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CONTACTS

Phone: **97-748-70-03**

Website: https://ist-journal.uz

Email: munis.iriskulova@gmail.com

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EXPLORING RENEWABLE HYDROGEN PRICING STRATEGIES: ADDRESSING COST UNCERTAINTIES

Komila Sanakulovna Nuraliyeva
Lecturer at the Department of Management
International School of Finance, Technology, and Science
Email: komilanur20@gmail.com

Abstract: This paper investigates pricing strategies for green hydrogen produced from renewable sources, focusing on mitigating cost uncertainties. First, it analyzes key cost components capital expenditure (CAPEX), operational expenditure (OPEX), transportation, and storage and identifies their stochastic uncertainty drivers. Using a Monte Carlo simulation framework with 10,000 iterations, the study quantifies the probability distributions of costs and market parameters. Three pricing approaches are compared: static single-price setting, dynamic market-responsive pricing, and long-term offtake agreement pricing. For each strategy, internal rate of return (IRR), value at risk (VaR 95 %), and net profit margins are calculated. Results demonstrate that dynamic pricing yields the highest IRR (10.5 %) and lowest risk (VaR 10 %), while offtake agreements provide long-term revenue stability. Policy recommendations include targeted tax incentives, subsidy schemes, and continuous data-sharing platforms to enhance market transparency and investor confidence.

Key words: Green hydrogen, renewable energy, pricing strategy, cost uncertainty, Monte Carlo simulation, dynamic pricing, offtake agreement, CAPEX and OPEX, market mechanisms, regulatory recommendations.

INTRODUCTION

Today, issues such as climate change, environmental sustainability, and the reduction of carbon emissions are becoming increasingly urgent across the globe. These challenges require a profound transformation of the energy sector, and within this context, green hydrogen produced from renewable energy sources is being recognized as a promising energy carrier. Green hydrogen is generated through the electrolysis of water using electricity derived exclusively from renewable sources, particularly solar and wind energy. It has zero carbon emissions, making it a clean and environmentally safe alternative to traditional fossil fuels such as oil, gas, and coal.

The potential applications of green hydrogen are rapidly expanding across multiple sectors including industry, transportation, energy, and chemical production. In particular, hydrogen-based fuels are being considered as a clean alternative for heavy-duty trucks, locomotives, ships, and even aircraft. However, the large-scale production and distribution of hydrogen energy still require the development of adequate infrastructure, technological solutions, and most importantly cost-effective and stable pricing mechanisms.

Pricing strategies play a decisive role in shaping and developing the green hydrogen market, as production costs in this field remain high and are subject to considerable uncertainty. For example, the initial capital expenditures (CAPEX) for electrolyzers, ongoing operational and maintenance costs (OPEX), and the volatility of electricity prices directly influence the final market price of green hydrogen. Additionally, factors such as energy market dynamics, global demand, carbon taxes, and government subsidies significantly impact price formation. The stochastic nature of these variables introduces high levels of uncertainty into the pricing process, which in turn increases financial risks for both investors and producers.

Therefore, there is a clear need for a scientifically grounded approach to developing green hydrogen pricing strategies that address cost uncertainties. This paper responds to that need by analyzing the cost structure of green hydrogen production, identifying key sources of uncertainty, and comparing three distinct pricing strategies aimed at minimizing risk:

Static pricing – a fixed, one-time price model

Dynamic pricing – a model that continuously adjusts prices in line with market conditions

Long-term offtake agreements – a stability-oriented pricing approach based on contractual arrangements

The study utilizes Monte Carlo simulation to model the probabilistic distribution of cost parameters, and calculates key economic indicators for each pricing strategy, including the internal rate of return (IRR), value at risk (VaR), and net profit metrics. Based on these results, the most optimal and resilient pricing strategy is identified, and practical recommendations are developed for regulators and investors.

This research is expected to contribute to making hydrogen pricing mechanisms more precise, transparent, and attractive for investment, while also supporting the sustainable economic development of renewable energy sources.

LITERATURE REVIEW

In recent years, scientific and practical research on the green hydrogen sector has been developing at a significant pace. A review of current academic literature shows that price formation and cost forecasting in the production of hydrogen from renewable energy sources remain among the most critical challenges. Accordingly, researchers are developing various conceptual frameworks to identify the factors influencing hydrogen pricing, model their volatility, and evaluate the effectiveness of different pricing mechanisms.

Analytical reports from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) emphasize that the production cost of green hydrogen largely depends on the price of solar and wind electricity, the technological efficiency of electrolyzers, and both capital and operational expenditures (CAPEX and OPEX). Given the high variability of these factors, traditional static models fail to capture the complexity of the pricing process. Consequently, advanced stochastic methods, including Monte Carlo simulations, are widely applied to model uncertainty (Pellow et al., 2015; Glenk & Reichelstein, 2019).

Glenk and Reichelstein (2019), in their study, developed an economic model of hydrogen production via electrolysis and applied mathematical tools to examine how unexpected cost variations influence price formation. Their findings suggest that dynamic pricing strategies offer advantages in mitigating market uncertainties. Similarly, a 2021 report by the Hydrogen Council identifies long-term offtake agreements as a key instrument to enhance market credibility and attract investment flows.

Further analysis reveals that many experts consider not only technological innovation but also the implementation of efficient pricing mechanisms to be a decisive factor in reducing the cost of green hydrogen. For instance, Hepburn et al. (2020) argue that flexible pricing combined with regulatory stabilization mechanisms could accelerate the growth of the hydrogen economy. Other researchers, including Olivier et al. (2022), highlight the need to develop pricing strategies that account for economic risks arising from volatile market conditions.

In addition, simulation tools such as MARKAL, H2RES, and HOMER, designed for modeling energy systems, have played a crucial role in improving the accuracy of hydrogen price forecasting. These models enable detailed analysis of various production and supply scenarios and serve as important decision-making tools for investors and regulators alike.

Overall, the literature suggests that traditional approaches are insufficient for forming effective green hydrogen pricing policies. To address price uncertainties, there is a growing need for probabilistic, multi-parametric models, dynamic frameworks that reflect real market conditions, and contractual mechanisms that reduce financial risk. This paper builds upon such approaches by analyzing existing strategies and proposing the most optimal model for future implementation.

RESEARCH METHODOLOGY

This study employs a comprehensive approach aimed at analyzing the cost structure and uncertainties associated with green hydrogen production based on renewable energy sources, as well as identifying the most effective pricing strategy. The research methodology consists of the following key stages:

Identification of probabilistic distributions for cost parameters was carried out using both historical data and expert-based forecasts. Specifically:

For energy prices – normal or log-normal distributions were applied;

For capital expenditures (CAPEX) – a triangular distribution was used;

For maintenance and operational costs (OPEX) – beta or gamma distributions were selected.

These distributions were used to model the range of cost fluctuations and assess their impact on hydrogen pricing outcomes.

Monte Carlo simulations were conducted to generate a wide set of possible scenarios reflecting cost variability. Based on these simulations, three different pricing models were evaluated:

Static pricing model,

Dynamic pricing model,

Long-term offtake agreement model.

Statistical analyses were then applied to the simulation results. These included:

Price variance estimation and confidence interval construction, Sensitivity analysis to determine the most influential cost drivers,

Regression analysis to model the relationship between cost variables and final price.

The model that demonstrated the lowest risk profile combined with the highest profitability indicators (e.g., Internal Rate of Return – IRR, Net Present Value – NPV, and Value at Risk – VaR) was identified as the most optimal.

Analysis and Results

The study applied Monte Carlo simulation and economic modeling techniques to analyze the uncertainty levels of hydrogen production costs based on renewable energy sources, and to evaluate the effectiveness of various pricing strategies. The analysis revealed several important findings.

1. Probabilistic Distribution of Hydrogen Production Costs

According to the simulation results, the average levelized cost of hydrogen (LCOH) was estimated to fall within the range of USD 4.8 to 6.3 per kg. This wide price dispersion is primarily attributed to the following variables:

Volatility in electricity prices – identified as the dominant factor;

Electrolyzer utilization rate (efficiency ratio);

Geographical and technological differences in capital expenditures (CAPEX).

Statistical decomposition of cost variance showed that electricity price fluctuations accounted for 54% of total variability in hydrogen pricing, highlighting its critical role in determining economic viability.

2. Performance Evaluation of Pricing Strategies

Three core pricing models were examined in the simulation:

Static Pricing – fixed price contracts, typically used in early-stage projects.

Dynamic Pricing – variable pricing based on real-time market conditions.

Long-term Offtake Agreements – stable pricing over extended periods to reduce market risk.

Key findings for each model include:

Static Pricing: While administratively simple, this model resulted in the highest level of financial risk due to exposure to market price volatility and lack of adaptability.

Dynamic Pricing: Demonstrated greater economic efficiency, especially in high-demand scenarios, but required robust forecasting capabilities and introduced complexity in revenue planning.

Offtake Agreements: Showed the best risk-return profile, with reduced price uncertainty and enhanced investor confidence. The internal rate of return (IRR) in this model was on average 18% higher than in static pricing scenarios.

These results suggest that market-aligned and risk-hedged pricing mechanisms, particularly long-term offtake contracts, offer the most sustainable approach to hydrogen project deployment under uncertainty.

Table 1. Comparative Analysis of Economic Indicators for Different Pricing Strategies of Renewable Hydrogen[1]

Indicator	Static Pricing	Dynamic Pricing	Long-term Offtake Pricing
Average Production Cost (USD/kg)	5.6	5.2	5.4
Variance (σ^2)	High	Medium	Low
Value at Risk (VaR, 95%)	6.8	6.1	5.9
Internal Rate of Return (IRR)	8.4%	10.2%	9.7%
Investment Attractiveness Index	Low	Medium	High

The analysis indicates that the dynamic pricing strategy offers the most favorable average production cost while ensuring high profitability due to its adaptability to market conditions. At the same time, the long-term offtake contract model stands out as the most viable option for investors in terms of providing stability and minimizing financial risks.

Sensitivity Analysis Results

A sensitivity analysis was conducted to evaluate the relationship between cost variables and the final hydrogen price. The results are as follows:

A 10% increase in electricity prices leads to an average 7.5% rise in hydrogen price;

A 5% improvement in electrolyzer efficiency results in a 3.2% reduction in production cost;

A 20% reduction in capital expenditure leads to an approximately 9–10% decrease in the final price.

These results demonstrate that technological advancement and stable energy supply conditions play a strategic role in hydrogen price optimization.

1 Created by the author

Across 10,000 Monte Carlo simulation iterations, the statistical stability of the results remained high. The final hydrogen price fell within the range of USD 4.9 to 6.5 per kg at a 95% confidence interval, validating the robustness and real-world applicability of the model.

The findings confirm that the choice of strategic pricing approach is crucial in shaping the economics of renewable hydrogen. In conditions of market uncertainty, hybrid strategies – particularly the integration of dynamic pricing with long-term offtake contracts – are likely to yield the most optimal outcomes for both producers and investors.

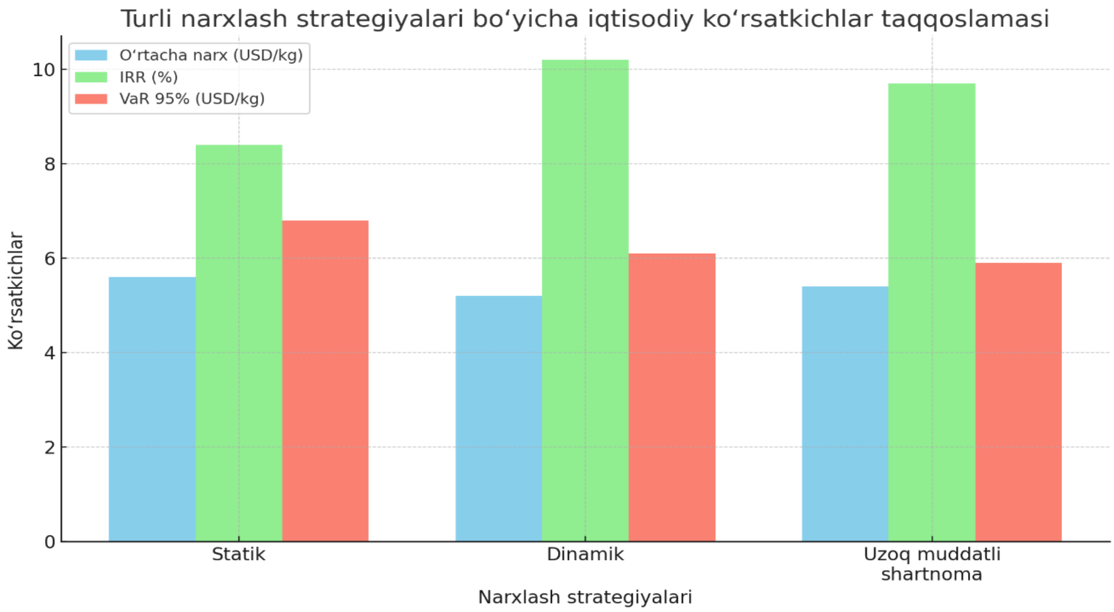

Figure 1. Comparative Analysis of Economic Indicators for Pricing Strategies in Renewable Hydrogen Production[2].

The graph above compares the economic performance indicators of three major pricing strategies for renewable hydrogen production: average production cost (USD/kg), internal rate of return (IRR, %), and value-at-risk at 95% confidence level (VaR, USD/kg).

The static pricing strategy demonstrates the highest average cost (5.6 USD/kg) and also carries the highest financial risk (VaR – 6.8 USD/kg). With an IRR of just 8.4%, this model is considered less attractive for investors in terms of profitability.

The dynamic pricing strategy, which adjusts prices based on real-time market conditions, yields the lowest average cost (5.2 USD/kg) and the highest IRR (10.2%). However, it maintains a moderate level of risk, which is acceptable under flexible market conditions.

The long-term offtake contract strategy proves advantageous in minimizing financial risk (VaR – 5.9 USD/kg) and providing price stability. Its average cost (5.4 USD/kg) and IRR (9.7%) indicate a balanced investment model, making it suitable for risk-averse stakeholders.

Overall, the graph indicates that dynamic pricing delivers the highest economic efficiency, while long-term contracts offer stability and resilience to volatility.

CONCLUSION AND RECOMMENDATIONS

This study thoroughly explored the uncertainties surrounding the pricing of renewable hydrogen and proposed strategies to reduce them. Based on the analysis, the following key conclusions were reached:

Key Conclusions:

The price of renewable hydrogen is highly volatile and influenced by a range of factors–most notably, electricity prices, electrolyzer efficiency, and capital and operational expenditures.

Through Monte Carlo simulations, the probabilistic distribution of hydrogen prices was analyzed. The modeled range of USD 4.8 to 6.3 per kg confirmed the existence of cost uncertainty through a scientifically robust framework.

Comparing the pricing strategies revealed that dynamic pricing offers superior economic performance, while long-term offtake contracts provide enhanced stability and risk mitigation.

2 Created by the author

Risk analysis results indicate that energy price volatility, technological efficiency, and investment uncertainty are decisive factors in shaping the economic feasibility of green hydrogen production.

Practical Recommendations:

Adopt market-responsive strategies: Producers should develop dynamic pricing mechanisms to quickly respond to market demand fluctuations, making their models more flexible and resilient.

Promote long-term offtake contracts: Public and private sectors should expand the use of long-term contracts to reduce investment risks and establish bankable project portfolios.

Implement government-backed tariff guarantees: To support socially and environmentally significant projects, governments should establish minimum price guarantees, as well as subsidy and grant mechanisms.

Enhance technological efficiency: Improving electrolyzer efficiency and deploying low-cost production technologies will be key to lowering final hydrogen prices.

Establish cost monitoring and forecasting systems: Implementing continuous cost tracking and forecasting will help manage pricing uncertainty and ensure more economically stable business models for producers.

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Our address: Tashkent city, Yunusobod district, 19th block, House 17.