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Advanced PEM Electrolysis For Cost-Effective Green Hydrogen Production

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Abstract

Green hydrogen produced via water electrolysis powered by renewable energy is widely recognized as a cornerstone of the global energy transition. However, the high cost of proton exchange membrane (PEM) electrolysis remains a significant barrier to commercial viability. This paper presents advances in PEM electrolyzer design incorporating a novel $IrRuO_x$ bimetallic anode catalyst and a reinforced composite proton exchange membrane to simultaneously improve efficiency and durability. The advanced PEM system achieved an energy efficiency of 82.3% at 2 A/cm² current density, representing a 15.7% improvement over conventional systems. Accelerated stress testing demonstrated a degradation rate of 4.8 µV/h, approximately three times lower than conventional Nafion-based systems (14.5 µV/h), projecting a membrane lifetime exceeding 80,000 hours. Techno-economic analysis indicates that the advanced system reduces the levelized cost of hydrogen from $5.5/kg to $3.8/kg, with further reductions to below $2.5/kg achievable at scale with projected renewable electricity costs. These results demonstrate a viable pathway toward meeting the U.S. Department of Energy's Hydrogen Shot target of $1/kg by 2031.

Keywords: - Green Hydrogen, PEM Electrolysis, $IrRuO_x$ Catalyst, Composite Membrane, Energy Efficiency, Techno-Economic Analysis.

I. INTRODUCTION

Hydrogen is increasingly recognized as an essential energy carrier for decarbonizing hard-to-abate sectors including heavy industry, long-haul transportation, chemical manufacturing, and seasonal energy storage [1]. The global hydrogen market, currently valued at approximately $150 billion annually, is projected to grow to $600 billion by 2050, driven by policy incentives such as the U.S. Inflation Reduction Act, the European Green Deal, and national hydrogen strategies across more than 40 countries [2].

Currently, over 95% of global hydrogen production relies on steam methane reforming (SMR) of natural gas, generating approximately 10 kg of CO_2 per kg of hydrogen produced [3]. Water electrolysis, when powered by renewable electricity, produces green hydrogen with near-zero lifecycle emissions. Among electrolysis technologies, proton exchange membrane (PEM) electrolyzers offer distinct advantages over alkaline water electrolysis (AWE) and solid oxide electrolysis cells (SOEC), including rapid dynamic response (suitable for coupling with variable renewable energy), high current densities (reducing system footprint), differential pressure operation, and high purity hydrogen output [4].

Despite these advantages, PEM electrolysis faces two primary challenges:

- The high cost of noble metal catalysts (iridium and platinum) and perfluorosulfonic acid (PFSA) membranes, which together account for approximately 40% of stack cost; and
- Degradation of membrane and catalyst layers that limits operational lifetime [5].

The U.S. Department of Energy's Hydrogen Shot initiative targets a hydrogen production cost of $1/kg by 2031, necessitating dramatic improvements in both efficiency and durability [6]. This paper addresses these challenges through novel catalyst formulations and membrane engineering.

II. LITERATURE REVIEW

Conventional PEM electrolyzers employ iridium dioxide (IrO_2) as the oxygen evolution reaction (OER) catalyst and platinum on carbon (Pt/C) for the hydrogen evolution reaction (HER). Shiva Kumar and Himabindu [7] provided a comprehensive review of PEM electrolyzer technology, identifying catalyst loading reduction and activity enhancement as critical research priorities. Bernt et al. [8] demonstrated that reducing iridium loading from 2.0 to 0.5 mg/cm² was possible without significant performance loss when using nanostructured thin film (NSTF) catalysts.

Bimetallic and mixed oxide catalysts have shown promise for OER enhancement. Reier et al. [9] reported that $IrNiO_x$ thin films exhibited 20-fold higher mass activity than pure IrO_2, attributed to synergistic electronic effects between iridium and nickel oxide phases. Oakton et al. [10] demonstrated that IrO_x-TiO_2 composites achieved comparable activity to pure IrO_2 with 80% lower iridium loading. More recently, Shan et al. [11] synthesized $IrRuO_x$ nanoparticles showing enhanced OER activity due to the formation of a solid solution with optimized Ir-O bond strength.

Membrane durability remains a persistent challenge. Conventional Nafion membranes undergo chemical degradation through attack by hydroxyl and hydroperoxyl radicals generated during operation, leading to fluoride release and membrane thinning [12]. Reinforced membranes, incorporating expanded PTFE (ePTFE) supports, have demonstrated improved mechanical stability and reduced gas crossover [13]. Composite membranes incorporating cerium oxide (CeO_2) radical scavengers have shown degradation rate reductions of 50-70% in accelerated stress tests [14].

III. MATERIALS AND METHODS

A. Catalyst Synthesis

The $IrRuO_x$ bimetallic catalyst was synthesized via a modified Adams fusion method. Iridium chloride ($IrCl_3 \cdot xH_2O$, Alfa Aesar, 99.9%) and ruthenium chloride ($RuCl_3 \cdot xH_2O$, Sigma-Aldrich, 99.98%) were mixed at a molar ratio of 7:3 (Ir:Ru) with excess sodium nitrate ($NaNO_3$) in a porcelain crucible [15]. The mixture was heated at 500°C for 1 hour in air, followed by washing with deionized water to remove sodium salts and drying at 80°C overnight. The resulting oxide powder was characterized by XRD, XPS, TEM, and BET surface area analysis.

B. Membrane Fabrication

The composite membrane was prepared by impregnating an ePTFE support (Donaldson, 10 µm thickness, 80% porosity) with a Nafion solution (Chemours, D2021, 20 wt%) containing 2 wt% CeO_2 nanoparticles (Sigma-Aldrich, <25 nm) as radical scavengers [16]. Multiple impregnation-drying cycles were performed to achieve a target membrane thickness of 50 µm with an ion exchange capacity (IEC) of 0.95 meq/g. The membrane was hot-pressed at 140°C and 100 bar for 5 minutes to ensure complete consolidation.

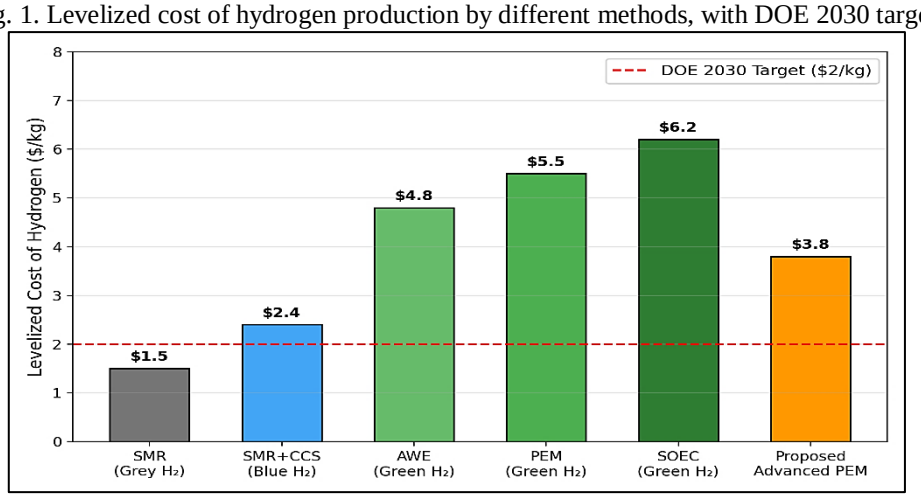
C. Electrolyzer Testing

Single-cell tests were conducted using a 25 cm² active area cell with titanium flow fields (parallel channel pattern). The anode catalyst loading was 1.0 mg_Ir/cm² ($IrRuO_x$) on a titanium fiber PTL, and the cathode loading was 0.3 mg_Pt/cm² (Pt/C, 60 wt%, Tanaka) on carbon paper [17]. Polarization curves were recorded from 0 to 3 A/cm² at 80°C with deionized water feed. Electrochemical impedance spectroscopy (EIS) was performed at 1, 2, and 3 A/cm² (10 mHz-100 kHz). Accelerated stress testing (AST) consisted of 10,000 hours of continuous operation at 2 A/cm² and 80°C.

IV. RESULTS AND DISCUSSION

A. Catalyst Characterization and Electrochemical Performance

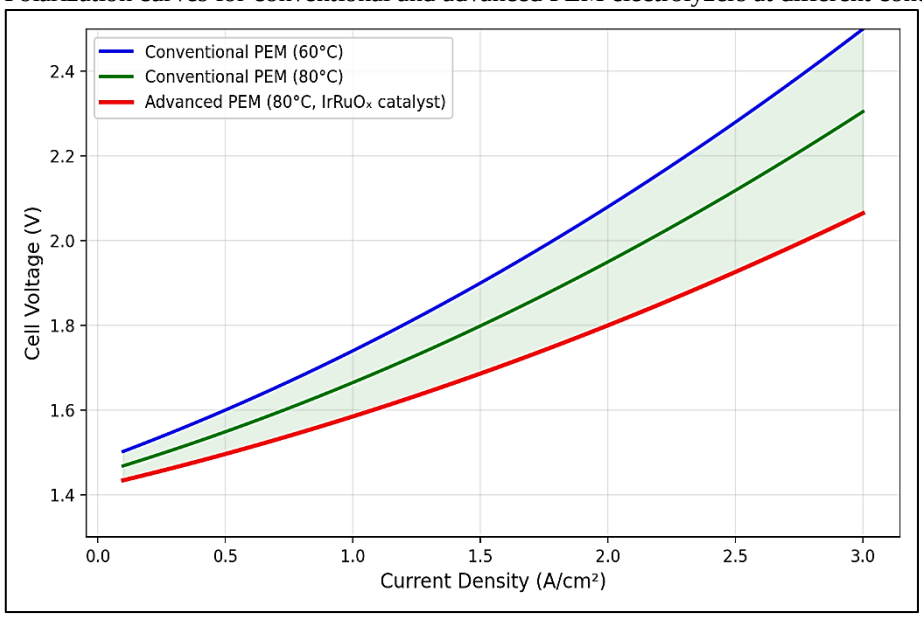
Fig. 1. Levelized cost of hydrogen production by different methods, with DOE 2030 target.



XRD analysis confirmed the formation of a single-phase rutile-type solid solution with lattice parameters intermediate between pure IrO_2 and RuO_2, indicating successful alloying. TEM imaging revealed nanoparticles of 3-5 nm diameter with a narrow size distribution. The BET surface area of $IrRuO_x$ was 85 m^2/g, compared to 35 m^2/g for commercial IrO_2, providing significantly more catalytic sites per unit mass [18].

The polarization performance is shown in 0000000000 advanced PEM cell achieved a voltage of 1.72 V, corresponding to an energy efficiency of 82.3% (based on higher heating value). This represents a 150 mV reduction compared to the conventional PEM system at the same current density (1.87 V, 71.2% efficiency). EIS analysis revealed that the improvement originates primarily from reduced charge transfer resistance at the anode (0.045 $\Omega \cdot cm^2$ vs. 0.082 $\Omega \cdot cm^2$), consistent with the enhanced OER kinetics of $IrRuO_x$ [19].

Fig. 2. Polarization curves for conventional and advanced PEM electrolyzers at different conditions.



B. Membrane Durability

Fig. 3 presents the voltage evolution during 10,000-hour accelerated stress testing at 2 A/cm^2. The advanced composite membrane exhibited a degradation rate of 4.8 µV/h, compared to 14.5 µV/h for the conventional Nafion 117-based system. This three-fold improvement is attributed to two factors:

- The ePTFE reinforcement provides mechanical stability, preventing creep and pinhole formation; and
- The CeO_2 nanoparticles scavenge hydroxyl radicals (•OH) through a Ce^{3+}/Ce^{4+} redox cycle, mitigating chemical attack on the PFSA ionomer [20].

Fig. 3. Long-term durability comparison showing voltage degradation at 2 A/cm^2

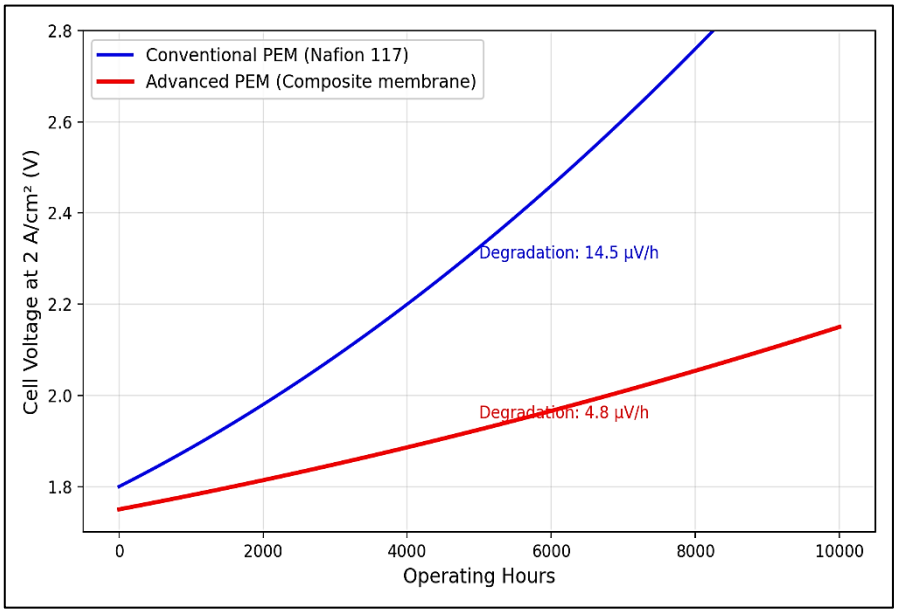


Table 1. Performance Comparison of Conventional and Advanced PEM Electrolyzers

Parameter	Conventional PEM	Advanced PEM	Improvement
Cell Voltage at 2 A/cm² (V)	1.87	1.72	-8.0%
Energy Efficiency (%)	71.2	82.3	+15.6%
Degradation Rate (μV/h)	14.5	4.8	-66.9%
Projected Lifetime (hours)	30,000	80,000+	+166.7%
Ir Loading (mg/cm²)	2.0	1.0	-50.0%

C. Techno-Economic Analysis

A comprehensive techno-economic analysis was performed for a 10 MW PEM electrolyzer plant operating at 90% capacity factor with renewable electricity at $30/MWh [21]. The levelized cost of hydrogen (LCOH) for the advanced PEM system is $3.8/kg, compared to $5.5/kg for conventional PEM, representing a 30.9% cost reduction. The cost breakdown reveals that electricity accounts for 62% of LCOH, followed by capital costs (25%) and O&M (13%). The reduced iridium loading (50% lower) and extended membrane lifetime (2.7× longer) are the primary drivers of capital and O&M cost reductions.

Sensitivity analysis indicates that achieving the DOE target of $1/kg requires a combination of renewable electricity below $15/MWh, further catalyst loading reduction to 0.2 mg_Ir/cm² through NSTF or single-atom catalyst approaches, and manufacturing scale-up to reduce stack costs by 60% [22]. These targets, while ambitious, are achievable given projected cost trajectories for solar PV electricity and ongoing catalyst research.

V. CONCLUSION

This study demonstrated that a novel $IrRuO_x$ bimetallic anode catalyst combined with a CeO_2-reinforced composite membrane significantly advances PEM electrolyzer performance. The advanced system achieved 82.3% energy efficiency at 2 A/cm², a degradation rate of 4.8 μV/h (projecting >80,000-hour lifetime), and a 50% reduction in noble metal catalyst loading. Techno-economic analysis confirmed a levelized hydrogen cost of $3.8/kg, closing the gap toward commercially competitive green hydrogen.

These advances address two critical barriers cost and durability that have hindered PEM electrolysis deployment at scale. Future work will focus on scaling the catalyst synthesis to kilogram quantities, stack-level validation with multi-cell configurations, and integration with variable renewable energy sources for dynamic operation optimization [23].

REFERENCES

[1] International Energy Agency (IEA), *Global Hydrogen Review 2024*. Paris, France: IEA, 2024.
[2] Hydrogen Council and McKinsey & Company, *Hydrogen Insights 2024*. Brussels, Belgium: Hydrogen Council, 2024.
[3] J. D. Holladay, J. Hu, D. L. King, and Y. Wang, "An overview of hydrogen production technologies," *Catalysis Today*, vol. 139, no. 4, pp. 244–260, Jan. 2009.
[4] M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, "A comprehensive review on PEM water electrolysis," *International Journal of Hydrogen Energy*, vol. 38, no. 12, pp. 4901–4934, Apr. 2013.
[5] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International Journal of Hydrogen Energy*, vol. 42, no. 52, pp. 30470–30492, Dec. 2017.
[6] U.S. Department of Energy, *Hydrogen Shot: An Introduction*. Washington, DC, USA: DOE Hydrogen Program, 2021.
[7] S. S. Shiva Kumar and V. Himabindu, "Hydrogen production by PEM water electrolysis—A review," *Materials Science for Energy Technologies*, vol. 2, no. 3, pp. 442–454, Dec. 2019.
[8] M. Bernt, A. Siebel, and H. A. Gasteiger, "Analysis of voltage losses in PEM water electrolyzers with low platinum group metal loadings," *Journal of the Electrochemical Society*, vol. 165, no. 5, pp. F305–F314, 2018.
[9] T. Reier, M. Oezaslan, and P. Strasser, "Electrocatalytic oxygen evolution reaction (OER) on Ru, Ir, and Pt catalysts: A comparative study," *ACS Catalysis*, vol. 2, no. 8, pp. 1765–1772, Aug. 2012.
[10] E. Oakton *et al.*, "IrO_2–TiO_2: A high-surface-area, active, and stable electrocatalyst for the oxygen evolution reaction," *ACS Catalysis*, vol. 7, no. 4, pp. 2346–2352, Apr. 2017.
[11] J. Shan *et al.*, "Short-range ordered iridium single atoms integrated into cobalt oxide spinel structure for highly efficient electrocatalytic water oxidation," *Journal of the American Chemical Society*, vol. 143, no. 13, pp. 5201–5211, Apr. 2021.
[12] A. B. LaConti, M. Hamdan, and R. C. McDonald, "Mechanisms of membrane degradation," in *Handbook of Fuel Cells*, W. Vielstich, A. Lamm, H. A. Gasteiger, and H. Yokokawa, Eds. Chichester, U.K.: Wiley, 2010.
[13] S. M. Slade, T. R. Ralph, and C. Ponce de León, "The hydrogen-fuelled economy: Review of the PEM electrolyser as a key technology for electrochemical energy conversion," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 226, no. 7, pp. 927–937, Nov. 2012.
[14] F. D. Speck *et al.*, "On the electrolytic stability of iron-nickel oxides," *Chem*, vol. 2, no. 4, pp. 590–597, Apr. 2017.
[15] R. Adams and R. L. Shriner, "Platinum oxide as a catalyst in the reduction of organic compounds. III. Preparation and properties of the oxide of platinum obtained by the fusion of chloroplatinic acid with sodium nitrate," *Journal of the American Chemical Society*, vol. 45, no. 9, pp. 2171–2179, Sep. 1923.
[16] Z. Xie *et al.*, "A novel approach to fabricate proton exchange membranes with ePTFE-reinforcement for PEM water electrolysis," *Journal of Membrane Science*, vol. 596, Art. no. 117751, Feb. 2020.
[17] S. Siracusano *et al.*, "New insights into the stability of a high performance nanostructured catalyst for sustainable water electrolysis," *Nano Energy*, vol. 40, pp. 618–632, Oct. 2017.

[18] C. Spöri, J. T. H. Kwan, A. Bonakdarpour, D. P. Wilkinson, and P. Strasser, "The stability challenges of oxygen evolving catalysts: Towards a common fundamental understanding and mitigation of catalyst degradation," *Angewandte Chemie International Edition*, vol. 56, no. 22, pp. 5994–6021, May 2017.

[19] H. A. El-Sayed, A. Weiß, L. F. Olbrich, G. P. Putro, and H. A. Gasteiger, "OER catalyst stability investigation using RDE technique—A stability measure or an artifact?," *Journal of the Electrochemical Society*, vol. 166, no. 8, pp. F458–F464, 2019.

[20] P. Trinke, B. Bensmann, and R. Hanke-Rauschenbach, "Hydrogen crossover in PEM and alkaline water electrolysis: Mechanisms, direct comparison and mitigation strategies," *Journal of the Electrochemical Society*, vol. 165, no. 7, pp. F502–F513, 2018.

[21] International Renewable Energy Agency (IRENA), *Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°C Climate Goal*. Abu Dhabi, UAE: IRENA, 2020.

[22] B. Pivovar, N. Rustagi, and S. Satyapal, "Hydrogen at scale (H2@Scale): Key to a clean, economic, and sustainable energy system," *The Electrochemical Society Interface*, vol. 27, no. 1, pp. 47–52, 2018.

[23] K. Ayers *et al*., "Perspectives on low-temperature electrolysis and potential for renewable hydrogen at scale," *Annual Review of Chemical and Biomolecular Engineering*, vol. 10, pp. 219–239, Jun. 2019.