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PLATINUM CATALYSIS IN FUEL CELL: AN OVERVIEW

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Abstract

Fuel cells are emerging as a promising clean energy technology in the global transition to sustainable power generation and can contribute to Sustainable Development Goal 7 (Affordable and Clean Energy). Platinum is the most frequently used electrocatalyst for fuel cells, as it is a highly efficient catalyst with excellent corrosion resistance and long-term stability in electrochemical processes. Platinum is widely used at both the anode and cathode in fuel cells and underpins fuel cell electrocatalysis, but this platinum-based catalyst layer typically accounts for around 15–20% of the total fuel cell stack cost, making it one of the main barriers to commercialization. This review provides a detailed examination of the use of platinum in fuel cells and discusses its geological history, physicochemical properties, industrial importance, and catalytic roles in proton exchange membrane fuel cells (PEMFCs), direct methanol fuel cells (DMFCs), direct ethanol fuel cells (DEFCs), and microbial fuel cells (MFCs). It integrates a geological perspective with catalytic applications and emerging catalyst development strategies to demonstrate the continued relevance of platinum for future fuel cell technology and to provide a comprehensive outlook on the future development of efficient, durable, and economically viable fuel cell technologies.

Keywords: Platinum, Fuel cell electrocatalysts, Proton exchange membrane fuel cells (PEMFCs), Direct methanol fuel cells (DMFCs), Clean energy technologies

1. Introduction

Fuel cells are seen by many people as a key solution for the 21st century [1], enabling clean, efficient production of power and heat from a range of primary energy sources. Fuel cells can vary from tiny devices producing only a few watts of electricity to large power plants producing megawatts. All fuel cells are based on a central design using two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them. A catalyst is often used to speed up the reactions at the electrodes. Fuel cell types are generally classified according to the nature of the electrolyte they use. Each type requires particular materials and fuels and is suitable for different applications [2][3]. The origins of fuel cell technology can be traced back to the early nineteenth century, when the underlying concept was first effectively demonstrated by Humphry Davy. This early work was subsequently advanced in 1832 by Christian Friedrich Schönbein, whose investigations laid further groundwork for the field. William Grove, a chemist, physicist and lawyer, is generally credited with inventing the first fuel cell in 1839. Central to the performance of many fuel cell systems is platinum, a metal

noted for its superior resistance to corrosion, its stability in air without oxidising and its overall chemical inertness. Platinum belongs to a broader family of platinum-group metals (PGMs) that also includes palladium, osmium, ruthenium, rhodium and iridium [3].

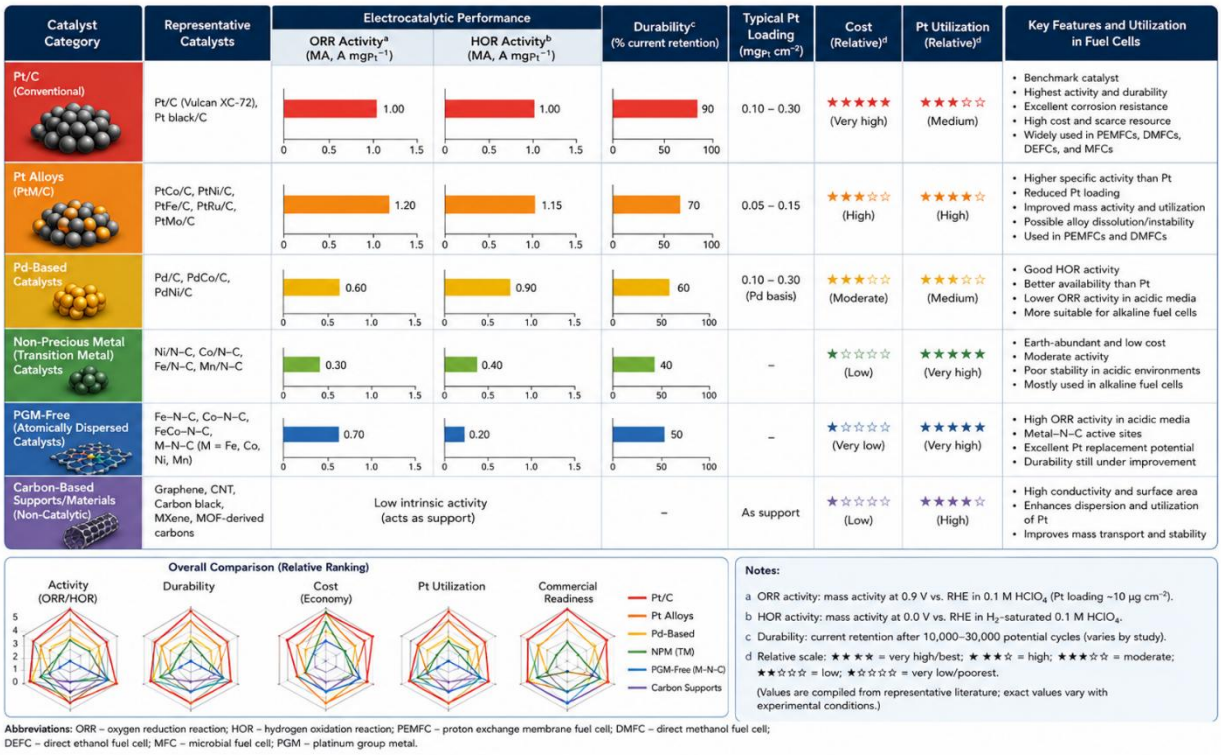

Figure 1: Comparison of platinum and alternative catalyst in fuel cells: performance and utilization

Within the fuel cell itself, these properties translate directly into catalytic function: platinum is highly effective at facilitating the oxygen reduction reaction (ORR) at the cathode and the hydrogen oxidation reaction (HOR) at the anode, the two electrochemical processes that together generate electrical current [4]. Its resistance to corrosion and chemical stability allow it to sustain this catalytic activity even under the highly acidic and oxidising conditions present within the cell, a demand that few other metals are able to withstand over extended operating periods. It is this combination of high intrinsic activity and long-term stability that has established platinum as the benchmark catalyst for fuel cell applications, even as its scarcity and cost continue to drive research towards more efficient and economical alternatives [5]. Beyond its role in fuel cells, platinum's most significant industrial application lies in the automotive sector, where it serves catalytic converters that facilitate the complete combustion of unburned hydrocarbons in vehicle exhaust systems. It is also used in jewellery, decorative items and dental work, reflecting its broader value as a precious and functionally versatile metal. Against this backdrop, this review examines the geological origin of platinum and its catalytic application in fuel cells, with particular attention to the functional properties of platinum in relation to its morphology, as well as the opportunities and challenges surrounding its industrial use. Figure 1 shows the comparison of platinum and alternative catalysts in fuel cells: performance and utilisation.

2. Platinum

Independently discovered in 1735 by Julius Scaliger and in 1741 by Charles Wood, platinum is named from the Spanish platina, meaning “little silver”. The metal is classified as precious owing to its scarcity and commercial demand [6]. It has a coefficient of expansion almost equal to that of soda-lime-silica glass and is therefore used to make sealed electrodes in glass systems. The presence of platinum wire can cause hydrogen and oxygen gas mixtures to explode. There are six naturally occurring isotopes, of which the most abundant are platinum-194, accounting for 33%, platinum-195 (34%), and platinum-196 (25%). The others are platinum-198 (7%), platinum-192 (1%), and platinum-190 (0.01%). The latter is weakly radioactive, witha half-life of 700 billion years, while the other five are non-radioactive [7]. Physically, platinum is heavy, soft, malleable (easy to work – only silver and gold are easier to shape), and ductile (easy to draw into wires), and has a fairly high melting point (~1770 °C or 3220 °F). Chemically, it is often described as a noble metal because it is so unreactive. It does not react with oxygen in air, so it does not rust or tarnish. It is also reasonably resistant to attack from acids [8].

In the early 1800s, platinum was used in fuel cells to promote the chemical reaction of hydrogen with oxygen. It is generally a good inert electrode because it is chemically unreactive. This makes it very useful in fuel cells. It can easily adsorb hydrogen and, being an inert metal, does not participate in redox reactions during the operation of the cell [9]. In hydrogen fuel cells, platinum is the best catalyst, but it comes with a high price tag [10]. In December 2018, platinum was a precious metal more rare than silver or gold [11]. Platinum is more expensive because it is rarer and mined much less than gold. Only 160 tonnes of platinum are mined annually, as opposed to 1,500 tonnes of gold. Also, platinum is denser than gold, so the same ring will weigh significantly more in platinum than in gold (and precious metals are priced by weight) [12]. Recently, scientists have been looking to create practical fuel cell catalysts that use far less of this costly precious metal. In new research from the U.S. Department of Energy's (DOE) Argonne National Laboratory, published in Science, scientists have identified a new catalyst with the effectiveness of the available platinum but using only about a quarter as much platinum as current technology [13]. Annual platinum demand was down slightly in 2017 at 7.8 million ounces, with supply at about eight million. Current projections from the World Platinum Council for 2018 are that supply will fall a little, and demand will rise, with the two remaining more or less in equilibrium. Roughly 75% of supply comes from mining and 25% from recycling. Of that mined supply, a good two-thirds comes from South Africa. Platinum’s fate is determined by one country in a way that no other commodity, except perhaps cobalt, is [14]. Figure 2 shows the platinum supply versus demand. The demand for 2018 can be cover by production. It shows that platinum is very important in industry, particularly for applications related to direct methanol fuel cells. Fluctuations of total supply in the range 7,265–8,080 koz can be recovered within the total demand. It shows that platinum production needs to increase so that industrial demand can be fully met [15].

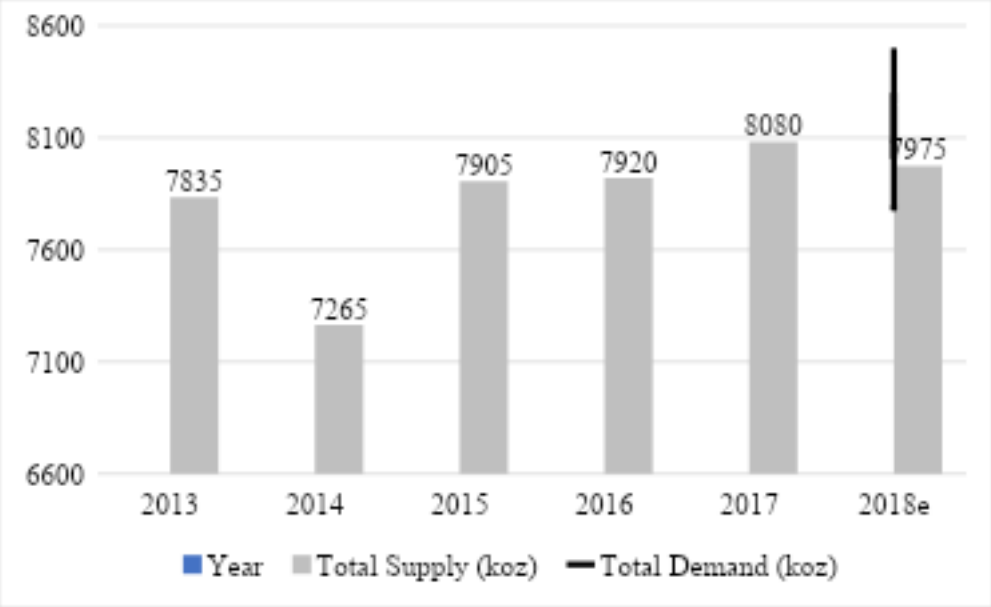

Figure 2: Platinum Supply vs. Demand (2013-2018) [16]

3. Geology

The majority of the world's platinum comes from South Africa, with Russia supplying the second highest yields and Colombia the third [17]. The gold-bearing sands of these three countries provide ideal geological conditions for recovering this very rare metal. The Bushveld Complex, located in South Africa, contains some of the richest ore deposits on Earth. The complex holds the world's largest reserves of platinum group elements (PGEs), which include platinum, palladium, rhodium, ruthenium, osmium and iridium, all of which are extremely rare in the Earth's crust. Platinum, the most abundant of these, is 30 times rarer than gold. Mined only in a few places worldwide, these elements are becoming increasingly important in applications such as pollution control [18]. The major geological feature associated with this wealth of mineral deposits is the Bushveld Complex (Figure 3), where its mineralised and non-mineralised layers extend, with little variation, for tens of kilometres along strike [19]. The Bushveld Complex, found in the northern part of South Africa, is the world's largest layered intrusion, is approximately 2 billion years old, and is divided into four different limbs: the northern, southern, eastern and western limbs [16,17]. In 1897, Gustaaf Molengraaff was the first to discover the Bushveld Complex [22]. The Bushveld Complex is a layered mafic intrusion with well-defined ore bodies consisting of stratiform chromitite layers concentrated within the critical zone; these are referred to as reefs. The Merensky Reef, UG2 Reef and Platreef are the main reef deposits, consisting mostly of continuous to discontinuous chromite layers with varying amounts of PGE mineralisation [23].

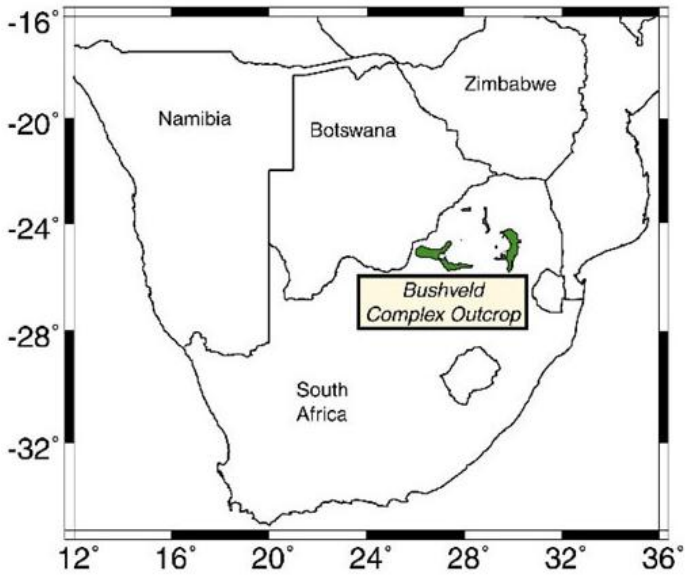

Figure 3: Map showing the position of the Bushveld Complex in South Africa [24]

Platinum is an extremely rare metal, occurring at a concentration of only 0.005 ppm in Earth's crust. It is sometimes mistaken for silver (Ag). Platinum is often found as native platinum and as an alloy with other platinum-group metals and iron, mostly as tabulated in Table 1. Native platinum is most often found in secondary deposits in alluvial sediments. The alluvial deposits used by pre-Columbian people in the Chocó Department, Colombia, are still a source of platinum-group metals. Another large alluvial deposit is in the Ural Mountains, Russia, and it is still mined [25]. Although platinum is rare, the methods for identifying where it is most likely located have become highly accurate, focusing on igneous deposits that show the tell-tale signs of prolonged heat and pressure [26]. By-product platinum is separated from the host metal during electrolytic refining. Placer platinum is concentrated by delicate gravity methods. Lode platinum is recovered by combined gravity and flotation methods. The individual metals of the platinum group are separated by complex refining processes. In addition to gold-bearing sands, deposits of platinum are often found in outcrops of plutonic rocks such as olivine and chromite. The formation of these rocks is a testament to platinum's pedigree, as all were exposed to extremely high temperature and pressure in order to produce this most valuable of metals [27]. Platinum is invariably associated with basic igneous rocks and with the ore minerals characteristic of those rocks. Most of the world's platinum is intimately associated either with chromite or nickel. Even platinum placers are derived from basic rocks rich in chromite. The platiniferous nickel ores also contain copper and appreciable quantities of gold and silver [28].

Table 1: Description critical zone, Bushveld Complex [29]

Merensky Reef	UG2 Reef	Platreef
~ Contains the base metal sulfide grains and associated platinum group minerals. ~ The Merensky Reef has been traced for 300 km around the entire outcrop of the eastern and western limbs of the Bushveld	~ The host rock of the UG2 chomitites is dominated by granular orthopyroxene. ~ The UG2 chromitites are underlain by pyroxenite footwall that is distinct from hanging wall pyroxenite.	~ The Lower Reef is composed of norites and feldspathic pyroxenites that have been recrystalled and overprinted. ~ The Central or Middle Reef is composed of igneous peridotite and recrystallized

Complex, and to depths of 5 km.	~ The Upper Reef is composed primarily of plagioclase-pyroxenite and norite

The chief uses for platinum are in the jewellery, electrical and dental industries. Its white colour and hardness make it a desirable setting for diamonds. In the electrical industry it is used for resistance and contacts in the more delicate instruments such as telephone and radios. Platinum finds wide uses in the chemical industry such as for containers, wire, electrodes, coils, acid making, x-ray equipment and as a catalyst. Large acid stills utilize considerable quantities. (Figure 4) show details platinum used.

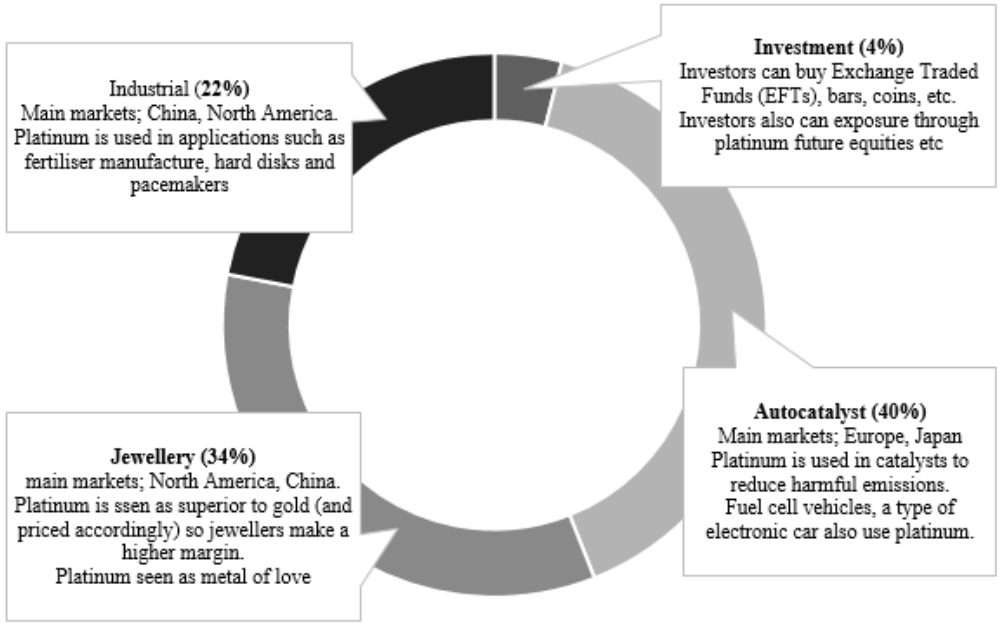

Figure 4: Major industrial application of platinum, including fuel cells, automotive catalytic converters, chemical processing, electronics, medical devices and jewelries [30].

In fuel cell application, platinum is considered the standard metal which breaking oxygen bonds apart to eventually form water in a process that requires a substantial amount of the catalyst [31]. The role of platinum in catalytic converters is to oxidise carbon monoxide (CO) and hydrocarbons. Platinum is particularly effective at this under oxygen-excessive conditions, so is often the metal of choice for diesel applications. Platinum works as a catalyst by collecting oxygen atoms (O), and letting them bind with the toxic carbon monoxide (CO), to create the less harmful carbon dioxide (CO_2). Platinum is most efficient catalysts for speeding up chemical reactions in hydrogen fuel cells. Oxygen molecules combine with electrons and hydrogen ions to form water at the cathode. At anode the, reaction is sluggish and speeding it up requires 10 times as much platinum as is used [32]. Platinum is an inert electrode, thus it do not participate in the cell reaction but provide a surface or platform for oxidation and reduction reaction.

4. Platinum as Catalyst

4.1 Direct Alcohol Fuel Cell

Bambagioni et al [33] explored on Pd and Pt–Ru anode electrocatalysts supported on multiwall carbon nanotubes and their use in passive and active direct alcohol fuel cells with an anion-exchange membrane (alcohol =methanol, ethanol, glycerol). The results obtained with Pt–Ru/MWCNT anodes in acid media are largely inferior to those provZided by Pd/MWCNT electrodes in alkaline media. Gupta et al. [34] applied polycrystalline deposits of platinum and platinum–ruthenium on a CuNi (70:30) alloy support. Novel CuNi alloy supported electrocatalyst synthesised from PTFE suspension of noble metal salts can be an alternative anode material for DAFC. DMFCs have many advantages, such as structural simplicity, instant refuelling [35] , high specific energy that is widely attained and safely stored [36], [37] high energy density of methanol, low operating temperature, and easy start up [35]. To maintain and improve all of these advantages, catalyst development is starting to attract developers' attention. Johanek et al. [38] reported vapor-feed low temperature direct methanol fuel cell with Pt and PtRu electrodes on chemistry insight. Energy efficiency of 30% and power density exceeding 70 mW cm^{-2} were achieved with Pt/C electrodes without any noticeable long-term degradation. Basri et al [39] study attempts to improve the performance of PtRu catalysts by adding nickel (Ni) and iron (Fe). The results, PtRuFeNi/MWCNT improves the reaction kinetics of anode catalysts for DMFCs and obtains a mass current of 31 A g^{-1} catalyst. Li et al [40] working on an enhanced activity of Pt/CNTs anode catalyst for direct methanol fuel cells using Ni_2P as co-catalyst. A novel Pt/Ni_2P/CNTs catalysts were prepared by the H_2 reduction method. The results the optimal Ni_2P loading amount for Pt/Ni_2P/CNTs catalyst was 6% with a MOR activity as high as 1400 mAmg^{-1} Pt.

In 2005, Mu et al [41] study on controllable Pt nanoparticle deposition on carbon nanotubes as an anode catalyst. The producer Pt/CNT composite shows higher electrocatalytic activities and catalyst tolerance that can be applied in DMFCs in comparison with the E-TEK catalyst. Prabhuram et al [42] explore on multi walled carbon nanotube supported PtRu for the anode of direct methanol fuel cells. Cyclic voltammetry results demonstrated that the MWCNT supported PtRu catalyst exhibited a higher mass activity (mA mg^{-1} of PtRu) for the methanol oxidation reaction than the carbon-supported. The direct methanol fuel cell performance test data showed that MWCNT-supported PtRu catalysts yielded about 35-39% higher power densities than the carbon-supported PtRu. In 2013, Zhou et al [43] studied on Pt based anode catalysts for direct ethanol fuel cells. Pt_1Ru_1/C further modified by Wand Mo showed improved ethanol electro-oxidation activity, but its DEFC performance was found to be inferior to that measured for Pt_1Sn_1/C. It was found that the single direct ethanol fuel cell having Pt_1Sn_1/C or Pt_3Sn_2/C or Pt_2Sn_1/C as anode catalyst showed better performances than those with Pt_3Sn_1/C or Pt_4Sn_1/C. Ishitobi et al [44] worked on Pt-Sn was supported on SiO_2 embedded carbon nanofiber as active anode catalyst for DEFC by expecting positive interactions between Pt-Sn-SiO_2. The composite catalyst, Pt_3Sn_1/SECNF, showed highest mass activity for the ethanol electrooxidation, which was 3.7 times higher than the activity of the commercial Pt/C (Pt/C_{com}) while maximum power density of DEFC single cell with the composite catalyst was 3.5 times higher than that with Pt/$C_{com.}$ Since 2003, the development of anode catalysts for a direct ethanol fuel cell being study by Vigier et al [45]. Ethanol electrooxidation was investigated at platinum-based electrodes: Pt, Pt–Sn, Pt–Re dispersed on a high surface area carbon powder. The results PtSn was the most active catalyst and PtSn electrocatalysts were the most selective towards the production of CO_2 compared to Pt and PtRe electrodes.

4.2 Proton Exchange Membrane Fuel Cell

Mohanta et al [46] prepared graphitized carbon by a promising stable cathode catalyst support material for long term PEMFC applications. The feasibility of a graphitized carbon (GC) as a cathode catalyst support for low temperature PEMFC is investigated. GC and CB supported Pt electrocatalysts were prepared via an already developed polyol process. Qu et al [47] worked on an effect of electrode Pt-loading and cathode flow-field plate type on the degradation of PEMFC. The decay of Pt/C catalyst in cathode is mainly caused by the corrosion of carbon support, and the degradation of anode Pt/C catalyst is a consequence of migra- tion and aggregation of Pt particles. Renzi et al [48] study low platinum loading cathode modified with $Cs_3H_2PMo_{10}V_2O_{40}$ for polymer electrolyte membrane fuel cells. The composite catalyst is prepared by mixing the POM salt with Pt/C by sonication. RRDE studies show better kinetics for ORR with low Pt loading at the electrode surface. A MEA is assembled by using a Pt/POM-based cathode, in order to assess performance in a working fuel cell.

Karthikeyan et al [49] work on highly durable platinum based cathode electrocatalysts for PEMFC application using oxygen and nitrogen functional groups attached nanocarbon supports. Compared to commercial Pt/C catalysts, durability show ~30% enhancement for the as prepared electrocatalysts due to the presence of large amount of pyrolic nitrogen and highly oriented graphitic nature of the catalyst supports. Roen et al [50] work on electrocatalytic corrosion of carbon support in PEMFC cathodes. The influence of platinum on the corrosion of carbon catalyst supports has been characterized by on-line mass spectroscopy during cyclic voltammetry, with varying Pt mass fraction, catalyst type, and temperature. The corrosion rate of carbon catalyst support is accelerated in the presence of Pt-containing catalysts. Yu et al [51] work on PtCo/C cathode catalyst for improved durability in PEMFCs. This work intends to evaluate the durability of PtCo/C cathode catalyst in a dynamic fuel cell environment with continuous water fluxing on the cathode. Cell performance enhancement by PtCo/C over Pt/C catalyst has been sustained over 2400 cycles and the overall performance loss of the PtCo/C membrane electrode assemblies (MEAs) was less than that of the Pt/C MEA.

4.3 Direct Methanol Fuel Cell

Bruno et al [52] platinum supported on mesoporous carbon as cathode catalyst for direct methanol fuel cells. Platinum nanoparticles supported on mesoporous carbon were obtained by an impregnation and reduction method with $NaBH_4$ as the reducing agent. The results obtained in this study show that the mesoporous carbon used as support improved the catalyst dispersion. Pt nanoparticles of 5.3 nm in size were obtained on MC, which is, on average, 25% smaller than those formed on Vulcan carbon under the same synthesis conditions. Makino et al [53] search an optimization of the sputter-deposited platinum cathode for a direct methanol fuel cell. Pt loading below 0.25 mg cm^{-2} achieved higher mass activities than that of 0.5 mg cm^{-2} prepared by the paste method, which was general conventional method. This result may suggest an increase in only electrochemically inactive Pt. Pt utilization efficiency can be found about ten times higher at Pt loading of 0.04 mg cm^{-2}. Moreover, addition of Nafion to sputter-deposited Pt cathodes is found possible to improve the catalyst activity for the ORR, but the excess Nafion over the optimum condition reduces the active sites.

Since 2003, Zhou et al [54] investigated on novel synthesis of highly active Pt/C cathode electrocatalyst for direct methanol fuel cell. The results this modified polyol process is simple and practical for the synthesis of highly dispersed Pt-based electrocatalysts with a narrow size distribution in the presence of high loading. The as-synthesized Pt/C electrocatalyst shows better electrocatalytic activity for oxygen reduction reaction in DMFC than that of the

commercial catalyst. Li et al [55] learned the nano-stuctured Pt–Fe/C as cathode catalyst in direct methanol fuel cell. Pt–Fe/C catalysts were prepared by a modified polyol synthesis method in an ethylene glycol (EG) solution, and then were heat-treated under H_2/Ar (10 vol. %) at moderate temperature (300 °C, Pt–Fe/C300) or high temperature (900 °C, Pt–Fe/C900). Further, Pt–Fe/C300 exhibits the higher ORR activity and better performance than other Pt/C or Pt–Fe/C catalysts in direct methanol single cell test, the increasing of cell performance may be attributed to more Pt^0 species existing and Fe ion corrosion from catalysts, which is believed to facilitate the H_2O_2 decomposition of Pt sites.

4.4 Microbial Fuel Cell

MFCs constitute a promising approach to wastewater treatment technology by capturing energy in the form of electricity or hydrogen gas [56]. Erable et al [57] run iron-nicarbazin derived platinum group metal-free electrocatalyst in scalable-size airbreathing cathodes for microbial fuel cells. Low-cost organic precursor was synthesized using Sacrificial Support Method (SSM). The tests in MFCs showed a maximum power density of 1.85 W m^{-2}. The MFCs performances due to the addition of Fe-NCB were much higher compared to the iron-free material. Considering the existing conditions, the higher overall power predicted was 3.6 mW at 22.2 S m^{-1} and at inter electrode distance of 1 cm. Kodali et al [58]investigate air breathing cathodes for microbial fuel cell using Mn-, Fe-, Co- and Ni-containing Platinum Group Metal-free Catalysts. Results showed that the addition of Mn, Fe, Co and Ni to AAPyr increased the performances compared to AC. The best performing catalyst (Fe-AAPyr) was then tested in MFC with increasing solution conductivity from 12.4 $mScm^{-1}$ to 63.1 $mScm^{-1}$. A maximum power density of 482±5 μWcm^{-2} was obtained with increasing solution conductivity, which is one of the highest values reported in the field. Kodali et al [59] report novel iron based catalysts synthesized using polymer salt pyrolysis technique were tested in RRDE and MFCs. Morphology of the novel catalysts showed a porous structure with graphitic flakes containing a large number of holes. The best electro-catalytic activity was achieved for PABA-850. The Fe-based catalyst was then integrated into air breathing cathodes and tested in the working MFCs. Fe-catalysts had the higher power density recorded that was 178 ± 3 μWcm^{-2} by PABA-850 and 173 ± 3 μWcm^{-2} by PABA-950. At last, AC had a power peak of 131 ± 4 μWcm^{-2}. Ghasemi et al [60] work on activated carbon nanofibers as an alternative cathode catalyst to platinum in a two-chamber microbial fuel cell. As a result, it was found that the MFC with the chemically activated carbon nanofibers (ACNFs) exhibited better catalytic activity than that of the physically activated ACNFs. The power per cost of ACNFs with 8 M KOH is 2.65 times greater than that of the traditionally used platinum cathode. Thus, ACNFs are a good alternative catalyst to Pt for MFCs.

5. Current Problems and Future Development

The fuel cell industry has weathered a challenging period of transition from research and development toward full commercialization, and although many manufacturers remain some distance from profitability, the long-term growth outlook stays promising [61]. In the fully sustainable energy system envisioned for the coming decades, hydrogen produced through renewable-powered electrolysis, or biofuels, is expected to serve as the primary fuel source. Yet in most current designs, the cathode and anode catalyst layers still rely on platinum (Pt), a scarce and costly precious metal that can account for 10–15% of total fuel cell stack cost. Without a reduction in Pt content, this share is projected to grow further as manufacturing volumes scale up, since platinum-group-metal (PGM) loading and system cost remain closely correlated year over year [62]. Platinum therefore continues to represent one of the principal

barriers to widespread commercial adoption of fuel cells, and reducing Pt loading without compromising catalytic performance has become a central research priority.

One well-established approach to improving cathode catalyst performance is alloying platinum with transition metals such as cobalt and nickel; however, these alloying elements are prone to leaching under fuel cell operating conditions, resulting in progressive performance degradation over time [63]. Recent work on core-shell catalyst architectures has sought to address this durability limitation directly, with reduced-Pt-content core-shell nanocatalysts shown to enhance both catalytic activity and structural stability compared with conventional alloy catalysts [64]. Building on this design philosophy, our own high-performing catalyst layer achieves a five-fold improvement in durability relative to a conventional design using the same alloy catalyst. The success of certain application segments in recent years has driven a move toward consolidating specific technologies into standard reference designs, with fuel cells increasingly developed as scalable energy solutions capable of serving multiple market segments, from auxiliary power units (APU) to unmanned aerial vehicles (UAV) [65].

Looking ahead, several complementary strategies are currently being pursued to improve platinum utilization efficiency and, ultimately, to reduce reliance on platinum-group metals altogether. These include: (i) alloying platinum with one or more other metals; (ii) depositing platinum as a surface or near-surface layer over a different base metal; (iii) employing a core–shell approach in which a cheaper metal core is coated with platinum; and (iv) alloying platinum followed by selective dealloying. Beyond these Pt-based strategies, growing attention is being directed toward platinum-group-metal-free (PGM-free) catalysts, such as iron–nitrogen–carbon (Fe–N–C) systems, alongside advances in nanostructured supports and membrane technology, which have recently improved power density and operational stability considerably [66]. Nevertheless, durability under real-world operating conditions remains the primary technical barrier constraining the commercial readiness of current PGM-free catalysts, suggesting that future development of fuel cell catalysis will likely follow a combined pathway: continued refinement of ultralow-Pt core-shell and dealloyed architectures in the near term, progressively complemented by PGM-free alternatives as their stability and activity converge with performance targets.

6. Conclusion

Platinum remains the most efficient catalyst for accelerating the electrochemical reactions within hydrogen fuel cells, owing to its unique ability to withstand the highly acidic operating environment that few other metals can tolerate; it is this same property, however, that anchors its position as the rate-determining component of catalytic performance, including its strong activity toward oxygen reduction and the decomposition of hydrogen peroxide into water and oxygen. Yet this catalytic advantage comes at a considerable cost, as platinum's scarcity and price have long constrained the broad, large-scale deployment of fuel cell technology. This scarcity is compounded by a highly concentrated global supply chain, with approximately 90% of the world's platinum originating from only two countries, South Africa and Russia, exposing the industry to significant geopolitical and economic risk. From a geological standpoint, platinum's rarity is further explained by its natural occurrence: it forms within ultramafic igneous rocks and is typically associated with minerals such as chromite and olivine, rarely crystallising in pure, well-formed structures and instead being recovered mainly as nuggets or fine grains disseminated through host rock. Taken together, these geological, economic, and supply-chain constraints underscore why reducing platinum content, without sacrificing catalytic efficiency, remains one of the most pressing challenges in advancing fuel cell

technology toward wider commercial viability, even as platinum's unmatched catalytic properties continue to affirm its central and, for the foreseeable future, largely irreplaceable role in this field. This challenge is closely aligned with several Sustainable Development Goals (SDGs): platinum-based fuel cells support SDG 7 (Affordable and Clean Energy) by enabling efficient, low-emission power generation, while efforts to reduce platinum loading and diversify supply chains contribute to SDG 9 (Industry, Innovation and Infrastructure) through the advancement of more resilient and sustainable catalyst technologies. Furthermore, mitigating dependence on a geographically concentrated and environmentally intensive mining supply chain speaks to SDG 12 (Responsible Consumption and Production), reinforcing the need for resource-efficient catalyst design as a pathway toward more equitable and sustainable global energy systems.

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Author Contributions

Omar Syah Jehan Elham: Conceptualization, supervision, writing—review and editing, funding acquisition. **Siti Kartom Kamarudin:** Conceptualization, supervision, writing—review and editing, funding acquisition. **Zulfirdaus Zakaria:** Literature investigation, data curation, writing—review. **Nur Hidayah Ahmad Zaidi:** Literature investigation, visualization, data curation. **Abul K. Azad:** Critical review, scientific validation, writing—review and editing. **Siti Hasanah Osman:** Conceptualization, literature investigation, methodology, data curation, visualization, writing—original draft, project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors have read and agreed to the published version of the manuscript.

References

[1] S. H. Osman *et al.*, “Review on Direct Methanol Fuel Cells : Bridging the Gap between Theory and Application for Sustainable Energy Solutions,” 2025, doi: 10.1021/acs.energyfuels.4c05357.

[2] Y. Luo *et al.*, “Development and application of fuel cells in the automobile industry,” *J. Energy Storage*, vol. 42, p. 103124, Oct. 2021, doi: 10.1016/J.EST.2021.103124.

[3] Q. Hassan, I. D. J. Azzawi, A. Z. Sameen, and H. M. Salman, “Hydrogen Fuel Cell Vehicles: Opportunities and Challenges,” vol. 15, no. 15, p. 11501, Jul. 2023.

[4] Z. A. Che Ramli *et al.*, "Evaluating electrocatalytic activities of Pt, Pd, Au and Ag-based catalyst on PEMFC performance: A review," *Int. J. Hydrogen Energy*, vol. 104, no. April 2024, pp. 463–486, 2025, doi: 10.1016/j.ijhydene.2024.04.177.

[5] H. Liu, Q. Song, Y. Xie, W. Zhang, Q. Xu, and H. Su, "Recent Progress of Low Pt Content Intermetallic Electrocatalysts Toward Proton Exchange Membrane Fuel Cells," *Catalysts*, vol. 15, no. 11, pp. 1–21, 2025, doi: 10.3390/catal15111070.

[6] D. Kharzeev, R. D. Pisarski, and M. H. G. Tytgat, "PARITY ODD BUBBLES IN HOT QCD."

[7] J.-P. Elsevier Science (Firm), A. Luguet, O. Alard, A. Bezos, and T. Meisel, *Chemical geology.*, vol. 248, no. 3–4. Elsevier Science Pub. Co.

[8] "USGS Mineral Resources Program Platinum-Group Elements-So Many Excellent Properties Great Dyke of Zimbabwe Implats Mimosa Project-South Hill Mine," 2014, doi: 10.3133/fs20143064.

[9] "17.2 Galvanic Cells – Chemistry." .

[10] *Fuel Cell Handbook (Seventh Edition)*. 2004.

[11] L. Chong *et al.*, "Ultralow-loading platinum-cobalt fuel cell catalysts derived from imidazolate frameworks," *Science (80-.).*, vol. 362, no. 6420, pp. 1276–1281, Dec. 2018, doi: 10.1126/science.aau0630.

[12] "Michael, Author at Michael Arthur Diamonds - Page 3 of 6." .

[13] S. Thomas and M. Zalbowitz, "Fuel Cells - Green Power," 1999.

[14] "Platinum is cheap – but will it ever get expensive again? - MoneyWeek." .

[15] J. Matthey, "PGM MARKET REPORT FEBRUARY 2018 1 Precious Metals Management," 2018.

[16] J. CIAMPAGLIA, "Special Report: The Platinum Opportunity," *Sprott USA*, 2018. .

[17] "Gold | The most precious of metals (Part 2)." .

[18] S. H. Richardson and S. B. Shirey, "Continental mantle signature of Bushveld magmas and coeval diamonds," *Nature*, vol. 453, no. 7197, pp. 910–913, Jun. 2008, doi: 10.1038/nature07073.

[19] G. Von and G. Lnstitute Lor Geological, "A REVIEW OF SOME RECENT CONCEPTS OF THE BUSHVELD GOMPLEX' WNN PARTICULAR REFERENCE TO SULFIDE MINERALIZATION," 1979.

[20] W. Hustrulid, W. Hustrulid, R. Bullock, and R. Bullock, *Underground mining methods: Engineering fundamentals and international case studies*. 2001.

[21] R. Ehrlich, "A century of miners' compensation in South Africa," *Am. J. Ind. Med.*, vol. 55, no. 6, pp. 560–569, Jun. 2012, doi: 10.1002/ajim.22030.

[22] R. J. Howarth, "A petrologist in South Africa: Frederick Henry Hatch and the Witwatersrand Goldfield," *Proc. Geol. Assoc.*, vol. 123, no. 1, pp. 189–209, Jan. 2012, doi: 10.1016/J.PGEOLA.2011.06.001.

[23] "USGS Scientific Investigations Report 2013–5090–Q: Platinum-Group Elements in Southern Africa—Mineral Inventory and an Assessment of Undiscovered Mineral

Resources.” .

[24] B. McCarthy, T. & Rubidge, “The Bushveld Complex - Wits University,” 2005. .

[25] “Platinum ~ Learning Geology.” .

[26] Mertie JB, “Economic geology of the platinum metals,” *Usgs P820*, 1969.

[27] “Geology of Platinum | Properties, Mining, and Formation of Platinum.” .

[28] “Platinum | Platinum | Metals.” .

[29] M. Becker, C. Brough, D. Reid, D. Smith, and D. Bradshaw, “Geometallurgical characterisation of the Merensky Reef at Northam Platinum Mine - Comparison of Normal, Pothole and Transitional reef types,” *Australas. Inst. Min. Metall. Publ. Ser.*, no. September, pp. 391–399, 2008.

[30] W. Platinum and I. Council, “Platinum Essentials October 2017.”

[31] O. S. J. Elham, S. K. Kamarudin, N. Shaari, A. M. Zainoodin, Z. Zakaria, and M. R. Yusof, “Development of Low-Cost Nafion-Lignin Composite Conductive Membranes for Application in Direct Methanol Fuel Cells,” *J. Environ. Chem. Eng.*, vol. 12, no. 1, p. 111514, 2023, doi: 10.1016/j.jece.2023.111514.

[32] F. Si, Y. Zhang, L. Yan, J. Zhu, M. Xiao, and C. Liu, “Electrochemical Oxygen Reduction Reaction,” *Rotating Electrode Methods Oxyg. Reduct. Electrocatal.*, pp. 133–170, Jan. 2014, doi: 10.1016/B978-0-444-63278-4.00004-5.

[33] V. Bambagioni *et al.*, “Pd and Pt – Ru anode electrocatalysts supported on multi-walled carbon nanotubes and their use in passive and active direct alcohol fuel cells with an anion-exchange membrane (alcohol = methanol , ethanol , glycerol),” vol. 190, pp. 241–251, 2009, doi: 10.1016/j.jpowsour.2009.01.044.

[34] S. Sen Gupta, S. S. Mahapatra, and J. Datta, “A potential anode material for the direct alcohol fuel cell,” vol. 131, pp. 169–174, 2004, doi: 10.1016/j.jpowsour.2004.01.009.

[35] O. S. . J. Elham *et al.*, “Energy Nexus From Methanol Concentration to Thermal Performance : Insight into Nafion / Lignosulfonate-Hydroxyapatite Composite Membranes for Direct Methanol Fuel,” *Energy Nexus*, vol. 19, no. July, p. 100494, 2025, doi: 10.1016/j.nexus.2025.100494.

[36] F. Ye, H. Liu, Y. Feng, J. Li, X. Wang, and J. Y. Acta, “A solvent approach to the size-controllable synthesis of ultrafine Pt catalysts for methanol oxidation in direct methanol fuel cells,” *Electrochimica*, vol. 117, pp. 480–485, 2014, doi: https://doi.org/10.1016/j.electacta.2013.11.171.

[37] W. Yuan, B. Zhou, J. Deng, Y. Tang, … Z. Z.-I. J. of, and undefined 2014, “Overview on the developments of vapor-feed direct methanol fuel cells,” *Elsevier*.

[38] V. Johánek, A. Ostroverkh, and R. Fiala, “Vapor-feed low temperature direct methanol fuel cell with Pt and PtRu electrodes: Chemistry insight,” *Renew. Energy*, vol. 138, pp. 409–415, Aug. 2019, doi: 10.1016/j.renene.2019.01.109.

[39] S. Basri, S. K. Kamarudin, W. R. W. W. Daud, Z. Yaakob, and A. A. H. H. Kadhum, “Novel anode catalyst for direct methanol fuel cells.,” *ScientificWorldJournal.*, vol. 2014, no. 547604, p. 547604, Apr. 2014, doi: 10.1155/2014/547604.

[40] X. Li, L. Luo, F. Peng, H. Wang, and H. Yu, “Enhanced activity of Pt/CNTs anode

catalyst for direct methanol fuel cells using Ni2P as co-catalyst," *Appl. Surf. Sci.*, vol. 434, pp. 534–539, 2018, doi: 10.1016/j.apsusc.2017.10.218.

[41] Y. Mu, H. Liang, J. Hu, L. Jiang, and L. Wan, "Pt–Co supported on single-walled carbon nanotubes as an anode catalyst for direct methanol fuel cells," *Electrochim. Acta*, vol. 109, no. 47, pp. 7276–7280, 2005, doi: 10.1021/jp0555448.

[42] J. Prabhuram, T. S. Zhao, Z. K. Tang, R. Chen, and Z. X. Liang, "Multiwalled carbon nanotube supported PtRu for the anode of direct methanol fuel cells," *J. Phys. Chem. B*, vol. 110, no. 11, pp. 5245–5252, 2006, doi: 10.1021/jp0567063.

[43] W. Zhou, Z. Zhou, S. Song, and W. Li, "Pt based anode catalysts for direct ethanol fuel cells," vol. 46, pp. 273–285, 2003, doi: 10.1016/S0926-3373(03)00218-2.

[44] H. Ishitobi, Y. Ino, N. N.-I. J. of H. Energy, and undefined 2017, "Anode catalyst with enhanced ethanol electrooxidation activity by effective interaction between Pt-Sn-SiO2 for a direct ethanol fuel cell," *Elsevier*.

[45] F. Vigier, C. Coutanceau, A. Perrard, E. M. Belgsir, and C. Lamy, "Development of anode catalyst for a direct methanol fuel cell veigar (2004)," pp. 439–446, 2004, doi: 10.1023/B:JACH.0000016629.98535.ad.

[46] P. K. Mohanta and F. Regnet, "Graphitized Carbon : A Promising Stable Cathode Catalyst Support Material for Long Term PEMFC Applications," 2018, doi: 10.3390/ma11060907.

[47] Q. Lijuan *et al.*, "Effect of electrode Pt-loading and cathode flow-field plate type on the degradation of PEMFC," 2018, doi: 10.1016/j.jechem.2018.09.004.

[48] M. Renzi, G. D'Angelo, R. Marassi, F. N.-J. of P. Sources, and undefined 2016, "Low platinum loading cathode modified with Cs3H2PMo10V2O40 for polymer electrolyte membrane fuel cells," *Elsevier*.

[49] N. Karthikeyan, B. Vinayan, M. Rajesh, K. B.-F. Cells, and undefined 2015, "Highly durable platinum based cathode electrocatalysts for PEMFC application using oxygen and nitrogen functional groups attached nanocarbon supports," *Wiley Online Libr*.

[50] E. S. Lett, P. A-a, L. M. Roen, C. H. Paik, and T. D. Jarvi, "Electrocatalytic Corrosion of Carbon Support in PEMFC Cathodes service Electrocatalytic Corrosion of Carbon Support in PEMFC Cathodes," vol. 7, no. 1, pp. 8–12, 2004, doi: 10.1149/1.1630412.

[51] P. Yu, M. Pemberton, and P. Plasse, "PtCo / C cathode catalyst for improved durability in PEMFCs," vol. 144, no. November 2004, pp. 11–20, 2005, doi: 10.1016/j.jpowsour.2004.11.067.

[52] M. M. Bruno, F. A. Viva, M. A. Petruccelli, and H. R. Corti, "Platinum supported on mesoporous carbon as cathode catalyst for direct methanol fuel cells," *J. Power Sources*, vol. 278, pp. 458–463, Mar. 2015, doi: 10.1016/j.jpowsour.2014.12.097.

[53] K. Makino, K. Furukawa, K. Okajima, and M. Sudoh, "Optimization of the sputter-deposited platinum cathode for a direct methanol fuel cell," *Electrochim. Acta*, vol. 51, no. 5, pp. 961–965, 2005, doi: 10.1016/j.electacta.2005.04.062.

[54] G. Wang *et al.*, "Novel synthesis of highly active Pt/C cathode electrocatalyst for direct methanol fuel cell," *Chem. Commun.*, no. 3, pp. 394–395, 2003, doi: 10.1039/b211075j.

[55] W. Li *et al.*, "Nano-stuctured Pt-Fe/C as cathode catalyst in direct methanol fuel cell," *Electrochim. Acta*, vol. 49, no. 7, pp. 1045–1055, 2004, doi: 10.1016/j.electacta.2003.10.015.

[56] B. Logan, *Microbial Fuel Cells Chapter 3 Voltage Generation*. 2008.

[57] B. Erable, M. Oliot, R. Lacroix, A. Bergel, … A. S.-E., and undefined 2018, "Iron-Nicarbazin derived platinum group metal-free electrocatalyst in scalable-size air-breathing cathodes for microbial fuel cells," *Elsevier*.

[58] M. Kodali *et al.*, "Mn Fe," *Electrochim. Acta*, 2017, doi: 10.1016/j.electacta.2017.02.033.

[59] M. Kodali, R. Gokhale, C. Santoro, A. Serov, K. Artyushkova, and P. Atanassov, "High Performance Platinum Group Metal-Free Cathode Catalysts for Microbial Fuel Cell (MFC)," vol. 164, no. 3, pp. 78–83, 2017, doi: 10.1149/2.0061703jes.

[60] M. Ghasemi, S. Shahgaldi, M. Ismail, and B. Hong, "Activated carbon nanofibers as an alternative cathode catalyst to platinum in a two-chamber microbial fuel cell," *Int. J. Hydrogen Energy*, vol. 36, no. 21, pp. 13746–13752, 2011, doi: 10.1016/j.ijhydene.2011.07.118.

[61] A. ur Rehman, M. J. Sanjari, R. M. Elavarasan, and T. Jamal, "Sustainability-aligned pathways for energy transition: A review of low-carbon energy network solutions," *Renew. Sustain. Energy Rev.*, vol. 226, p. 116428, Jan. 2026, doi: 10.1016/J.RSER.2025.116428.

[62] M. Bampaou and K. D. Panopoulos, "An overview of hydrogen valleys: Current status, challenges and their role in increased renewable energy penetration," *Renewable and Sustainable Energy Reviews*. 2025, doi: 10.1016/j.rser.2024.114923.

[63] M. Yasin *et al.*, "Pt-based electrocatalyst for hydrogen evolution in acidic electrolytes," *Electrochemistry Communications*. 2025, doi: 10.1016/j.elecom.2025.108057.

[64] R. M. A. Iqbal, M. Du, Z. U. Rehman, L. Sun, A. Munir, and F. Liu, "Surface segregation and reconstruction of core–shell electrocatalysts for water splitting," *J. Mater. Chem. A*, 2026, doi: 10.1039/D6TA01795A/1262239.

[65] L. V. Bühre, K. Khedekar, K. S. Reeves, H. Yu, S. M. Alia, and B. S. Pivovar, "The Impact of Catalyst Layer Composition and Structure on Performance and Durability of PEMWE Anodes," *Adv. Mater. Technol.*, 2025, doi: 10.1002/admt.202501870.

[66] L. MacDonald, D. Zhang, A. Alptekinoğlu, and A. K. Karamalidis, "Enhancing the Resilience of Platinum Group Metal Supply Chains: Mine to (Re)use," *Sustain. Dev.*, 2025, doi: 10.1002/sd.3499.