The Role of Platinum in the Green Energy Revolution

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Abstract

Platinum is an important element needed for producing “Green” hydrogen, hydrogen produced from renewable energy sources. This paper is a comprehensive overview of platinum, describing various factors from the geology of platinum to its use in modern technology. Platinum is a highly efficient catalyst used in electrolyzers to generate hydrogen from water and to build hydrogen fuel cells. Published theories describing the unique physics and chemistry of platinum in relation to interactions with hydrogen will be explored. The key advantages and disadvantages of platinum compared to alternative materials in the green hydrogen and fuel cell industry will be discussed. The current state of geological occurrences and rarity of platinum resulting in supply shortfalls and geopolitical challenges will be described.

Table of Context

1. Introduction

1.1 Background

Hydrogen has been used for many decades to power fuel cells to drive electrical motors. A major advantage of hydrogen power over internal combustion engines burning fossil fuels is that hydrogen fuel cells only emit water vapor, and no harmful CO_2 emissions (IEA). Therefore, hydrogen fuel cells will likely play a growing role in decarbonizing energy systems with the objective of minimizing humanity’s impact on climate change. Fuel cells have significant advantages over battery electric vehicles (BEVs) in heavy commercial vehicles such as tractors, buses, trucks, construction equipment and trains because hydrogen fuel cells are lighter and quick to re-fuel. The heavy-duty, long-haul segment, including trucks and intercity buses are more immediately competitive compared to BEVs than in the case of passenger cars. The direct electrification of regional bus operations and heavy-duty trucking for long-distance freight both face major challenges with larger battery capacity, long charging times and large power requirements. Trains, farm machinery, construction equipment, large ships, all face similar hurdles when considering zero carbon emission alternatives to internal combustion engines (ICEs) (IEA).

Several methods are used to produce hydrogen, but only recently has hydrogen been produced at a commercial scale using renewable energy instead of fossil fuels. “Green hydrogen” is the common name for producing hydrogen from renewable energy, where solar, wind or hydropower is used as a source of electricity in electrolysis of water to produce hydrogen (Crownhart).

Historically, most commercial hydrogen production has been generated whereby the hydrocarbon, methane gas, is combined with high temperature steam to generate both hydrogen and CO_2 gasses by a process known as steam-methane reforming (SMR). In 2019, ~75% of global hydrogen was being produced with this method (IEA). If the CO_2 is released into the atmosphere in the process, the resulting hydrogen is commonly called “gray hydrogen” (Crownhart). However, if the same SMR process is used, but the CO_2 is injected underground using carbon capture and storage (CCS) to minimize harmful CO_2 emissions which cause climate change; the resulting hydrogen is commonly called “blue hydrogen” (Crownhart). Adding CCS to SMR plants to generate blue hydrogen leads to higher cost hydrogen but results in approximately 9% to 25% lower greenhouse gas emissions compared to gray hydrogen, depending on the efficiency of the processes (Howarth). In the most promising regions of the world, costs for blue hydrogen in 2019 were in the range of USD $1.4–$1.5/kg of hydrogen, making it one of the lowest cost hydrogen production methods that purposefully aims to reduce greenhouse gas emissions (Figure 1).

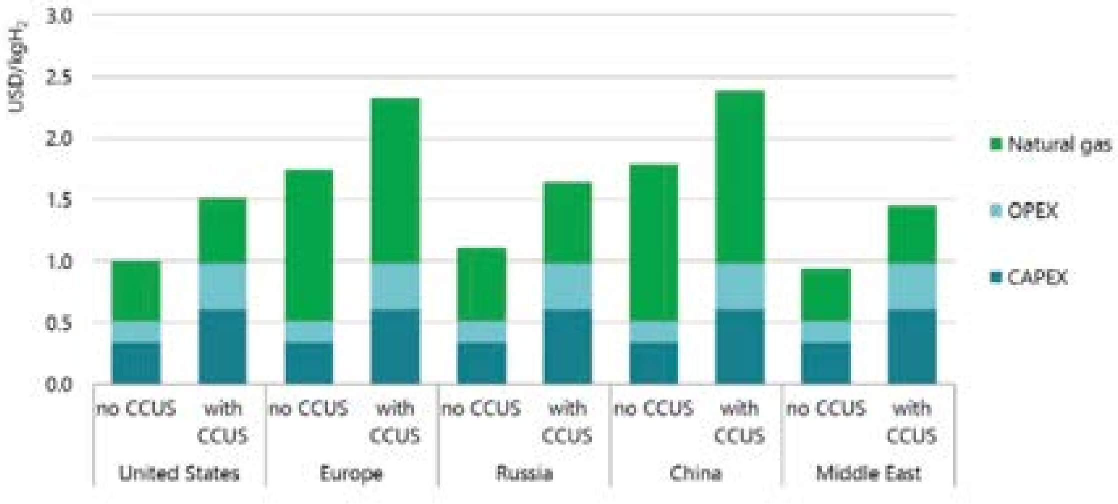


Figure 1: Hydrogen production costs using natural gas in different regions, 2018. (IEA)

A 2021 peer-reviewed paper by Howarth and Jacobson examined the lifecycle greenhouse gas emissions of blue hydrogen, accounting for emissions of both carbon dioxide and unburned fugitive methane (Howarth). They concluded that blue hydrogen is far from being low carbon, and its related greenhouse gas emissions are quite high, particularly when the release of fugitive methane is also accounted for (methane gas that escapes to the atmosphere from the total gas production and SMR process). Figure 2 Illustrates greenhouse gas emissions footprint per unit of heat energy of blue hydrogen compared to generating heat from burning natural gas, diesel fuel, and coal. Carbon dioxide equivalent emissions of fugitive, unburned methane are shown in red. This study quantified the surprisingly large contribution of leaking methane in the blue hydrogen supply chain. Because molecules of methane have a Global Warming Potential (GWP) approximately 86 times higher than CO_2, the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas. In this analysis, even coal and diesel oil burned for heat create lower greenhouse gas emissions than blue hydrogen (Howarth).

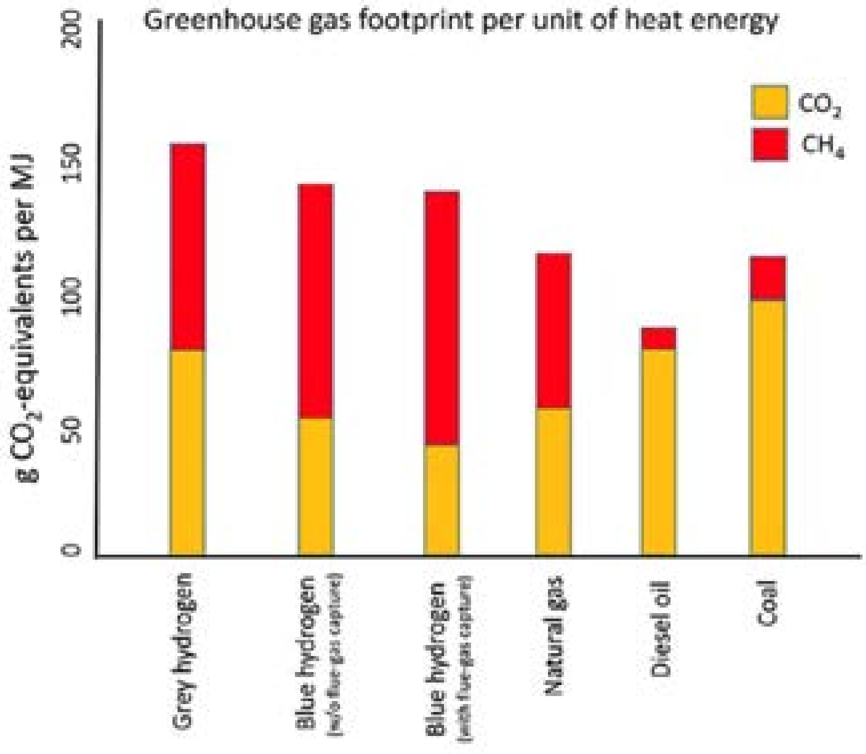


Figure 2: Greenhouse gas footprint per unit of energy compared to burning traditional fossil fuels. (Howarth)

Coal can also be used as a hydrocarbon source for hydrogen production. In 2019 coal as a source accounted for ~23% of global hydrogen production due to the dominance of coal-gasification used to generate hydrogen in China (IEA). Hydrogen production from coal using gasification is an established technology which has been used in the chemical and fertilizer industries for making ammonia. When coal is used as a source to produce hydrogen the process is commonly called “brown hydrogen or black hydrogen” (Crownhart). In 2019, ~130 coal gasification plants are in operation around the globe, > 80% located in China. Hydrogen production using coal produces CO_2 emissions of about 19 metric tons of CO_2 per metric ton of hydrogen, which is twice the CO_2 emissions compared to gray hydrogen from SMR natural gas (IEA).

One problem with green hydrogen is its cost of production compared to gray or blue hydrogen. In 2023, the average cost of producing green hydrogen in the US was ~$5/kg which is approximately double the cost of producing gray-hydrogen hydrogen with natural gas (USDE, 2024). However, government incentives and funding of research and development in the green hydrogen production sector in many nations aims to bring down the cost of green hydrogen production. A US Department of Energy initiative called the “Hydrogen Shot” is funding research and development of new technologies with the goal of reducing the cost of green hydrogen to less than $1/kg by 2032 to increase the use of green hydrogen in the USA (USDE). The precious metal, platinum, is an important component in making efficient and reliable devices which are used today to produce green hydrogen and to build hydrogen fuel cells which can be used to provide electrical power for vehicles without CO_2 or other harmful emissions.

1.2 Challenges of Using Hydrogen

Other important aspects of the hydrogen sector are storage, transmission, and distribution because at atmospheric conditions, hydrogen is a very low energy density fuel, so it is typically stored and transported at high pressure or in a chilled, liquid state (IEA). Various solutions to these challenges have been developed, including compressing hydrogen in its gaseous state and storing in pressurized tanks, or liquifying hydrogen and storing it in insulated tanks at a very low temperature (-240 deg C. at 12.7atm pressure or -253 deg C. at 1 atm pressure) (AirProducts). Hydrogen can also be combined with nitrogen to form ammonia, a high-density source of hydrogen that can readily be transported by standard chemical carrier tanker trucks or ships (IEA). Ammonia has been used to transport hydrogen for decades because global chemical and fertilizer industries have a long history of storing and transporting ammonia, including in oceangoing tankers. Ammonia can be burned as a fuel in various energy systems, but as of 2019, ammonia is not being commercially used to generate electrical power. Ammonia has several advantages as a transportation media for hydrogen. Ammonia (NH_3) is a compound of nitrogen and hydrogen, so it does not generate CO2 emissions when burned. Ammonia is a gas at atmospheric temperature and pressure, but it can be liquefied at -33°C, a much warmer temperature than liquid hydrogen. Liquid ammonia has a 50% higher volumetric energy density than liquid hydrogen. Ammonia has been used as a refrigerant, a chemical feedstock for nitrogen fertilizer, and in the explosives industries for over 100 years. Ammonia is toxic, so handling it requires safety protocols by trained operators, restricting its use to larger industrial-scale power plants. New projects are now underway to produce ammonia from renewable electricity. For example, a large ammonia plant was built in Australia in 2019 with a production capacity of 50 metric tons of ammonia per day using an electrolyzer powered by 30 MW of solar and wind generated electricity (IEA). Since the 1920's ammonia has also been made in Norway with green hydrogen produced from electrolyzers running on hydropower, with a few plants in Norway feeding the entire European demand for nitrogen fertilizers (IEA).

For small-scale mobile or stationary applications, hydrogen is mostly stored as a pressurized gas or liquid in tanks (AirProducts). However, larger-scale or international hydrogen trade in the future will demand different types of storage options. At an export terminal, hydrogen storage may be required for short periods prior to shipping. Hours or weeks of hydrogen storage are needed at vehicle refueling stations or in vehicles. Larger, long-term storage methods would be required if hydrogen were used to prepare for seasonal changes in electricity demand, or to provide electrical power system resilience (IEA). Underground geological storage in salt caverns or depleted natural gas fields is one option for large-scale hydrogen storage. Underground salt caverns have been used in the UK for hydrogen storage by the chemical industry since the 1970s and the United States since the 1980s (IEA).

1.3 Role in Addressing Climate Change

The increase in the Earth's global average surface temperatures has been measured as roughly 1-degree Celsius since the pre-industrial era, defined as 1850-1900 in NOAA's record. This may seem to be a small magnitude of warming, but a massive amount of heat energy needs to be added to the Earth's atmosphere to raise the average temperature even by 1 degree Celsius because of the tremendous size and heat capacity of the global oceans (R. Lindsey). This global warming has been largely driven by human emissions of greenhouse gasses, with CO_2 being the major contributor to this climate change. According to observations by the NOAA Global Monitoring Lab, CO_2 was responsible for approximately two-thirds of the total heating influence of all human-produced greenhouse gasses as of 2021 (Figure 3).

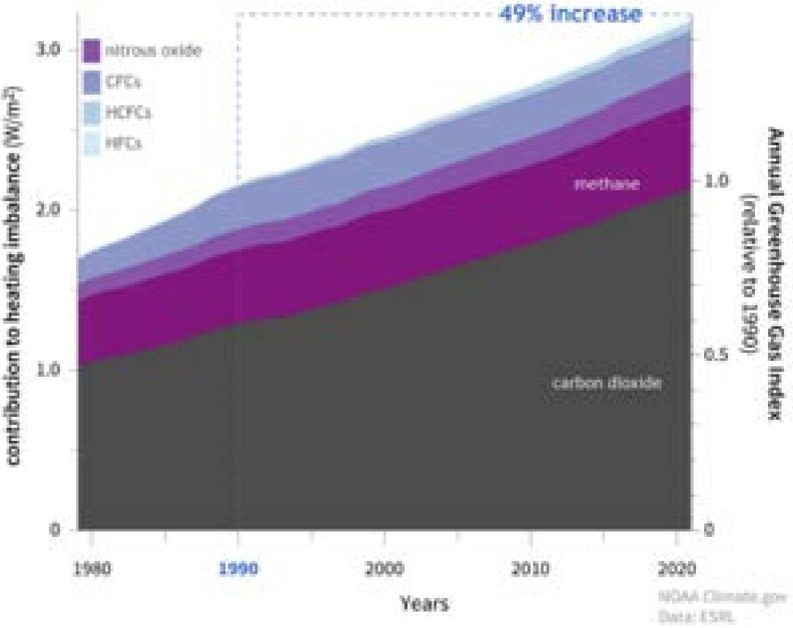


Figure 3: The heating influence caused by major human-produced greenhouse gasses: CO2 (gray), methane (dark purple), NO2 (medium purple), CFCs (lavender), HCFCs (blue), and HFCs (light blue), from 1980 until 2021. Note that CO2 is the largest contributor to the Earth's heating imbalance. (NOAA)

Measurements of CO_2 in the Earth's atmosphere have been accurately and continuously measured starting in 1958 at the Mauna Loa Observatory in Hawaii; the average annual CO_2 concentration has risen from 318 ppm in 1958 to 421.08 ppm in 2023 (Figure 4).

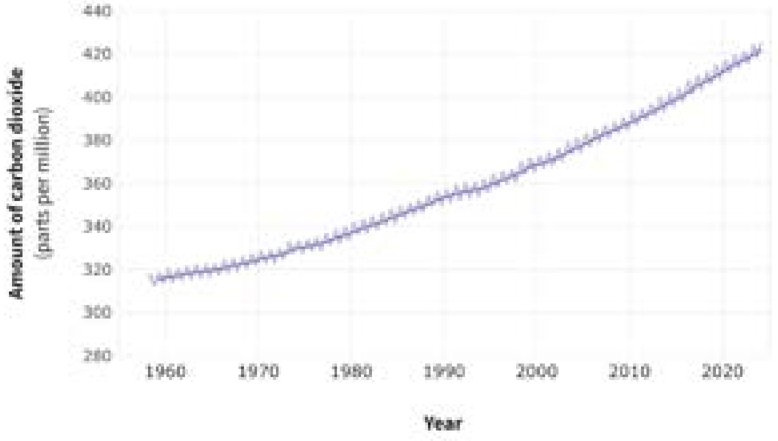
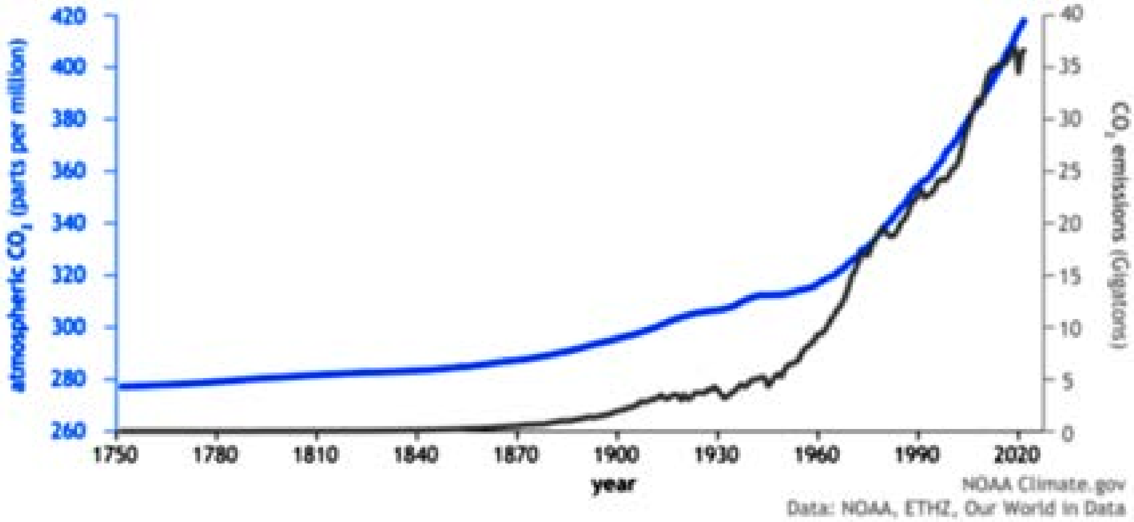


Figure 4: The modern record of atmospheric carbon dioxide levels recorded at the Mauna Loa Observatory in Hawaii. Note the steady increase in carbon dioxide concentration levels since records started in 1960. (NOAA2)

The annual CO_2 increase between 2022 and 2023 was 2.8 ppm, and this was the 12th year in a row where the amount of CO_2 in the atmosphere increased by more than 2 ppm. In the 1960s, the Earth's growth rate of atmospheric CO_2 was roughly 0.8± 0.1 ppm / year. Over the next fifty years, the annual CO_2 concentration growth rate tripled, reaching 2.4 ppm / year by the 2010s (NOAA2). The annual rate of increase in atmospheric CO_2 over the past 60 years is 100 times faster than previous natural increases, including those that led to the end of the last ice age 11,000 years ago (Figure 5) (NOAA2).

Carbon dioxide is produced by many complex processes, but fossil fuels (coal, natural gas, and oil) which are composed of hydrocarbon molecules containing carbon that plants pulled out of the atmosphere through photosynthesis over millions of years is the largest contributor to the ongoing CO_2 buildup in the atmosphere (NOAA). Humans are burning fossil fuels for energy in large volumes. Burning hydrocarbons and activities such as deforestation and farming have contributed to increasing CO_2 emissions into the Earth's atmosphere. A graph of global atmospheric carbon dioxide concentration compared to annual CO_2 emissions since 1750 illustrates that human caused emissions are the main cause for a drastic and accelerating CO_2 buildup in the atmosphere (Figure 5). Each year, human activities emit more CO_2 into the atmosphere than natural processes can remove, and this results in a net amount of carbon dioxide in the atmosphere to increase (NOAA). This net increase in CO_2 and the resulting global warming due to the greenhouse effect is a major driver for "green" or sustainable technologies that are needed to decrease the emissions of CO_2 into the atmosphere (NOAA).



NOAA Climate.gov
Data: NOAA, ETHZ, Our World in Data

Figure 5: CO2 concentration in Earth's atmosphere measured at the Mauna Loa Observatory in Hawaii, 1958-2023 (NOAA2)

It will be necessary to reduce CO_2 emissions massively, >80% reduction by 2050, to stabilize the carbon dioxide concentration of the Earth's atmosphere at a concentration of 450 ppm by 2050 which is consistent with the objective of limiting the global average temperature increase to plus 2°C in the year 2100 (Reverdiau). One key to global CO_2 reductions is a reduction in emissions from the road transportation sector (Reverdiau). The development of new types of vehicles powered by electric technologies is one way to meet this climate goal. There are currently three such technologies: Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) and Plug-in Hybrid Electric Vehicles (PHEVs).

While the use of hydrogen fuel cells does not generally contribute to greenhouse gas emissions, to date the production of most hydrogen is based on steam methane reforming of natural gas, resulting in significant CO_2 emissions (IEA). Hydrogen can be extracted from fossil fuels and biomass, from water, or from a mixture of both. Approximately 2% of global total primary energy demand is used to produce hydrogen today (IEA). Natural gas is currently the main source of hydrogen production, and steam methane reformers are the major method to produce hydrogen for the ammonia, methanol, and oil refinery industries. Natural gas accounts for approximately 75% of global hydrogen production, which is approximately around 70 million metric tons of hydrogen. 6% of global natural gas demand is consumed for this hydrogen production (IEA). Gray hydrogen based on SMR is the cheapest way to produce hydrogen today, but the associated greenhouse gas emissions are high, at 13.7 kg CO_2 for every 1 kg of hydrogen produced (Howarth). Coal is the second-largest source for hydrogen production today; coal is the source for ~23% of global hydrogen production and consumes ~2% of global coal demand (Howarth). Oil and electricity account for the remainder of the dedicated hydrogen production.

Hydrogen production today generates significant CO_2 emissions because it depends largely on fossil fuel sources. This results in total CO_2 emissions of , equivalent to the combined CO_2 emissions of Indonesia and the United Kingdom (IEA). Most of this CO_2 is emitted to the Earth's atmosphere as a climate harmful greenhouse gas. ~130 Mt CO_2 /year of this CO_2 is used in plants the production of urea fertilizer where concentrated CO_2 streams from steam methane reforming are captured and diverted to make fertilizer (IEA).

Green hydrogen produced from renewable energy technologies such as wind, solar, and hydropower present the opportunity for hydrogen to be used in a more environmentally sustainable manner (IEA). However, one key challenge for green hydrogen is to lower the cost of production in line with lower cost forms of hydrogen production from hydrocarbons. Green hydrogen production costs vary greatly depending on the location as illustrated in the 2019 IEA report. In 2019 the cost of hydrogen production made from electricity with combined solar and wind power varied from USD \$1.6/kg H_2 to over \$40 /kg H_2 per kg. The most favorable regions of the Earth are where both strong, regular winds and clear skies provide a good opportunity for combining solar and wind energy. Some promising areas include Patagonia, New Zealand, North Africa, the Middle East, Mongolia, most of Australia, and some areas of China and the United States (Figure 6).

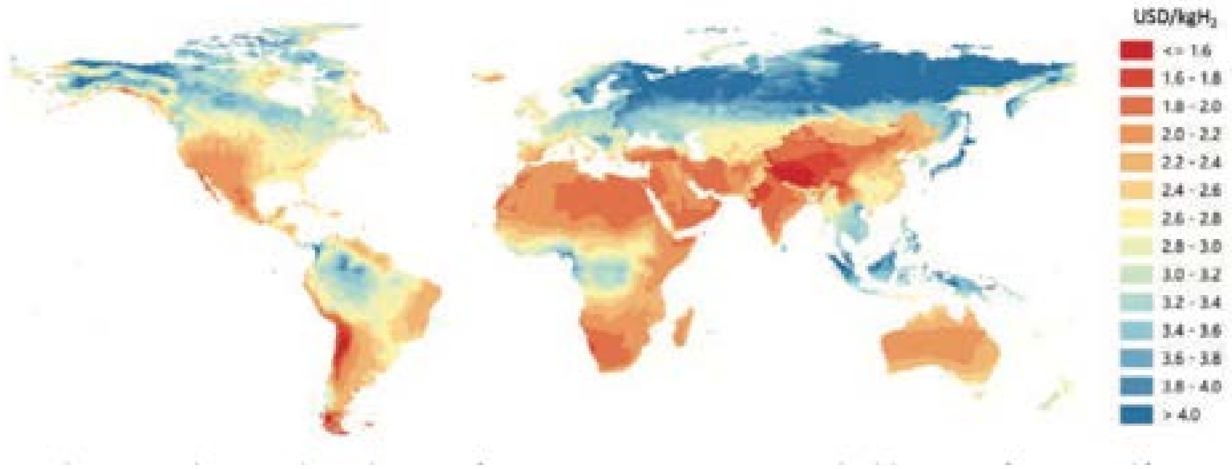


Figure 6: Cost of producing green hydrogen from solar and wind energy in various regions of the world. (IEA)

1.4 Hydrogen Use Case

Hydrogen is a suitable solution to replace a significant percentage of fossil fuels in heavy industries and commercial transportation, but the global production and distribution system is currently limited, and hydrogen is mostly not produced with renewable energy. The World Bank forecasts that green hydrogen will not surpass hydrogen generated from hydrocarbons until 2041 (Figure 7) (Moreira and Laing). Platinum is the standard element required as a catalyst for both green hydrogen production using electrolyzers and fuel cells, but platinum is expensive and future platinum ore mined from a limited number of geological deposits, creates possible geopolitical supply risks. Unfortunately, alternative catalyst materials to platinum have not been commercially successful yet.

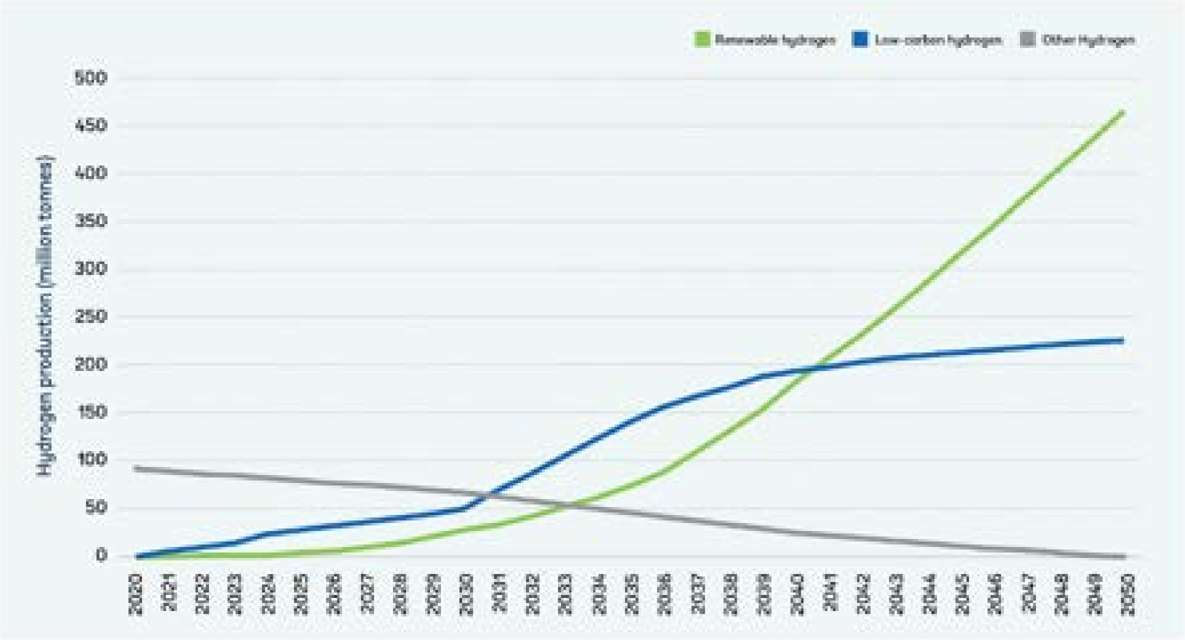


Figure 7: Projected annual hydrogen production by type of production pathway (Moreira and Laing)

This report will describe the role of platinum in the energy transition with a focus on the science of why platinum is the main catalyst used today. The analysis will also review recent developments in research to improve the cost and efficiency of both electrolyzers to produce hydrogen from renewable energy sources and to build improved fuel cells. Research into alternative materials to substitute for platinum, and drawbacks of relying on platinum for green hydrogen energy systems will also be discussed.

2. History of Hydrogen Use

2.1 Early Hydrogen Production

Hydrogen has been part of the energy industry for a long time. The first laboratory water electrolysis and fuel cells captured the imagination of engineers and science fiction writers like Jules Verne in the 1800s (DOE). Hydrogen was used as a fuel in the first internal combustion engines 200 years ago. Hydrogen gas lifted balloons in the 1700s and 1800s, and hydrogen was a major component of rocket fuel in NASA's missions to the moon in the 1960s and 1970s. Hydrogen is a key molecule in ammonia fertilizer made from natural gas and, earlier, from electricity and water hydrolysis, and this chemical fertilizer has maintained enough crops to feed a rapidly growing world for the last 100 years. Hydrogen has also been a key part of the energy industry since the 1960s, when its use became a standard in oil refining to produce fuels, plastics, and other petrochemicals (DOE). The demand for hydrogen for various purposes has steadily been growing since the 1970's, but today most hydrogen is used in the petroleum refining process to produce fuels such as gasoline and diesel (IEA).

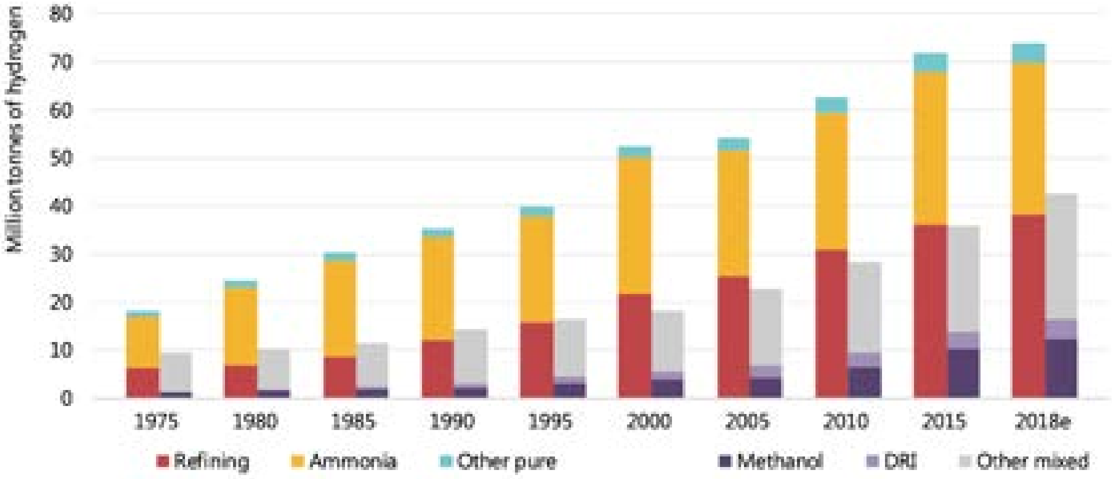


Figure 8: Global annual demand for hydrogen since 1975. (IEA)

2.2 Origins of "Green Hydrogen"

In the 1920s, British scientist and Marxist author J.B.S. Haldane introduced the concept of renewable hydrogen in his paper, Science and the Future, by writing, "There will be great power stations where during windy weather, the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen." (DOE)

In 1990, the first solar powered hydrogen production plant was built for research and testing in Germany at Solar-Wasserstoff-Bayern. In the same year, the U.S. Congress passed the Spark M. Matsunaga Hydrogen, Research, Development and Demonstration Act to fund hydrogen research and development in the US (DOE). Many new green hydrogen plants are planned across the globe, from Europe, Australia, Africa, Kazakhstan, and the Middle East (FuelCellWorks). Several recently announced projects claim to be the world's largest green hydrogen project, but one of the largest is certainly the NEOM plant under construction in western Saudi Arabia. When completed in 2026, it will produce 600 metric tons/day of green hydrogen by electrolysis production to 1.2 million metric tons/year of green ammonia. When completed, the project will mitigate the impact of 5 million metric tons of carbon emissions per year (NEOM).

2.3 History of Fuel Cells

In 1839, Swiss chemist Christian Friedrich Schoenbein discovered the fuel cell effect by combining hydrogen and oxygen gases to produce water and an electric current. In 1849, English scientist Sir William Grove "The Father of the Fuel Cell" demonstrated a fuel cell at a practical scale when he built and demonstrated an invention dubbed "the gas battery" (DOE). In

1959, Francis T. Bacon of Cambridge University built the first practical hydrogen-air fuel cell. The 5-kilowatt system was used to power a welding machine. Later in 1959, Harry Karl Ihrig built the first fuel cell vehicle which powered a small tractor. Hydrogen fuel cells, based on the 1959 Bacon design, have been used by NASA space flights to make on-board electricity, heat, and water for astronauts. In 1994, Daimler Benz demonstrated the NECA-I, its first hydrogen fuel cell vehicle, and the next year, The Chicago Transit Authority initiated a fleet of 3 hydrogen fuel cell passenger buses (DOE).

3. Hydrogen Electrolysis and Fuel Cells

3.1 Electrolysis in Hydrogen Production

One way of producing hydrogen is through the electrochemical process electrolysis of water. During the electrolysis process, an electric current is used to separate water molecules into its basic elements, hydrogen and oxygen (IEA). One important advantage of the electrolysis method is that there are no CO_2 emissions. The electrolysis reaction with the thermodynamic energy values is described in Equation 1. When the electric current is derived from a renewable source such as solar power, wind turbine, or hydroelectric power, it is known as green hydrogen (Crownhart).

$$H_2O_{(l)} + \underbrace{237.2\text{kJ mol}^{-1}}_{\text{electricity}} + \underbrace{48.6\text{kJ mol}^{-1}}_{\text{heat}} \rightarrow H_2 + 1/2O_2$$

Equation 1: Hydrolysis reaction with the thermodynamic energy values. (Carmo)

Three main electrolysis technologies are used to produce hydrogen from water: alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOECs) (IEA). The technical and economic characteristics of each method are summarized in Table 1. This paper focuses on PEM electrolysis, but a general description of the other two methods follows.

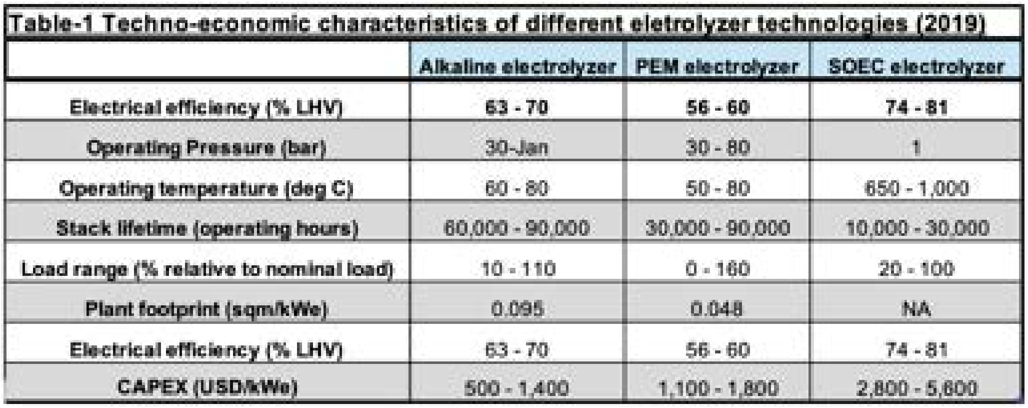


Table-1 Techno-economic characteristics of different eletrolyzer technologies (2019)

	Alkaline electrolyzer	PEM electrolyzer	SOEC electrolyzer
Electrical efficiency (% LHV)	**63 - 70**	**56 - 60**	**74 - 81**
Operating Pressure (bar)	30-Jan	30 - 80	1
Operating temperature (deg C)	60 - 80	50 - 80	650 - 1,000
Stack lifetime (operating hours)	60,000 - 90,000	30,000 - 90,000	10,000 - 30,000
Load range (% relative to nominal load)	10 - 110	0 - 160	20 - 100
Plant footprint (sqm/kWe)	0.095	0.048	NA
Electrical efficiency (% LHV)	63 - 70	56 - 60	74 - 81
CAPEX (USD/kWe)	500 - 1,400	1,100 - 1,800	2,800 - 5,600

Table 1: Techno-economic characteristics of different electrolyzer technologies. CAPEX refers to capital expenditures, the funds used to acquire and maintain the asset. (IEA)

Alkaline electrolysis is a technology which has been used commercially for over 100 years in the fertilizer and chlorine industries for hydrogen production. Many large alkaline electrolyzers with a capacity of up to 165 megawatts were built in the last century in countries with large hydropower electrical supplies such as Canada, Egypt, India, Norway and Zimbabwe (IEA). Most of these older, large alkaline electrolysis facilities were decommissioned when the alternative methods of natural gas and steam methane reforming for hydrogen production became common in the 1970s. Alkaline electrolysis has a relatively low installation cost compared to other technologies because precious materials such as platinum are not required.

However, there are three major drawbacks often associated with alkaline electrolyzers: low partial load range, limited current density, and low operating pressures. The first drawback with alkaline hydrolysis is that the diaphragm does not prevent all the product gasses from cross-diffusing through it, so the diffusion of oxygen into the cathode chamber reduces the efficiency of the electrolyzer, and oxygen will react with hydrogen and catalyzed back to water on the cathode side. Also, hydrogen diffusion into the oxygen evolution chamber also occurs and must be avoided to preserve the efficiency and safety. This is a serious issue at low loads where oxygen production rate decreases, thus drastically increasing the hydrogen concentration to dangerous levels (lower explosion limit >4 mol% H_2). The second drawback for alkaline electrolyzers is the low maximum achievable current density, due to the high ohmic losses across the liquid electrolyte and diaphragm. The third problem, also attributed to the liquid electrolyte, is the inability to operate at high pressure, which makes for a large sized design.

In 2023, one of the world's largest green hydrogen projects, Sinopec's 260MW Kuqa facility, was commissioned in northwest China; its electrical power comes from a large solar energy facility. Unfortunately, its alkaline electrolyzers have been operating at less than one third of its installed capacity due to various factors, including missing safety features and lower efficiencies than originally designed. When the input electric power supply drops below 50%, the electrolyzers stop producing hydrogen completely, causing reliability and safety issues related to renewable-energy fluctuations (Insight). This is a major problem for a hydrogen plant that derives most power from solar energy because every night the facility shuts down.

SOECs are the least developed electrolysis technology, and as of 2019 SOECs have still not been used at a commercial scale (IEA). SOECs use ceramics as the electrolyte, have low material costs, and do not require platinum group elements. SOECs work at high temperatures and are highly efficient. Because they use steam for electrolysis, they need a heat source. SOECs can be operated in reverse mode as a fuel cell (IEA). In this mode, these devices convert hydrogen back into electricity, which means SOECs could provide balancing services to the electric grid if combined with hydrogen storage. The main drawback of SOECs has been durability because the internal materials degrade under high operating temperatures (IEA).

3.2 Proton Exchange Membrane (PEM) Electrolysis

PEM electrolyzers were originally invented in the 1960s by General Electric Company to solve some of the problems of alkaline electrolyzers. The PEM method uses purified water as an electrolyte solution, so PEM does not need to recover or recycle the potassium hydroxide electrolyte solution that is necessary with alkaline electrolyzer technology (IEA). PEM systems are smaller, making them more suitable for most applications. PEM can produce highly compressed hydrogen gas for production and storage at refueling stations (IEA). PEM also offers flexible operation, and their operating range can quickly go from zero to full production. However, PEM electrolyzers require expensive platinum and iridium electrode catalysts and costly membrane materials, and their lifetime is currently shorter than that of alkaline electrolyzers. Their overall costs are currently higher than those of alkaline electrolyzers, so PEM has been less widely deployed, but PEM technology is rapidly growing today due to its compatibility with renewable energy sources (IEA).

Since 1990, there has been a rapid increase in new PEM electrolysis installations. Now, PEM accounts for the largest growth in new electrolyzer technology. Figure 9 illustrates the development of new electrolyzer capacity additions for energy projects globally. Prior to 2015, most new built electrolyzers were based on alkaline technology. However, between 2015 and 2019, as the growth in the number of electrolyzer projects rapidly grew, PEM systems became the dominant type of electrolyzer technology globally, with PEM technology chosen for 90% of the 100 new electrolyzer projects built during the most recent five-year period. Most new green hydrogen electrolyzer projects are being built in Europe, but similar facilities have also been announced in Australia, China and the Americas (IEA). Over the last 20 years, the average capacity of new electrolyzers has increased from 0.1 MWe to 1.0 MWe indicating a shift from small, demonstration facilities to commercial-scale plants. The growing economies of scale will contribute to lower unit capital costs in USD/kW and increase the supply of hydrogen sourced from PEM electrolyzers (IEA).

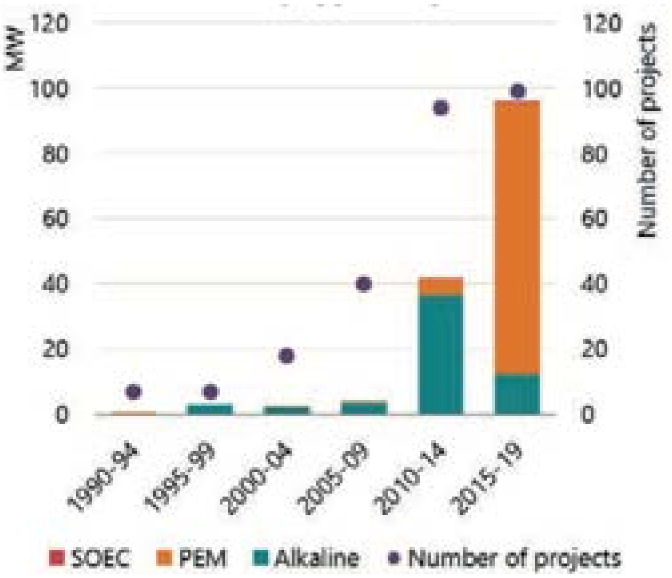


Figure 9: Development of electrolyzer capacity additions for energy purposes and their average unit size, 1990–2019. (IEA)

Figure 10 illustrates the economy of scale that comes from building larger electrolyzers. As the capacity of PEM electrolyzers is enlarged by combining several electrolyzer stacks to increase the overall capacity of the system, the capital cost efficiency of the system (USD/kW) can be reduced by up to 40% (IEA). The World Bank forecasts that most global hydrogen production will come from renewable sources by 2041 with the average size of green hydrogen projects increasing over time (Moreira and Laing).

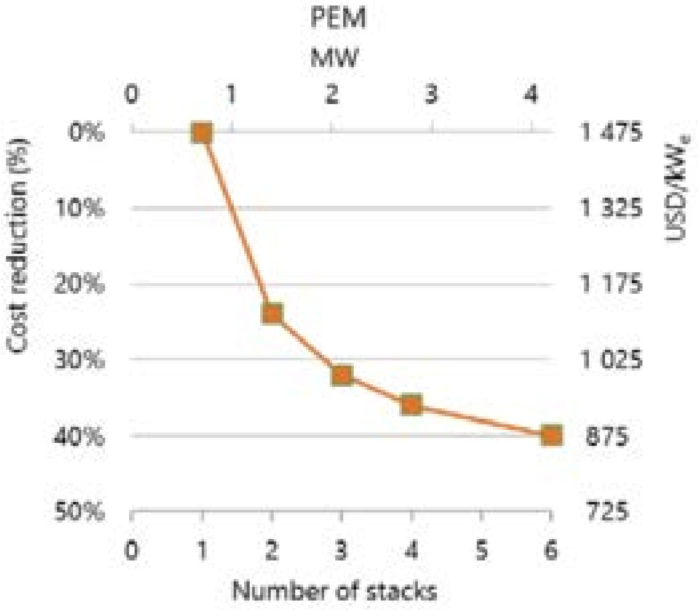


Figure 10: Expected reduction in electrolyzer CAPEX from the use of multi-stack systems. (IEA)

A global map from a 2022 World Bank report shown in Figure 11 describes 534 planned hydrogen projects across the value chain including: hydrogen production, large-scale industry projects, transportation, integrated hydrogen economies, and large infrastructure projects. The United States would require an estimated US $240 billion to see its announced projects through. Most of such projects are anticipated for large-scale industrial usage (Moreira and Laing).

Figure 11:Global hydrogen projects across the value chain. Giga-scale production is defined as renewable hydrogen >1 GW. (Moreira and Laing)

Carmo, et. al. published a 2013 comprehensive review on PEM water electrolysis, including how this type of electrolyzer works, a history of research and development, and a detailed summary of various published literature on PEM electrolyzer research. It focused on various attempts to improve the effectiveness, durability, and lower the cost of PEM systems (Carmo). In a PEM electrolyzer, platinum and iridium are used as catalysts at the cathode and anode respectively. These catalysts are applied directly with several different methods to a thin membrane acting as a solid polymer electrolyte. PEM electrolysis technology offers advantages over the other two electrolyzer technologies because PEM devices are compact and more able to operate under the intermittent nature of electricity from wind or solar sources, so PEM offers the performance and durability necessary for commercial scale green hydrogen systems (Carmo).

In the 1960s, General Electric developed the first water electrolyzer based on a solid polymer electrolyte concept to overcome the problems of alkaline electrolyzers (Russell JH, 1973). This new electrolyzer resolved the three major drawbacks often associated with alkaline electrolyzers including, increased load range, increased current density, and the ability to run at higher operating pressures. The solid polymer electrolyte concept was idealized by Grubb (Grubb, 1959), where a solid sulfonated polystyrene membrane was used as an electrolyte. This concept is referred to as proton exchange membrane or polymer electrolyte membrane (both with the acronym PEM) water electrolysis, and less frequently as solid polymer electrolyte (SPE) water electrolysis (Carmo). In PEM electrolysis, a thin (~100 mm) perfluoro sulfonate polymer membrane (PFS) is used as a solid electrolyte. This is a class of synthetic polymers with ionic properties that are called ionomers (Carmo). The commercially branded Nafion membrane, invented in the late 1960s by Dr. Walther Grot of DuPont Company, is one of the main types of materials used due to its excellent chemical and thermal stability, mechanical strength, and high proton conductivity (Carmo). However, this material has two key disadvantages, cost and disposal. Nafion disposal is problematic because its component chemicals contain fluorine (Carmo).

Carmo, et. al. 2013 describes concisely how a PEM water electrolyzer functions. In PEM water electrolyzers, water is supplied into the anode side of the cell, where oxygen evolution reaction OER) takes place. The water travels via small channels in the separator plates and diffuses through the current collector. The water then reaches the catalyst layer, where the molecules are split into electrons, oxygen, and protons. The oxygen gas flows back through the catalyst layer and current collector to the separator plates in the opposite direction from the flow of water, and then the oxygen leaves the cell. The electrons travel from the catalytic layer, through the current collector, then through the separator plates, and then the electrons go to the cathode side. The protons leave the anode catalytic layer through the ionomer, reaching the membrane and passing through to the cathode side. After reaching the catalytic layer these protons will combine with electrons to form hydrogen gas molecules. The hydrogen gas then flows across the cathode current collector and the cathode separator plate, and finally hydrogen leaves the cell (Carmo).

After 50 years of research, PEM electrolysis technology is still dependent on costly Nafion membranes, iridium for the anode, platinum for the cathode, and titanium for the current collectors and separator plates (Carmo). However, this situation can be attributed to the fact that not much research was done on PEM water electrolysis until the late 1990s (Carmo). The widespread concern about climate change, however, has generated new interest for PEM electrolysis to produce green hydrogen; evidence for this interest is seen in the rapid growth in recent publications on PEM electrolysis (Figure 12).

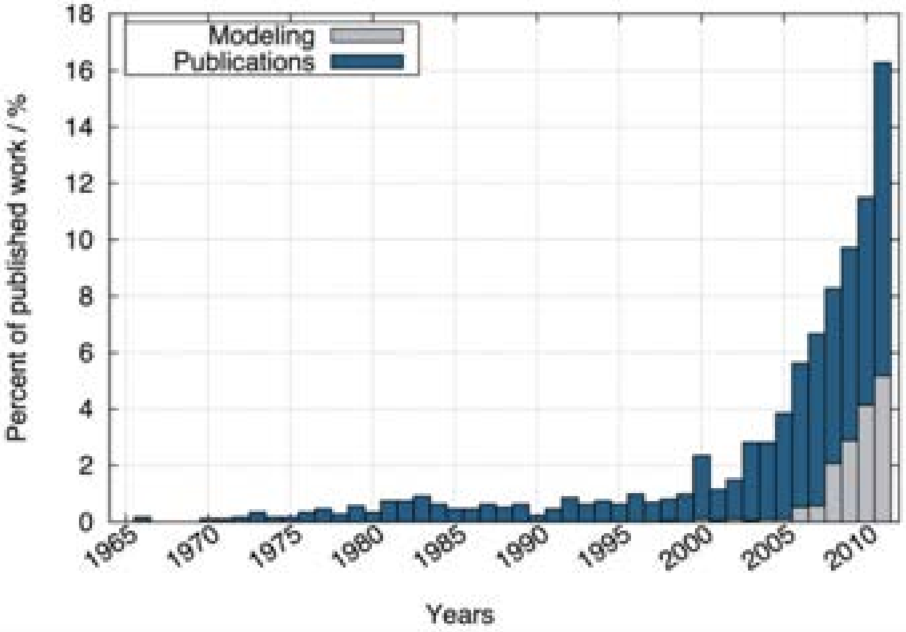
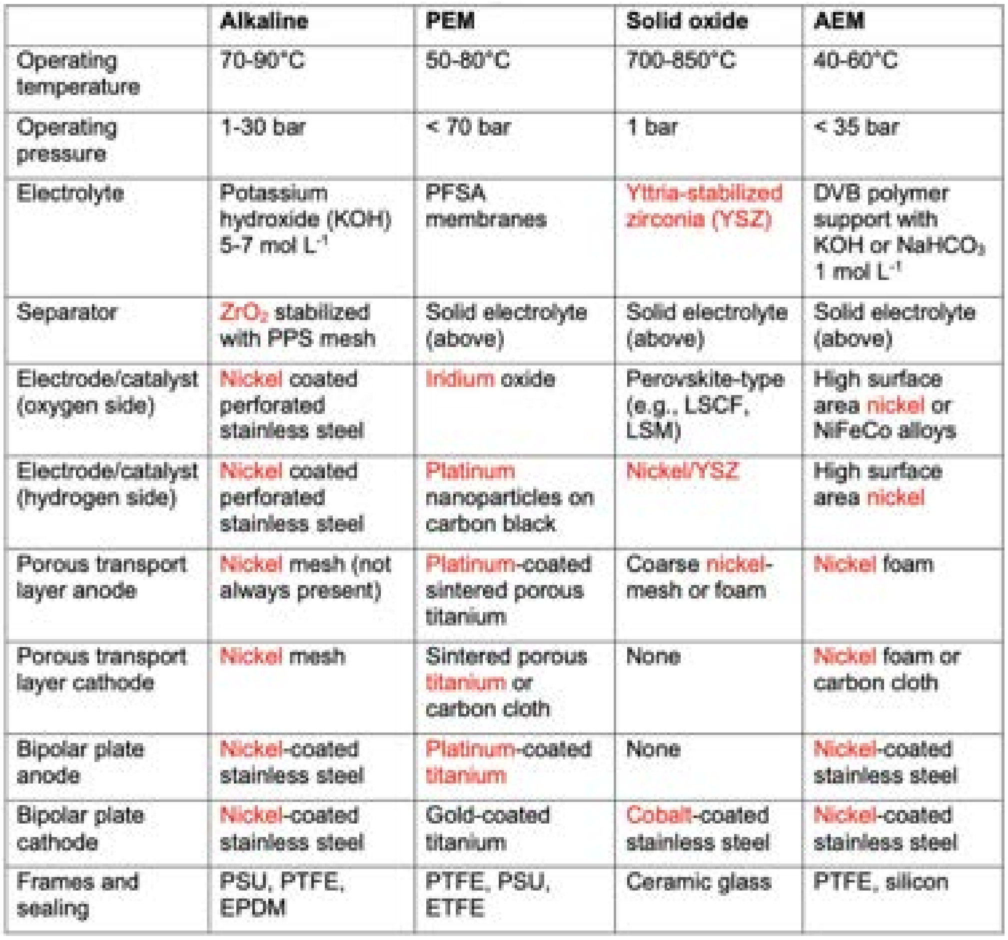


Figure 12: Number of publications as percentage of total publications directly related to PEM water electrolysis (Carmo)

Table 2 is a comparison of the critical raw material needed for various types of electrolyzers, including PEM. Platinum and iridium are two critical raw materials used in most PEM electrolyzers, but titanium is also required (Price).



	Alkaline	PEM	Solid oxide	AEM
Operating temperature	70-90°C	50-80°C	700-850°C	40-60°C
Operating pressure	1-30 bar	< 70 bar	1 bar	< 35 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 mol L^{-1}	PFSA membranes	Yttria-stabilized zirconia (YSZ)	DVB polymer support with KOH or $NaHCO_3$ 1 mol L^{-1}
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode/catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	Perovskite-type (e.g., LSCF, LSM)	High surface area nickel or NiFeCo alloys
Electrode/catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	Nickel/YSZ	High surface area nickel
Porous transport layer anode	Nickel mesh (not always present)	Platinum-coated sintered porous titanium	Coarse nickel-mesh or foam	Nickel foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	None	Nickel foam or carbon cloth
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	None	Nickel-coated stainless steel
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Cobalt-coated stainless steel	Nickel-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	Ceramic glass	PTFE, silicon

Table 2: Electrolyzer technologies compared with key raw materials highlighted in red. Note that platinum and iridium are both PGM elements needed for building PEM electrolyzers. (Price)

3.3 Fuel Cells

Proton exchange membrane fuel cells (PEMFCs) dominate the transportation fuel cell market, and platinum is the catalyst material used for both anode and cathode inside these fuel cells (Price). A fuel cell's technology is essentially the inverse of an electrolyzer, generating electricity through an electrochemical reaction of hydrogen and oxygen (Figure 13). At the anode side of a fuel cell, the anode splits the dihydrogen into electrons and two protons. The protons then pass through a porous, electrolyte membrane driven by the oxidative potential of free oxygen from the injected air, while the electrons are forced through a circuit generating an electrical current which can be used to power a motor (Price). Hydrogen gas is fed to the anode where it adsorbs onto the catalyst surface. The adsorbed hydrogen atoms each lose an electron (e^-) and are released from the metal surface as protons (H^+). The electrons flow to the cathode as current through an external circuit and the protons flow across the PEM towards the cathode. Air is fed to the cathode and oxygen is adsorbed onto the catalyst surface. This bound oxygen is subsequently protonated by incoming H^+ and reduced by incoming electrons to produce water, which is then released from the catalyst surface. This water is forced to exit the fuel cell by the hydrophobic nature of the surrounding media (Holton).

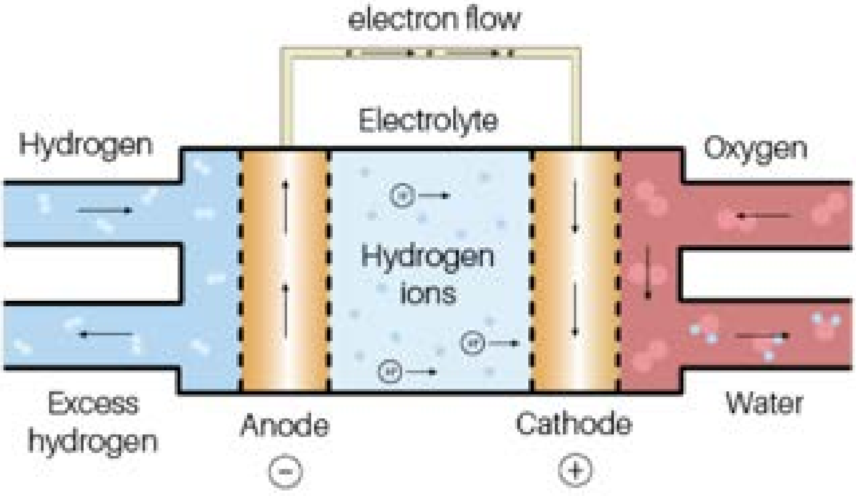


Figure 13: Schematic of proton exchange membrane (PEM) fuel cell. (Price)

A 2013 paper by Holton and Stevenson describes how PEMFCs work to generate electric power from hydrogen and various issues which make platinum and its alloys the best available materials to use for hydrogen fuel cells (Holton). This paper also documents why platinum is the only element which can meet the performance requirements while avoiding slow reaction kinetics, proton exchange membrane (PEM) system degradation due to hydrogen peroxide (H_2O_2) formation, and catalyst degradation due to metal leaching. Holton and Stevenson 2013 also discuss research into various performance enhancements of platinum in PEMFs.

A PEMFC electrochemically reacts hydrogen with oxygen to produce electricity with water as its only emission. These fuel cells can be used for transportation with no carbon dioxide emissions, so they are of considerable interest due to climate change concerns (Holton). Even when hydrogen is produced from fossil fuels such as the methane steam reformation process, when combined with carbon capture and storage, the high efficiency of fuel cells relative to internal combustion engines still offers the potential for reduced CO_2 emissions (CONCAWE). PEMFCs have been the main type of fuel cells used in the transportation market for numerous reasons. They have a unique set of advantages for cars, trucks, and heavy vehicles, including a low working temperature (80°C) so they can be started quickly; a high energy density; robust and simple mechanics; ability to run on pure hydrogen, resulting in zero CO_2 emissions; and use of ambient air for the oxygen supply (Holton).

PEMFCs currently use platinum as the catalyst at both the cathode and the anode, so these fuel cells have the potential to create considerable demand for platinum (The Fuel Cell Industry

Review). A recent US Department of Energy analysis indicates that platinum represents approximately 17% of the total cost of an 80 kW PEMFC system using 2012 technology at commercial scale production (Holton). Because platinum is a costly material, research is being conducted to develop substitute catalysts based on less expensive metals. Substitute catalysts would need to exceed platinum's performance, so the overall total system cost is improved (Holton).

The 2012 review of PEMFCs by Holton and Stevenson (Holton) focuses on the fundamental requirements for an idealized PEMFC electrode material and evaluates the performance of pure platinum compared to other pure metals and discusses other alternatives to improve fuel cell catalysts. Figure 14 illustrates that platinum has the highest activity of all bulk metals for metal hydrogen bonding energy; this is one of the major reasons that PEM fuel cells and electrolyzers use platinum as a catalyst.

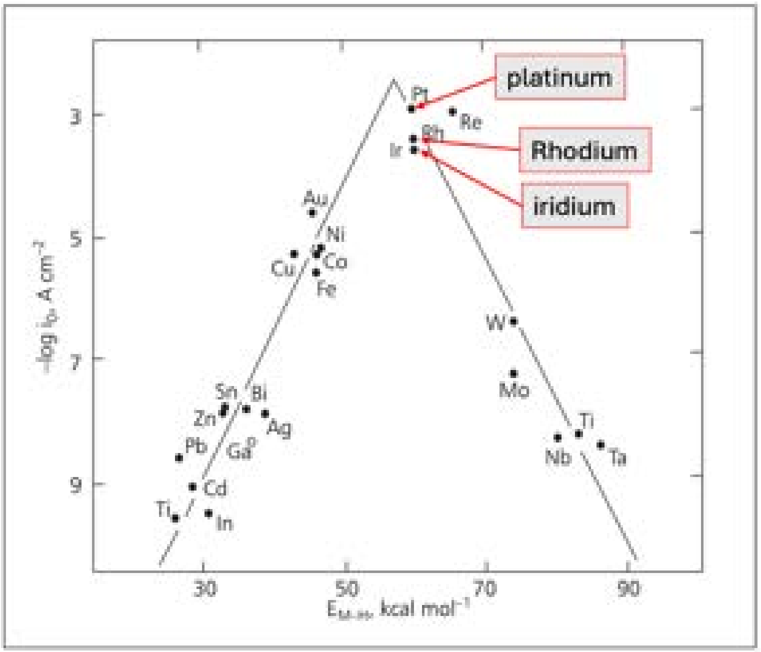


Figure 14: Exchange current densities for cathodic hydrogen evolution vs. the bonding adsorption strength of intermediate metal-hydrogen bond formed during the reaction itself; three PEM metals are highlighted at the top of the chart, with platinum at the top. (Holton)

Platinum is used as the catalyst for both the hydrogen oxidation reaction (HOR) occurring at the anode and the oxygen reduction reaction (ORR) at the cathode (Holton). In most PEMFCs, the platinum catalyst is deposited as small particles on the surface of somewhat larger carbon particles that act as a support matrix (Holton). At the anode, hydrogen flows into the fuel cell and reaches the platinum anode where the HOR takes place. Here the hydrogen adsorbs onto the surface of the platinum electrode, breaking the hydrogen–hydrogen bond to give adsorbed atomic hydrogen. Subsequent loss of an electron from each adsorbed hydrogen molecule leads to hydrogen leaving the surface as protons (H+).

The 2013 review by Holton and Stevenson also describes how the kinetics of the HOR on a platinum anode are very fast, so voltage losses are very small. As the HOR is fast, the focus of catalyst improvement has always been on the cathode process (Holton).

The ORR that occurs at the cathode is more complicated and characterized by slow reaction kinetics (Holton). The ORR is the most difficult challenge for PEMFCs because the catalyst material must be stable under very corrosive conditions at a fuel cell cathode. It also must be chemically active enough to be able to activate oxygen, and the cathode material must allow the release of the produced water from the catalyst's surface to release catalytic sites once the reaction is complete. Due to the difficulties of the ORR, the cathode requires a higher concentration of platinum, more than several times that of the anode (Holton). More than half of the voltage loss for a PEMFC system occurs at the cathode (Holton).

4. Platinum as a Catalyst

The electrode coating at the anode in PEM electrolyzers needs to be highly resistant to corrosion while supporting sufficient electrochemical activity, and iridium is one of the very few metals that meets these criteria (Price). The porous transport layer of a PEM electrolyzer requires significant amounts of titanium-based materials coated with platinum (Price). The 2013 review by Holton and Stevenson concluded that the great value of platinum as a catalyst in PEMFC systems is that it outperforms all other catalysts in each of three key areas: activity, selectivity and stability. Of all transition metals, platinum is the most ideal catalyst for both the HOR and ORR in the PEM fuel cells (Holton).

Platinum performance as a catalyst in fuel cells can also be improved by an order of magnitude if its electronic properties are fine-tuned by combining platinum with other metals as alloys. It is the performance of these modified platinum-alloy PEM fuel cells that represents the benchmark with which other new materials must compete (Holton).

Research into alternative metals to replace platinum for PEMFC systems using cheaper metals has not yet discovered a better material (Holton). Alternative systems containing other metals have fundamental limitations such as a lack of activity, poor selectivity leading to hydrogen peroxide formation, or catalyst degradation caused by a lack of stability under harsh fuel cell operating conditions (Holton).

Jaouen, et.al., 2018 reviewed the status, concepts and challenges to discover catalysts free of platinum group metals for building better and cheaper PEMFCs (Jaouen). A major challenge for the development of PEMFC technology is to replace platinum with platinum-free catalysts that perform in fuel cells with comparable activity and stability. The priority objective is the substitution of cathode catalysts used in the oxygen reduction phase, which account for more than 80% of platinum in current PEMFCs (Jaouen).

Jaouen, et.al., conclude that major breakthroughs have been achieved over the last decade in the design of catalysts based on Earth-abundant metals for catalyzing the ORR or

HOR that are compatible with PEMFC technology and operate with overpotential requirements similar to those of conventional platinum catalysts (Jaouen). The paper describes some advantages of these platinum-free alternatives, which can be less sensitive to poisoning, when the catalyst material degrades over time due to the harsh physical and chemical operating conditions. However, the authors also describe two key ongoing challenges that need to be overcome for any platinum substitute: 1. The electrochemical activities of substitutes are still lower than those of optimized platinum catalysts, and 2. The stability and durability of the catalyst materials during real world fuel cell operating conditions are still not high enough for commercial purposes.

5. Global Economics of the Platinum Supply Chain

5.1 Use Case for Platinum

Most PEM electrolyzer and fuel cell devices require platinum and iridium. Both metals are critical raw materials needed for hydrogen-based energy systems. Supply and demand of platinum group metals (PGM) are described in a 2023 report: Scoping Report on the Material Requirements for a UK Hydrogen Economy (Price). Platinum and iridium are two of the six platinum group metal (PGM) elements, which also include palladium, ruthenium, rhodium, and osmium (Figure 15). These six noble metallic elements occur together on the periodic table of elements because they have similar chemical and physical properties, and they usually occur together in the same mineral ore deposits. Platinum or palladium are often the main metals being mined commercially, and the other PGM metals are considered by-products that contribute small amounts to the producer’s revenues. Often, PGM metal ores are produced as byproducts of gold, nickel, or copper mining (Mungall). Increased demand for the minor PGM metals like iridium will contribute to higher prices. However, the primary producers (mining companies) will not produce more for fear of eroding the price of the main commodity, platinum (Price).

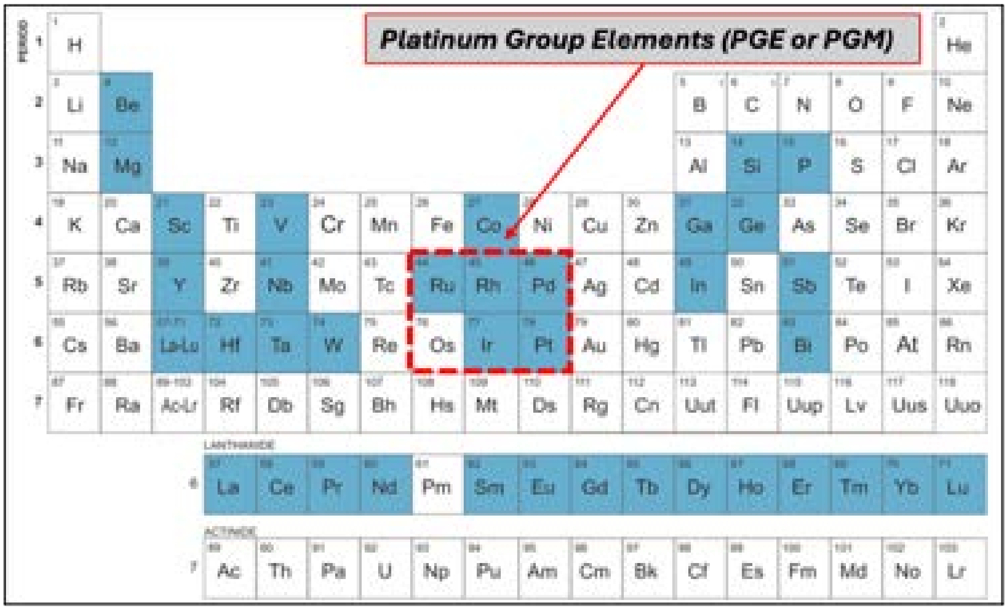


Figure 15: Mineral raw materials identified as critical by the EU in 2017; note the Platinum Group Elements (PGE):
platinum (Pt), Ruthenium (Ru), Rhodium (Rh), Palladium (Pd), Iridium (Ir), and Platinum (Pt). (BGS)

Depending on the composition of the ore that is mined, platinum is either considered a primary or secondary metal. In the largest platinum producing nation, South Africa, platinum is the primary metal mined. From 2018 and 2022, iridium production as a by-product of platinum production in South Africa was only 5% of platinum volumes mined (N. E. Idoine). However, in the largest Russian mine at Norilsk, platinum ore is secondary to nickel, resulting in Russian platinum production typically 23% of palladium volumes mined. (N. E. Idoine). In North America, platinum is a secondary by-product of palladium mining (Price).

Because platinum is such a critical raw material in green hydrogen production and in fuel cells, it is important to understand recent trends in the price of platinum and iridium, including factors that impact both the supply and demand of these precious metals. The price of platinum fluctuates higher and lower due to global supply and demand in a similar manner to other raw materials and commodities, but platinum has always been a precious metal which is difficult to find in sufficiently high concentration ores to justify mining (Price). In 2023, platinum and iridium costs represented ~4% of the entire cost of a PEM electrolyzer (Price). As of 2023, Platinum mining is highly geographically concentrated in South Africa, with two other countries, Russia and Zimbabwe, making up most remaining global platinum ore supplies (Figure 16). South Africa dominates the supply of platinum, maintaining production levels of between 112,000 and 142,000 kg per year over the last five years (N. E. Idoine), mostly produced from several different mines within the world's largest platinum ore deposit called the "Bushveld complex" discovered north of Johannesburg in 1924 (Mungall).

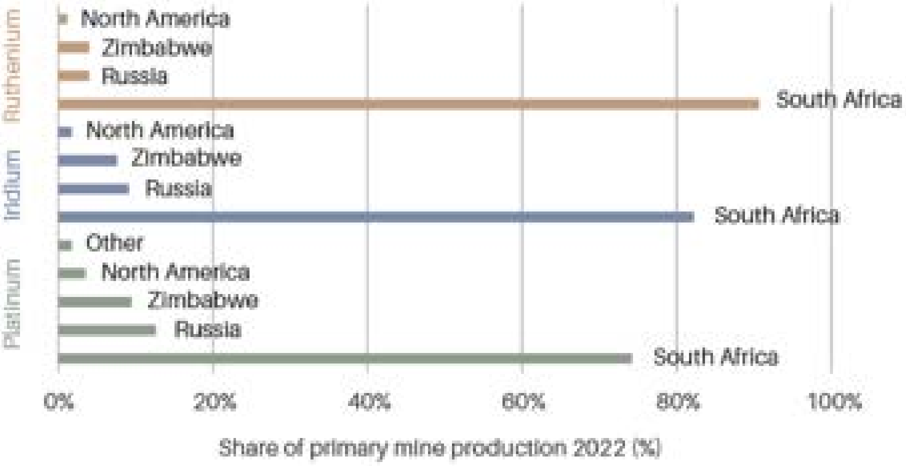


Figure 16: Share of primary (from mining) platinum, iridium and ruthenium production in 2022 (Price)

5.2 Platinum Supply, Geology, and Mining

Platinum production is supplied from two basic sources, ore that is mined from the ground, and recycling of platinum from existing devices such as vehicle catalytic converters and other machinery (IEA). Approximately 173,700 kg of platinum was produced globally by mining operations in 2022 (N. E. Idoine). 73% of platinum came from South Africa in that year (Price). The other major producing nations are Russia which produced 12% of global platinum; Zimbabwe produced 9%, and North America produced 4% of the world's mined platinum (Price). The British Geological Survey (BGS) published a report on the global supply of various minerals for the period 2018-2022 (N. E. Idoine). The report includes a table of platinum production by country of origin over this five-year period.

The geology of platinum ore deposits has been described previously (GeologyScience). A schematic lithospheric cross section of the Earth published by the British Geological Survey (BGS) illustrates the tectonic elements where various metals and critical raw materials and minerals are formed Figure 17. A more detailed textbook, Exploration for Platinum Group Elements, published by the Mineralogical Association of Canada (Mungall) is a thorough and detailed work describing the geological origins of platinum, its geochemistry, types of ore deposits, and case-histories of the largest platinum ore discoveries on Earth.

Most of the world's supply of platinum and platinum group elements (PGE) is produced from magmatic ores derived from basaltic magmas (Mungall). Platinum is originally formed in a variety of intrusive igneous rocks. The tectonic origins can be mid-ocean ridges or igneous intrusions related to mantle plumes and subduction zones. Platinum is typically formed in ultramafic rocks or hydrothermal rocks, which are high in magnesium and low in silica. These platinum bearing rocks include peridotite, pyroxenite, and dunnite and are typically found in areas of ancient continental crust or in ophiolite complexes (BGS). PGE metals also share with copper, gold, and silver (Cu, Ag, Au) a tendency to prefer the formation of covalent bonds with sulfur instead of ionized bonds with oxygen; this behavior puts PGE metals in the group of “chalcophile” (copper-loving) elements.

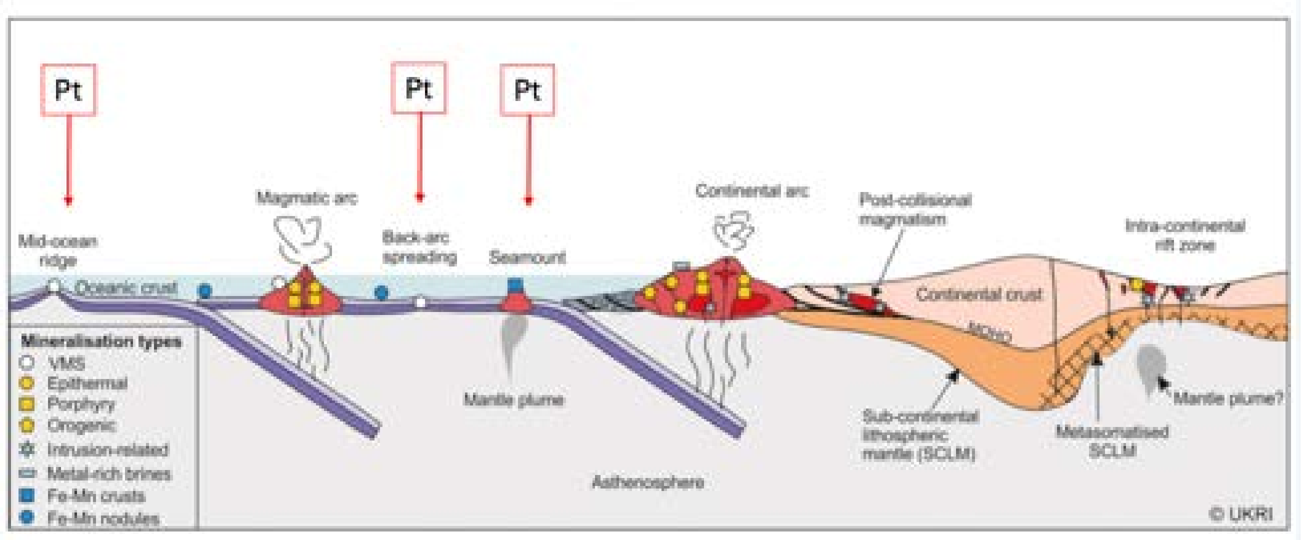


Figure 17: Geological occurrence of platinum and other PGM metal ores: Schematic lithosphere-scale section showing the geodynamic environments in which critical raw material deposits form (BGS).

5.3 Production Through Recycling

Platinum is one of the most highly recycled precious metals (Figure 18). Primary production from mining represents only 35% of future supply while 65% of platinum comes from recycling processes (Moreira and Laing). Platinum is recycled from used or discarded devices, jewelry, electronics, automobiles, medical equipment, etc. There are two types of recycling of platinum: open-loop and closed-loop processes (Price). Open-loop (secondary) recycling is the process that results in platinum available to new consumers. Closed-loop recycling takes place when industrial users of platinum (e.g. glass fabrication and fuel refining) continuously recycle and reuse platinum within the same facility, so this recycled volume of platinum is not available to other consumers. Open-loop recycling was responsible for 22% (48,000 kg) of global supplies of platinum in 2022 (Price).

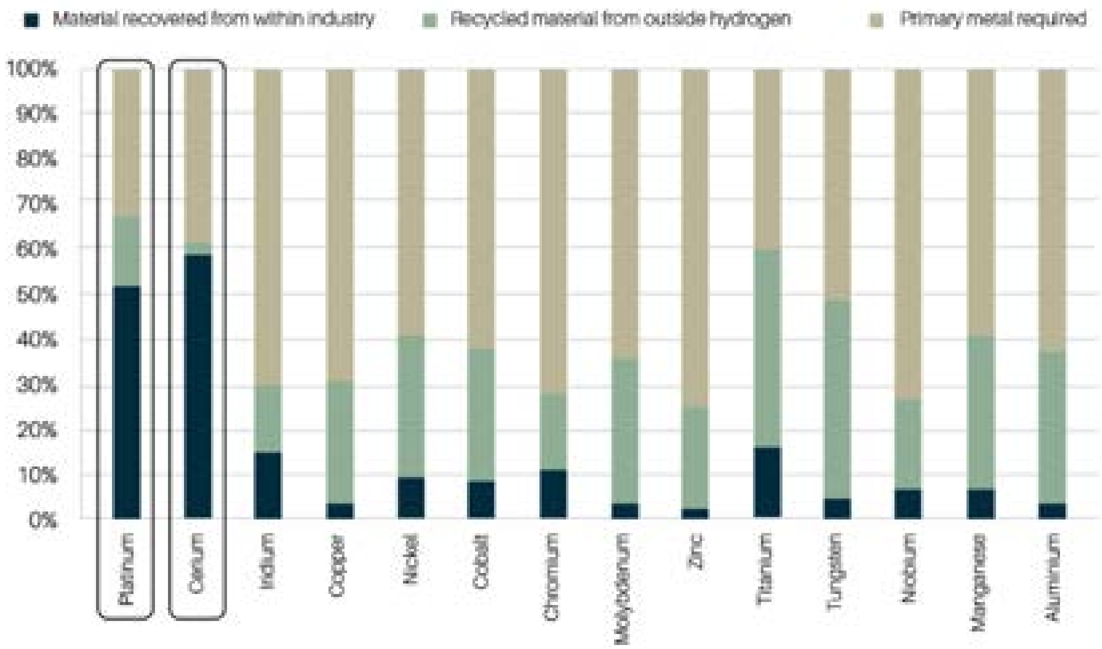


Figure 18: Sourcing rates of various metals through recovery, recycling, or mining (Moreira and Laing)

5.4 Platinum Demand

In 2022, the global hydrogen sector accounted for 2,740 kg of platinum which is only 1% of worldwide platinum demand (Price). In recent years, the top three industries creating demand for platinum are automobile emissions catalysts, jewelry, and industrial chemicals. The largest sector demand for platinum is from the automobile catalytic converter market which accounted for 43% of global platinum demand in 2022 (Price); the second largest sector demand comes from the jewelry business at 24% (Price). As of 2022, 12% of global platinum demand comes from the industrial chemical industry for production of silicone, nitric acid, and crude oil synthesis refining for fuel production (Price). Platinum's biocompatible characteristics mean that it is also useful in a variety of medical and dental procedures as well as in the pharmaceutical industry for cancer medications (Price).

Future demand for platinum and iridium is highly uncertain and complex because some industries related to hydrogen are ramping up while other industries, related to the traditional gasoline and diesel vehicles catalytic converters, are predicted to decrease as electric vehicles and fuel cell vehicles displace internal combustion engines. A 2022 World Bank forecast for the demand of platinum and iridium linked to PEM electrolyzers illustrates the range of uncertainty of future, cumulative demand from 2022-2050 from hydrogen production technology (Figure 19); this forecast illustrates that the growth in global demand for iridium from construction of new electrolyzers is predicted to be much higher than the growth in demand for platinum in most scenarios.

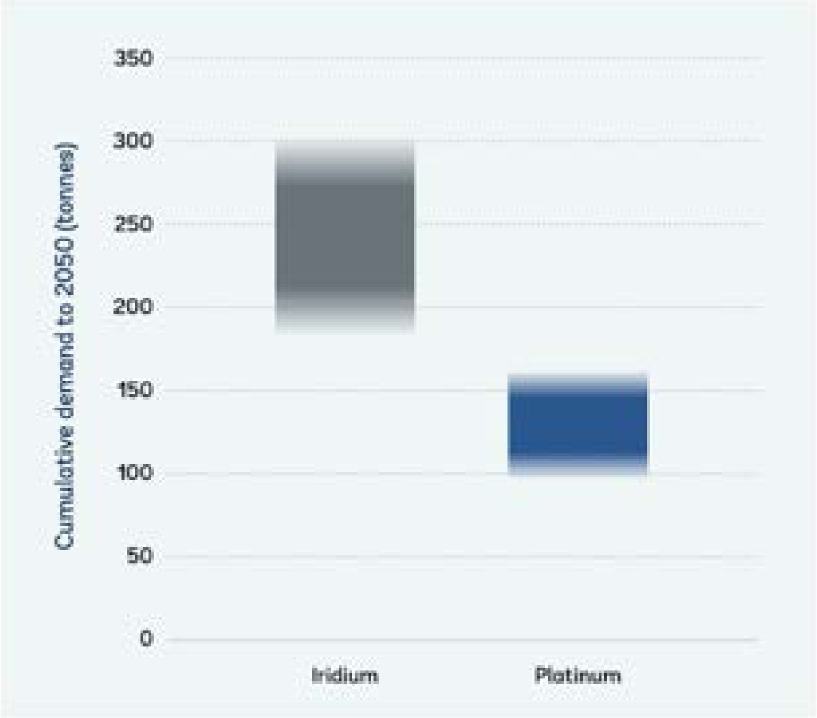


Figure 19: Projected range of cumulative gross demand up to 2050 for platinum and iridium from hydrogen production. (Moreira and Laing).

A similar chart from the same report illustrates the gross, cumulative demand for platinum related to hydrogen consumption, dominated by PEM fuel cells (Figure 20). This graph illustrates that the demand for platinum coming from hydrogen fuel cell manufacturing over the same period through 2050 is predicted to be much higher than the demand caused by electrolyzers in the hydrogen production business. Of course, these forecasts of future demand are based on many uncertain economic and technical factors, so the range on the charts reflect the World Bank's view of uncertainty in their forecasts (Moreira and Laing).

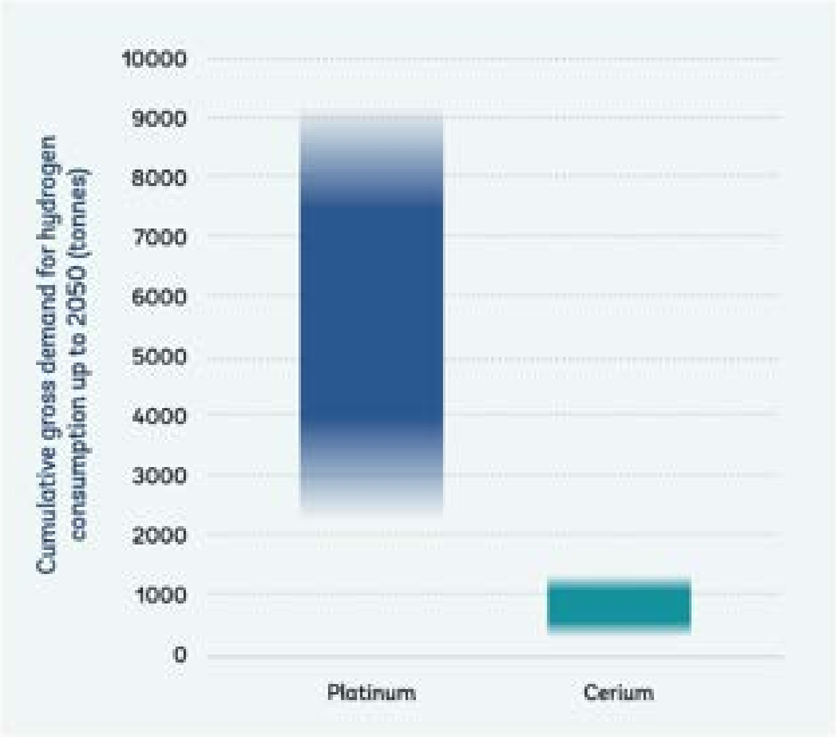


Figure 20: Projected range of cumulative gross demand up to 2050 for platinum and cesium from hydrogen consumption (Moreira and Laing)

Figure 21 illustrates the World Bank's 2022 forecast for future platinum demand from primary sources (from mining sources) due to the hydrogen sector until 2050 in 5-year increments. The future increase in demand for platinum from the hydrogen sector is predicted to peak in 2030's at 60 metric tons annually and fall off after 2040 (Moreira and Laing). This represents a large increase in the percentage of globally produced platinum required for the hydrogen sector over the next decade, but by 2040 the World Bank forecasts global platinum demand from the hydrogen sector to reduce to 10 metric tons annually, approximately the same demand as in the 2021-2025 period (Moreira and Laing).

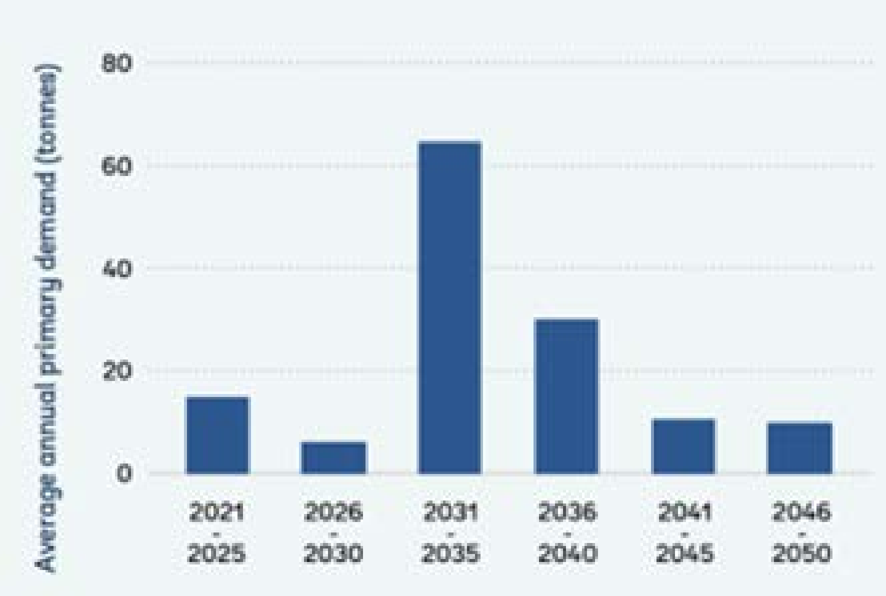


Figure 21: Projected time path for net demand for primary platinum sources (mining) from the hydrogen sector through 2050 in 5-year increments. (Moreira and Laing)

Figure 22 illustrates the forecast future increase in platinum and iridium demand from primary sources (mining only) by 2050 compared to 2022 (Moreira and Laing). The predicted growth in demand for iridium will be larger than platinum in most scenarios relative to current production levels, so it is likely that iridium will be even more critical than platinum in the future of green hydrogen production.

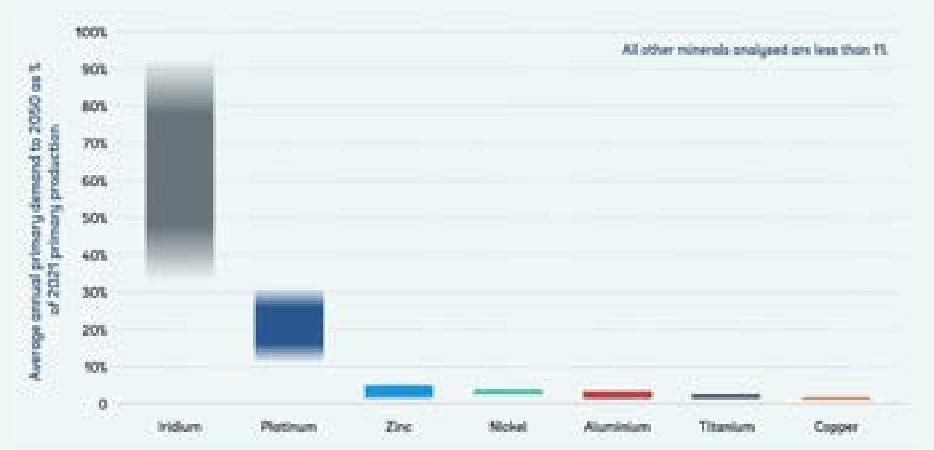


Figure 22: Projected average annual primary demand for critical metals (from mining sources) from the
hydrogen sector to 2050 as a percentage of current primary production. (Moreira and Laing)

Considering the World Bank's published forecasts for platinum demand from both hydrogen production and hydrogen consumption, the consumption side of the future hydrogen economy, especially PEM fuel cells, will dominate the future demand of platinum in the green energy industry. The cumulative demand from consumption of hydrogen from 2022 to 2050 is expected to be ~5,500 metric tons, while the cumulative platinum demand related to hydrogen production during the same period is expected to be only ~125 metric tons. Therefore, PEM fuel cell demand for platinum is likely to be approximately 40 times higher than demand created by PEM electrolyzers.

6. Discussion

There is substantial information in the literature about the beneficial material properties of platinum as a catalyst in hydrogen energy systems compared to alternative materials. Research into alternative metals could optimize for the areas where platinum is deficient, but the current state of technology suggests that platinum is still the best catalyst option for producing hydrogen from renewable energy and for consuming hydrogen with fuel cells. Researchers have also been continually optimizing the use of platinum in hydrogen energy systems by alloying platinum with other metals to minimize the amount of platinum required for PEM electrolyzers and fuel cells.

However, challenges related to platinum supply should not be ignored, including limited platinum mining locations, processing and supply chain complexities, and competing demand for platinum and iridium from other industries. Alternative supply pathways for platinum need to be explored if platinum is to remain the metal of choice in the future with respect to use in hydrogen energy systems.

The World Bank forecasts a 30% - 60% spike in global platinum demand from primary mining sources between 2030 and 2040. Unless additional primary platinum supplies become available, this could cause a strain on the supply of platinum during this period Figure 21. In 2022, more than half of global platinum supply was met from recycling of discarded equipment. This is an important aspect of platinum supplies; compared to other precious metals and critical materials, this is a very high percentage of supply that comes from recycling. This means that the global balance of platinum supply vs. demand (therefore its price) is highly dependent on maintaining economic and continuous recycling processes. The dependence of recycling in the platinum supply chain could create a dilemma in the future if recycling does not continue to produce a similar percentage of global supplies. In recent years, most platinum demand has been met by recycling of automobile catalytic converters.

However, given the rapid growth of electric vehicles, the available supply of platinum from recycled catalytic converters is likely to rapidly decline at some point in the future, when fewer ICE vehicles are scrapped. Rising demand for platinum related to hydrogen energy will probably drive an even larger need for both recycled platinum and primary mining of PEM ores which will play an increasingly critical role in the energy transition. Assuming this trend continues, the supply of recycled platinum from automotive catalytic converters will probably fall just when demand for platinum to manufacture more PEM fuel cells and PEM electrolyzers rapidly rises.

As many national and local governments adopt stricter regulations, limiting CO_2 emissions from industry and transportation, hydrogen produced from renewable energy sources will play an increasingly important role in meeting ever stricter emissions reduction targets. Blue hydrogen produced from natural gas sources has proven to be controversial because even though its CO_2 emissions are captured and stored underground, the total greenhouse gas emissions, including methane leaks, have been demonstrated by some researchers to be as high as from simply burning fossil fuels such as natural gas, diesel, or coal (Howarth). Therefore, an emphasis is now being placed on green hydrogen, which produces far lower greenhouse gas emissions. Forecasts of how rapidly green hydrogen production infrastructure will be built and tied into renewable energy systems are uncertain because these predictions are based on economic models and assumptions. Despite the uncertainty in the pace of adoption of hydrogen systems in the energy transition, PEM fuel cells and electrolyzers will likely play a key role in future reductions of CO_2 emissions from many hard to decarbonize industries and heavy vehicle transportation.

Battery electric vehicles (BEVs) have displaced millions of traditional ICE vehicles in many countries. While BEVs have arguably been contributing to decreased carbon emissions from light passenger vehicles, other forms of transportation and industry are more challenging to decarbonize due to various factors such as the heavy weight and long recharging intervals of batteries. Compressed hydrogen tanks have a higher energy density compared to lithium-ion batteries, so hydrogen fuel cells enable a greater range in vehicles than is possible with battery electric vehicles (IEA).

Traditional battery storage is not practical in many heavy transportation and industries (trucks, trains, aviation, construction equipment, and the manufacturing of steel, cement, and glass). These hard to decarbonize industries require low carbon energy solutions to replace hydrocarbon fuels and internal combustion engines that have been at the heart of these industries for many decades. Many researchers and government organizations expect that hydrogen will assist these industries to decarbonize when more low-carbon, green hydrogen and ammonia becomes widely available and distributed. More platinum supplies will probably be required to make this hydrogen from renewable energy sources.

There is a possible future dilemma related to global platinum vs. iridium supplies. Iridium is a byproduct of primary platinum mining and processing, so the only way to increase iridium supplies is by producing more platinum. An economic dilemma could be created if platinum is produced in larger quantities than demanded in the pursuit of larger iridium production. In this scenario, platinum prices would drop, and this could cause a disincentive for platinum mining and processing triggered by a greater demand for iridium vs. platinum used in PEM electrolyzers. This scenario is predicted by the World Bank’s 2022 report and illustrated in Figure 22. While any forecast is uncertain, this points to an economic dilemma facing the green hydrogen economy. At times when this scenario becomes a reality, producers and consumers of PGM metals should prepare for future potential instability in the price of both platinum and iridium. Like many other commodities, platinum will continue to experience price uncertainty resulting from the complex interplay of various supply and demand trends which will probably be exacerbated by the global energy transition.

Geopolitical considerations are an important issue which add to the uncertainty of future platinum supplies. 85% of platinum is produced in only two nations, South Africa and Russia, so any political or economic disturbance in either of these countries could cause platinum and iridium supply disruptions. Russia has a long history of international sanctions imposed on its businesses due to the annexation of Crimea in 2014, and then the full-scale invasion of Ukraine in February 2022. These sanctions have impacted many extractive industries such as oil and natural gas as well as mining. A growing list of Russian businesses have experienced export bans and restricted financial transactions. These sanctions are intended to degrade the Russian government's ability to fund the conflict in Ukraine, but economic sanctions often result in unanticipated negative side-effects such as supply disruptions of exported commodities (UKTreasury). South Africa is even more important than Russia as a primary source of platinum because 73% of global mined platinum comes from this nation. Unfortunately, South Africa has recently experienced frequent electrical power outages. The South African power outages have been caused by a lack of maintenance, which has been blamed on corrupt and incompetent government officials (Bloomberg). These power outages are essentially caused by domestic political problems, and the result has been widespread lack of electricity which has impacted the mining industry, including platinum mining operations. South African platinum-group metals output in 2023 was 6 per cent below producers' initial guidance and one of the worst years in the past two decades. Electrical power blackouts are expected to continue for years, until the South African government solves the electrical power problems by investing in maintenance and modernization (Bloomberg).

Several factors contribute to creating an incentive for research into platinum alternatives: geopolitical uncertainty, growing demand from the hydrogen sector, and the fact that platinum is inherently costly to mine and process. Alternative catalysts for fuel cells and electrolyzers will have a huge value if they can be improved to perform as well as platinum or iridium in the future. It is crucial that recycling continues to play a major role in the future because recycling is currently a larger source of platinum production than supplies from mining. There is a high value in improving the efficiency of platinum recycling processes, especially as more internal combustion engine passenger vehicles are replaced by BEVs. This situation will create a temporary glut of recycled platinum due to the increasing supply of discarded automotive catalytic converters. However, eventually fewer ICE vehicles will be built as the energy transition and anti-fossil fuel government policies take hold and the age of the internal combustion engine comes to an end. At that point, fewer recycled automobile catalytic converters will be available, and future platinum supply growth will rely on geologists to discover new supplies of platinum ore in the rocks of the Earth.

7. Concluding Remarks

This review highlights the role of platinum in the advancement of green hydrogen technologies, specifically with respect to hydrogen production from renewable energy sources and hydrogen consumption in PEM fuel cells. These hydrogen technologies are a crucial component of the energy transition which is needed to minimize the greenhouse gas emissions causing climate change. The geology of platinum has resulted in mining production from a small number of locations, concentrating platinum sources in only three nations and creating potential geopolitical risks that could impact the supply chain and economics of platinum. Surprisingly, more than half of platinum demand is met through recycling, so recycling will continue to play an important role as demand for platinum related to the hydrogen sector is expected to peak by 2040. Upon reviewing various peer-reviewed publications, it becomes evident that platinum is the superior catalyst in the production and utilization of green hydrogen. Despite these advantages, challenges such as the high cost of platinum, the geopolitics of future platinum supply, and sustainability of both primary platinum mining and recycling persist. This suggests that further research into promising alternatives such as alloys of platinum or new catalyst materials is warranted.

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