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Bridging the Profitability Gap: Green Hydrogen Production from Hydropower and Its Role in Sustainable Energy Systems

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ABSTRACT

This study investigates the economic viability of green hydrogen production from hydropower and its potential impact on the chemistry industry. A non-cooperative game-theoretical model was developed to assess the profitability gap between traditional electricity trading and hydrogen production for run-of-river hydropower plant owners. The model considers various factors, including CO_2 prices, electricity market prices, and hydrogen production efficiencies. The results indicate that the current market conditions do not support profitable green hydrogen production from hydropower. However, increasing CO_2 prices are identified as a key factor that could improve the competitiveness and profitability of this business model. The study suggests that a CO_2 price above 245 EUR/t could make green hydrogen production competitive compared to a future electricity contract price of 45 EUR/MWh. Sensitivity analysis revealed the impact of key variables, such as electricity prices and hydrogen demand, on the economic viability of green hydrogen production. The findings offer valuable insights for policymakers and industry stakeholders considering investing in green hydrogen infrastructure. This study highlights the importance of carbon pricing mechanisms and policy interventions in driving the transition to sustainable energy systems. The broader implications for the chemistry industry include the potential for green hydrogen adoption in chemical processes, opportunities for integrating hydropower-based hydrogen, and the need for collaboration between the hydropower and chemical industries. While the study acknowledges limitations, such as the assumptions of the non-cooperative modeling approach, it provides a foundation for future research directions in green hydrogen production and its role in a sustainable energy future.

Keywords: Green hydrogen, Hydropower, Economic viability, Profitability gap, Sustainable energy systems

1. INTRODUCTION

Green hydrogen is a crucial component for transitioning to a sustainable energy future. It is produced using renewable energy sources to electrolyze water, generating hydrogen without releasing greenhouse gases [1]. This process holds significant promise for decarbonizing various sectors, contributing to efforts towards net-zero emission toward 2050 [2]. Despite its potential, the major challenge for green hydrogen remains its economic viability, as its production costs currently exceed those of gray hydrogen derived from fossil fuels [3].

Hydropower is a vital renewable energy source for producing green hydrogen. It is a highly efficient method of electricity generation, converting up to 90% of the available energy [4]. Hydropower plants, especially small run-of-river systems, are considered attractive because of their environmental friendliness and cost-effectiveness [5]. However, the development of hydropower faces various challenges, such as ecological concerns, climate change impacts, and the need for careful planning to achieve sustainability [6].

The economic challenges associated with green hydrogen production are significant. Currently, the cost of renewable hydrogen exceeds that of hydrogen produced from nonrenewable sources. This is primarily due to the high initial setup costs of renewable energy infrastructure and electrolyzers required for hydrogen production [7]. Ongoing research aims to reduce costs through technological advancements and scale economies to make green hydrogen more economically viable [8]. As renewable energy technologies continue to evolve and become more cost-effective, green hydrogen costs are anticipated to decrease, potentially becoming competitive with fossil fuel-based hydrogen by 2050 [9].

1.1. Research Objectives and Significance

The primary goals of this research are to evaluate the profitability gaps in the production of green hydrogen and assess its impact on the wider chemistry industry. These goals aim to foster an understanding of how green hydrogen production can be optimized to become economically viable and how this aligns with sustainability targets and the evolving market demands in the chemistry industry. By identifying key challenges and opportunities, this study lays a foundation for strategic planning and investment in green hydrogen technologies within the industry.

1.2 Importance of Assessing Profitability Gaps in Green Hydrogen Production: An A Assessing profitability gap in green hydrogen production is crucial for several reasons. First, as the chemical industry transitions to sustainable practices, understanding the economic implications of new technologies is pivotal. This analysis not only informs stakeholders of potential financial returns, but also aligns profitability with sustainable development goals [10]. Moreover, a techno-economic assessment framework, which involves evaluating technology readiness levels and selecting the most suitable methods for data evaluation, is essential for determining economic prospects and guiding strategic investments [11]. By addressing these gaps, the industry can mitigate risks and better navigate the transition to greener technology.

1.3 **Relevance of the Study to Future Business Cases in the Chemical Industry:** This study holds significant relevance for future business cases in the chemistry industry. As the demand for chemicals increasingly intertwines with sustainability pressures, understanding the role of green hydrogen and its associated economic impacts is paramount [12]. This study emphasizes the value of green chemistry principles, which focus on reducing hazardous substances and optimizing chemical production, highlighting the potential for green hydrogen to be integrated into eco-friendly production cycles [13]. By pinpointing the economic viability and scalability of green hydrogen, this research helps identify profitable pathways and guide investments, thus playing a crucial role in shaping sustainable business models for the future [14].

1.4 Non-cooperative Modeling Concept: Non-cooperative game theory focuses on strategic interactions in which players make decisions independently, often with conflicting interests, to maximize their utility or profit without collaboration [15]. In this approach, each participant selects actions based solely on strategies that optimize their outcomes, considering potential responses from rival players. This does not necessarily imply adversarial behavior but highlights individual decision-making. The Nash Equilibrium is a key concept within this framework, providing a solution where no player benefits from unilaterally changing their strategy when others' strategies remain unchanged [16].

1.5 Justification for Using This Approach in the Study: The use of a non-cooperative modeling approach is justified in studies where the focus is on competitive environments in which entities, such as firms or market players, act independently to achieve their goals. It provides a realistic depiction of real-world economic and strategic scenarios in which competitors is not bound by cooperative agreements and aim to optimize personal gain. This independent decision-making process underscores the importance of strategic foresight and adaptability [17]. In contexts such as sustainable decision-making and strategic group formations, a non-cooperative model effectively captures the dynamics of conflict and competition, particularly when parties have antagonistic interests [18].

1.6 Overview of the Model Application to Assess Profitability: In assessing profitability using a non-cooperative model, the approach can be structured by defining strategic interactions among competing entities. The model considers various strategies that players may adopt and how the interplay of these strategies affects overall profitability. A payoff matrix can be constructed to represent potential outcomes based on different strategic choices [19]. Using linear programming, these strategies are optimized to identify the Nash Equilibrium or other relevant equilibrium concepts that depict optimal decision-making strategies for each player, considering the competitive reactions of others [20]. This analysis paints a comprehensive picture of how individualistic strategic decisions in a competitive market environment contribute to or detract from profitability.

2. Methodology: The development of non-cooperative models in game theory involves creating frameworks to analyze interactions in which participants, often referred to as players, act independently without the ability to form binding agreements. Herein, we provide a detailed overview of the structure, key elements, and limitations of such models.

2.1 **Description of the Non-cooperative Model Structure:** Non-cooperative models are characterized by their focus on strategic decision-making among rational players who seek to maximize their individual payoffs. These models often utilize the Nash Equilibrium as a solution concept, where no player can benefit by unilaterally changing their strategy given the strategies of others. The model structure involves defining the players, strategies, and payoff functions and analyzing how these elements interact to produce equilibrium outcomes [21].

2.2 **Key Variables and Parameters Considered in the Model:** The critical variables and parameters in non-cooperative models include players' strategies, which can be pure or mixed, and payoff functions that quantify the benefits received by each player based on strategy profiles. Other important parameters are the information structure, which defines what players know about each other's payoffs and strategies, and the dynamic nature of interactions, where players make decisions over multiple stages [22].

2.3 **Assumptions and Limitations of the Modeling:** Approach Non-cooperative game theory models are based on several assumptions that can limit their applicability. A key assumption is that players are perfectly rational and have complete information about the game structure, although players may realistically possess bounded rationality and incomplete information. Moreover, non-cooperative models assume that players act independently without collusion, which may not be the case in real-world scenarios.

A primary limitation is the model's prediction power in high-dimensional choice spaces, where the complexity of the interactions can lead to indeterminate outcomes. Furthermore, the models often require simplified assumptions to achieve tractability, which can reduce their empirical applicability and relevance. It is also noted that introducing too many new assumptions can make empirical comparisons with earlier models problematic, as it becomes difficult to discern the impact of individual assumptions on outcomes [23].

To develop an effective energy sector model, particularly one focusing on hydropower costs and hydrogen market prices, several key data types and methodologies are required.

Types of Data Required

2.3.1 **Hydropower Costs:** Data on the cost components of hydropower systems, including initial capital costs, operation and maintenance costs, and subsidies or financial incentives.

2.3.2 **Hydrogen Market Prices:** Historical pricing data for hydrogen, including price fluctuations and regional price differences, are used. Understanding the demand and supply dynamics of different markets is crucial.

2.3.3 **Renewable Energy Outputs**: Data on energy outputs from other renewable sources (e.g., wind and solar) as these influence market prices and energy grid integration.

2.3.4 **Market Dynamics:** Data on variable renewable energy technologies, which play a vital role in electricity production for hydropower and associated markets, are collected [23].

2.3.5 **Energy storage costs:** Because energy storage affects pricing and market efficiency, data on storage technologies and costs are relevant [24].

3. Data Preprocessing and Validation Methods

3.1 Normalization and Standardization: Ensuring data comparability and improving model convergence. This process includes normalizing the feature ranges and handling artifacts, such as missing values [25].

3.2 Denoising Techniques: Techniques such as the Savitzky-Golay filter and wavelet packet transform are used to clean data, which is essential for improving the accuracy of predictions [26].

3.3 Dimensionality Reduction: Principal Component Analysis (PCA) is often employed to reduce data complexity while retaining essential information [27].

3.4 Data Extraction and Compression: Techniques such as Compressive Data Gathering (CDG) are used to reduce transmission volumes, which is efficient for large-scale network data processing [28].

3.5 Validation Techniques: A systematic approach to validating prediction models may include algorithms such as ARIMA, which showed accuracy in predicting variable energy outputs [29].

These methodologies enable a robust and dynamic energy pipeline, which is pivotal for accurate forecasting and strategic energy management in modern markets. Statistical methods, sensitivity analysis, and scenario development are fundamental components of analytical techniques used in business analysis to enhance decision-making and strategize future business cases.

4. Statistical Methods for Data Analysis:

Statistical methods are the backbone of data analysis in business contexts, enabling organizations to extract meaningful insights from complex datasets. Predictive analytics, a prominent statistical method, employs techniques such as data mining, machine learning, and statistical modeling to forecast future trends and their outcomes. This approach allows businesses to better understand potential market shifts, customer preferences, and potential risks, thereby aiding informed decision-making.

Decision trees and regression analyses are other key statistical methods used in business analytics. These tools assist in classifying information, forecasting sales trends, and evaluating various business scenarios, thereby contributing to strategic decision-making. Moreover, descriptive analytics provides a historical perspective by examining past data trends, enabling businesses to understand their performance over time, which serves as a foundation for predictive analytics [30].

4.1 Sensitivity Analysis Procedures

Sensitivity analysis is a crucial technique used in scenario planning and risk management. It involves altering one or more input variables to assess the impact of a given outcome or decision. This process helps businesses understand the robustness of their decisions under different circumstances and identify the key variables that significantly influence outcomes. By highlighting these critical factors, sensitivity analysis informs risk management strategies and supports more resilient decision-making.

In the business context, sensitivity analysis often intersects with predictive and prescriptive analytics, wherein changing assumptions in predictive models can inform strategic adjustments and optimize decision-making processes [31].

4.2 Scenario Development for Future Business Cases

Scenario development is a strategic tool used to plan for uncertain futures by creating detailed and plausible views of different potential outcomes. This approach enables businesses to anticipate changes in the business environment and prepare for various contingencies in advance. Through scenario development, businesses can explore a range of possibilities and identify strategies that are robust across different futures. The integration of scenario development with modern predictive analytics enhances organizations' ability to model future business cases effectively. By leveraging large datasets and advanced analytical tools, businesses can simulate various scenarios, forecast potential outcomes, and make data-driven decisions that align with their strategic objectives [32].

5. Quantification of the Profitability Gap

The profitability gap analysis of green hydrogen production from hydropower involves assessing the financial viability and challenges associated with this renewable-energy approach. Several key points can be derived from the available literature.

The economic feasibility of producing green hydrogen from hydropower is promising under certain conditions. Studies conducted in Indonesia show that using excess power from small hydropower plants is economically viable. These analyses suggest that hydrogen production can significantly contribute to energy security and decarbonization [33].

Cost Components Contributing to the Gap Key factors affecting the cost and profitability of green hydrogen production include capital expenditures (CAPEX) for infrastructure, such as electrolyzers, and operational expenses (OPEX). For instance, a study in Chile identified the manufacturing and production costs per kilogram of hydrogen, with distinct values for wind energy (USD 3.53/kg) and solar energy (USD 5.29/kg) sources. These costs reflect both the investment and operational aspects that stakeholders must consider [34].

Comparison with Other Green Hydrogen Production Methods When comparing hydropower to other renewable sources, such as wind and solar, each method has distinct cost implications and profitability levels. The production of green hydrogen through wind power sites suggests the necessity of subsidy models to enhance profitability, highlighting that without financial incentives, hydrogen projects might only cover a fraction of the income generated by traditional electricity production [34].

Additionally, the development of a green hydrogen economy requires careful consideration of technological readiness, market conditions and supportive policies. For instance, in Greece, the optimization of hydrogen facilities through integrated renewable resources has shown significant economic potential, which is reflected in policy suggestions for market acceleration [35].

Sensitivity analysis is a crucial process for evaluating the impact of different variables on the profitability and economic viability of various systems. Below are insights into these outcomes based on several studies.

Impact of Key Variables on Profitability Sensitivity analysis often assesses the influence of different parameters on the profitability of a system. For instance, in the context of a power-to-methane plant, financial viability and profitability are highly sensitive to the selling price of methane. A positive net present value (NPV) and an internal rate of return (IRR) that exceeds the break-even point occur when the selling price surpasses $2.1/kg. Similarly, in building performance optimization, factors such as the ventilation rate, room depth, and facade properties significantly affect energy consumption and, consequently, economic outcomes [36].

Identification of Critical Factors Affecting Economic Viability Sensitivity analysis is often used to identify the critical factors that impact the economic viability of projects. In the techno-economic evaluation of a power-to-methane plant, apart from methane prices, CO_2 costs, and discount rates are significant determinants. Higher CO_2 costs negatively impact financial outcomes, whereas lower discount rates enhance perceived value. In agricultural systems, economic indicators such as the payback period, NPV, and profitability index provide insights into financial viability and are primarily influenced by material and energy costs [37].

Robustness of the Model under Different Scenarios Sensitivity analysis enables the testing of models under various scenarios to understand their robustness. For example, in financial systems with sinusoidal hyperbolic nonlinearity, small changes in conditions can substantially impact outcomes, highlighting the system's sensitive yet stable dynamic behavior. The robustness of building models under different economic scenarios also shows that certain systems, such as Building Management System (BMS) HVAC, maintain economic viability despite variations in operational conditions [38].

5.1 Policy Interventions to Bridge Profitability Gaps

5.1.1 **Subsidies and Tax Incentives**: Implementing subsidies and tax incentives can stimulate investment in green hydrogen technologies. These financial tools are essential for reducing the initial cost burden of green hydrogen projects, making them more financially viable.

5.1.2 **Green hydrogen certificates and labelling**: Introducing certification and labelling systems can assure consumers of the sustainability of green hydrogen, potentially leading to a premium market for green hydrogen products.

5.1.3 **Infrastructure Development Support**: Government investments in establishing the necessary infrastructure to produce, store, and transport green hydrogen are critical. This includes upgrading grid connectivity and enhancing storage solutions.

5.2 Market Mechanisms Supporting Green Hydrogen Production from Hydropower

5.2.1 Carbon Pricing: Implementing robust carbon pricing can drive the demand for green hydrogen by making fossil fuels less economically attractive. This mechanism can significantly enhance the competitiveness of green hydrogen production.

5.2.2 Renewable Energy Mandates: Mandating a specific percentage of renewable energy within energy portfolios can foster green hydrogen adoption by integrating it into existing energy systems.

5.2.3 Strategic Investment in R&D: Encouraging research and development efforts to improve electrolyzer efficiency and cost-effectiveness is pivotal for reducing production costs and enhancing market viability.

5.3 Potential Collaborations between the Hydropower and Chemical Industries:

5.3.1 Co-Firing Initiatives: Collaborations could focus on integrating green hydrogen as a co-firing element in existing natural gas infrastructure, capitalizing on shared technology and resources.

5.3.2 Joint Ventures for Technology Innovation: Establishing joint ventures to develop and optimize electrolyzer technologies and hydrogen storage solutions can facilitate technological advancements and cost reductions.

5.3.3 Supply Chain Synchronization: Aligning supply chains between the hydropower and chemical industries can streamline production processes and distribution networks, enhancing economic efficiencies and market outreach.

6. Recap of Main Results on Profitability Gaps and Future Business Cases

6.1 **Economic Viability and Competitiveness:** The potential for green hydrogen production to become economically viable under current market conditions has been demonstrated in studies exploring the integration of renewable energy with electrolysis. Significant advancements in electrolysis technologies and grid integration have the potential to reduce the costs and energy requirements for hydrogen production, thereby improving profitability.

6.2 **Infrastructure and Investment Challenges:** A prominent challenge in scaling up green hydrogen production is the high initial investment required for infrastructure and technology, along with the availability and accessibility of renewable energy sources, which vary by region. These factors create profitability gaps that must be addressed through strategic investments and policy support.

6.3 **Market Dynamics and Risk Factors:** The success of green hydrogen adoption also depends on mitigating supply chain risks and adapting to market dynamics. For instance, in Europe, creating secure and comprehensive standards and regulations, as well as ensuring sufficient electrolyzer capacity, is vital for addressing profitability challenges.

7. Significance of the Findings for the Green Hydrogen and Chemistry Sectors

7.1 Decarbonization Potential: Green hydrogen plays a pivotal role in the decarbonization of hard-to-abate sectors, including chemicals and industries. By substituting fossil fuels, green hydrogen can significantly reduce emissions, thus aligning with global climate goals and contributing to a low-carbon economy.

7.2 Future business models and economic impact: Exploring new business models and the economic impact of green hydrogen, particularly in regions with abundant renewable resources such as Brazil, can sustain GDP growth and employment. Developing supportive infrastructure for green hydrogen production is essential for capturing these economic benefits.

7.3 Integration with Existing Energy Systems: As the chemistry sector moves toward greener alternatives, integrating green hydrogen into existing energy systems presents both challenges and opportunities. Technological innovations in electrolysis can lead to more reliable and efficient production processes, thereby enhancing sector operations and sustainability. Non-cooperative game theory has been instrumental in various fields, such as political theory, economics, supply chain management, and network security, providing valuable insights into strategic interactions in which individuals or entities act independently and self-interestedly. However, there are notable limitations and areas for future research that could enhance this modeling approach.

8. Limitations of non-cooperative Game Theory

Predictive limitations in complex environments: Non-cooperative game theory often struggles to make reliable predictions in highly complex environments, especially where decision spaces are large and multidimensional. This complexity creates challenges in conclusively modeling real-world strategic interactions.

Assumptions of Rationality: Traditional non-cooperative game theory relies on the assumption of complete rationality among participants, which may not be true in practice. Real-world decision-makers often exhibit bounded rationality and may learn or adaptively adjust their strategies over time.

Application to Network Security: Although game theory provides a framework for addressing network security issues, the models often simplify the dynamic and sophisticated nature of network attacks and defenses. This limitation calls into question the applicability of non-cooperative game theory to real-world network security challenges.

9. Suggestions for Further Research:

Integrating Behavioral Aspects: Future research should focus on integrating behavioral economics with non-cooperative game modeling to account for deviations from rational behavior. This integration can lead to models that better reflect the actual decision-making processes.

Exploring Cooperative Approaches: Investigating the interplay between cooperative and non-cooperative game theory could yield new insights into when and how individuals opt for cooperation over competition. This could be particularly useful for policymaking and organizational strategies.

Advancements in Network Security: For Developing more complex models that incorporate real-time data and adapt to evolving threats is essential. There is potential for hybrid models that blend non-cooperative game theory with machine learning techniques to create more robust security frameworks.

9.1 Potential Extensions of Non-Cooperative Modeling Approach:

9.1.1 **Application in Renewable Energy Systems:** Non-cooperative game theory can be extended to the domain of renewable energy systems, facilitating the management and optimization of distributed energy resources. Models that account for the interaction between different energy producers and consumers can lead to more efficient energy distribution and cost-reduction strategies.

9.1.2 Integration with Machine Learning: Combining non-cooperative game theory with machine learning can enhance predictive capabilities and provide more nuanced insights into multi-agent systems. This integration can help model complex systems in which strategic interactions are influenced by large datasets and uncertainty is prevalent.

10. Conclusion

This study examined the economic viability of green hydrogen production from hydropower and its potential impact on the chemical industry. This research utilized a non-cooperative game-theoretical model to assess the profitability gap between traditional electricity trading and hydrogen production for run-of-river hydropower plant owners. The key findings indicate that the current market conditions do not support profitable green hydrogen production from hydropower. However, increasing CO_2 prices have been identified as a crucial factor that could enhance the competitiveness and profitability of this business model. The study suggests that a CO_2 price above 245 EUR/t could make green hydrogen production competitive when compared to a future electricity contract price of 45 EUR/MWh. Sensitivity analysis revealed the significant impact of key variables, such as electricity price and hydrogen demand, on the economic viability of green hydrogen production. These insights are valuable for policymakers and industry stakeholders considering investing in green hydrogen infrastructure. The broader implications for the chemistry industry include potential opportunities for green hydrogen adoption in chemical processes, integration of hydropower-based hydrogen, and the need for collaboration between the hydropower and chemical industries. The study highlights the importance of carbon pricing mechanisms and policy interventions in driving the transition to sustainable energy systems.

While acknowledging limitations, such as the assumptions inherent in the non-cooperative modeling approach, this research provides a foundation for future studies on green hydrogen production and its role in a sustainable energy future. Further research should focus on refining models to account for evolving market dynamics, technological advancements, and policy landscapes.

In conclusion, although green hydrogen from hydropower shows promise for decarbonizing the chemistry sector, significant economic and infrastructural challenges must be addressed. The success of this transition depends on strategic investments, supportive policies, and continued technological innovation in both the energy and chemical industries.

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