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Green Hydrogen Production Using Solar-Powered Electrolysis: Nanocatalyst Engineering, System Optimization, and Techno- Economic Assessment for Pakistan

Khitab Ur Rahman

Master student, Chemical Engineering and Technology
Shandong University of Science and Technology Shandong China
Email: khatab@sdust.edu.cn

Imran Hussain

Department of Physics Allama Iqbal Open University Islamabad
himran873@gmail.com

Talha

University of Makran
talha@uomp.edu.pk

ABSTRACT

Pakistan's severe energy security challenges, heavy reliance on imported fossil fuels, and exceptional solar resource base create both urgent necessity and unique opportunity for green hydrogen production via solar-powered electrolysis. This comprehensive review synthesizes recent advances in nanocatalyst engineering, water electrolysis technologies, geospatial planning, and techno-economic assessment specifically tailored for Pakistan's energy transition. The electrochemical water splitting process comprising hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) faces fundamental kinetic barriers that drive research toward earth-abundant transition metal nanocatalysts. Interfacial engineering strategies coupling NiFe-layered double hydroxides with MoS₂ scaffolds, defect engineering introducing oxygen vacancies, and single-atom catalyst architectures (e.g., Ru₁/D-NiFe LDH) demonstrate bifunctional HER/OER activities with overpotentials as low as 18 mV at 10 mA/cm², representing a 14% reduction in specific electrical energy consumption. Technology evaluation reveals critical trade-offs: Alkaline Water Electrolysis offers low capital costs (\$500–800/kW) and extended lifetimes (>80,000 hours) but limited dynamic response, whereas Proton Exchange Membrane Electrolysis provides rapid ramping (10–100%/second) at higher costs (\$1,000–1,500/kW). Geospatial modeling identifies 71,170 km² of suitable land across southern Sindh and Balochistan, yielding a technical green hydrogen potential of 68.96 Mt/year significantly exceeding domestic demand. Techno-economic analysis for a 100 MWp solar PV with 50 MW electrolyzer configuration establishes a baseline Levelized Cost of Hydrogen ranging from \$3.40–\$4.27/kg, with PV oversizing and hybrid electrolyzer architectures identified as critical

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optimization levers. Achieving cost targets below \$2.00/kg by 2030 requires coordinated advances in electrolyzer efficiency (70–74%), solar PV cost reduction (\$400–500/kW), and concessional financing mechanisms (7.5–8.5% WACC), positioning Pakistan as a potential competitive hydrogen supplier in South Asian and global markets.

Keywords— Green hydrogen, solar-powered electrolysis, Pakistan energy transition, nanocatalyst engineering, water splitting electrocatalysts, techno-economic assessment, Levelized Cost of Hydrogen (LCOH), alkaline water electrolysis, proton exchange membrane electrolysis, geospatial suitability, renewable energy policy

1. Introduction

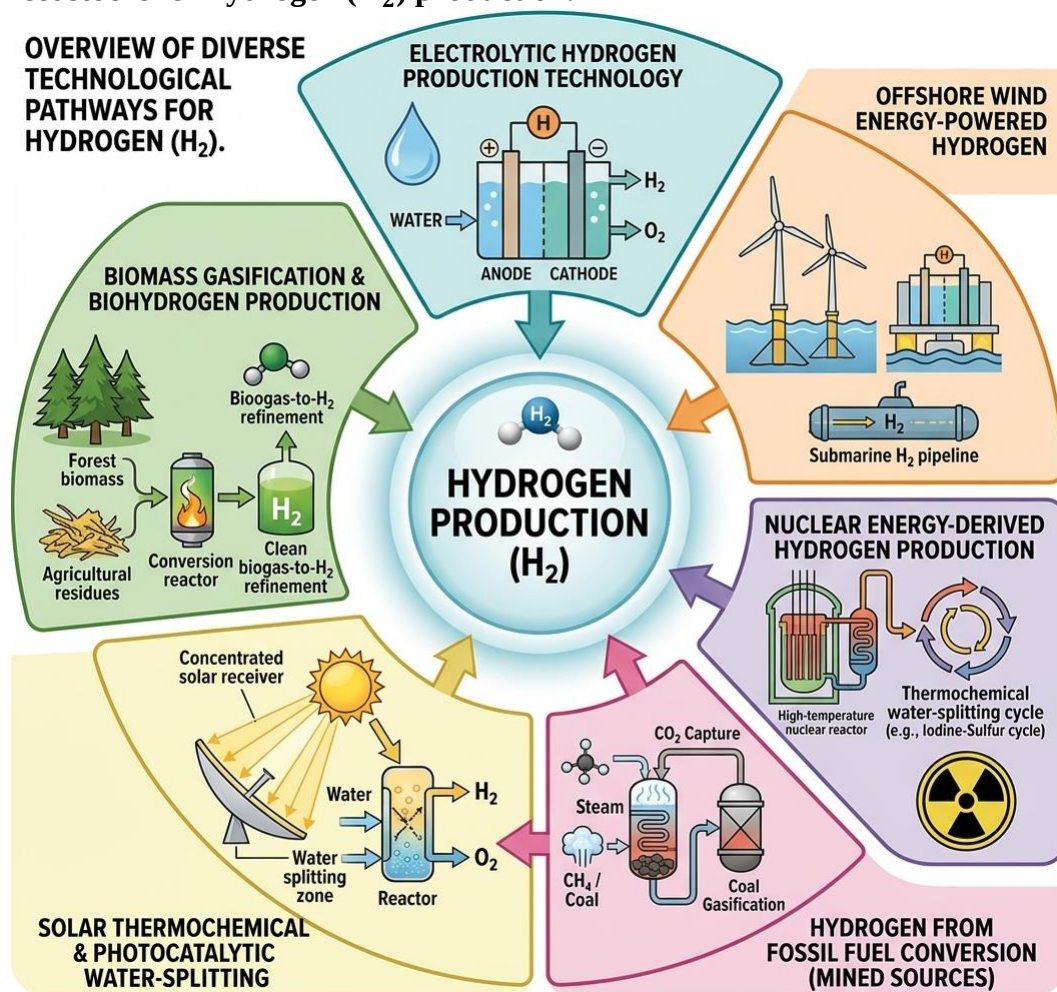
The global transition toward sustainable energy systems has positioned green hydrogen as a central zero-emission fuel and chemical feedstock capable of deep decarbonization across hard-to-abate sectors, including heavy transport, chemical synthesis, steelmaking, and seasonal energy storage (Algburi et al., 2025). Green hydrogen produced via water electrolysis powered exclusively by renewable energy sources offers a carbon-neutral energy vector that bridges variable renewable electricity generation with continuous industrial energy demand. Among the various renewable production pathways, solar photovoltaic (PV)-powered electrolysis is particularly attractive in regions endowed with high solar irradiance (Pathak et al., 2025).

Pakistan faces severe structural energy security challenges, high reliance on imported fossil fuels, and extreme vulnerability to climate change impacts. The national power generation architecture relies heavily on thermal sources (63%), with hydroelectricity contributing 25% and non-hydro renewable energy accounting for only 5.4%. To mitigate foreign exchange drain, reduce grid instability, and meet environmental obligations, the Government of Pakistan formulated the Alternative and Renewable Energy (ARE) Policy 2019 (Kundu et al., 2026). This policy framework sets explicit targets to achieve a 20% renewable energy generation capacity share by 2025 and 30% by 2030, which, when combined with hydroelectricity, targets a 60% clean power share. Pakistan possesses an exceptional solar resource base, receiving an average solar insolation of 5.5 kWh/m²/day and experiencing 8 to 10 hours of daily sunshine. Utilizing approximately 0.071% of Pakistan's total land area for solar PV generation could theoretically fulfill the nation's total domestic electricity demand (Elegbeleye et al., 2025).

Despite this theoretical resource base, the large-scale deployment of solar-driven green hydrogen systems remains constrained by the mismatch between intermittent solar supply and baseline industrial hydrogen demand, the high capital expenditure (CAPEX) of electrolyzer systems, catalytic kinetic overpotentials, and localized water scarcity. Overcoming these multi-dimensional bottlenecks requires integrated technical optimization, ranging from atomic-level electrocatalyst design to plant-level dynamic coupling and national geospatial planning (Jayachandran et al., 2024). This review provides a comprehensive synthesis of solar-driven green hydrogen production tailored for Pakistan, analyzing nanocatalyst engineering for water splitting, low-temperature

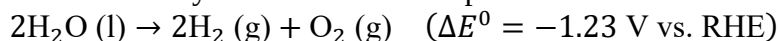
water electrolysis technologies, geospatial site selection, lifetime techno-economics, and strategic policy frameworks (Angelico et al., 2025).

Figure 1: Overview of diverse technological pathways and primary energy feedstocks for hydrogen (H₂) production.



2. Electrocatalyst and Nanocatalyst Engineering for Water Splitting

The electrochemical splitting of water splits molecules into molecular hydrogen and oxygen via two coupled electrochemical half-reactions: the cathodic Hydrogen Evolution Reaction (HER) and the anodic Oxygen Evolution Reaction (OER) (Tüysüz, 2024). The overall thermodynamic reaction is expressed as:



In operational systems, the actual cell voltage (V_{cell}) required to drive electrolysis significantly exceeds the thermodynamic minimum of 1.23 V due to intrinsic kinetic barriers, electrical resistance, and mass transport limitations:

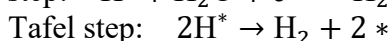
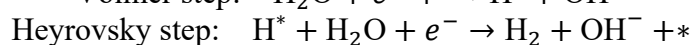
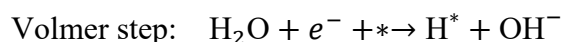
$$V_{\text{cell}} = 1.23 \text{ V} + \eta_{\text{HER}} + \eta_{\text{OER}} + iR_{\text{ohmic}} + \eta_{\text{mass transport}}$$

Where η_{HER} and η_{OER} represent the overpotentials of the cathode and anode reactions,

respectively, iR_{ohmic} denotes the internal ohmic drop across the membrane and electrolyte, and $\eta_{\text{mass transport}}$ accounts for concentration polarization at high operational current densities (Quan et al., 2024).

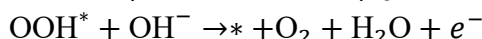
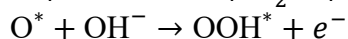
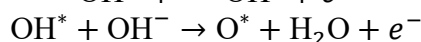
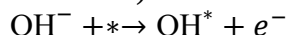
2.1 Reaction Kinetics and Catalytic Overpotentials

The HER pathway in alkaline media proceeds through a two-step reaction mechanism comprising the initial Volmer adsorption step followed by either the Heyrovsky or Tafel desorption steps:



Where $*$ denotes an active catalytic surface site and H^* represents adsorbed atomic hydrogen. In alkaline media, the additional energy barrier associated with breaking the H-OH bond during the initial Volmer step causes alkaline HER kinetics to be two to three orders of magnitude slower than in acidic media, making water dissociation the rate-determining step (Zou & Zhang, 2015).

The anodic OER is a complex four-electron transfer process involving sequential intermediate species (OH^* , O^* , and OOH^*):



Catalytic OER activity is governed by the Sabatier principle, where the binding free energy difference ($\Delta G_{\text{O}^*} - \Delta G_{\text{OH}^*}$) serves as a primary thermodynamic descriptor forming a volcano-shaped relationship with experimental reaction rates. Optimal catalytic activity occurs near the volcano apex, balancing intermediate adsorption and product release (Hayat et al., 2023).

2.2 Earth-Abundant Nanocatalyst Engineering Strategies

Platinum-group metals (PGMs) such as platinum (Pt/C) for HER and iridium/ruthenium oxides ($\text{IrO}_2/\text{RuO}_2$) for OER represent benchmark electrocatalysts. However, their extreme scarcity, high cost, and rapid dissolution under dynamic operational regimes severely restrict commercial scalability. Consequently, engineering nanostructured electrocatalysts based on Earth-abundant 3d transition metals (Ni, Fe, Co, Mo) has become essential for economical overall water splitting (Wang & Astruc, 2017).

Transition-metal layered double hydroxides (LDHs), particularly nickel-iron layered double hydroxide (NiFe-LDH), display exceptional intrinsic activity for the OER in alkaline environments due to favorable surface redox states and optimized intermediate adsorption energetics. Pure NiFe-LDH, however, suffers from poor electrical conductivity and sluggish HER kinetics, which limits its standalone performance as a bifunctional catalyst (Guo et al., 2024).

To overcome these intrinsic material limitations, interfacial engineering strategies have been developed to tune electronic density and surface reactivity. Coupling distinct catalytic phases such as assembling NiFe-LDH nanosheets onto molybdenum disulfide (MoS_2) scaffolds creates built-in electric fields across heterogeneous interfaces. The

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MoS₂ phase accelerates initial water cleavage, supplying protons to adjacent active sites, while the NiFe-LDH phase optimizes intermediate hydroxide adsorption, yielding bifunctional HER/OER activity (Bullock et al., 2020).

Concurrently, defect engineering and amorphization introduce oxygen vacancies or cation defects into crystalline structures, altering the localized electronic density of states, increasing electrical conductivity, and exposing a higher density of active surface sites. Chemical reduction treatments convert rigid crystalline domains into reactive amorphous/crystalline hybrid interfaces (Chen et al., 2023). Furthermore, anchoring isolated single metal atoms (such as single-atom Ru or Pt) onto nanostructured supports minimizes precious metal loading while maximizing atom utilization efficiency. For example, single-atom ruthenium stabilized on defective NiFe-LDH (Ru₁/D-NiFe LDH) achieves low HER overpotentials by optimizing intermediate hydrogen adsorption Gibbs free energy (ΔG_{H^*}) near zero (Kaushik & Moores, 2017).

Table 1: Electrocatalyst Performance Metrics for HER and OER in Alkaline Media

Electrocatalyst Architecture	Target Half-Reaction	Overpotential at 10 mA/cm ² (η_{10} , mV)	Tafel Slope (mV/dec)	Operating Durability (Hours)	Key Performance Enhancement Mechanism
Commercial Pt/C (20 wt%)	HER	35–45	30–38	24–48	High intrinsic reactivity; optimal ΔG_{H^*} binding energetics
Commercial IrO ₂	OER	290–310	65–75	12–24	Optimal intermediate binding; high dissolution under transient loads
Pristine NiFe-LDH	OER	280–310	60–70	50–100	Efficient O-O coupling; limited by baseline electrical

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					conductivity
Amorphous/Crystalline NiFe-LDH	OER	223	52	>100	Oxygen vacancy defects enhance electron transport and active site exposure
Hierarchical MoS ₂ /NiFe-LDH	HER / OER (Bifunctional)	98 (HER) / 225 (OER)	48 / 55	>80	Interfacial charge transfer accelerates Volmer step during alkaline HER
Single-Atom Ru ₁ /D-NiFe LDH	HER / OER (Bifunctional)	18 (HER) / 195 (OER)	28 / 42	>100	Isolated atomic Ru sites tune local coordination and lower H [*] desorption barriers
Quaternary NiFeCrCo-LDH	HER / OER (Bifunctional)	145 (HER) / 181 (OER)	41 / 46	>100	Multi-metallic entropy tuning optimizes electronic structure across sites

Atomic-scale electron transport tuning directly governs system-level energy consumption. Reducing the operational cell voltage of an industrial electrolyzer stack at 500 mA/cm² from 2.00 V down to 1.72 V achievable via defect-engineered single-atom catalysts corresponds to a 14% direct reduction in specific electrical energy consumption per kilogram of hydrogen produced. At megawatt scale, this kinetic enhancement yields major operating cost savings, directly altering downstream economic viability (Zia et al., 2026).

3. Water Electrolysis Technologies and System Optimization

Selecting and optimizing water electrolysis technology is critical for coupling water splitting units with variable solar photovoltaic power systems. Four primary low- and high-temperature water electrolysis technologies exist: Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Electrolysis (PEMWE), Anion Exchange Membrane Electrolysis (AEMWE), and Solid Oxide Electrolysis Cells (SOEC) (Al-Mandhari et al., 2026).

3.1 Technology Evaluation and Operational Trade-Offs

Alkaline Water Electrolysis (AWE) represents the most mature technology, utilizing non-precious nickel and iron electrocatalysts suspended in liquid potassium hydroxide (KOH, 20–40 wt%) with a porous diaphragm separator. AWE benefits from low capital costs (\$500 – \$800/kW) and extended stack lifetimes exceeding 80,000 hours. However, liquid electrolyte inertia and bubble accumulation limit its dynamic ramping rates and operational range (typically 20%–100% of nominal load). Rapid solar irradiance fluctuations can push AWE units below minimal load thresholds, risk gas crossover and efficiency loss unless buffered by power electronics or battery storage (Pretel et al., 2015).

Proton Exchange Membrane Electrolysis (PEMWE) utilizes a solid acidic polymer electrolyte membrane and noble metal catalysts (Pt cathode, IrO₂ anode). PEMWE operates at high current densities (1.0 – 2.0 A/cm²) and offers rapid dynamic response times measured in seconds. This dynamic capability allows PEMWE to follow real-time solar PV generation curves. However, high stack CAPEX (\$1,000 – \$1,500/kW), expensive titanium bipolar plates, and shorter stack lifetimes (40,000–50,000 hours) increase overall lifetime baseline costs (McJunkin et al., 2024).

Anion Exchange Membrane Electrolysis (AEMWE) is designed to combine the advantages of AWE and PEMWE. Operating with an anion-conductive polymer membrane in pure water or dilute alkaline solutions (0.1 M KOH), AEMWE uses non-precious transition metal catalysts while retaining high current density, differential pressure operation (up to 30 bar), and fast dynamic response characteristics. While membrane stability under basic regimes remains an active area of development, AEMWE provides a promising low-cost pathway for variable renewable energy integration (Vásquez et al., 2025).

Solid Oxide Electrolysis Cells (SOEC) operate at high temperatures (500 – 1,000°C) using ceramic solid oxide electrolytes. High-temperature operation drastically lowers electrical energy requirements by substituting electrical energy with industrial waste heat or concentrated solar thermal energy, yielding system efficiencies exceeding 85%. However, intense thermal stress, long warm-up times, and susceptibility to thermal cycling make standalone SOECs less suitable for direct coupling with variable, non-baseload solar PV plants (Seferagić et al., 2020).

Figure 1: Schematic diagram of a direct solar photovoltaic (PV)-powered polymer electrolyte membrane (PEM) water electrolysis system for hydrogen and oxygen generation.

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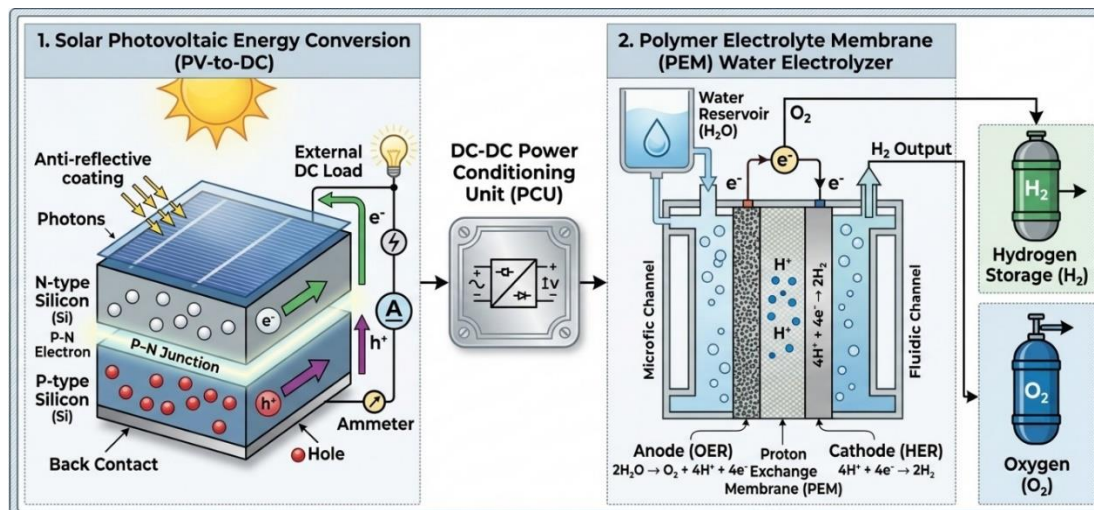


Table 2: Technical and Operational Characteristics of Water Electrolysis Technologies

Technical Parameter	Alkaline Water Electrolysis (AWE)	Proton Exchange Membrane (PEMWE)	Anion Exchange Membrane (AEMWE)	Solid Oxide Electrolysis (SOEC)
Operating Temperature (°C)	60–80	50–80	50–80	500–1,000
Operating Pressure (bar)	1–30	30–80	1–30	1–10
Current Density (A/cm ²)	0.2–0.6	1.0–2.0	0.4–1.0	0.3–1.0
Lower Heating Value Efficiency (%)	62–70	67–75	65–72	80–90 (with heat)
Dynamic Cold Start Time	30–60 minutes	5–15 minutes	5–15 minutes	Hours
Dynamic Ramp Rate (%/second)	0.2–1.0	10–100	10–50	<0.1
Catalytic Material Base	Non-precious (Ni, Fe)	Noble metals (Pt, IrO ₂)	Non-precious (Ni, Fe, Co)	Non-precious ceramics / Perovskites
Estimated Stack CAPEX (\$/kW)	500–800	1,000–1,500	600–1,000	1,500–2,500
Stack Lifetime	>80,000	40,000–50,000	20,000–	10,000–

(Operating Hours)			40,000	30,000
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3.2 System Optimization, Intermittency Management, and PV Oversizing

Coupling variable solar PV capacity directly with water electrolysis units presents a core operational challenge: solar diurnal cycles and cloud transients lead to low annual electrolyzer capacity factors (typically 20%–25% without storage). Because electrolyzer CAPEX represents a substantial component of total system Net Present Cost (NPC), running electrolyzers at low-capacity factors increases capital debt servicing per unit of produced hydrogen (Al-Mandhari et al., 2026).

To optimize system efficiency and economics, system architects utilize strategic PV oversizing relative to electrolyzer capacity. Oversizing the DC solar PV capacity relative to the electrolyzer nameplate capacity (for instance, configuring a 100 MWp PV array with a 50 MW electrolyzer stack, establishing a PV-to-electrolyzer capacity ratio of 2.0) extends the daily operating window during which the electrolyzer runs at full 100% capacity. Although midday solar oversizing leads to intentional power curtailment or requires secondary battery storage capture, it increases electrolyzer utilization hours per year. This higher capacity factor lowers overall levelized hydrogen production costs (Dou et al., 2026).

An emerging system architecture couples low-cost AWE stacks with dynamic PEMWE or AEMWE units to form a hybrid electrolyzer plant. In this configuration, baseline steady solar power feeds the lower-cost AWE units, while rapid power transients and peak solar spikes are absorbed by the flexible PEMWE/AEMWE units. This hybrid approach improves plant load factors while protecting capital-intensive hardware from accelerated dynamic degradation (Oyakhilome & Koffa, 2026).

3.3 Upstream Water Supply via Seawater Desalination

Water is the primary chemical feedstock for green hydrogen synthesis. Stoichiometrically, splitting water requires 8.93 kg of pure, demineralized water per kilogram of hydrogen generated ($2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$). Considering practical system purging, water treatment efficiency losses, and cooling stack requirements, actual system water consumption ranges between 10 and 15 kg H_2O /kg H_2 (Incer-Valverde et al., 2023).

In hyper-arid, water-stressed regions suitable for solar production, relying on scarce local freshwater or groundwater supplies is unsustainable. Integrating Reverse Osmosis (RO) seawater desalination provides a viable, scalable water feedstock solution for coastal deployments. Modern seawater RO desalination systems operate at specific energy consumptions of 3.0 – 4.0 kWh/m³ of produced freshwater, operating at recovery ratios of roughly 30%–40% (Moon et al., 2025).

Techno-economic modeling reveals that integrating seawater RO desalination units into solar-hydrogen production hubs adds minimal cost to overall hydrogen generation. Desalinated water production costs typically average \$0.80 – \$1.20/m³ (\$0.0008 – \$0.0012/kg H_2O). Consequently, the water feedstock cost including seawater intake, multi-stage RO filtration, polishing demineralization, and environmental brine treatment contributes less than \$0.02 – \$0.05/kg to the final Levelized Cost of

Hydrogen (LCOH). This accounts for less than 1.5% of overall hydrogen production costs. Thus, water scarcity does not present an economic barrier to green hydrogen production in coastal, hyper-arid regions (Rödl, 2024).

4. Geospatial, Technological, and Environmental Dynamics in Pakistan

4.1 Geospatial Land Suitability and Resource Clustering

High-resolution Geographic Information System (GIS) modeling reveals that approximately 8.07% of Pakistan's total land area (equating to roughly 71,170 km²) meets land suitability and environmental criteria for utility-scale solar green hydrogen production facilities. Geospatial exclusion criteria account for topography, slope limits (<5%), proximity to road and power transmission infrastructure, water access, ecological buffer zones, and localized water stress parameters (Cao et al., 2024).

The spatial distribution of suitable land is concentrated in continuous geographical clusters ranging from 1,000 km² to 4,000 km² across southern Sindh and southern/western Balochistan. The Southern Sindh Corridor (including Thatta, Badin, and Hyderabad) is characterized by high solar irradiance, flat topography, proximity to Port Qasim, and access to both Arabian Sea water resources and existing national transport infrastructure. Concurrently, the Balochistan Coastal and Inland Basins (including Gwadar, Pasni, and Chagai) possess global horizontal irradiance (GHI) exceeding 2,100 kWh/m²/year and vast uninhabited land areas ideal for multi-gigawatt utility-scale solar-hydrogen production hubs (Toba et al., 2023). Geospatial modeling indicates that Pakistan possesses a technical green hydrogen production potential of 68.96 million metric tons per year (Mt/year), significantly exceeding domestic energy demand and positioning Pakistan as a potential competitive hydrogen supplier in South Asia and global export markets (Laasasenaho et al., 2019).

4.2 Climate Interactions and Seasonal Variability

System performance modeled across Pakistan's geographic zones must account for microclimatic conditions, seasonal ambient temperature shifts, and dust accumulation. High ambient summer temperatures in inland Balochistan and Sindh (frequently exceeding 40 – 45°C) induce thermal derating in PV modules, reducing peak daytime voltage output. Furthermore, monsoon weather systems introduce seasonal solar variations (Anwar et al., 2025). Analysis reveals a drop in monthly solar power production during the summer monsoon period (June through September). Solar yield drops during these wet months reduce electrolyzer load factors. Mitigating this seasonal drop requires hybridizing solar PV installations with coastal wind turbines capitalizing on the heavy summer coastal wind corridor in Sindh and Balochistan or maintaining auxiliary energy storage capacity to stabilize year-round production outputs (Saleem et al., 2025).

4.3 Environmental Life Cycle Assessment (LCA) and Sectoral Decarbonization

A cradle-to-grave Life Cycle Assessment (LCA) demonstrates that shifting from gray hydrogen (produced via natural gas Steam Methane Reforming, generating 9 – 12 kg CO₂/kg H₂) to solar-powered electrolysis in Pakistan yields environmental benefits. Realizing Pakistan's technical green hydrogen yield of 68.96 Mt/year offers

an annual greenhouse gas reduction potential of 308.0 Mt of CO₂-equivalent emissions (Baumgärtner et al., 2021).

This emissions reduction capacity aligns with domestic decarbonization targets across several key national sectors. Pakistan's agriculture sector depends heavily on nitrogenous fertilizers (urea). Replacing domestic fossil-gas-derived gray hydrogen with solar green hydrogen for green ammonia synthesis eliminates process-level carbon emissions while shielding agricultural supply chains from volatile imported gas prices. Concurrently, displacing high-sulfur diesel fuel in heavy transport and natural gas in steelmaking with green hydrogen reduces localized air pollution and cuts industrial emissions. Finally, converting green hydrogen into green ammonia or methanol enables clean energy transport via Port Qasim and Gwadar, positioning Pakistan to comply with international carbon policies such as the European Union's Carbon Border Adjustment Mechanism (CBAM) (Bach, 2023).

5. Techno-Economic Assessment and Policy Roadmap for Pakistan

5.1 Discounted Cash Flow Modeling and LCOH Formulations

Evaluating the economic feasibility of solar-powered green hydrogen facilities relies on a discounted cash flow architecture to determine the Levelized Cost of Hydrogen (LCOH) in U.S. dollars per kilogram (\$/kg H₂). LCOH reflects the minimum price at which hydrogen must be sold to offset total lifetime project expenditures over an operational life of N years (Galevskiy & Qian, 2025).

$$\text{LCOH} = \frac{\sum_{n=0}^N \frac{\text{CAPEX}_n + \text{OPEX}_n}{(1+r)^n}}{\sum_{n=1}^N \frac{\text{TH}_n}{(1+r)^n}}$$

Where CAPEX_n represents total capital investment expenditure in year n , OPEX_n represents operational and maintenance expenditures (including stack replacement costs, water feedstock, and insurance), TH_n is the annual metric mass yield of hydrogen produced (kg H₂), and r denotes the real discount rate / Weighted Average Cost of Capital (WACC) (Ishimoto et al., 2024).

5.2 Capital Cost Allocation and Net Present Cost (NPC) Structure

Financial modeling of a baseline 100 MWp solar PV plant integrated with a 50 MW water electrolyzer and storage system establishes an overall 20-year Net Present Cost (NPC) of approximately \$285 million. Annual hydrogen yield for this plant configuration ranges between 2,850 and 3,600 metric tons/year, achieving an overall system solar-to-hydrogen efficiency of ~12% (Algburi et al., 2025).

The solar PV installation represents the largest investment component at \$150 million (~53% of NPC), followed by the electrolyzer plant at \$90 million (~32% of NPC, including periodic stack overhauls every 8 to 10 years). Hydrogen compression and storage systems account for \$35 million (~12%), while ongoing operational and maintenance (O&M) activities represent \$10 million (~3%). Under contemporary financial parameters in Pakistan, the baseline LCOH spans \$3.40 to \$4.27/kg H₂. Alkaline electrolyzers currently deliver a lower average LCOH (\$3.40 – \$3.90/kg) compared to PEMWE units (\$3.80 – \$4.27/kg) due to lower initial stack capex

(Pathak et al., 2025).

Table 3: Baseline Techno-Economic Parameters and LCOH Sensitivity Breakdown for Solar-Hydrogen Systems in Pakistan

Economic / Technical Variable	Baseline Scenario (2024–2025)	Moderate Technology Target (2030)	Advanced Long-Term Target (2050)	Impact Magnitude on LCOH
Solar PV Installed CAPEX (\$/kWp)	600–750	400–500	250–350	Very High (PV accounts for ~53% of NPC)
Electrolyzer System CAPEX (\$/kW)	700–1,200	350–500	150–250	High (Electrolyzer accounts for ~32% of NPC)
System WACC / Discount Rate (r , %)	10.0–12.0	7.5–8.5	5.0–6.0	Critical (1% WACC shift alters LCOH by ~8–10%)
Annual Solar PV Yield (kWh/kWp/year)	1,800–2,100	2,000–2,200	2,100–2,300	High (Directly governs capacity factor)
Stack Operational Efficiency (LHV, %)	63–68	70–74	75–80	Moderate (Reduces required PV nameplate capacity)
Modeled Levelized Cost (LCOH, \$/kg H ₂)	\$3.40–\$4.27	\$2.10–\$2.80	\$1.20–\$1.75	Primary Economic Performance Output

5.3 Second-Order Economic Insights and Financial Sensitivity Analysis

Analyzing LCOH sensitivities reveals critical economic trade-offs for project developers. Green hydrogen assets are front-loaded capital investments. In developing economies like Pakistan, macroeconomic factors and perceived sovereign risk elevate debt interest rates, driving discount rates (WACC) to 10%–12%. Modeling demonstrates that a 2% increase in project WACC raises LCOH by roughly \$0.40 – \$0.50/kg H₂, often exceeding the total cost impact of technological efficiency gains. Establishing concessional debt facilities or international climate risk guarantees is therefore essential for project bankability (Hayat et al., 2023).

Concurrently, optimizing PV-to-electrolyzer capacity ratios presents an operational lever. While oversizing PV arrays causes power curtailment during peak midday periods, it increases total electrolyzer full-load operation from ~2,000 hours to over 3,500 hours annually. This higher utilization spreads fixed electrolyzer capital

amortization costs over a larger volume of produced hydrogen, driving down net LCOH despite raw energy curtailment losses (Kaushik & Moores, 2017).

5.4 Governance Framework, Policy Barriers, and Strategic Roadmap

Deploying green hydrogen infrastructure in Pakistan requires resolving key regulatory, institutional, and policy bottlenecks. Current policy challenges center on fragmented institutional oversight divided across multiple federal bodies, including the Alternative Energy Development Board (AEDB), the Power Purchase and Infrastructure Board (PPIB), and the National Electric Power Regulatory Authority (NEPRA) (Hayat et al., 2023). Integrating these bodies into a unified governance framework is necessary to streamline permitting for large-scale solar-hydrogen facilities. Concurrently, existing power grid regulations lack clear, low-cost green wheeling tariffs (Angelico et al., 2025). Without dedicated wheeling provisions, off-grid or semi-grid-connected solar-hydrogen facilities face high transmission charges when transferring energy between generation sites and industrial demand centers. Furthermore, while they ARE Policy 2019 establishes general renewable capacity targets (30% by 2030), Pakistan lacks a dedicated national green hydrogen roadmap specifying production mandates, blending targets for natural gas networks, or export standards (Kundu et al., 2026).

Conclusion

The transition toward solar-powered green hydrogen production in Pakistan represents both a technical imperative and economic opportunity to address the nation's structural energy insecurity, foreign exchange drain from fossil fuel imports, and climate change vulnerabilities. This comprehensive review establishes that Pakistan possesses exceptional solar irradiance (5.5 kWh/m²/day) and vast geospatial land resources (71,170 km² suitable) capable of generating 68.96 Mt/year of green hydrogen substantially exceeding domestic demand and unlocking export potential. However, realizing this potential requires coordinated advances across three interconnected domains: nanocatalyst engineering, electrolysis system optimization, and techno-economic policy frameworks. At the atomic scale, earth-abundant nanocatalysts based on Ni, Fe, Co, and Mo have emerged as viable alternatives to platinum-group metals, with interfacial engineering, defect chemistry, and single-atom anchoring strategies demonstrating HER overpotentials as low as 18 mV and OER overpotentials of 195 mV at 10 mA/cm². These advances translate directly to system-level energy savings: reducing industrial electrolyzer cell voltage from 2.00 V to 1.72 V at 500 mA/cm² corresponds to a 14% reduction in electrical energy consumption per kilogram of hydrogen a critical lever for techno-economic viability. The bifunctional catalyst architectures that integrate HER- and OER-active phases into monolithic electrodes promise simplified cell designs and reduced manufacturing complexity, accelerating commercial deployment. At the systems engineering level, matching electrolyzer technology to solar PV intermittency remains the central operational challenge. Alkaline water electrolysis provides the lowest capital cost (\$500–800/kW) and longest stack lifetime (>80,000 hours) but suffers from limited dynamic range (20–100% load) and slow ramp rates (0.2–1.0%/second). Proton exchange membrane electrolysis enables rapid dynamic response (10–100%/second) at substantially higher capital costs (\$1,000–1,500/kW) and reduced lifetimes (40,000–50,000 hours). The emerging hybrid

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architecture coupling low-cost AWE for baseload solar production with flexible PEMWE or AEMWE for transient capture offers an optimal pathway that maximizes annual capacity factors while protecting capital-intensive hardware from degradation. Strategic PV oversizing (PV-to-electrolyzer ratios of 2.0) extends electrolyzer full-load operation from ~2,000 to >3,500 hours annually, reducing fixed cost amortization despite midday power curtailment. Integration of reverse osmosis seawater desalination adds negligible cost (<\$0.05/kg H₂) to coastal deployments, effectively decoupling hydrogen production from Pakistan's water-stressed inland regions. The techno-economic assessment establishes that baseline Levelized Cost of Hydrogen ranges from \$3.40–\$4.27/kg for a 100 MWp solar PV with 50 MW electrolyzer plant, with solar PV installation representing 53% of net present cost, electrolyzer systems accounting for 32%, and compression/storage contributing 12%. Financial sensitivity analysis reveals that a 2% increase in project weighted average cost of capital driven by perceived sovereign risk in developing economies raises LCOH by \$0.40–\$0.50/kg, often exceeding the total impact of technological efficiency gains. This underscores the critical importance of concessional debt facilities, international climate risk guarantees, and blended finance mechanisms to reduce financing costs and enable bankable project economics. The projected cost trajectory declining to \$2.10–\$2.80/kg by 2030 and \$1.20–\$1.75/kg by 2050 positions Pakistan competitively in emerging hydrogen markets, provided policy frameworks align with technology deployment. Strategic policy recommendations emerge from this integrated analysis: (1) establishing a unified national green hydrogen governance framework that consolidates oversight across the Alternative Energy Development Board, Power Purchase and Infrastructure Board, and National Electric Power Regulatory Authority; (2) implementing dedicated green wheeling tariffs to enable cost-effective power transmission from solar-rich provinces (Sindh and Balochistan) to industrial demand centers; (3) developing a national green hydrogen roadmap specifying production mandates, natural gas blending targets, and export quality standards; (4) prioritizing coastal hydrogen hubs at Port Qasim and Gwadar for integrated solar-wind-hydrogen-desalination clusters; and (5) leveraging carbon border adjustment mechanisms and international climate finance to accelerate project deployment. The convergence of advanced nanocatalyst engineering, optimized electrolysis system architectures, and enabling policy frameworks creates a viable pathway for Pakistan to transform its energy landscape moving from fossil fuel dependence toward a hydrogen-based economy that enhances energy security, reduces greenhouse gas emissions by up to 308 Mt CO₂-equivalent annually, and positions the nation as a competitive green hydrogen supplier in South Asian and global markets. The technical potential is established; the economic trajectory is favorable; the strategic imperative is clear. Realizing this vision requires sustained investment in research and development, public-private partnerships for scaling manufacturing, and international collaboration for knowledge transfer and project finance. Pakistan stands at the threshold of a renewable energy revolution, and green hydrogen powered by its abundant solar resources and enabled by cutting-edge nanocatalysis offers a transformative solution to its energy challenges while contributing meaningfully to global climate action.

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