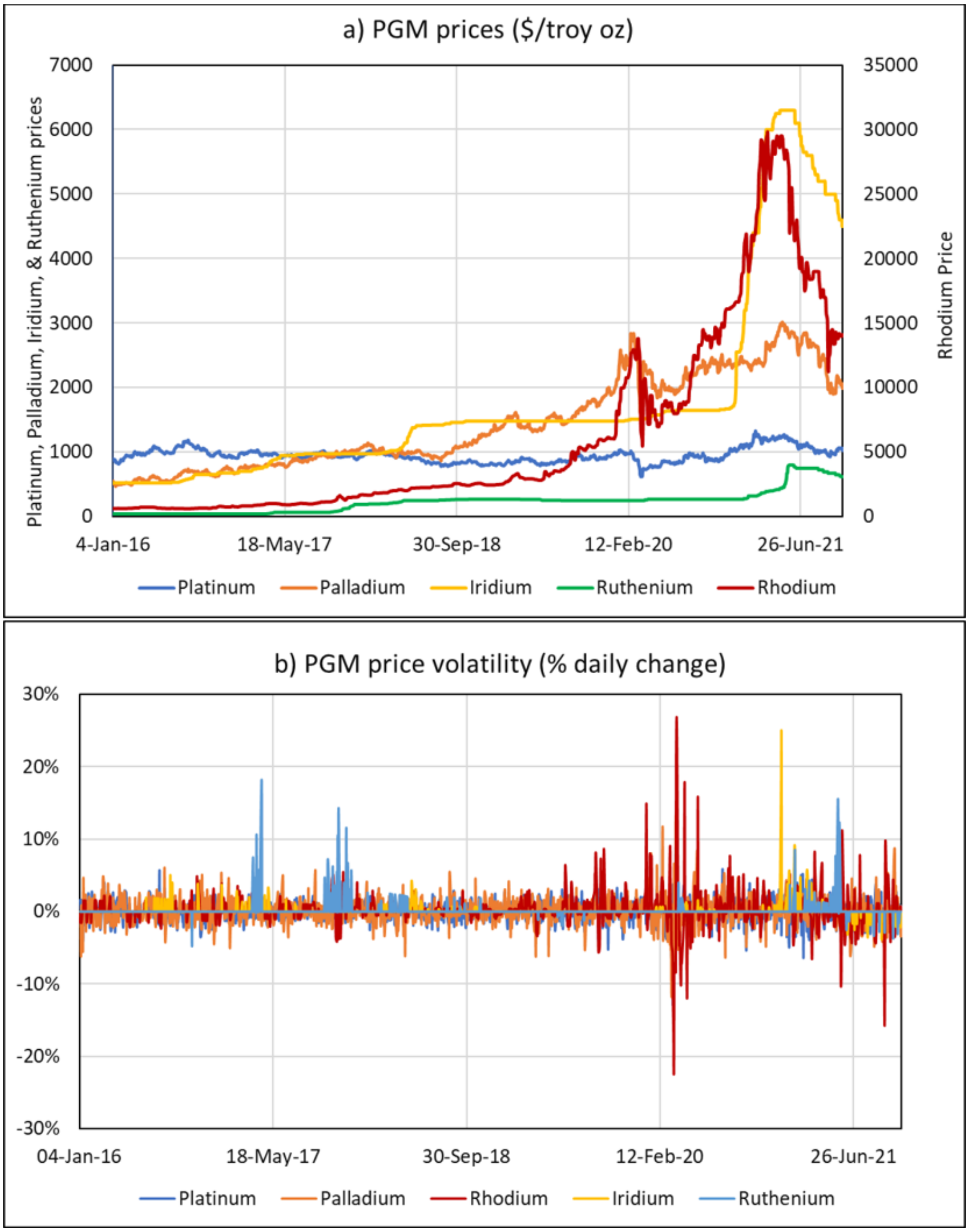


Figure 10. (a) PGM prices; (b) PGM price volatility [64] [60]

Current PGM production is also challenged by serious environmental and social impacts. Environmental impacts primarily result from water contamination due to acid drainage and toxic metals in mine tailings, dams, and dumps. [65] Social impacts include mine strikes, health and safety, fatalities, and violence. Among vulnerabilities of South Africa PGM mining, the largest producer of Pt and Ir, are technical operations challenged by mining depth; infrastructure challenges with securing energy and water supplies; social issues including mine strikes and related violence; [14] and health issues associated with silica dust and toxic metals in mine tailings dams and dumps. [65]

In the case of Ir, a large disparity between supply and demand could occur in the future. In 2020, world production of Ir was 8.17 tonnes. To meet global decarbonization goals with current PEM water electrolyzer technologies, more than a ten-fold increase in Ir production would be required within the next ten years. Recent growth in Ir production, however, has been less than 10% per year. Further, Ir is a minor component of the overall PGM mined (~1% of PGM), so its sales alone cannot currently support new mining prospects. The expected reduction in Pt, Pd, and Rh for catalytic converters will further challenge the economic viability of increasing Ir production, especially if companies shut down mines because of decreased demand for their main products. Pd-rich mines, such as those in Russia, may be at highest risk, as the decline in Pd demand is not expected to be mitigated by the adoption of fuel cell and PEM water electrolyzer technologies. However, other uses of Pd will likely be pursued. In the event that these forecasted market shifts occur, PGM mining and production business models will need to adapt.

The evaluation of supply chain risks is supported by several published methodologies and analysis that identify PGM as critical materials. These studies highlight elements of risk associated with their supplies. The DOE has assessed the criticality of materials based on their importance to clean energy (clean energy demand and substitutability limitations) and their supply risk (basic availability; competing technology demand; political, regulatory, and social factors; co-dependence on other markets; and producer diversity). [55] McCullough and Nassar [66] assessed critical materials on supply risk (country concentration of supply), production growth (production growth necessary to meet future demand), and market dynamics (price volatility) for identifying potentially critical materials. Table 6 summarizes vulnerability metrics for each of the PGM.

Table 6. Vulnerability metrics for U.S. PGMs

Indicator	Platinum	Palladium	Rhodium	Iridium	Ruthenium
HHI – country concentration of operating PGM mines (Monopoly = 10,000)	4873	3160	7275	7023	8470
Geopolitical sensitivity (based on weighted avg. World Bank Regulatory Quality index)	53.9	51.7	55.1	54.9	57.5
U.S. consumption as a percent of global mine production	32%	51%	91%	20%	46%
U.S. net import reliance	79%	40%	100%	100%	100%
Byproduct commodities	No	Yes	Yes	Yes	Yes
Price volatility	$20	$56	$508	$51	$8
Human Development Index 2019 (United States = 0.926)	0.73	0.79	0.71	0.71	0.71
Fraser Institute metric: Investment Attractiveness Index 2020 (United States = 70.51)	58.8	66.3	57.6	56.9	57.0
Environmental Performance Index (United States = 69.3)	45.7	50.4	43.7	43.7	43.5

Table Notes: Factors calculated as a weighted average of PGM production by country:

- The Herfindahl-Hirschman index (HHI) measures the country concentration of production, and for this table is calculated as the sum of the squared country market shares (in percent) of each country where the PGM mines or resources are located. Monopoly markets have an HHI of 10,000, HHI values > 2,500 are considered to be highly concentrated.
- Geopolitical sensitivity; weighted average of World Bank 2020 Regulatory Quality index Ranks (0-100) by country; for all countries rated: highest = 99.0; lowest =1.0. [67]
- U.S. consumption as a percentage of global production (USGS data for 2020, based on apparent consumption data reported for Pd and Pt, and import data for Rh, Ir, and Ru). [2]
- Net import reliance metric based on the USGS annual Mineral Commodities Summaries [5]
- Byproduct commodities: Yes = red, No = green; based on Nassar et al. [11]
- United Nations Human Development Index; Values derived as weighted average of mining output by country. [68]
- Price volatility. Calculated as the standard deviation of daily price changes from January 2020 to October 2021.
- Fraser Institute Investment Attractiveness Index considers policy factors (regulations, taxes, infrastructure) and the mineral potential of the region. Values derived as weighted average of mining output by country. Source: Fraser Institute Annual Survey for Mining Companies 2020, Scored 1-100; For all countries rated: highest = 91.05 ; lowest = 44.04. [69]

- Environmental Performance Index assesses environmental health and ecosystem systems. Values derived as weighted average of mining output by country. For all countries rated: highest = 82.5, lowest = 22.6. [70]

3.2.2 Assessment of Risk Factors for PGM Catalysts

The risks and resilience of PGM catalysts are largely related to PGM supply, coproduction, demand, and prices. Regarding supply, the current PGM market and coproduction constraints likely will not support the Ir supply required to meet projected deployment of PEM electrolyzers without dramatic change to today's technology. PGM demand will be disrupted as the global market transitions away from fossil fuels and thus away from PGM catalysts that support the petroleum and petrochemical industries. The consequences of these transitions and potential market inefficiencies on PGM prices and catalyst markets are uncertain.

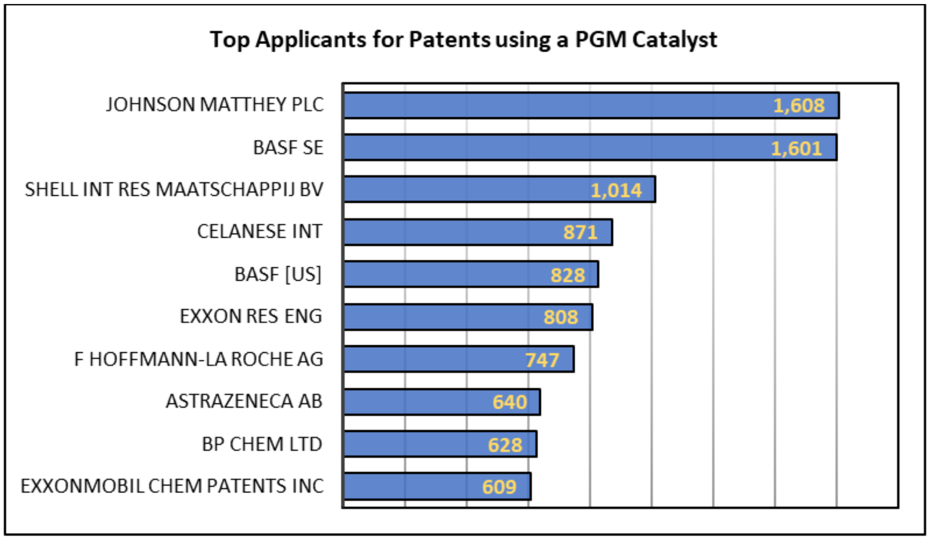
At the elemental level, PGMs are broadly difficult to substitute in their various applications. Nassar [11] reviews the substitution of PGMs across each of their major end-uses, including catalytic converters, petroleum and chemical catalysts, and non-catalytic uses. The author finds that substitution has occurred over the span of many years for most PGM applications to the point that additional substitution is unlikely to occur without a drastic change in the PGM market. In the case of PGM catalysts, their superior performance (e.g., higher selectivity, faster reaction rates, lower energy use) and their established, efficient PGM recycling systems disincentivize substitution. Additionally for some applications, PGM catalyst substitutes require harsher operating conditions, leading to higher operating costs and, in some cases, the expenditure of capital to upgrade equipment.

As Nassar [11] notes, however, a significant portion of current PGM catalyst demand supports the production and use of fossil fuels that will decline as decarbonization technologies are adopted. Uncertainty associated with this transition intensifies PGM catalyst market risks. The uncertain phase-out of internal combustion engines is a key contributor to this uncertainty, as catalytic converters account for the largest demand for PGMs. The adoption of PEM electrolyzers and fuel cells could mitigate demand reductions of Pt. However, while PEM electrolyzer adoption could help Pt demand, the Ir demand associated with existing technologies is a serious bottleneck.

While substitution of PGMs at the elemental level is challenging in most applications, extensive research has been conducted to find alternatives. One example is the search for alternatives to Pt in fuel cell applications using such earth-abundant materials as nickel, molybdenum, and copper. To date, partial substitution of Ir with Ru or Pt in PEM electrolyzer anode catalysts in PEM has been studied and appears promising. [30] However, these substitutions have been found to negatively affect performance. Research into finding PGM-free materials as replacements for Ir has also gained significant traction with promising data in recent years. Their performance, however, is not yet sufficient to be practical substitutions for Ir in meeting future hydrogen demand. [30] Alkaline and solid oxide water electrolyzers, that do not contain Ir, provide alternatives to PEM water electrolyzers. These technologies, however, have performance limitations and disadvantages.

Patent data shown in Figure 11 (a) suggests that both companies that produce PGM catalysts (e.g., Johnson Matthey, BASF) and those that use PGM catalysts in their processes (e.g. Shell, Exxon) are active in R&D. The patent analysis also suggests significantly fewer patents are filed for PGM catalyst manufacturing than for PGM catalyst use, and that only one company (BASF - note BASF[US] is the North American affiliate of BASF incorporated in Germany) is a top ten filer for both.

The patent search results (see Figures (A1a &b) in Appendix (A) also show that the largest number of PGM catalyst patents were filed in the United States (42%), while the largest number of patents for manufacturing of PGM catalysts were filed in Korea (32%), followed by the United States (27%). Additionally, patent applications for PGM catalyst and PGM catalyst manufacturing have declined year-to-year after 2011 (see Figures (A2 a,b) in Appendix (A)), which could be an indicator of a mature market. One caveat: these results may not be conclusive as they would not have captured patents that mention individual PGMs instead of the using the all-inclusive "PGM" terminology.



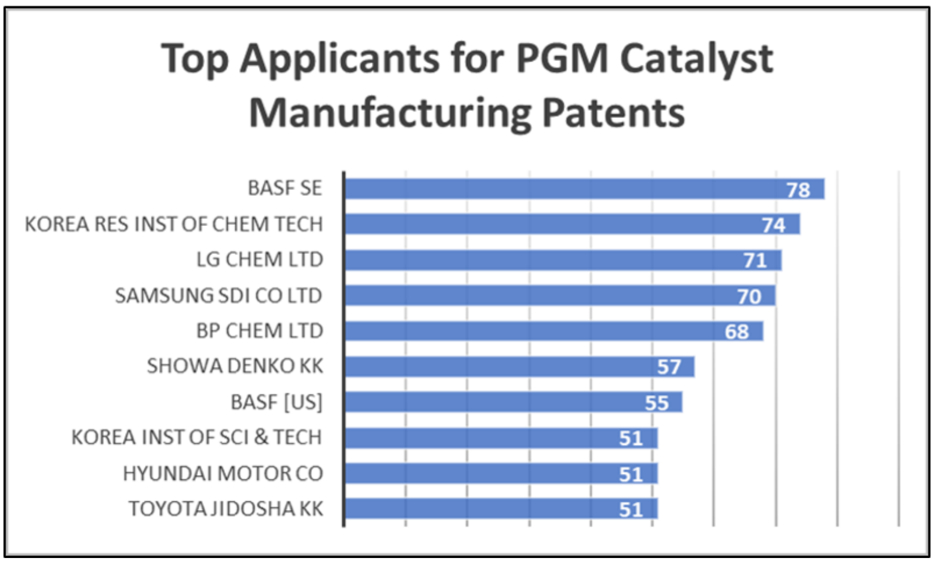


Figure 11. PGM catalyst and PGM catalyst manufacturing patents

(a) Patent applications with an application date after January 1, 2001 and publication date before November 10, 2021 which also contained these keywords in the title, abstract, or claims: catalyst and ("platinum group" OR (platinum OR (Pt)) OR (palladium OR (Pd)) OR (iridium OR (Ir)) OR (rhodium OR (Rh)) OR (ruthenium OR (Ru)).

(b) Patent applications with an application date after January 1, 2001 and publication date before November 18, 2021 which also contained these keywords in the title, abstract, or claims: ("platinum group" OR (platinum OR (Pt)) OR (palladium OR (Pd)) OR (iridium OR (Ir)) OR (rhodium OR (Rh)) OR (ruthenium OR (Ru))) and catalyst within 3 words of production, manufactur-, or fabricat-.

The information and indicators discussed in this section were used to qualitatively assess the PGM catalyst supply chain for various questions related to developing a domestic supply chain. See Table A4 in Appendix A.

3.2.3 Resilience - PGM Production

PGM mining and refining will need to evolve to meet future demands as the world transitions to decarbonization technologies. Figure 12 shows estimated global demands for Pd, Rh, and Ru. Demand projections for Pt and Ir are shown in Figure 13a and b, respectively. No demand or production data are available for Os. The declines in Pd and Rh demand are estimates of the reduction in catalyst converter demand as battery and fuel cell electric vehicles replace internal combustion engines estimates based on the IEA's Sustainable Development Scenario projections. [71] Should these projections be realized, changes in the relative demands of co-produced PGM will occur and potentially affect the resilience of their supply chains.

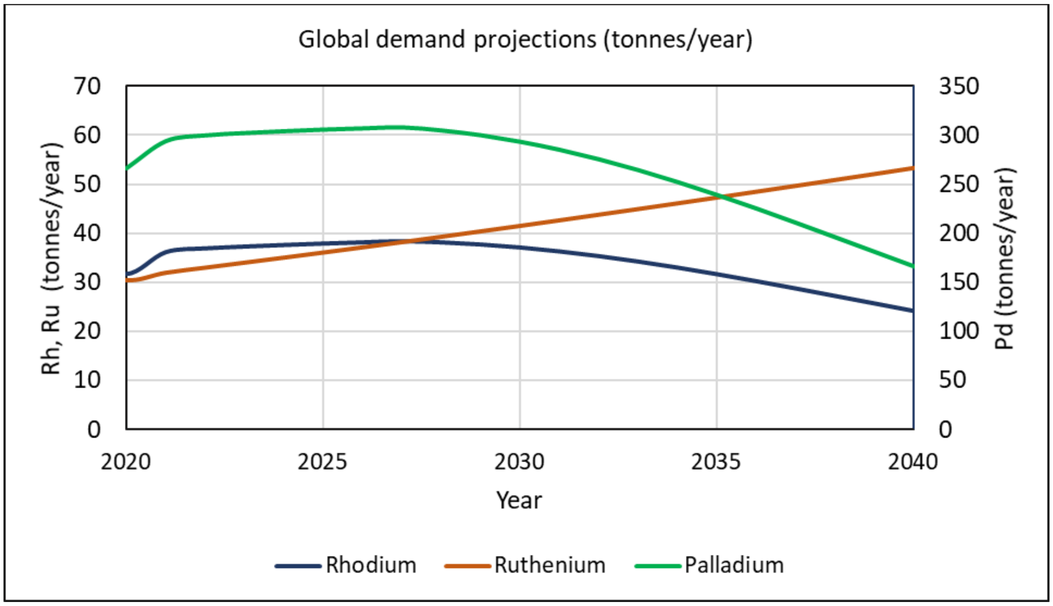


Figure 12. Global demand projections for Rh, Ru, and Pd (PGM demands for applications excluding those for decarbonization technologies and catalytic converters were derived from the OECD real GDP forecasts).

The Ir market is likely to be the most stressed by decarbonization actions, due to its use as an anode catalyst in PEM water electrolysis for hydrogen production as illustrated in Figure 13(a). Ir applications take advantage of the metal's high density, melting point, hardness, corrosion-resistance, and catalytic properties. Ir crucibles are used by electronics manufacturers to fabricate single crystals that need to be processed at temperatures greater than 1000 °C, including those for light-emitting diodes and surface acoustic wave filters used in wireless telecommunication equipment including mobile phones. Ir catalysts and electrocatalysts are used in the chemical industry, including in the production of acetic acid and chlorine. Ir is also used in spark plugs, pacemakers, and as a hardening agent for Pt.

The United States does not currently have domestic capacity for the separation of mined PGMs, and thereby does not produce Ir. In 2020, the United States imported Ir from South Africa (59%), Germany (19%), Russia (10%), United Kingdom (8%), Japan (3%), and Italy (<1%). [2] Assuming existing technologies and decarbonization goals, Ir demand for PEM water electrolysis far exceeds current global production. Further, Ir accounts for only 1% of PGM in ores, so its production to meet demand shown in Figure 12(a), which would require several new mine start-ups, would not be financially feasible for miners or refiners.

Pt supply is also important to global decarbonization goals as it is used in PEM fuel cells and electrolyzers. Figure 13(b) shows the projected global demand for Pt. For this PGM, declines in Pt demand for catalytic converters will be mitigated by increases in demand to support production of PEM electrolyzers and fuel cell electric vehicles. [71]

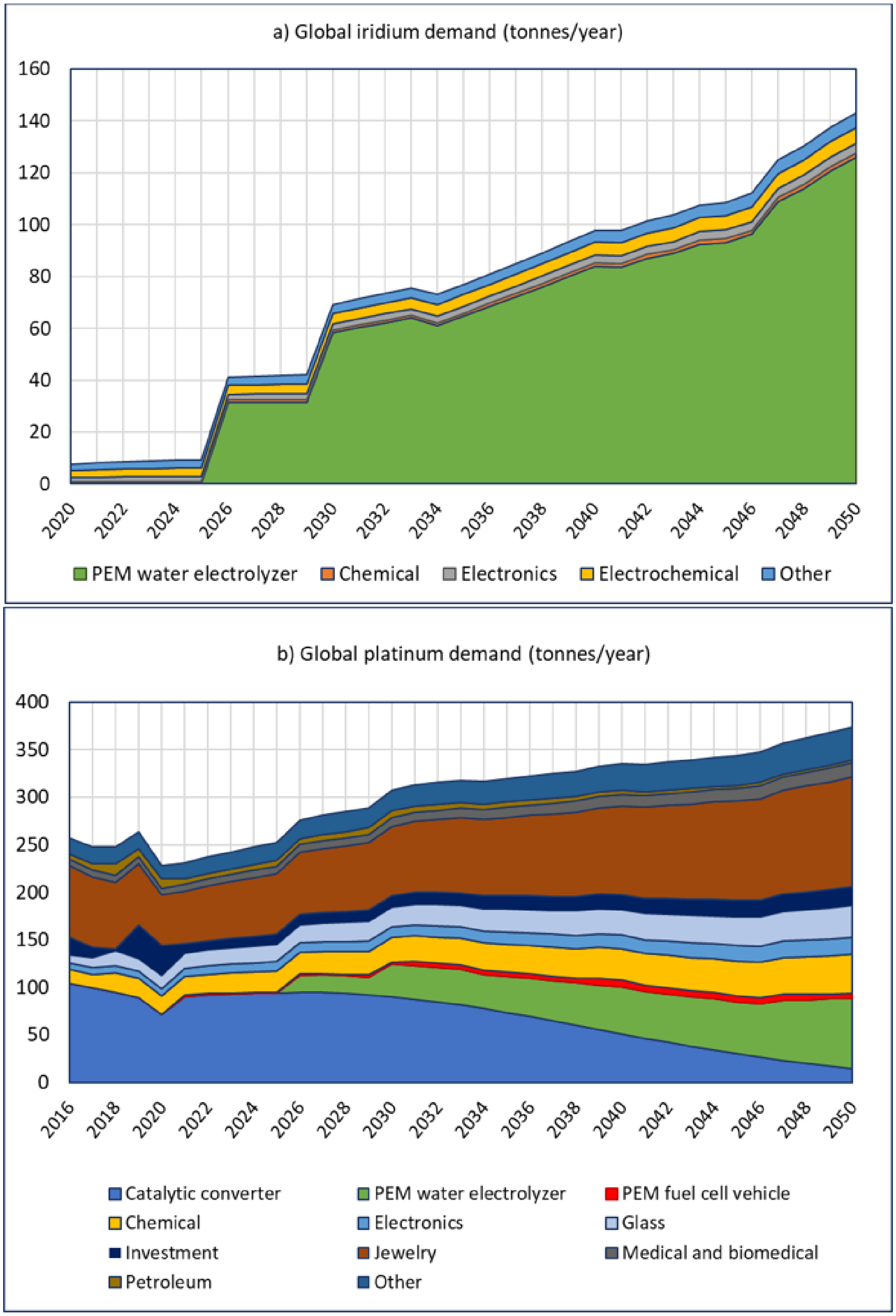


Figure 13. a) Historical and future demand for Ir (a) and Pt (b) in tonnes/year. [6] PEM water electrolyzer demands for Pt and Ir based on companion report for HFTO. [9]

3.2.4 Resilience - PGM Catalysts

Other than three-way catalyst production for catalytic converters, PGM catalysts are usually produced in small quantities through batch processes. Within the United States, several manufacturing facilities produce PGM catalysts for chemical production and petroleum refining. These facilities generally have state-of-the-art manufacturing capability and knowhow built up over many decades. For example, Honeywell – UOP manufactures its own refining catalysts and sells them as part of petroleum processing technology packages to refineries worldwide.

The United States has leading manufacturing facilities for production of three-way catalysts and catalytic converters for transportation applications. Their production directly supports major domestic automobile producers such as GM, Ford, and others.

The key factor affecting U.S. resilience in the supply of electrocatalysts for next generation clean energy technology is the PGM supply chain, particularly Ir supply. Limited world reserve of PGMs will become a significant threat to technology cost and market penetration. Developing a new mine and increasing production output could take over 10 years given positive market signals. This time lag should be factored into the future PGM catalyst production plan.

3.2.5 Resilience - PGM Recycling

As discussed in detail in Section 2.2.3, technologies for recovery of PGM from catalysts are relatively mature, especially through pyrometallurgical and hydrometallurgical methods [42]. The United States is already a major producer of PGMs from recycled sources and is a major importer of PGM scrap. Catalytic converters account for about 40% (Pt) to 80% (Rh) of PGM demand, with secondary streams providing 20% - 40% of total PGM supplies. [6, 22]

There is, however, a lack of scalable, tailor-made recovery systems for the PGM-containing membrane electrode assemblies in PEM electrolyzers and fuel cells. [50] Technological barriers to recycling include separation of the gas diffusion layer from the membrane electrode assemblies, preservation of other valuable components such as ionomer membrane and carbon support [72], and the potential off-gassing of hydrogen fluoride in efficient PGM recovery processes. [72]

The study of efficient, scalable, and safe recycling of membrane electrode assemblies remains an active area of research, with a small number of industries and stakeholders engaging in efforts to mitigate the technological barriers to recycling. These projects include innovations in efficient recovery of PGMs with processes that don't emit hydrogen fluoride (HF) (limited to laboratory-level demonstrations) or novel recycling solutions for PEMs and SOFCs. [73, 74] Further mitigation strategies include pyrometallurgical processes with HF scrubbers, some of which are in use within industry. [75]

3.3 U.S. Competitiveness

3.3.1 PGM Production

As the PGM mines in the United States have been operational for many years, they are competitive in global markets. However, while PGM are mined in the United States, they are not refined to individual metals in country. As described previously, the mixed PGMs from these mines are exported to South Africa where they are processed to produce individual PGMs. According to the USGS, Pd and Pt mined in the United States amounted to 14 tonnes of Pd and 4 tonnes of Pt in 2020, and their combined mine production accounted for less than 5% of global production for the two PGM. [2]

Collectively, these data suggest that the United States is under-resourced in PGM and strengthens the need for maintaining trade relations with PGM-producing nations and increasing domestic secondary recovery of PGM.

3.3.2 PGM Catalysts

The major PGM catalyst usage at present is for catalytic converters for ICE-based passenger vehicles, buses, and trucks. With anticipated acceleration of next-generation clean energy technology such as fuel cells and water electrolyzers, the production of PGM catalysts for these applications could significantly increase. Table 7 provides information, though incomplete, on global PGM catalyst manufacturers and applications they serve.

Although some small electrocatalyst production companies operate in the United States, no large PEM fuel cell or electrolyzer catalyst manufacturing capacity exists here due to the current lack of demand for these products. PGM catalysts used in fuel cell research are supplied predominately from producers outside the United States, including Johnson Matthey (UK), Umicore (Belgium), and Ishifuku (Japan). Given that the quantity of PGM electrocatalyst for PEM fuel cells and electrolyzers is currently small, transportation between the United States and global suppliers is generally not a major concern. The countries with high capacity of PGM electrocatalyst production are industrialized nations and not in geopolitical conflict with the United States. Investing scale-up capacity for producing PGM electrocatalysts in the United States should not be a major technology barrier if there is a positive market visibility and economic incentive.

Table 7. Global catalyst/catalyst precursor producing companies (not inclusive of all market players)

Companies	Countries	PGM Catalyst Applications - Examples
Johnson Matthey	United Kingdom	Catalytic converters, ammonia cracking, steam reforming, PEM fuel cells, PEM electrolyzers; PGM recycling
BASF	United States/ Germany	Catalytic converters, PGM recycling, PGM catalyst precursors, organic and fine chemical synthesis
Umicore	Belgium	Catalytic converters, ammonia oxidation, PGM recycling
Ishifuku	Japan	PEM fuel cells
W.C. Heraeus	Germany	Reforming, hydrogenation
Clariant	Switzerland	Hydrogenation, isomerization
Honeywell UOP	United States/UK	Oil refining and petrochemicals - reforming, isomerization, dehydrogenation hydrogenation
Axens	United States/ Canada	Oil refining and petrochemicals – reforming, isomerization, hydrogenation

3.3.3 PGM Catalyst Recycling

According to the USGS, secondary refiners in the United States produced approximately 63 tonnes of Pd and 33 tonnes of Pt in 2020.[2] As a comparison, U.S. mines produced 14.6 tonnes of Pd and 4.2 tonnes of Pt in the same year. While information on what specific PGM containing catalysts or materials account for the U.S. refining output, recycling of catalytic converters is likely a major source. Companies that recycle PGM catalysts in the United States include Sibanye-Stillwater, BASF, Umicore, Tenneco, Continental AG, APC Automotive Technologies, among many others. [23]

The United States currently has no commercial-scale capacity for recycling and recovering PGM from PEM electrolyzers nor fuel cells because these industries are not mature domestically or globally and the technologies are in their early stages of development and deployment. Commercializing recycling capability for these products requires addressing unique technology challenges – such as preserving valuable ionomer membrane and carbon support components, and avoiding fluoride off-gassing – as well as recovery logistics challenges, especially for a technology that still has significantly low adoption rates.

Even if current pilot-scale efforts involving a small number of industries and stakeholders successfully address recovery technology scale-up barriers via tailor-made, process-intensified recycling solutions, the low volume and density of end-of-life PEM electrolyzers and fuel cells could make the cost of transport to dedicated centralized recycling facilities prohibitive for individual customers without adequate incentive. However, by leveraging the existing robust infrastructure for collecting and recycling catalytic converters, the United States could become competitive in this area in the future. This transition will require understanding the technical and processing gaps that need to be bridged in order to use existing PGM recycling infrastructure. In addition, ensuring a closed-loop supply chain could be achieved by requiring suppliers to offer "buy back" incentive programs and address the collection logistics challenge.

3.4 Key Vulnerabilities and Causes

This section describes issues underpinning the current resilience and competitiveness of the PGM catalyst supply chain. From this discussion, several vulnerabilities associated with the supply chain present weaknesses that, if left unresolved, could hinder the success of important technology pathways and solutions, and the ability of the United States to meet its climate and decarbonization goals. Vulnerabilities for the United States in the PGM catalyst supply chain include:

- Paucity of publicly available data for characterizing and assessing PGM catalyst supply chains, particularly those for the chemical and emerging decarbonization industries
- Current technology for energy-efficient PEM water electrolysis that depends on Ir supply
- Geographic concentration of PGM production
- Reliance on scarce minerals sourced by environmentally hazardous extraction processes and challenging social issues.
- Geographic concentration of PGM production, including mining, refining, and separation.
- Global PGM market instability.
- Demand uncertainty associated with nascent industries supporting decarbonization goals.

These vulnerabilities, and their root causes, are discussed in more detail in the following subsections. Content for these sections was drawn heavily from 2020 annual and corporate social responsibility reports of the five companies listed in Table 4.

3.4.1 Paucity of Publicly Available Data for Characterizing and Assessing PGM Catalyst Supply Chains and Their Applications in Support of Decarbonization Goals

While data on global PGM mining and production are broadly available, data and information on PGM catalyst markets, supply, and demand are not freely accessible. The catalyst industry is highly competitive and reliant on intellectual property for sustaining their businesses. However, information is important for both public and private decision makers to support RDD&D, policy development, and capital investment that will effectively advance progress in decarbonizing global economies. Mechanisms for sharing data and information with these objectives will need to be developed and pursued.

3.4.2 Current Technology for Energy-efficient PEM Water Electrolysis that Depends on Ir Supply

Global production of Ir in 2020 was 8.17 tonnes. Assuming existing PEM water electrolysis anode catalyst technology of 0.45 kg/MW Ir loading, annual Ir global demand could peak at 126 tonnes/yr in 2050, and annual U.S. Ir demand could peak at 35 tonnes/yr in 2050. [9] Today, the United States has no capacity for producing Ir. While Ir is mined by Sibanye-Stillwater in Montana, it is exported for separation and refining in South Africa.

While there is potential for substituting Ir with other materials for some of its applications (see Table A5 in Appendix A), the substitution that is possible with today's anode technology will not be sufficient to allow PEM water electrolyzer adoption goals to be met. Further, new mine starts with the sole purpose of increasing supply of Ir, without expectations of a proportional increased sales of Pt and Pd, are unlikely.

As reported in the Electrolyzer and Fuel Cell Supply Chain Report, Ir recycling infrastructure with end-of-life recycling rates of 90% and low catalyst loading targets of 0.05 kg/MW will be needed to support future demand for green hydrogen production via PEM water electrolysis. [9]

3.4.3 Geographical Concentration of PGM Production

PGM supply and resources are geographically concentrated in South Africa and Russia, and lesser so in the United States, Canada, and Zimbabwe. As shown in Table 6, the HHI for each of the PGM is above 2500, indicating highly concentrated markets. Additionally, PGM recovered from mines in the United States are separated into individual PGM in South Africa, leading to the country having a 100% net import reliance for PGM that are minimally recovered from end-of-life products in the United States, specifically Rh, Ru, and Ir.

South Africa, a historically stable trading partner with the United States, is the largest producer of Pt, Rh, Ru, and Ir. The major PGM mining companies are stockholder-owned and publicly traded, and provide some transparency in their operations and management. However, PGM supply from South Africa has been and could in the future be curtailed by social unrest, mine fatalities and injuries, equipment failure, water and electricity supply and aging infrastructure, and environmental contamination events. Rolling blackouts are common in South Africa, where about 85% of electricity is generated from coal and 95% of the country's electricity is produced by a state-owned power company, Eskom. [76] Aging power plants, debt, and maintenance backlogs threaten electricity supply in the country and potential loss of PGM production.

The stability of trade with Russia, the largest Pd-producing country, is less certain. Additionally, one Russian company, Norilsk Nickel (Nornickel), holds a near monopoly on PGM produced in Russia, thereby increasing Pd supply risks. On the other hand, Nornickel is a stockholder-owned, publicly traded company, providing some transparency on their operations and sustainability. The company co-produces PGM with nickel, copper, and gold. Since 2010, their Pd sales have outpaced production with the differential met by inventories, a situation that could forebode a future supply deficit. Material risks outlined in the company's 2020 annual report include tighter environmental regulations, work-related injuries, information security, power outages, lack of water resources, and workforce tensions. [19]

According to the USGS, mines in Canada and Zimbabwe produced Rh, Ru, and Ir in addition to Pt and Pd. Neither country was a major supplier of PGM to the United States. In 2020, the United States imported only Pd from Canada, accounting for 7.6% of the Pd imported to the country. While the United States has diplomatic and economic ties with Zimbabwe, the State Department has noted state-sanctioned violence against peaceful protestors, labor leaders, and political opponents in the country. In 2020, the United States did not import PGM from Zimbabwe, however, the vulnerabilities of their supply are relevant to global markets.

3.4.4 Reliance on Scarce Minerals Sourced by Environmentally Hazardous Extraction Techniques and Challenging Social Issues

PGM mining and refining are energy-, water-, and maintenance-intensive processes. A 2017 life cycle assessment of PGM production found mining and ore beneficiation use the greatest share of power (72%) with smelting and PGM refining accounting for most of the rest (27%). [77] Water is chiefly used for flotation, dust suppression, cooling, and air pollution control. PGM mining and production are asset-intensive operations that heavily rely on equipment maintenance to sustain profitability and minimize environmentally damaging discharges.

Environmental pollution from PGM mining includes toxic mine tailings, run-off, dust, noise, contaminated wastewater, and process emissions. Rock drilling, milling, and dredging create respirable dust. Explosions and leaks have occurred in operating smelters.

Publicly owned PGM mining companies address climate change in their risk assessments and management. They have goals to achieve carbon neutrality within the next few decades, and they report on greenhouse emissions, energy and material consumption, waste disposal, and water withdrawal. In Russia, permafrost thawing, attributed to climate change, increases the risk of collapsing buildings and structures.

Social issues of PGM consumption vary by company and mine location. Common among PGM-producing companies are the dangerous conditions of underground mining. While mining companies are focusing on and making progress in improving health and safety of their employees, none of the five companies achieved their goal of zero fatalities in 2020. [17-21] As one action to reduce health and safety risks, mining companies are turning to automation.

In South Africa, mines are located in impoverished regions with high unemployment, minimal basic services, and lack of economic opportunities – conditions that spawn protests, worker strikes, and civil action. Nornickel also identifies risks engendered by deterioration of social and economic conditions in their operating regions.

Major PGM mine owners (the five mining companies included in Table 4) are committing to and reporting progress in Corporate Sustainability Governance (CSG), and setting goals to reduce their energy and water consumption and carbon emissions, while improving the health, safety, and development of their employees and local communities.

3.4.5 Global PGM Market Instability

While the stability of PGM mining and supply is supported by publicly owned corporations, the PGM market is challenged by some inefficiencies. For example, PGM prices experience high dynamic variation and manipulation by the suppliers/traders when a new demand or technology is announced. In their markets, PGM are priced in U.S. dollars, while the operational and capital costs for foreign mining companies are paid in the currency. In 2020, volatility of the South African Rand affected the profitability of PGM companies incorporated in that country.

In comparison to commodity metals, PGM are produced in a small number of mines and refineries. This vulnerability was evident in 2020, when equipment failures and COVID-19 measures led to mine shutdowns and a 16% decrease in PGM production.

3.4.6 Demand Uncertainty Due to Nascent Industry Supporting Decarbonization Goals

While based on demonstrated and well-understood science, some decarbonizing technologies that rely on PGMs have yet to be broadly commercialized, specifically PEM water electrolyzers and fuel cells. As emergent technologies, future adoption patterns of these technologies are uncertain. Their adoption will be dependent on a wide range of interdependent and currently uncertain factors, such as technology performance, availability of supporting infrastructure (e.g., hydrogen fueling facilities for PEM fuel cell vehicles), comparative costs of competing technologies, and policies across the globe.

Additionally, future demand for catalytic converters will affect the PGM primary and secondary markets. Catalytic converters currently account for the largest PGM (Pt, Pd, and Rh) demands. In 2020, PGM demand for catalytic converters fell by 13% due to the COVID-19 related economic slowdown. Their demand is expected to increase in the short term as countries, including China and India, have enacted stricter emission standards. Then, as electric and fuel cell vehicle adoption increases over the next decade, the demand for catalytic converters is expected to decline. While the effect of this transition on the availability of Ir supply to meet PEM water electrolyzer demand is uncertain, it is unlikely to be positive.

3.5 Potential Future Vulnerabilities

As the adoption of key decarbonization technologies (PEM water electrolyzers and FCEV) continues to grow, their demand is likely to exacerbate many of the vulnerabilities that currently exist in the PGM catalyst market. Future risks include supply risks, demand risks, and technology risks.

Supply risks:

- Reliance on PGMs, both scarce and byproduct materials, from mines and refineries that are energy, water, carbon, and capital intensive and cause damage to the environment and have adverse effects on workers and communities. Further, PGM mines are capital intensive and require 10+ years to assess, develop, construct, and start production. Without certainty in future PGM demands, the consequent financial risks may discourage new mine start-ups.
- PGM currently supplied by secondary sources will decline as the use of catalytic converters are replaced by electric and fuel cell vehicles over time, reducing PGM supply for other applications. While PGM recovery from end-of-life PEM electrolyzers and fuel cells could be possible, these technologies will not enter the secondary market for 10-20 years from when they are first commercialized at scale. Also, technologies for PGM recovery from these products are underdeveloped.
- As ICE vehicle demand declines, so will the demand for catalytic converters and thereby the demand for Pt, Pd, and Rh used in these applications. While such Pt demand reduction may be mitigated with the adoption of PEM water electrolyzers and fuel cells (particularly for heavy vehicles), the demands for Pd and Rh will not. This risk could be most significant for Pd rich mines, such as those in Russia, Canada, and the United States.

Demand risks:

- PGM for catalysts are leased or purchased by the catalyst buyer. Volatility in PGM prices, which can be caused by speculator purchases/sale, temporary supply issues, or other market failures, can be particularly disruptive for demand growth of emergent technologies, such as PEM water electrolyzers and fuel cells.
- Fuel cell vehicle driven PGM consumption in the rest of the world may not be in sync with U.S. objectives. For example, as the United States shifts fuel cell vehicles from light-duty to heavy-duty vehicles, other countries, particularly in Japan, Korea, and more recently China, plan to increase deployment of light-duty fuel cell vehicles. Their demands could impact the PGM cost and availability in global markets, thereby affecting the U.S. markets and decarbonization goals.

Technology risks:

- The viability of PEM water electrolyzers will require successful RDD&D to significantly reduce the Ir loading of the anode catalyst. Without progress in this reduction, the widespread adoption of PEM water electrolyzers will likely not occur. While there are other water electrolyzer technologies that could support green hydrogen production, PEM water electrolyzers have technology advantages that make them more attractive for wide-spread adoption. This research is being conducted by industry, academia, and other
- The transition of PGM catalyst applications from internal combustion engines (Pt, Pd, and Rh for catalytic converters and oil refining) to hydrogen economy technologies (Pt, Ir) will stress the PGM and PGM catalysts markets. Technology shifts, which are currently uncertain, will be required to rebalance these markets.
- Recovery of PGM from PEM electrolyzers and fuel cells will require several process steps, including collecting end-of life products, dismantling complex products, and separating the PGM from other components with the expectation of recovering them for reuse or recycling. Adapting to future PGM market demand may also require separating the individual PGM and purifying the PGM to high-grade sponge or powder. While RDD&D investment is important to develop efficient and environmentally friendly recycling technologies, successful outcomes from these investments are uncertain.
- While technologies for recycling Pt, Pd, and Rh from end-of-life catalytic converters are mature, recovery of PGM from PEM water electrolyzers and fuel cells are less so. Recycling PEM assemblies has been an active research area for manufacturers and research organizations, particularly in Europe and with a focus on PGM recovery. For example, Ballard reports that their recycling technology recovers ~95% of the Pt in PEM fuel cells. [78] The United States government, however, has been less active in recycling technology RD&D. To further enable recycling, PEM assemblies need to be designed for recycling and avoid the use of coatings or designs that reduce the recovery rate of critical materials.
- Decarbonization of medium- and heavy-duty vehicles will likely depend more on PEM fuel cell technology than light-duty vehicles, due to their higher energy density requirements. These vehicles include delivery trucks, utility vehicles, buses, marine vessels, and trains. These applications currently require power stacks with three to five times more PGM catalyst than those for light-duty vehicles, challenging their design and adoption.

4 Key U.S. Opportunities and Challenges

4.1 U.S. Opportunities

In the context of the PGM catalyst supply chain, the United States can pursue a number of opportunities related to emerging technologies that support decarbonization of the ESIB. This section highlights those opportunities in PGM production, PGM catalyst manufacturing, and PGM containing decarbonization technologies.

Take a leadership role in innovation and adoption of decarbonization technologies, including PEM water electrolyzers and fuel cells. The United States has the resources to capitalize on the green hydrogen economy in tandem with other countries as the world transitions to a carbon-free future. This transition could be supported by developing and implementing a long-term RDD&D plan targeted at increasing the performance of PEM technologies, reducing the costs of PEM manufacturing, and developing cost-effective end-of-life reuse, refurbishment, and recycling technologies. Further, the United States could inform RDD&D investments with analysis of pathways that enable transitions in the PGM and PGM catalyst industries, which are currently driven by catalytic converter (Pt, Pd, Rh) markets, to those designed to succeed in the hydrogen economy (Pt, Ir) markets.

Provide informational support to PGM catalyst industries to enable decarbonization. A deep and structured analysis of how the transition towards decarbonization technologies could affect domestic and global PGM catalyst manufacturers and reliant industries can inform government funded RDD&D expenditures and enabling policies. For that purpose, the United States should compile detailed information on the PGM catalyst supply chain and manufacturers, with particular focus on catalysts supporting decarbonization technologies and efficient chemical production. Quantified energy and materials savings associated with PGM catalyst applications could inform the prioritization of PGM catalyst investments.

Develop substitutes to reduce reliance on Ir-based catalysts. The United States has a strong position in developing PGM catalysts as well as PEM water electrolyzer and fuel cell technologies. Applying the country's intellectual capital with a multi-pronged, multi-year RDD&D and commercialization program could advance these technologies. Particular emphasis should be given to develop substitutes for Ir-based catalysts in PEM water electrolyzers and to support the chemical and catalyst industries through their decarbonization transitions. Advancing novel ideas and technologies for replacing PGM in these applications could also be pursued. RDD&D supported by the United States could provide intellectual protection to support the success of manufacturers in the United States and allied nations.

Develop and commercialize technologies for recovering PGM from end-of-life decarbonization technologies. The United States currently produces refined PGM from secondary sources, primarily catalytic converters. Recycling of petroleum and chemical PGM catalysts is also well established. However, the transition to decarbonized transportation and industry will require different technologies for PGM recovery. RDD&D and industry supports could be directed at developing and deploying economically viable technologies for recovering PGM from end-of-life decarbonization technologies.

Expand PGM mining and refining in the United States. Unlike most countries (excluding South Africa, Russia, Canada, and Zimbabwe), the United States has PGM reserves important to the transition. To meet future challenges, these reserves will need to be mined and refined with net-zero carbon production. RDD&D focused on PGM mining and refining should prioritize improved environmental performance as well as health and safety of workers and neighboring communities. Such expansion must be subject to strict environmental and sustainability standards. Further, U.S. mining laws and regulations should be examined and strengthened to ensure these standards can be met.

4.2 Challenges to Realizing Opportunities

To enable the transition of the PGM catalyst supply chain to support the production of decarbonization technologies, RD&D, information, manufacturing, and policy challenges need to be overcome.

Information gap in PGM catalyst manufacturing processes and data. The current opacity of the PGM catalyst manufacturing system and supply chain engenders information challenges for achieving decarbonization goals. While there is abundant academic and patent literature on catalyst formulations and lab procedures, significantly less information is freely available on manufacturing technologies and producing companies. The PGM catalyst markets are competitive, and as a result, data on catalyst compositions and manufacturing and compositions are largely proprietary. Additionally, the large number and continual development of new PGM catalysts intensifies this information gap. Effort to compile qualitative and quantitative data on PGM catalysts, manufacturing, and supply chains is itself a challenge.

Dependence of PEM water electrolysis on Ir-based catalysts. A key barrier to the adoption of PEM water electrolyzers for production of hydrogen is the high Ir content of currently state-of-the art electrolyzer anodes. Because of co-production issues, Ir content reductions of as much as 80-90% will be needed to support this technology. Challenges to overcome include: 1) advancing technology to achieve an anode catalyst loading of 0.05 g/kW or lower; 2) establishing a PEM water electrolyzer recycling and Ir recovery infrastructure, and 3) achieving end-of-life recycling rates of 90%.

Lack of infrastructure to recycle emerging electrolyzer and fuel cell technologies. Technical, operational, and economic challenges for maximizing recovery of PGM from end-of-life products, particularly fuel cells and PEM water electrolyzers, need to be addressed. The United States may not have the required infrastructure in place, and their recycling may be less profitable than it is for existing PGM-containing scrap. Additionally, efficient technologies for recycling these end-of-life products have not yet been developed and demonstrated.

Potential disruption from changing demand in the PGM catalyst industries. Decarbonization will disrupt the PGM and PGM catalyst industries. We currently lack the information and understanding of these potential impacts on domestic and global PGM mines and manufacturers of PGM catalysts as well as on petroleum refining and petrochemical manufacturing that may be displaced by the transition. These knowledge gaps will hinder the development of effective strategies, investment, and policies for retaining PGM catalyst research, development, and manufacturing expertise and capacity in the United States

Environmental, energy, and societal burdens of PGM mining and refining. Environmental, energy, water, and societal burdens challenge PGM mining and PGM catalyst manufacturing in the United States and foreign countries. While major PGM mining companies are pursuing environmental and social sustainability goals, issues remain. To achieve decarbonization goals, a greater prioritization is needed for the development and deployment of technologies that improve the sustainability of domestic and foreign PGM production and PGM catalyst manufacturers. Improved mining laws and regulations could help incentivize these improvements.

5 Conclusions

The unique chemical and physical properties of PGMs make them excellent catalytic agents. PGM catalysts have been applied extensively in emissions control, petroleum refining, and commodity and fine chemicals production. PGMs are expected to play a critical role in emerging energy efficiency and renewable energy applications, such as PEM water electrolyzers and fuel cells as well as electrocatalytic conversions of nitrogen to ammonia and carbon dioxide to chemicals and fuels. Existing technologies for PEM water electrolyzers use Pt (cathode) and Ir (anode) catalysts, while fuel cells use Pt catalysts for both electrodes. Among the PGMs, Ir is the least abundant accounting for <2 % of PGM mine production in 2020. This study highlights the need to develop substitutes to reduce reliance on Ir-based anode catalysts in PEM water electrolyzers.

PGM resources occur in only a few countries worldwide, with the majority of production and reserves in South Africa and Russia. Two PGM mines operate in the United States; however, their PGM concentrates are exported to South Africa for separation to individual PGMs. In these mining complexes, PGMs are co-produced with base metals such as copper and nickel, increasing their supply risk. The majority of PGM mines and refineries are publicly owned and operated, providing some transparency as well as corporate social responsibility. On the other hand, they are currently energy-, water-, carbon-, and capital-intensive and burdened by environmental and societal issues.

Secondary production of PGMs represents a significant share of total global annual production. In the United States and globally, recovery of PGM (Pt, Pd, and Rh) from catalytic converters accounts for the majority of their secondary supply. As internal combustion engines are replaced by battery and fuel cell technologies, the infrastructure and technologies for PGM recovery will need to transition as well. This need provides an opportunity for the United States to lead in the RDD&D focused on establishing robust technologies for recovering PGM from PEM water electrolyzers, fuel cells, and other emergent PGM catalysts.

The manufacturing of PGM catalysts is complex, diverse, and proprietary. The catalyst industry is highly competitive and relies on intellectual property for sustaining their businesses. Information and analysis are, however, needed to map, identify, and address United States vulnerabilities for manufacturing PGM catalysts important to commercializing decarbonization technologies. Mechanisms for sharing data and information with these objectives will need to be established to effectively support these industries.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

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Appendix A: Additional Tables

Table A1. PGM consumption by end-use (tonnes) [6]

Year	2016	2017	2018	2019	2020	2021
Platinum						
Catalytic converter	104	100	95	89	71	91
Chemical	14.8	14	20.4	20.8	19.9	19.7
Electronics	7.2	7.2	7.5	7.2	7.5	8.7
Glass	7.7	9.8	15.6	13.7	14.1	16
Investment	19.3	11.2	2.1	35	32	9.6
Jewelry	75	74	70	64	53	56
Medical and biomedical	6.8	6.8	7.2	7.5	6.7	7.2
Petroleum	5.8	7.1	11.6	8	9.4	5.4
Other	16.6	17.9	18.4	18.3	14.3	16.8
Total gross demand	257	248	248	263	228	229
Palladium						
Catalytic converter	250	263	275	301	266	294
Chemical	13.1	13.4	19.1	15.7	18	20.1
Dental	13.3	12.2	11.1	9.8	7	7.6
Electronics	27.2	26.3	23.9	22	20	20.4
Investment	-20.1	-12	-17.8	-3	-6	-2.9
Jewelry	6	5	5	4	3	3
Other	4.8	4.5	5.4	5.5	4	4.5
Rhodium						
Catalytic converter	25.1	25.9	27.7	32.0	29.4	32.7
Chemical	2.0	2.4	2.0	1.9	1.7	2.3
Electronics	0.1	0.2	0.2	0.2	0.2	0.2
Glass	2.6	3.1	3.2	1.5	0.2	0.6
Other	1.3	0.6	-0.4	0.6	0.2	0.3
Total gross demand	31.1	32.2	32.7	36.2	31.7	36.1
Ruthenium						
Chemical	11.3	11.2	11.1	12.5	11.4	11.4
Electronics	13.6	13.6	13.2	12.5	11.8	12.4
Electrochemical	4.6	4.3	4.1	4.3	4.1	4.3
Other	4.8	5.4	5.8	4.3	3.2	3.9
Total gross demand	34.3	34.5	34.2	33.6	30.5	32.0
Iridium						
Chemical	0.7	0.5	0.6	0.7	0.8	0.8
Electronics	3.1	2.3	1.6	1.7	1.6	1.8
Electrochemical	1.8	2.7	2.4	2.8	2.7	3
Other	2.6	2.7	2.8	2.9	2.3	2.7
Total gross demand	8.2	8.2	7.4	8.1	7.4	8.3

Table A2. Share of global PGM mine production by country and material, 2020 [2]

Country	Palladium	Platinum	Iridium	Rhodium	Ruthenium	Total PGM
South Africa	33.9%	67.6%	83.0%	84.7%	91.9%	54.0%
Russia	42.9%	13.9%	3.1%	8.0%	3.3%	26.9%
Zimbabwe	5.9%	9.1%	10.2%	6.0%	3.4%	7.0%
Canada	9.2%	4.2%	3.7%	1.3%	1.3%	6.3%
United States	6.7%	2.5%	-	-	-	4.2%
China	0.6%	1.5%	-	-	-	0.9%
Finland	0.4%	0.8%	-	-	-	0.5%
Australia	0.2%	0.1%	-	-	-	0.1%
Colombia	-	0.2%	-	-	-	0.1%
Ethiopia	-	<0.1%	-	-	-	<0.1%
Serbia	0.05%	<0.1%	-	-	-	<0.1%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table A3(a). USGS data – U.S. imports of Pt in 2020

TABLE 2

U.S. IMPORTS FOR CONSUMPTION OF PLATINUM, BY COUNTRY OR LOCALITY[1]

	Grain and nuggets		Sponge		Other unwrought		Semimanufactured forms		Coins	
Country or locality	Quantity, Pt content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)
2019	360	$12,700	26,200	$726,000	3,880	$168,000	10,600	$320,000	1,320	$40,600
2020:										
Australia	--	--	--	--	--	--	3	55	1,190	36,000
Austria	--	--	--	--	2	64	177	11,100	145	4,630
Belgium	--	--	4,040	115,000	--	--	--	--	--	--
Brazil	--	--	13	333	--	--	--	--	--	--
Canada	138	4,060	--	--	--	--	363	11,100	584	19,500
China	--	--	--	--	--	--	(2)	7	20	553
Colombia	311	187	(2)	3	313	8,850	--	--	--	--
Costa Rica	--	--	--	--	--	--	995	34,600	--	--
Czech Republic	--	--	--	--	--	--	22	946	--	--
France	--	--	54	1,640	--	--	123	3,910	--	--
Germany	(2)	4	4,620	134,000	739	25,100	3,830	192,000	5	212
India	--	--	116	3,310	9	462	(2)	2	--	--
Italy	(2)	6	3,310	94,200	1	22	7	155	--	--
Japan	--	--	874	25,200	804	22,600	19	485	1	6
Korea, Republic of	--	--	63	1,840	--	--	11	392	--	--
Mexico	2	60	--	--	--	--	44	1,740	--	--
Norway	--	--	249	6,700	--	--	94	4,620	--	--
Poland	--	--	--	--	--	--	1	65	--	--
Russia	--	--	1,970	50,600	88	2,220	(2)	12	(2)	4
Singapore	--	--	--	--	1,230	127,000	247	8,730	--	--
South Africa	--	--	14,100	400,000	993	30,700	53	1,940	471	11,800
Switzerland	15	463	636	17,700	1,080	34,300	17,000	492,000	--	--
Taiwan	--	--	--	--	--	--	952	23,500	--	--
Thailand	--	--	--	--	2	72	(2)	14	--	--
United Kingdom	--	--	894	22,900	114	3,220	1,870	65,300	88	2,600
Other	--	--	(2)	3	1	34	2	56	(2)	2
Total	162	4,780	30,900	874,000	5,370	255,000	25,900	853,000	2,510	75,300

[r]Revised. -- Zero.

[1]Table includes data available through June 9, 2021. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Less than ½ unit.

Source: U.S. Census Bureau.

Table A3(b). USGS data for U.S. imports of Pd, Ir, Os, Ru, and Rh in 2020

TABLE 3

U.S. IMPORTS FOR CONSUMPTION OF PLATINUM-GROUP METALS, BY COUNTRY OR LOCALITY[1]

	Palladium[2]		Iridium[2]		Osmium[2]		Ruthenium[2]		Rhodium[2]		Waste and scrap	
Country or locality	Quantity, Pd content (kilograms)	Value (thousands)	Quantity, Ir content (kilograms)	Value (thousands)	Quantity, Os content (kilograms)	Value (thousands)	Quantity, Ru content (kilograms)	Value (thousands)	Quantity, Rh content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)
2019	84,300	$3,770,000	875	$38,300	(3)	$2	11,200	$91,600	15,000	$1,660,000	35,200 r	$1,100,000
2020:												
Australia	--	--	--	--	--	--	--	--	--	--	326	11,500
Austria	78	4,950	--	--	--	--	--	--	--	--	--	--
Belgium	4,850	328,000	--	--	--	--	--	--	1,360	357,000	181	7,000
Brazil	--	--	--	--	--	--	--	--	--	--	2,950	46,100
Canada	5,780	377,000	--	--	--	--	--	--	9	506	8,440	311,000
China	1	40	--	--	1	17	--	--	(3)	24	186	14,600
Colombia	--	--	--	--	--	--	--	--	--	--	92	2,620
Dominican Republic	1	3	--	--	--	--	--	--	--	--	145	3,810
Egypt	--	--	--	--	--	--	--	--	--	--	300	9,230
France	(3)	12	--	--	--	--	--	--	--	--	587	20,300
Germany	3,530	174,000	310	10,300	--	--	2,800	24,900	3,390	1,170,000	3,170	169,000
Hungary	--	--	--	--	--	--	--	--	--	--	107	7,440
Italy	12,600	228,000	4	154	--	--	1,170	11,400	6,370	250,000	1,630	53,200
Japan	1,100	24,500	56	1,540	--	--	129	925	77	20,100	6,250	180,000
Korea, Republic of	485	34,300	--	--	--	--	6	41	150	54,300	--	--
Malaysia	--	--	--	--	--	--	--	--	(3)	5	478	11,700
Mexico	28	872	--	--	--	--	--	--	--	--	9,080	266,000
Netherlands	--	--	--	--	--	--	--	--	--	--	239	5,620
New Zealand	--	--	--	--	--	--	--	--	--	--	97	3,190
Norway	180	12,100	--	--	--	--	--	--	24	8,770	(3)	14
Poland	--	--	--	--	--	--	--	--	--	--	279	10,400
Russia	23,800	1,680,000	163	7,210	--	--	133	1,150	1,410	456,000	--	--
Saudi Arabia	--	--	--	--	--	--	--	--	--	--	1,430	52,200
Singapore	--	--	--	--	--	--	--	--	--	--	1,180	47,800
South Africa	20,500	1,390,000	960	45,200	--	--	7,050	56,100	7,510	2,200,000	86	5,340
Sweden	--	--	--	--	--	--	--	--	--	--	218	22,100
Switzerland	1,840	128,000	--	--	--	--	--	--	36	11,900	1	32
Thailand	--	--	--	--	--	--	--	--	--	--	1,270	41,600
United Arab Emirates	--	--	--	--	--	--	--	--	--	--	514	27,900
United Kingdom	1,580	108,000	128	5,680	--	--	2,660	22,700	337	67,500	148,000	152,000
Other	30	443	--	--	--	--	--	--	(3)	9	686	21,600
Total	76,400	4,490,000	1,620	70,100	1	17	13,900	117,000	20,700	4,590,000	188,000	1,500,000

[r]Revised. -- Zero.

[1]Table includes data available through June 9, 2021. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Unwrought and other forms.

[3]Less than ½ unit.

Source: U.S. Census Bureau.

Table A3(c). USGS data for U.S. exports of Pd, Pt, (Ir, Os + Ru), and Rh in 2020

TABLE 4

U.S. EXPORTS OF PLATINUM-GROUP METALS, BY COUNTRY OR LOCALITY[1]

	Palladium		Platinum		Iridium, osmium, ruthenium		Rhodium		Waste and scrap	
Country or locality	Quantity, Pd content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)	Quantity, gross weight (kilograms)	Value (thousands)	Quantity, Rh content (kilograms)	Value (thousands)	Quantity, Pt content (kilograms)	Value (thousands)
2019	55,500	$1,620,000	17,400	$547,000	1,330	$19,300	1,210	$152,000	20,800	$724,000
2020:										
Australia	63	2,090	73	1,800	79	2,090	--	--	--	--
Austria	1	6	1	32	--	--	--	--	2	56
Belgium	914	61,000	451	13,000	(2)	3	116	39,300	1,980	68,700
Brazil	402	29,000	268	7,450	(2)	3	11	4,890	--	--
Canada	3,410	236,000	329	11,500	1	8	17	5,770	12	374
China	770	36,800	236	5,670	108	1,390	120	26,700	--	--
Costa Rica	14	530	894	16,100	12	392	--	--	--	--
Czech Republic	5	200	--	--	--	--	--	--	2	131
Denmark	4	176	--	--	--	--	--	--	--	--
Dominican Republic	(2)	4	7	266	--	--	--	--	--	--
Estonia	(2)	21	7	197	--	--	--	--	--	--
Finland	7	111	(2)	4	--	--	--	--	--	--
France	218	5,250	74	1,910	70	770	--	--	--	--
Germany	4,090	202,000	3,230	135,000	284	2,490	112	38,500	8,140	436,000
Hong Kong	701	39,200	197	5,160	121	4,620	129	38,700	15	459
Hungary	1	3	3	51	--	--	--	--	--	--
India	864	59,500	616	17,300	4	55	3	879	--	--
Indonesia	54	240	(2)	3	--	--	--	--	--	--
Ireland	134	2,520	345	9,210	2	19	--	--	--	--
Israel	242	9,650	14	343	--	--	--	--	--	--
Italy	5,460	387,000	2,180	63,000	146	3,290	19	7,250	508	18,600
Japan	1,290	81,500	2,100	71,200	233	3,170	95	34,500	12,000	430,000
Korea, Republic of	903	53,800	2,260	85,900	1	14	212	54,300	(2)	10
Kuwait	5	239	--	--	--	--	--	--	--	--
Laos	--	--	9	357	--	--	--	--	--	--
Macau	3	100	3	36	--	--	--	--	--	--
Malaysia	3	39	1	25	3	46	--	--	2	80
Mexico	94	2,520	1,260	36,600	36	452	1	409	--	--
Netherlands	2	86	3	102	--	--	--	--	--	--
New Zealand	16	737	3	84	--	--	(2)	27	--	--
Norway	8	47	27	1,040	--	--	--	--	--	--
Poland	6	82	2	74	--	--	--	--	--	--
Russia	--	--	52	1,740	--	--	--	--	3	190
Singapore	34	875	675	19,800	--	--	--	--	1	16
South Africa	3	21	372	21,900	7	129	519	134,000	87	4,050
Switzerland	13,300	616,000	9,340	269,000	129	4,430	56	20,200	1,330	41,400
Taiwan	1,080	52,600	106	3,210	182	1,020	(2)	24	(2)	9
Thailand	108	3,050	50	1,330	1	41	--	--	--	--
United Kingdom	14,300	1,020,000	3,630	129,000	19	420	64	20,700	9,170	398,000
Vietnam	2	47	15	446	--	--	--	--	--	--
Other	10	229	13	407	(2)	14	(2)	49	1	40
Total	48,600	2,900,000	28,900	930,000	1,440	24,900	1,470	426,000	33,200	1,400,000

-- Zero.

[1]Table includes data available through June 9, 2021. Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Less than ½ unit.

Source: U.S. Census Bureau.

Table A4. Assessment Table

Component	SC segment/ process	sub-segment/ product	Significant domestic suppliers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost competitive among US suppliers	Cost competitive between US suppliers vs. global suppliers	Is foreign supply diversified?	Is foreign supply from reliable trade partners?	Is there sufficient effort to address environmental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build a domestic capability for this product/ component?
Raw materials	Mining and processing	PGM-containing ore	Yes	yes	Maybe	Yes	Yes	Maybe	Yes	No	Maybe	No	No	Maybe
	Processing	Converter matte	Maybe	yes	Maybe	Yes	Yes	Maybe	Yes	No	Maybe	No	No	Maybe
	Base metal separation	PGM concentrate	Maybe	yes	Maybe	Yes	Yes	Maybe	Yes	Maybe	Maybe	No	No	Maybe
	Precious metal separation	Pt	Maybe	yes	yes	Yes	Yes	Maybe	Yes	Maybe	Maybe	No	No	Maybe
		Pd	Maybe	yes	yes	Yes	Yes	Maybe	Yes	Maybe	Maybe	No	No	Maybe
		Rh	No	yes	yes	Yes	Yes	No	No	No	Maybe	No	No	Maybe
		Ru	No	Maybe	Maybe	Maybe	Maybe	No	No	No	Maybe	No	No	Maybe
		Ir	No	yes	yes	Yes	Yes	No	No	No	Maybe	No	No	Maybe
		Os	No	Maybe	Maybe	maybe	maybe	No	No	No	Maybe	No	No	Maybe
	Production from scrap	Secondary PGM material	Maybe	Yes	Yes	Maybe	Yes	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe
Catalyst manufacturing		Pt-based catalyst	no	Yes	Yes	Yes	Yes	No	Yes	Maybe	Maybe	Yes	Maybe	Yes
		Pd-based catalyst	Maybe	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	Maybe	Yes	Maybe	Yes
		Ir-based catalyst	no	Yes	Yes	Yes	Yes	No	No	Maybe	Maybe	Yes	Maybe	Yes
		Other PGM-based catalysts	Maybe	Yes	Yes	Yes	Maybe	maybe	Maybe	Maybe	Maybe	Yes	Maybe	Yes
Component manufacturing	Electrolyzers	PEM Electrolyzers	Yes	No	Yes	Yes	Yes	Maybe	Yes	No	Maybe	Yes	Maybe	Maybe
		AW Electrolyzers	Maybe	Maybe	Yes	Yes	Yes	Maybe	No	Maybe	Yes	Yes	Maybe	Yes
		SOEC Electrolyzers	Yes	No	Yes	Yes	Yes	No	No	Maybe	Yes	Yes	Maybe	Maybe
	Fuel cells	PEM FCs	maybe	Maybe	Yes	Yes	Yes	No	Yes	Maybe	Maybe	Yes	Maybe	Yes
		AW FCs	No	No	Yes	Yes	Yes	Maybe	Maybe	Maybe	Yes	Yes	Maybe	Yes
		SO FCs	Maybe	Maybe	Yes	Yes	Yes	Maybe	Maybe	Maybe	Yes	Yes	Maybe	Yes
	Catalytic converter	Catalytic converter	yes	Yes	Maybe	Yes	Maybe	Yes	Yes	Yes	Yes	Yes	Maybe	Yes
End product	Hydrogen	Green Hydrogen	No	Maybe	Yes	Yes	Yes	Yes	Yes	/A	Maybe	Yes	Yes	Yes
	FCEVs	FCEVs	Maybe	Maybe	Yes	Maybe	Yes	Maybe	Maybe	Maybe	Maybe	Yes	Yes	Yes
End-of-life product collection	Collection of scrap for recycling	Scrap	Yes	Yes	Yes	Maybe	Yes	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe	Maybe

Table A5. Non-Catalytic Applications for Ir and potential substitutes. [13]

Application	PGM	Substitution
Jewelry	Pt, Ir, Pd Alloys	White gold nickel, zinc, antimony
Crucibles	Pt-Rh Ir (for most demanding applications)	No known substitutes
Filters	Ir	Lithium tantalate filters for mobile phones
Contacts	Rh, Ru, Ir	Hardening contacts for applications such as reed switches. Substitute with older technology
Electrolyzers	Pt, Ir in PEM	Active R&D to find substitutes, partial substitution of Ir with Pt, Ru
OLEDs	Ir organometallics	Pt, Pd substitute in some applications
Pacemakers	Pt, Pt-Ir (10–20%)	Application for pacing electrodes. Key property is electrical conductivity
Defibrillators	Pt, Pt-Ir	Provide high energy cardioversion pulse for defibrillation. Potential : Pt-coated tantalum electrodes
Brain pacemakers	Pt-Ir	Silicon electrodes being tested
Fountain pen nib tips	Ir, Os, Ru, Pt for hardening nibs	PGM chosen for wear and corrosion resistance. Alternatives: rhenium and tungsten
Scientific	Pt electrodes Pt Ir	Electrochemistry—counter electrodes. Possible substitution with titanium
Ballast	Pt-Ir electrodes	Ballast sterilization anodes, substitute with other sterilization methods

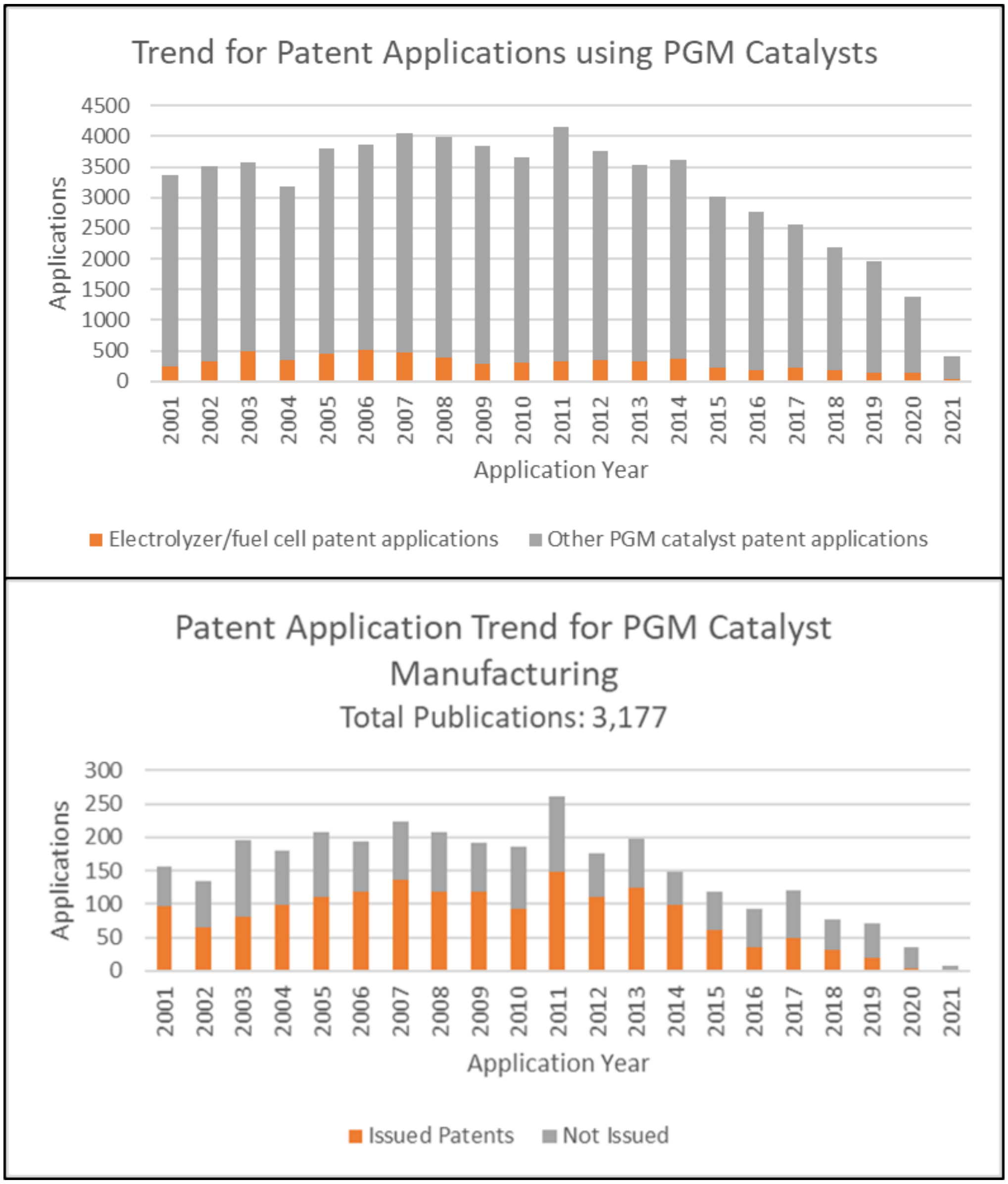

Figure A1. a) annual patent applications for PGM catalysts and electrolyzer/fuel cells; and b) annual patent applications for PGM catalyst manufacturing.

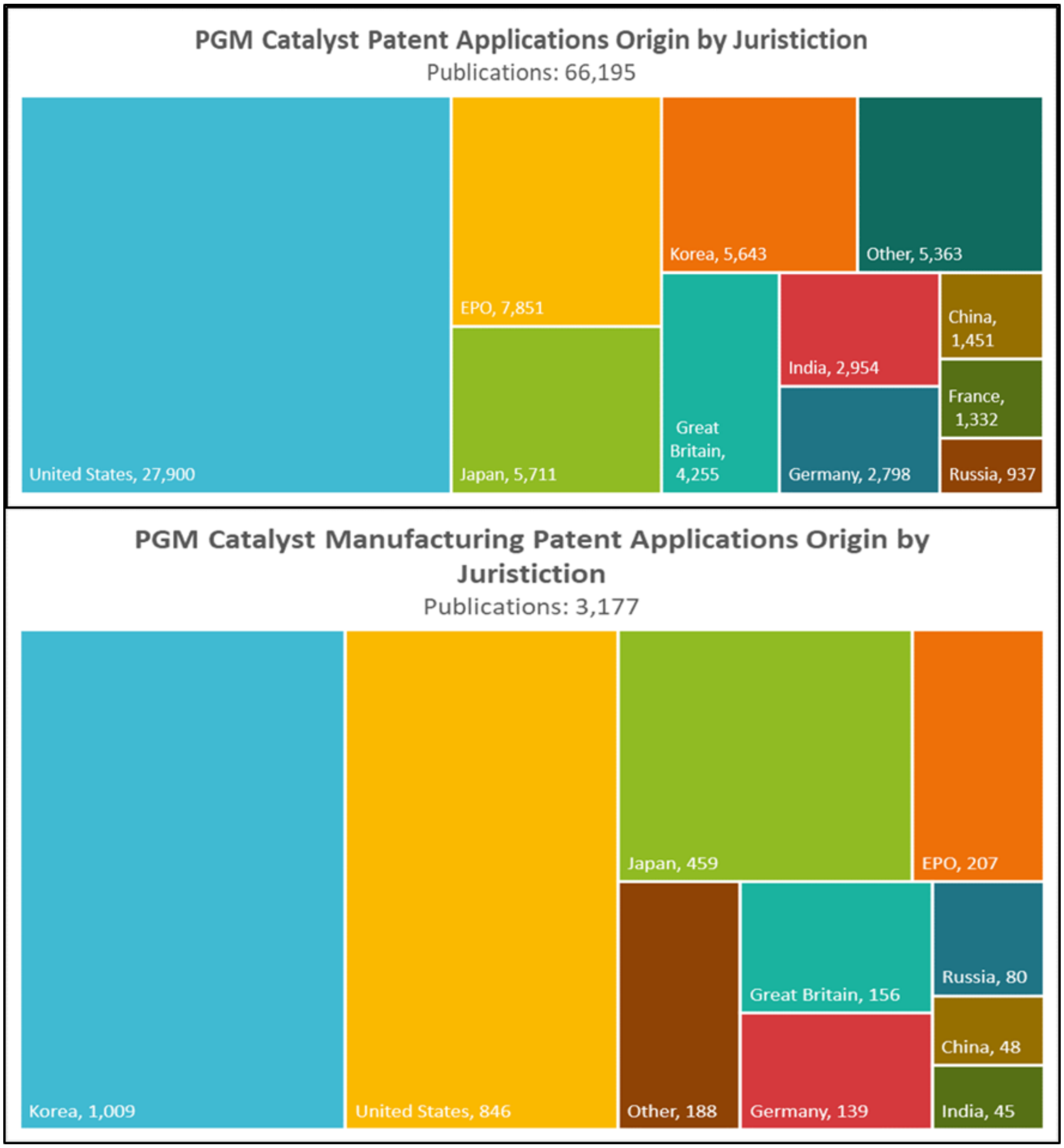

Figure A2. (a) PGM catalyst patent applications - 66,195 total published applications from 2001 to present; (b) top ten applicants of these patents; and (c) PGM catalyst patent applications by country

Appendix B: Additional Technical Details from Supply Chain Mapping

B.1 PGM Production

B.1.1 Supplementary Information on U.S.-based Stillwater Mine

Concentrated ores from the Stillwater and East Boulder mines are smelted in the company's Columbus Metallurgical Complex in Columbus, Montana. The smelter at this facility has a design capacity of 9.1 t/h and is operated at 90% capacity utilization. Other process equipment at the plant include a concentrate drying plant, electric furnaces (2), top blown rotary convertors (2), a matte granulator, gas handling equipment, and a solution regeneration system. The plant also houses a base metals refinery that uses sulfuric acid to separate the PGM by dissolving the nickel, copper, cobalt, and residual iron from the smelter product.

Sibanye Stillwater also recycles spent automotive catalytic converters at their Columbus facility, recovering 26.1 tonnes PGM in 2020.[79] The spent catalytic converters are either purchased by the company or toll processed for a fee.[80]

B.1.2 Examples of PGM Catalyst Precursors Catalyst Production Processes

PGM precursors are specific to catalyst end use: Precursors are PGM compounds that are designed to facilitate the manufacturing of specific catalysts. For example, hexachloroplatinic acid, or H_2PtCl_6, is made by a reaction between Pt metal and a mixture of concentrated nitric and chloric acid. It is water-soluble and can be transferred to the surface of the catalyst supports such as carbon or refractive oxide through wet-incipient methods before being reduced to finely dispersed elemental Pt as active catalyst.

The conversion of raw PGM to catalyst precursors also usually happens at the production site. For example, PGM precursors manufactured by Johnson Matthey include, among many others, ammonium tetrachloroplatinate, palladium chloride solid, chloroiridic acid solution, and rhodium acetate dimer.[81] Due to the limited quantity involved, catalyst precursors are often produced through batch processes. Due to its high cost and low quantity, the shipment cost for the precursor is less significant compared to the PGM catalyst materials and production. Therefore, the PGM catalyst producers are distributed globally.

PGM catalysts are produced in the forms of organometallics, inorganic salts, and finely dispersed metals over high surface area supports. Organometallic PGM catalysts are often used to promote fine chemical and pharmaceutical production, either through homogeneous or heterogeneous catalytic reactions. They are usually produced at small quantities with high cost. Inorganic PGM salts are often used as the precursors to prepare heterogeneous catalysts by first dissolving in solvent such as water followed by impregnation or the wet incipient method to transfer over the support materials. PGMs mostly used for industrial processes include Pt, Rh, Pd, Ru, and Ir.

Though the catalyst industry is dominated by Pt, Pd also is used widely for promoting catalysis for hydrogenation, dehydrogenation, and petroleum cracking. A large number of carbon–carbon bond coupling reactions in organic chemistry are facilitated by Pd compound catalysts. Pd can also serve as the replacement for Pt in emission control catalyst. The following sections discuss some representative examples of PGM catalyst application and manufacturing processes.

B.1.2.1 Catalytic Converters

Three-way catalyst manufacturing is a continuous process using PGM precursors, often in the form of nitrate aqueous solutions. These precursors are mixed with high surface area inorganic supports such as γ-alumina, and additives such as cerium carbonate to form a "catalyst slurry."

B.1.2.2 Fuel Cells

PEM fuel cells and alkaline electrolyte membrane fuel cells are generally operated at ambient or slightly higher than ambient temperature (typically at 80 °C), whereas solid-oxide fuel cells operate at high temperatures (>700 °C). PEM fuel cells operate through proton conductive membrane electrolyte, and alkaline electrolyte membrane fuel cells operate based on hydroxyl group conductive membrane. Solid-oxide fuel cells operate based on the conduction of oxygen ions through ceramic membranes required for the oxide reduction reaction and at the anode for the hydrogen oxidation reaction. Alkaline electrolyte membrane fuel cells do not need Pt at the cathode; however, they do use Pt at the anode. Solid oxide fuel cells do not require PGM catalyst.

At present, a number of commercial PEM fuel cell vehicles are already on the market. Their application relies on the high ion conductivity of PEM, leading to more compact system designs with better volumetric density, smaller footprint, low operating temperature, less corrosive to the system, and improved durability.

Precursors such as platinum sulfite, chloroplatinic acid, or tetraammineplatinum nitrate in aqueous solution are often used to deposit Pt over the catalyst support through redox reaction or impregnation, followed by chemical reduction to convert ionic Pt to metallic form. For example, Pt sulfite reacts with hydrogen peroxide through a redox reaction in the aqueous mixture containing carbon to form uniformly dispersed Pt particles over the carbon support. The Pt-functional group in chloroplatinic acid is in the form of negatively charged ion whereas in tetraammineplatinum nitrate the Pt functional group is a positively charged ion. They adsorb differently in the deposition chemistry over the support with positively charged or negatively charged counter ions. Hydrogen is often used as the reducing gas. The objective is to achieve high dispersion and BET surface areas with Pt particle size controlled at the range between 2 nm to 5 nm. Such particle size range is considered to provide the best combination of the catalytic activity and durability. New manufacturing technology to further improve catalyst activity while reducing the Pt metal usage involves the introduction of a second, lower-cost transition metal like Co or Ni to form alloy particles with unique structure, such as a core-shell structure with transition metal core and platinum metal shell. Such alloy formation typically occurs at temperatures above 700 °C during the annealing step in a reducing or inert environment.

B.1.2.3 Electrolyzers

PEM water electrolyzers and alkaline water electrolyzers are generally operated at ambient or slightly higher than ambient temperature whereas solid oxide water electrolyzers operate at high temperatures (>700 °C). In water electrolyzers, hydrogen is produced at the cathode through a hydrogen evolution reaction, and O_2 is produced through an oxygen evolution reaction.

The Pt/C catalyst in the cathode of PEM water electrolyzer is produced by the method similar to that used in PEM fuel cells. The anode catalyst is manufactured through direct oxidizing iridium compound in air or oxygen.

B.1.2.4 Other Current and Nascent Electrocatalytic Technologies

Electrocatalytic production of chemicals is thermodynamically controlled by the Gibbs free energy, which is more efficient compared to that of heat-driven catalytic reaction dominated by Carnot cycle. Therefore, it represents a critical solution for improving energy efficiency.

Similar to PEM water electrolyzers, electrocatalytic CO2 reduction reaction and electrocatalytic N2 reduction reaction also have an anode and a cathode with electrocatalysts applied to both electrodes. For example, various low-cost, PGM-free catalysts using earth-abundant materials have been developed for the CO2 reduction reaction electrolyzer cathode where reduction of CO2 to chemicals occurs. The counter electrochemical reaction at the anode, however, involves oxidation of water to oxygen (i.e., the OER process). This counterreaction requires a catalyst similar to that used in PEM water electrolyzers anode (i.e., Ir), since they involve the same electrocatalytic process. Similarly, OER also represents the counter electrochemical reaction at the anode in NRR electrolyzer where nitrogen is reduced to ammonia at the cathode.

B.1.2.5 Petroleum Refining and Chemical Productions

Catalytic reforming process: In this process, heavy naphtha is re-formed to produce aromatics and iso-paraffins as well as hydrogen. U.S. gasoline specifications require an octane of 87, which is obtained via blending multiple product streams with various octane numbers. Reformate, the product stream from the catalytic reforming process, is generally a significant octane-boosting stream. Relative to heavy naphtha with octane of 50-60, the reformate (with high share of aromatics and iso-paraffins) has a much higher octane number (greater than 90), with the expense of yield decrease.

Isomerization: The feedstock is light naphtha, mainly consisting of normal pentane and hexane with a research octane number (RON) of 60-70. Isomers are formed via isomerization, with the product octane number reaching 82-84 (for once through) and 87-93 with recycling. Although the isomerization process increases the octane number, it also increases product Reid vapor pressure (RVP), which is strictly capped by regulations.

Hydrocracking: The hydrocracking unit is important process unit to favor distillate production by cracking the more aromatic feedstock, whereas the Fluidized Catalytic Cracking (FCC) unit favors gasoline production by cracking the more paraffinic feedstock. Hydrocracking catalyst often consists of acidic support (e.g., silica alumina) and active metal (active for hydrogenation), which often consists of Ni, W, Mo, Co., etc, [33, 82] PGM such as Pt or Pd could also enhance hydrogenation. Hydrocracking processes are not only used to process refinery streams (gasoil, residual stream) towards distillate production, but also can be used to dewax in the lubricant production.

Hydrogenation and dehydrogenation: For example, Pt-based catalyst is used to dehydrogenate propane to propylene that is used as a feedstock for polypropylene production. Conventionally, propylene is produced via steam cracking along with ethylene production. The recent shale boom shifted U.S. steam cracking feedstock from naphtha to the lighter ethane or natural gas liquids (NGL), resulting in the reduced yield of propylene. Meanwhile, the demand of polypropylene is increasing globally. Consequently, the on-purpose propylene production process via propane dehydrogenation (PDH) has been expanding in capacity in both the United States and globally. [83, 84]

Nitric acid and acetic acid production: Due to the high exothermicity and fast reaction kinetics, the nitric acid catalytic process is typically carried over PGM metal gauzes with high space velocity. At present, the ternary Rh-Pt-Pd alloys developed by Johnson Matthey (ECOCAT™) represents the state-of-the-art catalyst with better durability and low installation weight requirement.

The catalysts used in the production of acetic acid are molecular compounds of Rh or Ir ligated by CO and iodine. The homogenous catalysis reaction occurs in the batch reactor, followed by catalyst separation/recovery and distillation steps. The Ir-based catalytic process (Cativa™) developed by BP Chemicals in the 1990s represents the most advanced method currently being used in U.S. and other manufacturing sites globally.

B.1.3 End-of-life Product Recovery

At this size reduction stage of catalytic converter recycling, a small amount of the three-way powder is taken to sample and assay via equipment such as X-ray fluorescence or inductively coupled plasma-optical emission spectrometry. [85] This analysis is the basis of payment for collectors who sell "on assay" rather than on a per-converter basis. The homogenization step includes screening and blending with weighted flux and metal-collector streams determined by the downstream separation strategy.

B.1.3.1 Pyrometallurgical Processes

The sintering process recovers the PGM materials by targeted reduction of PGM oxides at high temperature, and typically activated by plasma-generated radicals. Studies have shown that catalysts recovered via plasma-sintering retained their original catalytic efficiency, and have lower environmental footprint compared to the other pyro-metallurgical pathways [86, 87], although some studies suggest a reduction of effective specific particle surface area. [88]

The volatilization process involves selective chlorination to form chloride complexes with the PGM metals from the pretreated scrap, followed by separation via volatilization, exploiting the physico-chemical property differences such as vapor pressures or adsorption affinity to activated carbon between the metal chlorides, with reported recoveries of PGMs at between 80% and 90%. [86, 89] Other studies have explored carbon monoxide as a reducing agent with promising results; using chlorine combined with CO-extracted PGM-chloride complexes yielded recoveries of about 93-96%. [89] A key challenge with chlorination is the emission of hazardous carbon monoxide and chlorine gases, which penalize the environmental footprint.

The smelting process is the more widely used pyro-metallurgical pathway because of its effectiveness at concentrating PGMs prior to recovery by refining. In this process, the pretreated catalyst is mixed with flux material, collector material and reducing agent in the homogenization step, then smelted in a furnace at high temperatures. The collector material – copper, iron, matte, lead, or mixed materials such as in PCBs – collects the PGMs into an enriched alloy while the catalyst carrier materials like alumina separate out via the slag stream. [41] The price of the alloy ingot recovered at this stage is determined according to the PGM purity, and is subject to market volatility. This step may be spread across different companies, limited by company capabilities (some companies lack an in-house assay laboratory or smelting capabilities). The downstream separation and purification process depends on the choice of collector material; with copper collection, the smelting occurs at around 1450 °C – 1600 °C, followed by electrolysis to recover the copper cathode, and further refining to recover the PGMs. [42, 86] The reported individual PGM recovery depends on collector technology and ranges from 88% to 93% (Matte) [90] up to 99% (copper, iron and PCB). [86] Many processes recover PGM concentrates, which proceed to a downstream hydrometallurgical purification step to separate out the individual PGMs, as well as the individual base metals. [42, 91]

B.1.3.2 Hydrometallurgical Process

The process starts with leaching the homogenized PGM feedstock using mineral acids such as sulfuric, chloride and nitric acids, cyanides, hydroxides, and carbonates. [92] Hot water has also been used as a leaching media when preceded by a roasting step, and the leaching process can be enhanced by a number of processes such as mechanical agitation. Leaching in chlorine media is generally considered favorable because PGM chlorine complexes formed are stable in acidic conditions and can be effectively dissolved by careful pH control. [44, 93] The PGMs from the pregnant leach solutions can subsequently be extracted via a number of processes, including precipitation, solvent extraction, or ion-exchange (as illustrated in Figure 9). [94, 95] The choice of solvents for precipitation and solvent extraction depends on a number of factors, including number of metals (impurities) in solution, target recovery specs (individual elements or alloys), as well as other operational considerations. Other proposed strategies include molecular recognition and the use of deep eutectic solvents. [96, 97] In general, the hydrometallurgical process produces PGM salts/complexes, which can be refined or electrowon to create the metallic ore.

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