Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA27577

Platinum-Based Catalysts for the Hydrogen Evolution Reaction: Recent Advances in Preparation and Performance

Yingxuan Leng

School of Chemistry, University of Birmingham, Birmingham, United Kingdom
yxl1760@student.bham.ac.uk

Abstract. Hydrogen evolution reaction (HER) via water electrolysis is a promising route for sustainable hydrogen production with minimal environmental impact. Platinum (Pt)-based catalysts are well known for their exceptional HER activity; however, the high cost of Pt as a precious metal and the tendency of single Pt atoms to aggregate—thereby reducing catalytic performance—pose significant challenges. To address these limitations, researchers have developed a variety of strategies for synthesizing Pt-based catalysts. This review highlights three recent advances in catalyst design and engineering: nanostructuring, alloying, and support engineering. These strategies simultaneously enhance catalytic activity via structural optimization and mitigate material costs. Representative studies in both acidic and alkaline media are discussed to illustrate how structural innovations improve HER performance. By summarizing the latest progress, existing challenges such as poor long-term stability, limited activity in alkaline environments, and difficulties in large-scale synthesis are identified, and guidance for the rational design of next-generation Pt-based catalysts with high efficiency, durability, and cost-effectiveness for practical hydrogen production is provided. Future directions may include the development of novel low-Pt or Pt-free materials, innovative synthesis techniques and investigation of new application domains.

Keywords: platinum-based catalysts, hydrogen evolution reaction, electrocatalysts, water electrolysis, climate change

1. Introduction

Global warming is mainly due to greenhouse gas emission. And among all types of greenhouse gases, carbon dioxide (CO_2) is the one that causes the most significant effect due to its high atmospheric concentration and heat-trapping abilities [1]. Therefore, to decrease the effect of global warming, the amount of carbon dioxide emission must be decreased. As reported by the Global Carbon Project (2024), global CO_2 emissions reached 41.6 billion metric tons, with fossil fuel combustion accounting for 37.4 billion metric tons (90% of total emissions) [2]. This is nearly 90% of the total CO_2 emission. Therefore, to decrease CO_2 emission, an alternative fuel must be developed to substitute fossil fuel. Hydrogen energy is one of the new energy sources that has developed rapidly these years. Unlike conventional energy sources, hydrogen is not a primary energy but rather an energy carrier that requires production from other sources. It needs to be

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.KA27577

produced using energy from another source and then stored for future use [3]. Thus, hydrogen energy, especially produced via water electrolysis, has gained significant attention as a clean and sustainable alternative to fossil fuels. Water electrolysis comprises two coupled half-reactions: the hydrogen evolution reaction (HER) and oxygen evolution reaction (OER). HER is the hydrogen producing step that most studies focus on. It has many advantages, such as high purity of hydrogen production, mild reaction condition and low carbon emission [4]. Catalyst plays an important role in HER which can reduce overall energy consumption of the process and improve the efficiency of energy conversion. Platinum-based catalysts are usually considered to be the most effective electrocatalysts for HER [5]. This paper provides a concise review of recent progress in the design, synthesis, and performance optimization of platinum-based catalysts for the hydrogen evolution reaction. Particular attention is given to emerging strategies for improving catalytic efficiency, such as nanostructuring, alloying, and support engineering. This overview aims to highlight the materials innovation trends that are shaping the future of sustainable hydrogen energy.

2. HER mechanism & Pt's role under Acidic and Alkaline conditions

Recent theoretical research indicates that HER typically follows a two-step process, regardless of whether the proton source is hydronium (H_3O^+) or water (H_2O) molecules. The initial step, known as the Volmer step, involves the adsorption of a hydrogen atom (denoted as H*) onto the catalyst surface through an electron transfer from the electrode to the proton donor.

Step1-Volmer step:

In acidic conditions: $H_3O^+ + e^- + {}^* \longleftrightarrow H^* + H_2O$;

In alkaline conditions: $H_2O + e^- + {}^* \longleftrightarrow H^* + OH^-$

The * represents an active catalytic site on the catalyst.

Following the Volmer step, molecular hydrogen (H_2) is produced via one of two possible reaction pathways. The first, called the Heyrovsky mechanism, occurs when the surface coverage of H* is relatively low. In this electrochemical desorption step, the adsorbed hydrogen atom combines with an incoming proton donor and an electron to produce H_2.

Step2-pathway 1-Heyrovsky step:

In acidic conditions: $H_3O^+ + e^- + H^* \longleftrightarrow H_2 + {}^*$;

In alkaline conditions: $H_2O + e^- + H^* \longleftrightarrow H_2 + {}^* + OH^-$

Alternatively, if the surface has a high concentration of adsorbed hydrogen atoms, the reaction may proceed via the Tafel step, a chemical desorption process. In this route, two adjacent H* species on the catalyst surface recombine to release molecular hydrogen.

Step2-pathway 2-Tafel step:

In both acidic and alkaline conditions: $2H^* \longleftrightarrow H_2 + 2^*$[4]

Many types of catalysts can be used in HER. The Sabatier principle states that the binding strength between catalysts and reactants should be balanced. Insufficient interaction prevents molecules from attaching to the catalyst, thereby stopping the reaction. Excessive interaction, on the other hand, restricts the dissociation of the reactants. A crucial criterion for evaluating the interaction strength (whether too strong or too weak) is to examine the Gibbs free energy of each catalyst. Gibbs free energy (G) is a thermodynamic potential defined as $G=H-TS$, where H is enthalpy, T is temperature, and S is entropy. The change in Gibbs free energy (ΔG) determines the thermodynamic feasibility of a reaction: $\Delta G<0$ indicates a spontaneous process, $\Delta G=0$ corresponds to equilibrium, and $\Delta G>0$requires external energy input. In catalysis, ΔG governs the equilibrium position and the stability of reaction intermediates, while the catalyst accelerates the reaction by lowering the activation free energy without altering ΔG. For example, in the hydrogen evolution reaction (HER),

DOI: 10.54254/2755-2721/2026.KA27577

the Gibbs free energy of hydrogen adsorption (ΔG_{H*}) is a key descriptor, with values close to 0 eV indicating optimal binding strength for efficient catalysis. By plotting a volcano graph to show values of ΔG_{H*} of several kinds of catalysts in HER, it is clear to see that the value of platinum is nearly 0, which shows the strength of interaction between platinum and hydrogen ion is most suitable [6].

3. Materials innovation of platinum-based catalysts for HER

Despite its numerous advantages, platinum also has significant drawbacks. Platinum is a precious metal, which makes it expensive. The catalytic activity of platinum is relatively low under highly acidic or alkaline conditions [7]. Therefore, many scientists are focused on innovating platinum-based catalysts to reduce costs and enhance activity and stability. In the following review, Tafel slope and overpotential are used as standards to compare recently developed platinum-based catalysts with platinum catalysts. Overpotential is used to overcome the intrinsic activation barriers present on both cathode and anode, as well as some other resistances, such as solution resistance and contact resistance. The Tafel slope is related to the catalytic mechanism of HER. Both values are desirable to be small. The reference value for the Tafel slope is 34.3 mV dec-1 (value of the Pt-C catalyst, which is the most widely used HER catalyst commercially), and for overpotential, the value is close to 0 when current density reaches 10 mAcm-2, the better. A typical Pt-C catalyst has an overpotential of 32 mV [8].

3.1. Nanostructuring

Nanostructuring is an effective strategy to optimize the performance of Pt-based electrocatalysts by creating more exposed Pt surface atoms and active sites per unit mass. This strategy enhances electrochemically active surface area (ECSA), exposes high-activity facets, and facilitates shorter electron-ion transport pathways. Platinum nanoparticles are a kind of 0D catalyst. 0D structures confined at the nanoscale in all three dimensions, typically including nanoparticles, nanodots, and quantum dots. However, although platinum has high electric conductivity, platinum nanoparticles are easy to aggregate, which greatly lowers their catalytic activity. To solve this problem, Tang et al. developed Platinum Nanoparticles Bonded with Carbon Nanotubes (Pt-NPs-bonded@CNT) by using $H_2PtCl_6 \bullet 6H_2O$ and acid to synthesize. Transmission electron microscopy (TEM) analysis reveals that Pt-NPs-bonded@CNT features Pt nanoparticles strongly anchored on carbon nanotubes with diameters of only a few nanometers, which is able to accelerate electron transmission by reducing the electron transfer energy barrier. The Tafel slope value for Pt-NPs-bonded@CNT is 28.6 mV dec^{-1} and the overpotential is 31 mV; both are lower than the values of Pt-C. It was further demonstrated that Pt nanoparticles anchored on carbon nanotubes through Pt–C bonding deliver excellent intrinsic electrocatalytic activity for HER in both acidic and alkaline electrolytes [9].

Gao et al. reported a method to synthesis platinum nanomembrane which is a 2D catalyst made by the polymer surface buckling-enabled exfoliation (PSBEE) method. 2D structures are defined as nanoscale in thickness but extended in two directions, such as nanofilms, nanosheets, and graphene-like materials. This catalyst is used under acidic conditions. The platinum nanomembranes synthesized have a thickness between 5 and 28 nm. This nanomembrane is composed of highly distorted nanocrystals that contain heterogeneous elastic strains. The plentiful atomic-scale defects (such as vacancies) introduced by lattice distortion, together with the resulting heterogeneous strains, synergistically enhance the HER catalytic performance of Pt nanomembranes. The Tafel

DOI: 10.54254/2755-2721/2026.KA27577

slope of this type of membrane is 30 mV dec^{-1}, which is lower than 34.3 mV dec^{-1}. The overpotential of the platinum nanomembrane is 26 mV, which is far lower than 32 mV [10].

3.2. Pt-based alloys and heterostructures

Alloying is a strategy that enhances catalytic activity through three mechanisms: electronic structure tuning, synergistic active sites, and cost reduction. Alloying introduces a second metal which modifies the d-band center position of Pt, thereby optimizing the hydrogen adsorption free energy (ΔG_{H*}). This avoids overly strong adsorption as well as overly weak adsorption. Part of the Pt is replaced with cheaper metals, significantly reducing Pt content and lowering the overall cost. New interfaces formed by alloying can generate additional catalytic sites.

Ru exhibits high activity for water activation and dissociation, particularly under alkaline conditions, where its performance surpasses that of platinum. These properties render Ru a promising HER catalyst. However, H and OH adsorb on Ru strongly which hinders the desorption of H_2. To solve this problem, Huang et al. reported a method to prepare P-doped Ru-Pt alloy catalyst support on carbon nanotubes which is called the (Ru-P)#Pt/C alloy catalyst and has the ratio of Pt to Ru being about 14.4%. The Tafel slope of (Ru-P)#Pt/C is 27 mV dec^{-1} and the overpotential is 17 mV; both are lower than the values of Pt-C. Pt atoms are thought to be dispersed on the surface of P-doped Ru nanoparticles. The cooperative interaction between P-doped Ru sites and Pt sites is considered to markedly enhance the kinetics of water dissociation and hydrogen desorption, respectively [11].

As an early transition metal, vanadium exhibits multiple accessible oxidation states, enabling it to tune the electronic structure of the host material and enhance catalytic activity. Vanadium is also able to induce a synergistic effect between the host material and heteroatom. Moreover, vanadium is relatively cheap and abundant, which allows it to become a noticeable option in commercialization. Da et al. reported a Pt_3V alloy catalyst (a-Pt_3V) for HER by using the thermal shock technique and the facile electrochemical activation to synthesis. The Tafel slope of a-Pt_3V is 36 mV dec^{-1} , which is very close to 34.3 mV dec^{-1} and the overpotential is 20 mV which is lower than the value of Pt -C. The above results express that the adsorption energy is weakened for intermediates on a-Pt_3V, thus indicating enhanced HER activity. Overall, the formation of a-Pt_3V alloy can cause a strong V-Pt bonding effect which can improve the catalytic activity and stability of Pt catalysts [12].

Alloying with Pt enhances the dispersibility and catalytic activity of platinum. Peng et al. reported a catalyst with individually dispersed Pt active sites and tunable Pt–Ni interactions, deposited on carbon-encapsulated nanotube frameworks (Pt/Ni-DA). Using a coprecipitation method, they synthesized Pt-Ni alloys with highly dispersed Pt atoms on Ni nanoparticles, followed by carbon encapsulation to form a protective coating layer. The Tafel slope of Pt/Ni-DA is 34.32 mV dec^{-1}, and overpotential at i mA cm^{-2} is 18 mV. Pt/Ni-DA is effective under acidic conditions. It is demonstrated that the Pt content influences both the spatial distribution of active sites and the electronic configuration, the latter being altered by the accommodation effect between Ni and Pt, which together lead to improved catalytic activity [13].

3.3. Support engineering

The utilization of Pt can be improved by increasing the surface-to-volume ratio. Currently platinum nanoparticles are usually dispersed on high-surface-area carbon supports. However, carbon has weak interaction with Pt particles which makes the particles easy to migrate over the surface during the reaction process which weakens the HER efficiency. To overcome this problem, scientists are

DOI: 10.54254/2755-2721/2026.KA27577

focusing on 'strong metal-support interaction(SMSI)' which can increase the activity and stability of catalysts. Strong metal–support interaction (SMSI) modifies the properties of metal catalysts through electronic and geometric effects. Electronic effect is about electron transfer. Electron transfer at the metal–support interface shifts the metal's d-band center, thereby tuning the adsorption strength of reactants and intermediates to enhance activity and selectivity. Geometric effect happens when partial encapsulation or structural modification by reduced support species can block undesired active sites, stabilize small metal clusters, and improve catalyst stability [14].

Smiljanic et al. reported a method to improve catalytic activity of Pt by supporting it on a conductive titanium oxynitride (TiONx). The catalyst is denoted as Pt/TiONx. Pt/TiONx has a strong SMSI effect which means it can tune the electronic structure of Pt active sites, and induce strong binding between Pt particles and TiONx. A stronger binding provides two benefits for HER: first, it reduces the detachment and coalescence of Pt NPs, thus keeping the Pt NPs well dispersed and the platinum surface area maximized during the reaction. Second, it is known that supports that bind metal NPs stronger affect their reactivity such that NPs bind small adsorbates weaker, provided that adsorbates bind mostly covalently. The improvement is shown by the result: The Tafel slope of Pt/TiONx is 29.5 mV dec^{-1} and overpotential is 20 mV. Both results are lower than the value of Pt-C [14].

High-entropy oxides (HEOs) have gained increasing attention in recent years due to their single-phase structure and unique properties. These materials compensate for the incompatibility between constituent elements, thereby increasing the system's configurational entropy. Fan et al. reported Pt/$(FeCoNiCrAl)_3O_4$ as a novel HER catalyst, where $(FeCoNiCrAl)_3O_4$ serves as the HEO substrate. They use the so-gel method to prepare single-phase $(FeCoNiCrAl)_3O_4$ which has high purity. $(FeCoNiCrAl)_3O_4$ was used as a substrate, then, highly dispersed Pt nanoparticles were loaded on to it by using an impregnation method. They adjusting the impregnation concentration and found that when the concentration is 0.6g·L^{-1}, rather than existing exclusively in a fine granular state, the $(FeCoNiCrAl)_3O_4$ was observed in both granular and flake-like forms. This indicates that at this concentration, $(FeCoNiCrAl)_3O_4$ is more favorable to disperse Pt. The catalyst synthesized at this concentration is denoted as 0.6-Pt/HEO. The electrochemical evaluation demonstrates that 0.6-Pt/HEO achieves a Tafel slope of 25.9 mV dec^{-1} with an overpotential of 22 mV. Such performance implies that the HEO substrate optimizes the electrochemical surface area as well as electron transfer, which accounts for the superior HER activity of Pt/$(FeCoNiCrAl)_3O_4$. These results confirm HEO as a promising support material for noble metals, combining enhanced catalytic performance with cost reduction in electrocatalysis [15].

4. Discussion

However, despite significant progress in catalyst design and performance optimization, several critical challenges persist and continue to hinder the large-scale application of Pt-based catalysts for HER. The cost of platinum-based catalysts is still relatively high. The main reason is because platinum is a kind of precious metal and is only concentrated in several countries, lacking a stable supply. Taking the platinum usage of transportation fuel cells as an example, the global Pt resources currently known about would keep 500 million fuel cell vehicles in operation for just 15 years. This is enough to show the scarcity of platinum [16]. Moreover, although nanostructuring can produce effective catalysts, it also will pollute air, water, and soil because nanoparticles are too small to be detected [17]. In addition, many scientists are focused on increasing the Pt loading on the catalyst, but this action would cause mass-transport limitations in HER under acidic conditions [18].

DOI: 10.54254/2755-2721/2026.KA27577

Future efforts in HER catalyst research are expected to focus on developing Pt-free electrocatalysts with catalytic activity comparable to Pt, thereby reducing costs. Studying machine learning approaches particularly by leveraging larger datasets and advanced models is also important. Models such as deep neural networks can predict key catalyst features including stability and charge transfer resistance. By combining these computational strategies with DFT simulations, guidance for structural optimization can be provided. On the materials side, tailoring defects, engineering heterointerfaces, and constructing core–shell architectures have shown great promise in accelerating charge transport and improving hydrogen adsorption/desorption kinetics. Equally important is the improvement in sustainable synthesis pathways, for instance, employing biomass-derived carbon supports. This method could offer both economic and environmental advantages. Finally, the close integration of DFT calculations with experimental evidence is essential to unravel mechanistic insights into hydrogen adsorption, electron transfer, and structural–electronic correlations. This will drive the development of next-generation HER catalysts that are both highly active and durable [19].

5. Conclusion

Platinum-based catalysts exhibit outstanding performance for the HER, but their industrial application is limited by high cost, low abundance, and reduced activity under extreme pH conditions. Recent research has focused on improving their efficiency and stability through nanostructuring, alloying, and support engineering. Nanostructures enhance surface area and atom utilization; alloying with metals like Ru, Ni, or V optimizes electronic properties and reaction kinetics; and advanced supports improve dispersion and durability via strong metal–support interactions. All methods effectively improve catalytic activity and lower the cost. Platinum-based catalysts have broad application prospects in HER, but to achieve their widespread use in sustainable hydrogen production, numerous challenges must still be overcome. Through continuous material innovation and engineering optimization, researchers aim to develop efficient, stable, and cost-effective platinum-based catalysts, thereby contributing significantly to the carbon reduction in the energy system.

References

[1] Mohajan, H. (2011). Greenhouse gas emissions increase global warming.
[2] Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., ... & Zeng, J. (2024). Global carbon budget 2024. Earth System Science Data Discussions, 2024, 1-133.
[3] Edwards, P. P., Kuznetsov, V. L., & David, W. I. (2007). Hydrogen energy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1853), 1043-1056.
[4] Zhou, Z., Pei, Z., et al. (2020). Electrocatalytic hydrogen evolution under neutral pH conditions: current understandings, recent advances, and future prospects. Energy & Environmental Science, 13(10), 3185-3206.
[5] Cheng, N., Stambula, S., et al. (2016). Platinum single-atom and cluster catalysis of the hydrogen evolution reaction. Nature communications, 7(1), 13638.
[6] Jaramillo, T. F., Jørgensen, K. P., Bonde, J., Nielsen, J. H., Horch, S., & Chorkendorff, I. (2007). Identification of active edge sites for electrochemical H2 evolution from MoS2 nanocatalysts. science, 317(5834), 100-102.
[7] Zhai, W., Ma, Y., Chen, D., Ho, J. C., Dai, Z., & Qu, Y. (2022). Recent progress on the long-term stability of hydrogen evolution reaction electrocatalysts. InfoMat, 4(9), e12357.
[8] Park, H., Lee, E., Lei, M., Joo, H., Coh, S., & Fokwa, B. P. (2020). Canonic-like HER activity of Cr1–xMoxB2 solid solution: overpowering Pt/C at high current density. Advanced Materials, 32(28), 2000855.
[9] Tang, H., Kojima, T., Kazumi, K., Fukami, K., & Sakaguchi, H. (2024). Platinum nanoparticles bonded with carbon nanotubes for high-performance ampere-level all-water splitting. ACS omega, 9(19), 21378-21387.

DOI: 10.54254/2755-2721/2026.KA27577

[10] Gao, X., Dai, S., et al. (2024). Ultra-efficient and cost-effective platinum nanomembrane electrocatalyst for sustainable hydrogen production. Nano-Micro Letters, 16(1), 108.
[11] Huang, R. Q., Liao, W. P., Yan, M. X., Liu, S., Li, Y. M., & Kang, X. W. (2023). P-doped Ru-pt alloy catalyst toward high performance alkaline hydrogen evolution reaction. Journal of Electrochemistry, 29(5), 3.
[12] Da, Y., Jiang, R., et al. (2023). Development of a novel Pt3V alloy electrocatalyst for highly efficient and durable industrial hydrogen evolution reaction in acid environment. Advanced Energy Materials, 13(16), 2300127.
[13] Peng, Y., Ma, K., et al. (2023). Tunable Pt–Ni interaction induced construction of disparate atomically dispersed Pt sites for acidic hydrogen evolution. ACS Applied Materials & Interfaces, 15(22), 27089-27098.
[14] Smiljanic, M., Panic, S., et al. (2022). Improving the HER activity and stability of Pt nanoparticles by titanium oxynitride support. ACS catalysis, 12(20), 13021-13033.
[15] Fan, M. Y., et al. (2024). High-entropy oxide-supported platinum nanoparticles for efficient hydrogen evolution reaction. Rare Metals, 43(4), 1537-1546.
[16] Sealy, C. (2008). The problem with platinum. Materials Today, 11(12), 65-68.
[17] Sotropa[1], R. M. B. (2018). The advantages and disadvantages of nanotechnology. Romanian Journal of Oral Rehabilitation, 10(2).
[18] Hansen, J. N., et al. (2021). Is there anything better than Pt for HER?. ACS energy letters, 6(4), 1175-1180.
[19] Arshad, U., Tang, J., & Shao, Z. (2025). Replace Platinum for Hydrogen Evolution Reaction in the Cathode of Proton Exchange Membrane Water Electrolyzers. SusMat, 5(2), e267.