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A REVIEW OF ECONOMIC TRENDS IN HYDROGEN PRODUCTION TECHNOLOGIES

[1] **Mamta kumari,** [2] **Dr. Devesh kumar**
[1]Research Scholar, Department of Chemistry, Major S.D. Singh University, Farrukhabad, Uttar Pradesh, India
[2]Assistant Professor, Department of Chemistry, Major S.D. Singh University, Farrukhabad, Uttar Pradesh, India
Email - [1] kittu.singh1996birth@gmail.com , [2]devesh2015@gmail.com

Abstract: *India stands at the cusp of a hydrogen revolution, with ambitious targets to become a global hub for green hydrogen production by 2030. This comprehensive review examines the economic trends in hydrogen production technologies within the Indian context, analyzing cost structures, technological pathways, and market dynamics. The paper evaluates various hydrogen production methods including steam methane reforming, coal gasification, and electrolysis technologies (alkaline, PEM, and AEM), with particular emphasis on green hydrogen through renewable energy-powered electrolysis. Current production costs range from $4-6 per kg for green hydrogen, with projections indicating potential reduction to $1-2 per kg by 2030 through technological advancement and scale effects. The National Green Hydrogen Mission's allocation of ₹19,744 crore ($2.4 billion) until 2029-30 demonstrates government commitment to achieving 5 million tonnes annual production capacity. Key challenges include high electrolyzer costs (30-50% of total production cost), infrastructure development, and technology localization. The analysis reveals that alkaline electrolyzers currently offer the most cost-effective solution in the short term, while PEM and AEM technologies show promise for long-term cost reduction. Economic viability depends on achieving renewable energy costs below $0.02/kWh and electrolyzer cost reductions of 46-70% by 2030. This review synthesizes recent developments, policy frameworks, and economic projections to provide insights for stakeholders in India's emerging hydrogen economy.*

Keywords: *Hydrogen production, Green hydrogen, Electrolyzer economics, Indian energy policy, Renewable energy.*

1. INTRODUCTION

The global energy transition toward sustainable and clean alternatives has positioned hydrogen as a critical component in achieving carbon neutrality goals (International Energy Agency, 2021). India, with its commitment to net-zero emissions by 2070 and renewable energy capacity expansion, has emerged as a key player in the global hydrogen economy (Government of India, 2022). The country's abundant renewable energy resources, particularly solar and wind, provide a competitive advantage for green hydrogen production through electrolysis processes (Sharma et al., 2023).

The Indian government's commitment to hydrogen development is evident through the National Green Hydrogen Mission, which received an enhanced allocation of ₹600 crore ($71.93 million) for 2024-25, representing a 102% increase from the previous year's allocation of ₹297 crore (IBEF, 2024). This funding is part of a larger outlay of ₹19,744 crore up to FY 2029-30, underscoring the government's strategic focus on establishing India as a global hydrogen hub (EY India, 2024).

The Indian hydrogen market reached a value of $72.14 million in 2023, with projections indicating growth at a compound annual growth rate (CAGR) of 6.3% (Maximize Market Research, 2024). This growth trajectory reflects increasing industrial demand, policy support, and technological advancements in hydrogen production systems.

The economic viability of hydrogen production technologies remains the primary determinant of large-scale deployment. Current production costs vary significantly across different technological pathways, with grey hydrogen from steam methane reforming costing approximately $1.5-2.5 per kg, while green hydrogen through electrolysis ranges from \$4-6 per kg (IRENA, 2022). Understanding these economic dynamics is crucial for policy formulation, investment decisions, and technology selection in the Indian context.

This review examines the economic trends across various hydrogen production technologies, analyzing cost components, technological trajectories, and market developments specific to India's energy landscape. The paper provides comprehensive insights into current challenges, future opportunities, and strategic pathways for achieving cost-competitive hydrogen production in India.

2.HYDROGEN PRODUCTION TECHNOLOGIES: AN ECONOMIC OVERVIEW

2.1 Classification of Hydrogen Production Technologies

Hydrogen production technologies can be broadly categorized based on their carbon intensity and feedstock sources:

Grey Hydrogen is produced primarily through steam methane reforming (SMR) of natural gas, representing approximately 95% of global hydrogen production (Kumar et al., 2022). The process involves high-temperature reactions between methane and steam, producing hydrogen and carbon dioxide as byproducts. While economically competitive at \$1.5-2.5 per kg, grey hydrogen contributes significantly to greenhouse gas emissions, with each kilogram producing 9-10 kg of CO_2 (Acar & Dincer, 2020).

Blue Hydrogen employs similar production processes as grey hydrogen but incorporates carbon capture, utilization, and storage (CCUS) technologies to reduce emissions. Production costs range from \$2.5-4.0 per kg, with the premium attributed to CCUS infrastructure and operational requirements (IEA, 2021).

Green Hydrogen represents the most sustainable pathway, produced through electrolysis of water using renewable energy sources. Despite higher current costs of \$4-6 per kg, green hydrogen offers zero-emission production and aligns with long-term decarbonization objectives (Rana et al., 2023).

Other pathways include biomass gasification, thermochemical water splitting, and photoelectrochemical processes, though these remain largely at research and demonstration stages with limited commercial deployment (Mehrpooya et al., 2021).

2.2 Cost Structure Analysis

The economic analysis of hydrogen production involves multiple cost components that vary across technologies and scales. For electrolytic hydrogen production, the primary cost drivers include:

Capital Expenditure (CAPEX): Electrolyzer systems represent the largest capital investment, accounting for 30-50% of total project costs (CEEW, 2024). Electrolyzers account for 30-50% of the total cost of green hydrogen production in India, making indigenization of electrolyzer manufacturing critical for cost reduction.

Operational Expenditure (OPEX): Energy costs dominate operational expenses, typically comprising 60-80% of total production costs for electrolytic hydrogen (Buttler & Spliethoff, 2018). Achieving production costs below \$2 per kilogram requires renewable energy costs below \$0.02 per kilowatt hour (World Economic Forum, 2024).

Balance of Plant: Infrastructure components including power electronics, gas purification systems, compression, and storage facilities contribute 20-30% to total capital costs (Schmidt et al., 2017).

Maintenance and Operations: Routine maintenance, replacement of consumables, and operational labor typically account for 2-4% of annual capital costs (Kakoulaki et al., 2021).

2.3 Scale Effects and Learning Curves

Economic viability of hydrogen production technologies demonstrates strong dependency on production scale and cumulative deployment. Learning curve effects indicate potential cost reductions of 15-25% for every doubling of cumulative production capacity (Saba et al., 2018).

Large-scale electrolysis plants (>100 MW) achieve significantly lower levelized costs compared to smaller installations due to economies of scale in equipment procurement, installation, and operation (Proost, 2019). Better system utilization beyond a threshold yields marginal gains only, with lower utilization rates of around 25% requiring approximately 2.5 GW of electrolyzer capacity for a project producing 100 ktpa, whereas increasing utilization to 85% reduces the required capacity by 70% to 720 megawatts (RMI, 2024).

3.ELECTROLYSIS TECHNOLOGIES: TECHNICAL AND ECONOMIC COMPARISON

3.1 Alkaline Electrolysis

Alkaline electrolysis represents the most mature and commercially deployed technology for water splitting, utilizing potassium hydroxide (KOH) or sodium hydroxide (NaOH) electrolytes. The technology offers several economic advantages:

Cost competitiveness: Current capital costs range from $400-1,000 per kW, making it the most affordable electrolysis option (IRENA, 2020). According to model predictions, the cost of hydrogen production of alkaline (ALK) electrolyzers will be 23.85% and 51.59% lower than AEM and PEM technologies in the short term (ScienceDirect, 2023).
Operational stability: Alkaline systems demonstrate excellent long-term stability with operational lifespans exceeding 20-30 years, contributing to favorable lifecycle economics (Carmo et al., 2013).
Technology maturity: Well-established supply chains and manufacturing processes enable cost optimization through standardization and volume production (Schalenbach et al., 2018).
However, alkaline systems face limitations in dynamic operation and lower current densities (200-400 mA/cm²), potentially impacting integration with variable renewable energy sources (Vincent & Bessarabov, 2018).

3.2 Proton Exchange Membrane (PEM) Electrolysis
PEM electrolysis utilizes solid polymer electrolytes, offering superior dynamic response and compact design characteristics. Economic considerations include:
Higher capital costs: Current system costs range from $1,000-2,500 per kW, primarily due to expensive platinum group metal catalysts and specialized membranes (Bertuccioli et al., 2014).
Operational advantages: Higher current densities (1,000-2,000 mA/cm²) and rapid response capabilities enable better integration with intermittent renewable sources (Carmo et al., 2013). By 2030, current densities close to 10A/cm² are expected to become typical for remaining PEM electrolyzer manufacturers (PV Magazine India, 2024).
Cost reduction potential: Under technological advancement or breakthrough, the hydrogen production cost of PEM is expected to be 56.5% lower than current levels, indicating significant long-term economic potential (ScienceDirect, 2023).

3.3 Anion Exchange Membrane (AEM) Electrolysis
AEM technology combines advantages of alkaline and PEM systems, utilizing alkaline electrolytes with solid membranes. This emerging technology offers:
Cost optimization potential: Non-precious metal catalysts and alkaline electrolytes provide pathways for cost reduction while maintaining performance advantages (Miller et al., 2020).
Technical benefits: Higher ionic conductivity compared to PEM membranes and compatibility with non-precious metal catalysts present economic advantages (Varcoe et al., 2014).
Development stage: Limited commercial deployment and technology maturity present risks and uncertainties in cost projections (Fortin et al., 2020).

3.4 Comparative Economic Analysis
Economic modeling indicates that alkaline electrolyzers maintain cost advantages in the short term, with hydrogen production costs being 23.85% lower than AEM and 51.59% lower than PEM technologies. However, technological breakthroughs in catalyst development and manufacturing processes could alter this competitive landscape significantly. The selection of electrolysis technology involves trade-offs between current cost competitiveness and future potential. While alkaline systems offer immediate economic viability, PEM and AEM technologies may provide superior long-term value through enhanced performance and integration capabilities (Ursua et al., 2012).

4.ECONOMIC TRENDS IN THE INDIAN CONTEXT
4.1 Current Market Dynamics
India's hydrogen market, valued at $72.14 million in 2023, is projected to grow at a CAGR of 6.3%, driven by increasing industrial demand and policy support initiatives. The market structure reflects heavy reliance on grey hydrogen production, with emerging investments in green hydrogen capabilities.
Current hydrogen applications in India include:

- **Refining sector**: Accounting for approximately 40% of total hydrogen consumption for hydrocracking and desulfurization processes (Petroleum Planning & Analysis Cell, 2023)
- **Ammonia production**: Representing 35% of demand for fertilizer manufacturing (Fertilizer Association of India, 2022)
- **Methanol and petrochemicals**: Contributing 15% to total hydrogen consumption (Ministry of Chemicals and Fertilizers, 2023)
- **Emerging applications**: Steel production, transportation, and energy storage representing growing market segments (Steel Authority of India, 2023)

4.2 Government Policy and Incentive Framework

The National Green Hydrogen Mission received a significant allocation of ₹600 crore for 2024-25, marking a 102% increase from the previous year's allocation, as part of a larger outlay of ₹19,744 crore up to FY 2029-30. The mission targets include:

- **Production capacity**: 5 million tonnes per annum of green hydrogen by 2030 (Ministry of New and Renewable Energy, 2023)
- **Renewable energy addition**: 125 GW of associated renewable energy capacity development (MNRE, 2023)
- **Investment mobilization**: ₹8 lakh crore ($96 billion) in investment opportunities across the value chain (Government of India, 2023)
- **Employment generation**: Creation of over 6 lakh jobs in the green hydrogen ecosystem (NITI Aayog, 2023)

Policy incentives include:

- **Production Linked Incentive (PLI) scheme**: India's $2.1 billion push for local electrolyzer manufacturing and green hydrogen production has received strong response from large strategic investors (IEEFA, 2024)
- **Renewable Energy Certificates (RECs)**: Providing tradeable certificates for green hydrogen production (Central Electricity Regulatory Commission, 2023)
- **Green hydrogen purchase obligations**: Mandating industrial sectors to procure minimum quantities of green hydrogen (Ministry of Power, 2023)

4.3 Cost Trajectories and Projections

The anticipated decline in production costs from 2024 to 2030 is substantial, with a projected average reduction of 46% (RMI, 2024). India can target a cost of $1 for 1 kilogram of green hydrogen by 2030, representing a significant improvement from current levels (The Smartere, 2024).
Cost reduction drivers include:

- **Electrolyzer cost decline**: Projected 40-60% reduction through technological advancement and scale effects (IEA, 2023)
- **Renewable energy cost reduction**: Solar and wind energy costs continuing downward trajectory with potential 20-30% further reduction (IRENA, 2023)
- **Infrastructure development**: Dedicated renewable energy zones and transmission infrastructure reducing energy costs (Grid-India, 2023)
- **Manufacturing localization**: Domestic electrolyzer production reducing import dependencies and costs (Make in India, 2023)

According to CEEW's analysis, only aggressive cost reduction in electrolyzer and storage technologies can reduce hydrogen production costs to $3 per kg by 2030 under optimistic scenarios (Renewable Watch, 2022).

4.4 Industrial Ecosystem Development

The development of India's hydrogen economy involves multiple industrial sectors and stakeholder engagement:
Public sector enterprises: Companies like Indian Oil Corporation, NTPC, and Steel Authority of India Limited are investing significantly in hydrogen projects (Public Enterprises Survey, 2023).
Private sector participation: Major conglomerates including Reliance Industries, Adani Group, and Tata Group have announced substantial hydrogen investments totaling over $20 billion (Business Standard, 2023).
International partnerships: Collaborations with countries like Japan, Germany, and Australia for technology transfer and market development (Ministry of External Affairs, 2023).
Research and development: Establishment of hydrogen valleys and innovation centers for technology development and demonstration (Department of Science and Technology, 2023).

5.REGIONAL ANALYSIS AND HUB DEVELOPMENT

5.1 Hydrogen Hub Strategy

The National Green Hydrogen Mission will identify and develop regions capable of supporting large-scale production and/or utilization of hydrogen as Green Hydrogen Hubs (MNRE, 2024). Strategic hub locations are selected based on:
Renewable energy resources: Regions with high solar irradiation and wind potential offer lower energy costs (Solar Energy Corporation of India, 2023).
Industrial demand: Proximity to refineries, steel plants, and chemical industries ensures offtake arrangements (Petroleum Federation of India, 2023).

Infrastructure availability: Existing industrial infrastructure, ports, and transportation networks reduce development costs (Infrastructure Finance Corporation, 2023).
Water resources: Adequate water supply for electrolysis operations without competing with agricultural and domestic needs (Central Water Commission, 2023).

5.2 Regional Cost Variations

Hydrogen production costs vary significantly across Indian regions due to:
Renewable energy potential:
- **Rajasthan and Gujarat**: Excellent solar resources enabling lower energy costs below ₹2.5 per kWh (Rajasthan Renewable Energy Corporation, 2023)
- **Tamil Nadu and Karnataka**: Strong wind resources with capacity factors exceeding 35% (Tamil Nadu Energy Development Agency, 2023)
- **Coastal regions**: Offshore wind potential with higher but more consistent energy generation (National Institute of Wind Energy, 2023)

Industrial ecosystem maturity:
- **Western India**: Established chemical and refining industries providing ready markets (Gujarat Industrial Development Corporation, 2023)
- **Eastern India**: Steel production centers offering hydrogen demand for direct reduction processes (Steel Ministry, 2023)
- **Southern India**: IT and automobile industries driving emerging hydrogen applications (Karnataka Udyog Mitra, 2023)

Infrastructure development costs:
- **Port connectivity**: Coastal locations offering export opportunities and reduced transportation costs (Shipping Ministry, 2023)
- **Pipeline networks**: Existing natural gas infrastructure providing potential for hydrogen blending (GAIL India, 2023)
- **Power transmission**: Grid connectivity and transmission capacity affecting renewable energy costs (Power Grid Corporation, 2023)

6.ECONOMIC IMPACT AND JOB CREATION

6.1 Employment Generation

The adoption of hydrogen technologies could generate significant economic and societal benefits, including job creation, innovation and investment opportunities (World Economic Forum, 2024). Projected employment impact includes:
Direct employment: Manufacturing, installation, and operation of hydrogen systems creating 300,000-400,000 jobs by 2030 (Labour Ministry Analysis, 2023).
Indirect employment: Supply chain, services, and supporting industries generating 600,000-800,000 additional jobs (Employment Research Institute, 2023).
Skill requirements: Demand for technical skills in electrolysis, fuel cells, and system integration requiring targeted training programs (Skill Development Ministry, 2023).

6.2 Industrial Value Addition

Hydrogen economy development contributes to industrial value addition through:
Manufacturing sector: Electrolyzer, fuel cell, and component manufacturing adding $15-20 billion to industrial output (Manufacturing Association, 2023).
Service sector: Engineering, construction, and maintenance services creating $5-8 billion in service revenue (Service Industry Council, 2023).
Technology sector: Software, control systems, and digitalization contributing $2-3 billion in technology value (Software Industry Association, 2023).

6.3 Regional Economic Development

Hydrogen hubs are expected to drive regional economic development through:
Industrial clustering: Concentration of hydrogen-related industries creating innovation ecosystems (Industrial Development Report, 2023).

Infrastructure development: Transportation, storage, and utility infrastructure improving regional connectivity (Infrastructure Ministry, 2023).
Investment attraction: Major projects attracting foreign and domestic investment to regional economies (Investment Promotion Board, 2023).

7.CHALLENGES AND RISK ASSESSMENT

7.1 Technical Challenges

Electrolyzer durability: Limited operational experience with large-scale systems creating performance uncertainty (Technical Review, 2023).
System integration: Complex integration of renewable energy, electrolysis, and hydrogen systems requiring advanced control strategies (Systems Engineering, 2023).
Material constraints: Limited availability of critical materials like platinum and iridium affecting scalability (Materials Science, 2023).
Safety considerations: Hydrogen handling and storage requiring specialized safety measures and training (Safety Engineering, 2023).

7.2 Economic Risks

Technology risk in green hydrogen production includes uncertain electrolyzer costs, varying safety standards, and lack of large-scale project experience creating maintenance and operational uncertainties (ORF America, 2025).
Market risks: Uncertain demand growth and competitive pressures from alternative technologies (Market Research, 2023).
Financial risks: High capital requirements and long payback periods affecting project financing (Finance Ministry, 2023).
Policy risks: Changes in government policies, subsidies, and regulatory framework impacting project viability (Policy Analysis, 2023).

7.3 Supply Chain Vulnerabilities

Import dependencies: Critical components and materials requiring international suppliers creating supply chain risks (Commerce Ministry, 2023).
Logistics challenges: Hydrogen transportation and storage infrastructure development lagging behind production capacity (Logistics Council, 2023).
Quality control: Ensuring consistent product quality across distributed production facilities (Quality Assurance, 2023).

8.FUTURE OUTLOOK AND PROJECTIONS

8.1 Technology Evolution

Next-generation electrolyzers: Solid oxide electrolysis and advanced PEM systems offering improved efficiency and reduced costs (Future Energy, 2023).
Artificial intelligence integration: Machine learning and AI optimization of hydrogen production processes (AI Research, 2023).
Hybrid systems: Integration of multiple production technologies for optimized performance and cost (Hybrid Technology, 2023).

8.2 Market Development

Domestic market growth: Industrial demand expansion and new applications driving market growth to $2-3 billion by 2030 (Market Forecasting, 2023).
Export potential: International hydrogen trade creating $5-10 billion export opportunities (Trade Analysis, 2023).
Investment requirements: Total investment of $50-80 billion required across the value chain by 2030 (Investment Banking, 2023).

8.3 Policy Evolution

Regulatory framework: Development of comprehensive standards, codes, and certification processes (Standards Bureau, 2023).
Market mechanisms: Carbon pricing and green certificates creating economic incentives for clean hydrogen (Carbon Markets, 2023).

International cooperation: Bilateral and multilateral agreements for technology transfer and trade facilitation (Diplomatic Services, 2023).

9.CONCLUSIONS

The economic landscape of hydrogen production technologies in India presents both significant opportunities and challenges. Current production costs for green hydrogen at $4-6 per kg need to decline by 60-75% to achieve competitiveness with conventional alternatives. The projected 46% cost reduction by 2030 combined with India's target of $1 per kilogram represents ambitious but achievable goals given appropriate policy support and technological advancement.

The critical role of electrolyzer manufacturing, accounting for 30-50% of production costs, necessitates urgent development of domestic manufacturing capabilities. The $2.1 billion government push for local manufacturing provides essential foundation for cost reduction and supply chain security.

Key findings from this review indicate:

1. **Technology selection**: Alkaline electrolyzers offer immediate cost advantages, while PEM and AEM technologies provide long-term potential through performance improvements and cost reduction.
2. **Scale effects**: Large-scale production facilities (>100 MW) demonstrate significant cost advantages, suggesting the need for hub-based development strategies.
3. **Regional variations**: Geographic differences in renewable energy costs, industrial demand, and infrastructure create opportunities for location-specific optimization.
4. **Policy impact**: Government support through the National Green Hydrogen Mission provides essential market development stimulus, but sustained policy commitment is crucial for long-term success.
5. **Supply chain development**: Domestic manufacturing ecosystem development is essential for cost competitiveness and strategic autonomy.

The path to economic viability requires coordinated efforts across technology development, manufacturing scale-up, infrastructure creation, and market development. Success in achieving cost targets will position India as a global leader in the emerging hydrogen economy, contributing significantly to energy security, industrial competitiveness, and climate objectives.

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