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Economic Analysis of Hydrogen Production and Storage Systems Utilizing Renewable Energy Sources

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Abstract: By converting to an environmentally friendly energy system, water electrolysis technology based on renewable sources (like solar photovoltaic and wind power) has presented a sustainable route to carbon-neutral hydrogen generation. In this paper, we introduce a complete techno-economic characterization of renewable electric hydrogen production technologies within storage systems. Our review presents existing pricing profiles including electrolysis capital investment costs, renewable energy pricing systems, and operating parameters. We cover various storage forms (compressed gaseous hydrogen, cryogenic liquid hydrogen, geological formations) and three main electrolyzer technology stacks: alkaline electrolyzers (AEL), proton exchange membrane electrolyzers (PEM), and solid oxide electrolysis cells (SOEC). For these reasons, Levelized Cost of Hydrogen (LCOH) is considered the most significant economic indicator of these experiments. With data available that provides a glimpse of the potential cost reductions associated with scale-up of the manufacturing process, technological advancement, and decreasing costs associated with renewable energy, we sought to explore potential cost reductions regarding cost of this process. The total cost of producing low-carbon hydrogen is currently estimated at between $4 and $8 per kilogram, but it is projected to drop to $2 per kilogram by 2040, which is expected to be comparable to the cost of producing hydrogen from fossil fuels. To ensure the success of this technology, it is essential to develop integrated plans that combine, a supportive policy framework and the use of new methods to increase the efficiency of electrolysis, while maintaining reasonable cost-effectiveness, Total costs of producing low-carbon hydrogen.

Keywords: Green Hydrogen, Water Electrolysis, Hydrogen Storage, LCOH (liquid-cost hydrogen), Carbon Decarbonization, Renewable Energy Integration.

Introduction

The international call for a transition to renewable energy has spurred intensive efforts in developing alternative energy carriers for use in situations where direct electrification is difficult. Industries such as heavy industry, long-distance transport, and the development of chemical industries face particular challenges in implementing decarbonization efforts using conventional electrification strategies. In this regard, hydrogen produced using water electrolysis with renewable electricity—or "green hydrogen"—has emerged as a flexible alternative with potential for energy storage and use as a feedstock (International Renewable Energy Agency, 2020a). Unlike conventional hydrogen production methods, such as steam methane reforming, which produce carbon dioxide, hydrogen production by electrolysis is completely carbon-neutral when combined with renewable energy sources. Furthermore, green hydrogen can solve the intermittency problem of variable renewable energy (VRE) systems by providing for seasonal energy storage at scales that cannot be realized through battery strategies (Glenk & Reichelstein, 2019). This dual role of energy delivery and storage makes hydrogen an essential component of future energy architectures. However, large market hydrogen adoption in terms of economic barriers must be addressed. Modern production costs are far more than those related to fossil-based alternatives mainly due to three major drivers: price of renewable energy, capital invested in electrolyzers, and utilization of potential (Schmidt et al., 2017; Fasihi & Bogdanov, 2021). Storage infrastructure is also a significant economic factor that must be thoughtfully assessed. Industrial stakeholders and research institutions have therefore allocated significant resources towards technology innovation, scale of manufacturing, and policy intervention (Hydrogen Council, 2021). Informed decisions for investors, policymakers and technology developers with current and anticipated trajectories about the current and future economic landscape are very much still crucial. This study addresses this need through a systematic techno-economic analysis relating to renewable hydrogen systems.

Objectives:

This study includes the following five main objectives:

- Describe existing electrolysis systems and storage systems with their corresponding cost structures
- Identify and quantify determinants of Levelized Cost of Hydrogen (LCOH)
- Assess contemporary costs and project future cost trajectories across technology pathways
- Examine LCOH sensitivity to critical system parameters
- Delineate economic barriers and pathways toward cost competitiveness with conventional hydrogen production.

Methodology

Economic Assessment Framework

This analysis uses the LCOH (Low-Cost Adjusted Hydrogen) metric, which represents the average cost of producing one kilogram of hydrogen over the project's lifetime. This metric facilitates direct comparison between different production configurations and timeframes. The LCOH formula includes both capital and operating expenditures divided by annual hydrogen production:

$$LCOH = (Capex \times CRF + Opex_{annual}) / H_2\ Production_{annual}$$

Where the Capital Recovery Factor (CRF) annualizes capital expenditure:

$$CRF = [i(1+i)^n] / [(1+i)^n - 1]$$

Here, *i* denotes the discount rate and *n* represents project lifetime in years.

Costs of capital expenditure also consist of cost of electrolyzer stack, balance of plant components (power conditioning units, water treatment, site preparation), as well as installation costs. Capital expenditures for storage infrastructure have separate treatment because they are based on application-specific requirements. Fixed (maintenance, labor, insurance) and variable (electricity, water, consumables) factors are part of operating expenses.

Hydrogen Production Calculation

Annual hydrogen production derives from electrolyzer nameplate capacity, temporal availability, and system efficiency:

$$\boldsymbol{H_2\ Production_{annual} = (P_{nom} \times CF \times 8760)\ /\ SEC}$$

Where:

- P_{nom} = Electrolyzer nominal capacity (kW)
- CF = Capacity factor (fraction of time at nominal operation)
- SEC = Specific energy consumption (kWh/kg H_2)

labor, insurance) and variable elements (electricity consumption, water, consumables).

Key Assumptions and Parameters

- Project Duration: The analysis considers an operational life of 20 to 30 years, including a periodic need to replace stack components contingent on technology maturity.
- Electricity Pricing: Prices are determined by Levelized Cost of Electricity (LCOE) for utility-scale solar PV, or onshore wind installations in resource-rich areas, generally found through power purchase agreements (PPA) or grid connection through renewable energy certificates.
- System efficiency: Values specific to each technology include the energy system efficiency and the auxiliary system loss in terms of specific energy consumption.
- Capacity factor: Represents actual operating hours compared to the theoretical maximum hours and is affected by the availability of renewable energy resources, grid integration capabilities, and market demand cycles.
- Storage Economics: Due to the application-sensitive nature of this study, it analyses each parameter separately--notably, CAPEX ($/kg H_2), and Opex (operational expenses).

Sensitivity Analysis

Sensitivity analysis in this analysis we evaluate the sensitivity of LCOH to five essential parameters:

- Electrolyzer capital cost ($/kW)
- Electricity price ($/kWh)
- Capacity factor (%)

- Discount rate (%)
- System efficiency (kWh/kg H_2) .

This investigation synthesizes publicly available data from authoritative sources:

- International Energy Agency (IEA) reports
- International Renewable Energy Agency (IRENA) publications
- National Renewable Energy Laboratory (NREL) technical databases
- Peer-reviewed scientific literature
- Industry white papers and technical reports

Result and Discussion

Technology Assessment

Electrolyzer Technologies

Table 1 presents a comprehensive comparison of the three principal electrolysis technologies suitable for renewable hydrogen production.

Table 1. Comparative Analysis of Electrolyzer Technologies for Green Hydrogen Production

Feature	Alkaline Electrolyzer (AEL)	Proton Exchange Membrane (PEMEL)	Solid Oxide Electrolyzer (SOEC)
Electrolyte	Liquid KOH solution	Solid polymer membrane (e.g., Nafion)	Solid ceramic (e.g., YSZ)
Operating Temp	60-80°C	50-80°C	700-850°C
Current Density	Medium (0.2-0.4 A/cm²)	High (1-2 A/cm²)	Very High (0.3-2+ A/cm²)
Dynamic Response	Slow (Minutes)	Very Fast (Seconds)	Slow-Moderate (Minutes)
Part-Load Range	Limited (20-100%)	Wide (0-160%)	Limited (TBD)
H_2 Output Pressure	Low (<30 bar)	High (up to 200 bar)	Low-Medium
Impurity Tolerance	High (tolerates some impurities)	Very Low (requires pure water)	Low(susceptible)to contaminants)
Technology Maturity	Mature (Commercial)	Commercializing (Rapidly Scaling)	R&D / Early Commercial
Stack Lifetime (hrs)	60,000-90,000	30,000-80,000 (Improving)	<20,000 (Key R&D Focus)
Capex(2023),$/kW)	700 - 1,100	1,000 - 1,800	>2,500 (Projected)
Efficiency (kWh/kg H_2, LHV)	~48-55	~50-60	~38-45 (High Temp Advantage)
Main Cost Drivers	Stack materials, BoP	Membrane, Platinum catalysts	Ceramic materials, Seals, BoP
Advantages	Low cost, Robust	Fast response, Compact, High pressure	Highest efficiency (theoretical), Potential for heat integration
Challenges	Slow response, Corrosive electrolyte, Low pressure	High cost, Sensitivity to water purity, Precious metals	High temp degradation, Limited lifetime, Thermal cycling

- Alkaline Electrolyzers are the most mature technology with many decades in the industrial environment.
- PEM Electrolyzers provide high dynamic efficiency and are attractive for interfacing with variable renewable technology. They are small enough with high pressure operation to minimize compression needs. However, the higher costs of capital on high cost membrane materials and platinum-group catalysts are currently hindering their full use.
- Solid Oxide Electrolyzers work at high temperature and have the highest potential for economic efficiencies and could work well for integrating industrial waste heat. Yet, high temperature material degradation, shorter stack life, and early stage of commercialization present formidable obstacles to further R&D.

Storage Technologies

Hydrogen storage represents a critical system component with substantial cost implications.

Table 2. Comparative Analysis of Hydrogen Storage Technologies

Technology	**Compressed Gas (CGH_2)**	**Liquid Hydrogen (LH_2)**	**Metal Hydrides**	**Liquid Organic H_2 Carriers (LOHC)**
State	Gas (350-700 bar)	Liquid (-253°C)	Solid	Liquid (Ambient T&P)
Energy Density	Low	Medium	Medium-High	Medium
Vol. Density (kg H_2/m^3)	20-40 (700 bar)	71	50-110	50-60
Scale Suitability	Small-Mid Scale	Mid-Large Scale	Small-Mid Scale	Small-Large Scale
Capex (\$/kg H_2 stored)	High (Tanks)	Very High (Liquefaction + Tanks)	High	Medium-High
Opex (\$/kg H_2)	Medium (Compression)	High (Liquefaction, Boil-off)	Low-Medium	Medium (Dehydrogenation)
Storage Duration	Days-Weeks	Weeks (Boil-off loss)	Months	Months-Years
Energy Losses	Compression (5-15%)	Liquefaction (30-40%)	Charging/Discharging	Dehydrogenation (20-30%)
Applications	Transport, Short-term buffering	Transport, Space, Peak Shaving	Portable, Niche	Transport, Export, Seasonal

- Compressed Gas Storage constitutes the largest application and has the simplest technical and cost advantage, in terms of short-term use. Nevertheless, the pressure rating is associated with significant compression energy requirements and pressure vessel price increases.

- Liquid Hydrogen Storage has better volumetric density, but energy loss during liquefaction is high (30-40%), and it still shows continuous boil-off loss. Excluding specialized applications these components make it unfeasible economically.
- Metal Hydrides allow neutral hydrogen to be absorbed and released in solid-state materials in a reversible manner with very good volumetric density, and also provide long-term stability. However, high material cost and low absorption kinetics limit the market.
- Liquid Organic Hydrogen Carriers present a green solution for the uptake of hydrogen as ambient liquid with existing infrastructure. However, dehydrogenation energy requirements and catalyst costs need further optimization (which shows excellent long-distance transport and seasonal storage potential). Results from Economic Analysis.

Economic Analysis Results

Current LCOH Estimates

Table 3. Levelized Cost of Hydrogen Ranges (2023-2024 Estimates)

Scenario Description	Electrolyzer Type	Storage Included	Capacity Factor (%)	Electricity Cost (\$/kWh)	LCOH Range (\$/kg H_2)	Primary Cost Driver(s)
"Best Case" (Ideal Site)	PEM or AEL	No	>60%	<0.02 (Very low LCOE)	2.5 - 4.0	Electrolyzer Capex/Efficiency
"Average Case" (Good Site)	AEL	No	50-60%	0.03 - 0.04	4.0 - 6.0	Electricity Cost
"Average Case" (Good Site)	PEM	No	50-60%	0.03 - 0.04	4.5 - 7.0	Electricity Cost + Capex
"Higher Cost Case" (Less Ideal)	PEM	No	30-40%	0.05 - 0.07	7.0 - 10.0+	Electricity Cost + Low CF
With Compression Storage (CGH_2, 500 bar)	Any	Yes (CGH_2)	50-60%	0.03 - 0.04	+0.5 - 1.5	Storage Capex/Opex
With Liquefaction Storage (LH_2)	Any	Yes (LH_2)	50-60%	0.03 - 0.04	+2.0 - 4.0+	Liquefaction Capex/Energy
Off-grid w/ Dedicated Renewables & Buffering	AEL/PEM	Yes (Minimal)	~40-50%	N/A (Implicit)	6.0 - 10.0+	High Capex (Renew + Electrolyzer), Low CF
Steam Methane Reforming (SMR) w/CCS (Grey/Blue)	N/A	N/A	>90%	N/A	1.0 - 2.5 (+ CCS cost)	Natural Gas Price, CCS Cost

Sensitivity Analysis

Table 4 quantifies LCOH sensitivity to key system parameters, providing insights for optimization strategies and investment prioritization.

Table 4. Parameter Sensitivity Analysis

(Baseline: AEL, CF=55%, Electricity=$0.035/kWh, Capex=$900/kW, LCOH=$4.5/kg)

Parameter	Change	Impact on LCOH ($/kg)	% Change from Baseline
Electricity Price ($/kWh)	+50% ($0.0525)	~$6.2	+38%
	-50% ($0.0175)	~$2.8	-38%
Electrolyzer Capex ($/kW)	+50% ($1350)	~$5.8	+29%
	-50% ($450)	~$3.2	-29%
Capacity Factor (%)	+50% (82.5%)	~$3.3	-27%
	-50% (27.5%)	~$8.2	+82%
Stack Lifetime (hrs)	+50% (e.g., 90k hrs)	~$4.3	-4%
	-50% (e.g., 30k hrs)	~$4.8	+7%
Discount Rate (%)	+50% (e.g., 9%->13.5%)	~$5.0	+11%
	-50% (e.g., 9%->4.5%)	~$4.0	-11%

Discussion

Sprints for Cost Competitiveness

Reversing the current price gap with fossil-based hydrogen production (around $1.5-2.5/kg for SMR with carbon capture) would take a concerted effort from multiple angles (and) the following:

- Cost-saving of Renewable Energy: Considering that power is the largest source of operating costs with low-cost renewables providing the majority of electricity (usually 50-75% of LCOH), we cannot emphasize enough the importance of low-cost renewable energy. Prospects for solar PV and wind LCOE reductions are expected to persist and be sustained in the region with optimal geotechnicals providing sub-$20/MWh electricity costs by 2030-2035 (IRENA, 2023). Geographical localization of hydrogen manufacturing in regions already rich in renewables may potentially be the most cost-effective option, independent of potential transport costs.
- Cost savings in Electrolyzer: Scale up of manufacturing and technology maturity will drive significant reduction on capital cost. 40-60% of industry reductions expected by 2030 with the potential to go to $300-500/kW for mature technologies (NREL, 2023; IEA, 2023). The reduction of the cost of power (LCOH) caused by these cuts would have a relatively big cost reduction of LCOH between $1-1.5/kg with the operating condition.
- Maximize capacity factor: A challenge and opportunity for maximizing electrolyzer usage. Systems connected to the grid have the potential to have higher capacity factors, but are subject to an uneven electricity price structure. However, dedicated renewable systems incur greater utilization (usually around 30–50% for solar while 40–60% for wind) but enjoy better integration. A promising compromise that may reach 60–70% of

capacity factors lies in hybrid configurations, where a number of renewable sources were combined, with minimal amounts of storage added.

- Improved operational efficiency is achieved from incremental efficiency improvements which are individually modest but combined lead to cost savings. PEM and SOEC technologies in particular have promising advancement potential via improved catalysts, membrane preparation, and thermal balance tuning.
- Learning effects and scale economies: Past trials in solar PV and wind show a significant reduction in cost through the accumulation of production volumes. Learn rates similar to those for electrolyzers also indicate that cost decreases as the company expands its production from current megawatt-scale to gigawatt-scale facilities will continue.

Storage infrastructure imposes large additional costs

yet in an entirely different manner depending on the type of technology chosen, requirements for its use, etc. Compressed gas storage provides the most economical option for daily or weekly buffering, with an approximate cost of \$0.5-1.5/kg on the LCOH. Long-duration storage or applications needing a much larger volume density may require alternative methods. Geological storage, however, in salt caverns—which is not fully investigated in this research—may also offer lower costs for very large size long-duration storage. However, such installations may not be easy to get started with but benefit from an overall low energy requirement to run for the duration of days and days to come.

Policy and Market Matters.

The economic feasibility needs to be measured not just from the cost of production. The commercial application is also significantly influenced by several non-technical aspects:

- Carbon pricing frameworks and regulatory systems. Carbon pricing support or regulatory controls play a key role in increasing the competitiveness of green hydrogen compared to fossil fuels. High carbon costs, exceeding US\$50-75/ton of CO2, have begun to offset the cost differences under suitable production conditions.
- Policy levers like offtake accords or compulsory hydrogen blending can act as risk mitigators for investors or financing opportunities at a discount.
- Production capacity — the development of hydrogen distribution and usage infrastructure takes coordination.
- The geospatial clustering of production and consumption can reduce the initial infrastructure requirements during deployments.

Future Outlook

Projections from various organizations (the International Energy Agency, the International Renewable Energy Agency, the National Renewable Energy Laboratory, the Hydrogen Council, and others) point to the same conclusions: the price of hydrogen will fall to \$2–3/kg by 2030 and could even drop below \$2/kg by 2040 under an optimistic scenario. Without carbon pricing, these costs could remain competitive with fossil fuel-based alternatives, incentivizing widespread adoption. However, achieving these projections requires sustained progress in all the areas mentioned above, but this cannot be accomplished in isolation. Geographical disparities will persist, with sites boasting exceptional renewable resources receiving less funding than others, and location-based demand in areas far from nearby demand achieving competitiveness many years before less fortunate locations.

Conclusion

This technical and economic study of renewable hydrogen production systems yields several key findings:

- Electricity economics prevail: Between 50% and 75% of the total cost of hydrogen production comes from renewable sources. This makes inexpensive renewable resources the most important factor determining commercial viability. This means that a solar site cost less than \$0.02/kWh can produce hydrogen for \$2.5-4.0/kg with current technology.
- Electrolyzer capital costs remain high but recoverable: The existing commercial technologies, for example, costs \$700-1,800/kW, remain prohibitive. On the manufacturing scale-up side, this figure translates to 40-60% reductions by 2030, but also allows further \$1-1.5/kg LCOH reduction.
- Economics (Capacity Factor) is critical: Low Utilisation also incur high cost penalties, especially in capital sensitive systems. Approaches for >60% capacity factors, in grid connection, hybrid renewable system or modest storage is crucial for financial performance.
- Storage consumes many resources: Although necessary in many applications, storage facilities greatly escalate delivered costs of hydrogen. Short duration applications require compressed gas storage which is the most economical alternative (+\$0.5-1.5/kg), whereas liquefaction results in severe penalties (+\$2-4/kg).
- Cost competitiveness achieved by 2030-2040: Under conditions such as renewable electricity <\$20/MWh, electrolyzer capex \$300-500/kW, better efficiencies, longer stack lifetimes, and high utilization (>60%) and scaling manufacturing and policy support, hydrogen production costs well below \$2/kg can be achieved in parity to fossil-based alternatives.
- Geographical and temporal differences substantial: Regions of outstanding renewable resources with appropriate regulatory regimes will, if combined, come to competition much earlier than average sites so are likely to have first-mover advantages and concentrate investment.
- The transition to economically efficient green hydrogen production is a complex issue requiring coordinated technological, operational, and regulatory innovations. While current costs are two to four times higher than fossil fuel-based alternatives, there is significant potential for cost reduction, which could make green hydrogen a cornerstone of carbon-free energy supply chains within the next 20 years.

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