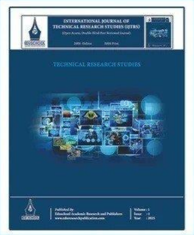
EDUSCHOOL
ACADEMIC RESEARCH & PUBLISHERS

INTERNATIONAL JOURNAL OF
TECHNICAL RESEARCH STUDIES (IJTRS)
(Open Access, Double-Blind Peer Reviewed Journal)
ISSN Online: 3139-1788



Green Hydrogen Production Using Proton-Exchange-Membrane Water Electrolysis

Jeeva Chacko

Principal, Department of Zoology, St. Mary's Arts and Science College, Cherupanathady, India

Article information

Received: 28th February 2026
Received in revised form: 31st March 2026
Accepted: 4th May 2026
Available online: 9th June 2026

Volume: 2
Issue: 2
DOI: https://doi.org/10.63090/IJTRS/3139.1788.0015

Abstract

Green hydrogen produced by water electrolysis powered by renewable electricity is widely regarded as an indispensable energy carrier for decarbonizing sectors that resist direct electrification, including steel, ammonia, refining, and heavy transport. Among the electrolysis technologies, proton-exchange-membrane (PEM) water electrolysis is especially well suited to coupling with intermittent renewables owing to its high current density, compact footprint, rapid dynamic response, and ability to operate at high differential pressure. This paper reviews the operating principles of PEM electrolysis and develops an electrochemical model that resolves the cell voltage into its reversible, activation, ohmic, and concentration components to quantify the trade-off between energy efficiency and hydrogen-production rate. The model is used to compare PEM with alkaline and solid-oxide electrolysis and to estimate the levelized cost of hydrogen (LCOH) as a function of electricity price and capacity factor. At a current density of 2 A/cm-squared the modeled PEM cell operates at a voltage efficiency of about 74 percent, and the LCOH analysis shows that hydrogen approaches the cost-competitiveness target of roughly two US dollars per kilogram only when low-cost electricity is available at a high capacity factor. The study identifies efficiency, durability, and electricity cost as the principal levers for scaling green hydrogen.

Keywords:- Green Hydrogen, PEM Electrolysis, Water Electrolysis, Renewable Energy, Levelized Cost of Hydrogen, Electrochemistry, Decarbonization.

.

I. INTRODUCTION

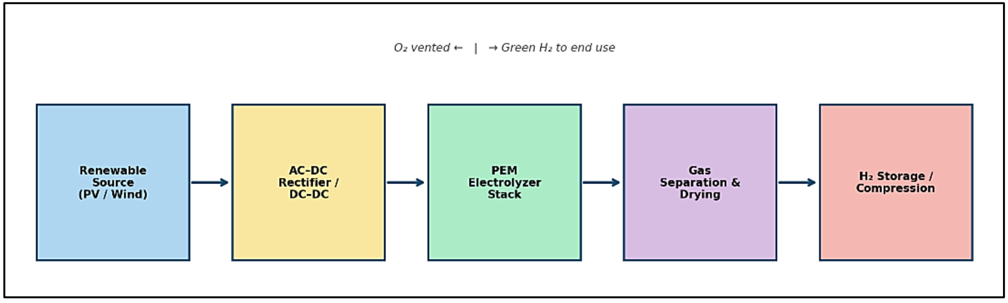
Limiting global warming requires the decarbonization not only of electricity generation but also of industrial and transport sectors whose emissions are difficult to abate through electrification alone [1]. Hydrogen has re-emerged as a central pillar of these strategies because it can serve simultaneously as a chemical feedstock, a high-temperature industrial fuel, a long-duration energy store, and a transport fuel, while emitting only water at the point of use [2]. The decisive question is how the hydrogen is produced: today the overwhelming majority is derived from fossil natural gas by steam-methane reforming, a process that releases substantial carbon dioxide. Hydrogen generated by water electrolysis powered by renewable electricity termed green hydrogen offers a genuinely low-carbon pathway [3].

Water electrolysis splits water into hydrogen and oxygen using electricity, and three technologies dominate the landscape: alkaline electrolysis, the mature and lowest-capital-cost option; proton-exchange-membrane (PEM) electrolysis, which uses a solid polymer electrolyte; and solid-oxide electrolysis, a high-temperature technology of high efficiency but limited maturity [4]. PEM electrolysis has attracted particular attention for renewable-coupled deployment because its solid-polymer membrane permits high current densities, a compact and pressurized design, a wide and responsive operating range, and rapid start-up, all of which align with the variable and intermittent output of wind and solar generation [5], [6].

Despite this promise, the cost and durability of PEM electrolyzers, and above all the price of the renewable electricity that drives them, remain barriers to large-scale adoption [7]. This paper provides an engineering-level analysis of PEM water electrolysis aimed at clarifying these levers. The contributions are:

- A concise review of PEM electrolysis principles set against competing technologies;
- An electrochemical cell model that decomposes the polarization behavior and quantifies the efficiency-versus-production-rate trade-off; and
- A levelized-cost analysis that situates green hydrogen against cost-competitiveness targets as a function of electricity price and capacity factor.

Figure 1: Renewable-coupled PEM water-electrolysis system, from variable generation through power conditioning, the electrolyzer stack, and gas processing to hydrogen storage.



II. BACKGROUND AND RELATED WORK

A. Water-Electrolysis Technologies

Comprehensive reviews have charted the status and prospects of the principal electrolysis technologies [8], [9]. Alkaline electrolysis, employing a liquid potassium-hydroxide electrolyte and operating for decades at industrial scale, offers the lowest capital cost and uses non-noble catalysts, but it is limited in current density and responds sluggishly to fluctuating power [10]. Solid-oxide electrolysis operates at high temperature and can reach very high electrical efficiency by drawing part of the energy as heat, yet its ceramic cells suffer from degradation and thermal-cycling constraints that keep it at an early stage of commercialization [4]. PEM electrolysis occupies the middle ground, combining high current density and dynamic flexibility with a compact pressurized design, at the cost of expensive iridium and platinum catalysts and an acidic membrane environment [11].

B. PEM Cell Fundamentals

In a PEM electrolysis cell, water supplied to the anode is oxidized to oxygen, protons, and electrons; the protons migrate across the perfluorosulfonic-acid membrane to the cathode, where they recombine with electrons to form hydrogen [5]. The cell voltage exceeds the thermodynamic reversible voltage of 1.23 volts by the sum of three overpotentials: an activation overpotential associated with the sluggish oxygen-evolution reaction, an ohmic overpotential dominated by membrane and contact resistance, and a concentration overpotential arising from mass-transport limitations at high current density [12]. Reducing these losses through improved catalysts, thinner membranes, and optimized porous transport layers is the central objective of PEM cell development [13].

C. Coupling with Renewable Energy

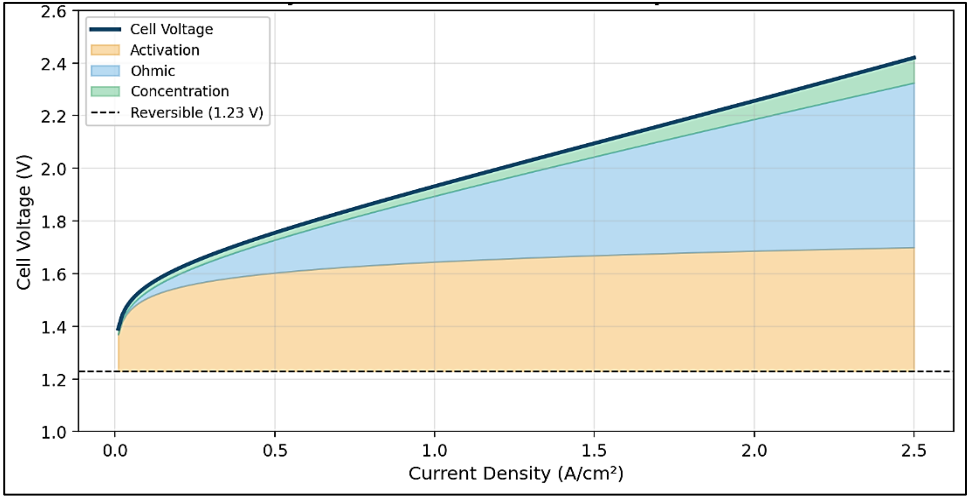
The integration of electrolyzers with variable renewable sources requires power-electronic conditioning to convert and regulate the supply to the stack, and the design of these rectifier and DC-DC stages materially affects overall system efficiency and the electrolyzer's response to fluctuating input [14], [15]. Demonstration projects coupling multi-megawatt PEM electrolyzers directly with wind and solar plants have validated dynamic operation under real renewable profiles and identified the importance of well-matched stack sizing and power conditioning [16]. National and international roadmaps now position such renewable-coupled electrolysis at the center of hydrogen-economy strategies [2], [3].

III. ELECTROCHEMICAL MODEL AND METHODOLOGY

A. Polarization Model

The cell voltage was modeled as the sum of the reversible voltage and the activation, ohmic, and concentration overpotentials. The activation term follows a Tafel relationship dominated by the anodic oxygen-evolution reaction; the ohmic term is proportional to current density through the area-specific resistance of the membrane and components; and the concentration term rises steeply as transport limits are approached at high current density [12], [17]. Representative parameters for a perfluorosulfonic-acid membrane operating near eighty degrees Celsius were adopted from the literature, yielding the polarization curve and overpotential decomposition shown in Fig. 2.

Figure 2: Modeled PEM electrolyzer polarization curve with the activation, ohmic, and concentration contributions to the overpotential.



B. Efficiency and Cost Metrics

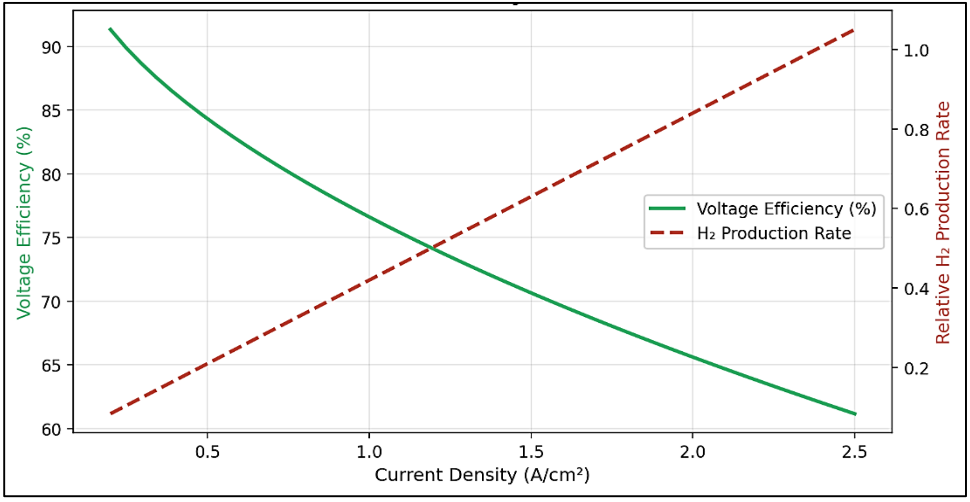
The voltage efficiency was defined relative to the thermoneutral voltage of 1.48 volts, so that efficiency falls as cell voltage rises with current density [9]. The hydrogen-production rate scales linearly with current through Faraday's law, establishing a fundamental trade-off: higher current density increases throughput and reduces capital cost per unit output but lowers efficiency and raises the electricity required per kilogram of hydrogen. The levelized cost of hydrogen (LCOH) was estimated from the capital cost, the capacity factor, the electricity price, and the system efficiency, following established techno-economic frameworks [7], [18].

IV. RESULTS AND DISCUSSION

A. Polarization and Efficiency

Figure 2 shows that at low current density the activation overpotential of the oxygen-evolution reaction dominates, whereas at high current density the ohmic and concentration terms grow and drive the cell voltage upward. Figure 3 translates this into the efficiency-throughput trade-off: voltage efficiency declines from about 88 percent near 0.2 A/cm-squared to roughly 74 percent at 2 A/cm-squared, while the hydrogen-production rate rises in direct proportion to current. The choice of operating point therefore balances the lower capital cost obtained at high current density against the higher electricity consumption it entails, a balance that depends sensitively on the price of electricity [13], [17].

Figure 3: Trade-off between voltage efficiency and hydrogen-production rate as a function of current density.



B. Technology Comparison

Table 1 compares PEM with alkaline and solid-oxide electrolysis across the engineering parameters most relevant to renewable coupling. PEM offers the highest current density and the fastest dynamic response, alkaline the lowest capital cost and longest demonstrated lifetime, and solid-oxide the highest efficiency but the least maturity and poorest load-following ability [4], [8], [10]. For direct coupling to wind and solar, the dynamic agility and pressurized compact design of PEM are decisive advantages, which is why it features prominently in recent large-scale projects [16].

Table 1. Comparison of Water-Electrolysis Technologies

Parameter	Alkaline	PEM	Solid Oxide
Operating temperature (°C)	60–80	50–80	650–850
Current density (A/cm²)	0.2–0.5	1.0–2.5	0.3–1.0
System efficiency (% LHV)	63–71	60–68	75–85
Dynamic response	Slow	Fast	Slow
Maturity	Mature	Commercial	Emerging

C. Levelized Cost of Hydrogen

Figure 4 presents the modeled LCOH as a function of electricity price for three capacity factors. The analysis confirms that electricity cost is the single largest contributor to green-hydrogen cost: at a low capacity factor the fixed capital is spread over little output and the cost is high regardless of electricity price, whereas at a high capacity factor with inexpensive electricity the LCOH approaches the widely cited cost-competitiveness target of about two US dollars per kilogram [7], [19]. Table 2 summarizes the principal cost drivers and the direction in which each must move to reach that target.

Figure 4: Levelized cost of green hydrogen versus electricity price for capacity factors of 30, 50, and 90 percent.

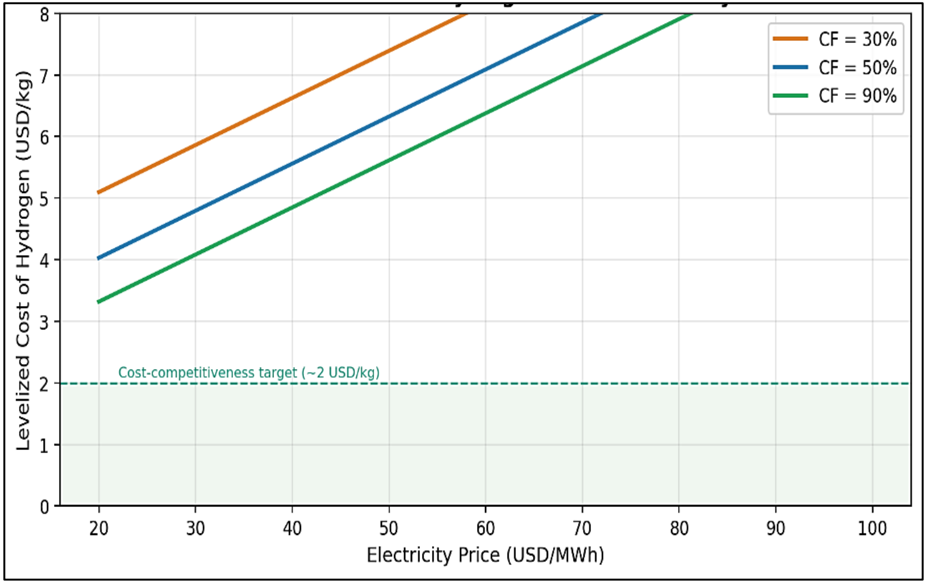


Table 2. Principal Cost Drivers of Green Hydrogen via PEM Electrolysis

Cost Driver	Current Range	Target Direction	Impact on LCOH
Electricity price (USD/MWh)	30–80	Decrease	High
Capacity factor (%)	30–90	Increase	High
Stack capital (USD/kW)	700–1400	Decrease	Medium
System efficiency (% LHV)	60–68	Increase	Medium
Stack lifetime (kh)	40–80	Increase	Medium

D. Durability and Outlook

Beyond efficiency and cost, the durability of the PEM stack governs both the replacement interval and the effective LCOH. Degradation mechanisms include catalyst dissolution, membrane thinning, and passivation of transport layers, which are aggravated by the on-off cycling characteristic of renewable operation [11], [20].

Reducing the loading of scarce iridium catalysts while preserving activity and durability is among the most pressing research challenges for terawatt-scale deployment. The collective trajectory of falling renewable electricity prices, declining stack costs, and improving durability supports the expectation that green hydrogen will become cost-competitive in favorable locations within this decade [3], [19].

V. CONCLUSION

This paper analyzed green hydrogen production by PEM water electrolysis from an engineering perspective. An electrochemical model decomposed the cell voltage into its reversible, activation, ohmic, and concentration components and quantified the trade-off between voltage efficiency, which fell from about 88 percent to 74 percent as current density rose to 2 A/cm-squared, and hydrogen-production rate. A comparison with alkaline and solid-oxide electrolysis confirmed PEM as the technology best matched to direct renewable coupling, and a levelized-cost analysis identified electricity price and capacity factor as the dominant determinants of competitiveness, with green hydrogen approaching the two-dollar-per-kilogram target only under low-cost, high-utilization conditions.

Future work will extend the model to dynamic operation under measured renewable profiles, incorporate degradation-coupled cost models that capture the feedback between cycling and stack lifetime, and evaluate system-level integration with hydrogen storage and downstream industrial demand to optimize the full production chain [16], [18].

REFERENCES

[1] Intergovernmental Panel on Climate Change, Climate Change 2022: Mitigation of Climate Change. Cambridge, U.K.: Cambridge Univ. Press, 2022.

[2] International Energy Agency, The Future of Hydrogen: Seizing Today's Opportunities. Paris, France: IEA, 2019.

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

[4] M. A. Laguna-Bercero, “Recent advances in high temperature electrolysis using solid oxide fuel cells: A review,” J. Power Sources, vol. 203, pp. 4–16, Apr. 2012.

[5] M. Carmo, D. L. Fritz, J. Mergel, and D. Stolten, “A comprehensive review on PEM water electrolysis,” Int. J. Hydrogen Energy, vol. 38, no. 12, pp. 4901–4934, Apr. 2013.

[6] S. A. Grigoriev, V. N. Fateev, D. G. Bessarabov, and P. Millet, “Current status, research trends, and challenges in water electrolysis science and technology,” Int. J. Hydrogen Energy, vol. 45, no. 49, pp. 26036–26058, Oct. 2020.

[7] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, “Future cost and performance of water electrolysis: An expert elicitation study,” Int. J. Hydrogen Energy, vol. 42, no. 52, pp. 30470–30492, Dec. 2017.

[8] A. Ursua, L. M. Gandia, and P. Sanchis, “Hydrogen production from water electrolysis: Current status and future trends,” Proc. IEEE, vol. 100, no. 2, pp. 410–426, Feb. 2012.

[9] K. Zeng and D. Zhang, “Recent progress in alkaline water electrolysis for hydrogen production and applications,” Prog. Energy Combust. Sci., vol. 36, no. 3, pp. 307–326, Jun. 2010.

[10] J. Brauns and T. Turek, “Alkaline water electrolysis powered by renewable energy: A review,” Processes, vol. 8, no. 2, Art. no. 248, Feb. 2020.

[11] M. Bernt, A. Siebel, and H. A. Gasteiger, “Analysis of voltage losses in PEM water electrolyzers with low platinum group metal loadings,” J. Electrochem. Soc., vol. 165, no. 5, pp. F305–F314, 2018.

[12] P. Choi, D. G. Bessarabov, and R. Datta, “A simple model for solid polymer electrolyte (SPE) water electrolysis,” Solid State Ionics, vol. 175, nos. 1–4, pp. 535–539, Nov. 2004.

[13] S. Shiva Kumar and V. Himabindu, “Hydrogen production by PEM water electrolysis – A review,” Mater. Sci. Energy Technol., vol. 2, no. 3, pp. 442–454, Dec. 2019.

[14] B. Yodwong, D. Guilbert, M. Phattanasak, W. Kaewmanee, M. Hinaje, and G. Vitale, “AC–DC converters for electrolyzer applications: State of the art and future challenges,” Electronics, vol. 9, no. 6, Art. no. 912, Jun. 2020.

[15] D. Guilbert and G. Vitale, “Dynamic emulation of a PEM electrolyzer by time constant based exponential model,” Energies, vol. 12, no. 4, Art. no. 750, Feb. 2019.

[16] M. Kopp, D. Coleman, C. Stiller, K. Scheffer, J. Aichinger, and B. Scheppat, “Energiepark Mainz: Technical and economic analysis of the worldwide largest power-to-gas plant with PEM electrolysis,” Int. J. Hydrogen Energy, vol. 42, no. 19, pp. 13311–13320, May 2017.

[17] F. Marangio, M. Santarelli, and M. Cali, “Theoretical model and experimental analysis of a high pressure PEM water electrolyser for hydrogen production,” Int. J. Hydrogen Energy, vol. 34, no. 3, pp. 1143–1158, Feb. 2009.

[18] A. Buttler and H. Spliethoff, “Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review,” Renew. Sustain. Energy Rev., vol. 82, pp. 2440–2454, Feb. 2018.

[19] G. Glenk and S. Reichelstein, “Economics of converting renewable power to hydrogen,” Nat. Energy, vol. 4, no. 3, pp. 216–222, Mar. 2019.

[20] S. M. Alia, S. Stariha, and R. L. Borup, “Electrolyzer durability at low catalyst loading and with dynamic operation,” J. Electrochem. Soc., vol. 166, no. 15, pp. F1164–F1172, 2019.