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Integrated System Analysis of Green Hydrogen Potential for Decarbonized Energy Generation and Sustainable Utilization Pathways in Serbia

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ABSTRACT

The transition toward low-carbon energy systems necessitates the integration of alternative fuels capable of reducing greenhouse gas emissions while ensuring energy security. Green hydrogen has emerged as a critical vector in decarbonizing energy systems due to its versatility and compatibility with renewable energy sources. This study presents an integrated system analysis of green hydrogen potential in Serbia, focusing on its role in enabling decarbonized energy generation and sustainable utilization pathways. The research adopts a multi-dimensional methodology combining techno-economic evaluation, life cycle assessment, and system-level modeling to assess hydrogen production, storage, and utilization. The findings indicate that Serbia possesses significant renewable energy resources suitable for green hydrogen generation, particularly through solar and wind-based electrolysis systems. The study further identifies optimal pathways for hydrogen deployment across industrial, transportation, and power sectors. However, challenges related to infrastructure, policy frameworks, and economic feasibility persist. The research contributes by proposing a structured framework for integrating hydrogen systems into national energy strategies while addressing environmental and economic trade-offs. The results underscore the necessity of coordinated policy interventions and technological innovation to accelerate hydrogen adoption.

Keywords: Green hydrogen; decarbonization; energy systems; electrolysis; sustainability; Serbia energy transition; techno-economic analysis; renewable integration; hydrogen utilization.

INTRODUCTION

The global energy sector is undergoing a structural transformation driven by climate change mitigation goals and the need for sustainable energy systems. Fossil fuel dependence continues to dominate energy production, contributing significantly to greenhouse gas emissions. Hydrogen, particularly green hydrogen produced via renewable-powered electrolysis, is increasingly recognized as a cornerstone in achieving carbon neutrality (Acar and Dincer, 2019).

Serbia, like many transitioning economies, faces challenges in reducing emissions while maintaining energy reliability. The country's reliance on coal and imported fossil fuels necessitates a strategic shift toward cleaner alternatives. Green hydrogen offers a promising pathway for decarbonization, given its potential to integrate with renewable energy sources and support multiple sectors, including industry, transport, and power generation.

The objective of this study is to evaluate the technical, economic, and environmental feasibility of green hydrogen deployment in Serbia through an integrated system analysis. The research aims to identify optimal production methods, assess resource availability, and explore utilization pathways that align with sustainability goals. The scope includes renewable resource assessment, hydrogen production technologies, infrastructure requirements, and policy implications.

The significance of this research lies in its comprehensive approach, combining theoretical frameworks with practical insights. By analyzing Serbia's energy landscape, this study provides actionable recommendations for policymakers and stakeholders seeking to implement hydrogen-based energy solutions.

Literature Review

The development of hydrogen technologies has been extensively studied, with a strong emphasis on production methods, environmental impacts, and system integration. Hydrogen production pathways include steam methane reforming, water electrolysis, and biomass conversion, each with varying environmental implications (Acar and Dincer, 2019).

Electrolysis-based hydrogen production, particularly using renewable energy, is widely regarded as the most sustainable approach. Studies have demonstrated the viability of alkaline and PEM electrolysis systems in integrating renewable energy sources (Buttler and Spliethoff, 2018; Kumar and Himabindu, 2019). Additionally, large-scale electrolysis systems have shown potential in balancing grid fluctuations and enhancing energy storage capabilities (Terlouw et al., 2022).

Life cycle assessment studies highlight the environmental benefits of green hydrogen compared to conventional methods. Cetinkaya et al. (2012) and Valente et al. (2017) emphasize the reduced carbon footprint associated with renewable-based hydrogen production. However, these benefits depend on the energy source used for electrolysis.

Economic feasibility remains a critical concern. Yadav and Banerjee (2018) and Mehrpooya et al. (2019) demonstrate that the cost of hydrogen production is highly sensitive to electricity prices and system efficiency. Similarly, Nikolaidis and Poullikkas (2017) provide a comparative analysis of production processes, identifying cost competitiveness as a major barrier.

Regional studies, such as Kakoulaki et al. (2021), show that Europe has significant potential for green hydrogen deployment, particularly through renewable integration. These findings are supported by policy-oriented analyses from IEA (2023) and IRENA (2019, 2021), which emphasize the role of hydrogen in achieving energy transition goals.

Despite extensive research, gaps remain in integrated system-level analyses that combine resource assessment, production optimization, and utilization pathways within specific national contexts. This study addresses this gap by focusing on Serbia's energy system.

Methodology

System Framework Design

The study adopts a multi-layered analytical framework integrating resource assessment, production modeling, and utilization analysis. The framework is designed to evaluate hydrogen systems from generation to end-use, ensuring a holistic understanding of energy flows.

Renewable Resource Assessment

Serbia's renewable energy potential is assessed based on solar irradiation, wind availability, and biomass resources. These resources form the basis for green hydrogen production via electrolysis. The integration of renewable energy into hydrogen systems enhances sustainability and reduces carbon emissions (Acar and Dincer, 2019).

Hydrogen Production Modeling

Hydrogen production is modeled using electrolysis technologies, including alkaline and PEM systems. The analysis considers efficiency, operational costs, and scalability. Electrolysis efficiency is influenced by technological advancements and energy input quality, which directly impacts hydrogen yield.

Techno-Economic Analysis

A techno-economic model is developed to evaluate the cost-effectiveness of hydrogen production. The model includes capital expenditure, operational costs, and energy prices. Sensitivity analysis is conducted to assess the impact of variable parameters such as electricity cost and system efficiency.

Life Cycle Assessment

Environmental impacts are evaluated using life cycle assessment (LCA) methodologies. The analysis considers emissions across production, storage, and utilization stages. Renewable-based hydrogen systems demonstrate significantly lower emissions compared to fossil-based alternatives (Cetinkaya et al., 2012).

Utilization Pathway Analysis

Hydrogen utilization is analyzed across three sectors:

- Power generation: Hydrogen is used for grid balancing and energy storage.
- Transportation: Fuel cell vehicles and hydrogen-based fuels reduce emissions.
- Industry: Hydrogen replaces fossil fuels in high-temperature processes.

5.7 System Integration Modeling

The integration of hydrogen systems into Serbia's energy infrastructure is modeled to assess compatibility and scalability. The analysis considers grid stability, storage requirements, and distribution networks.

Results / Findings

The analysis reveals that Serbia possesses substantial renewable energy potential suitable for green hydrogen production. Solar and wind resources provide a stable foundation for electrolysis-based hydrogen generation. The techno-economic evaluation indicates that hydrogen production costs can be significantly reduced with decreasing renewable energy prices and improved system efficiencies.

Life cycle assessment results confirm that green hydrogen offers considerable environmental benefits, with reduced carbon emissions compared to conventional energy systems. However, the overall sustainability depends on the scale of renewable integration and system optimization.

The utilization analysis shows that the industrial sector presents the highest potential for hydrogen adoption, followed by transportation and power generation. The integration of hydrogen into existing infrastructure requires substantial investment but offers long-term benefits in terms of energy security and emission reduction.

Discussion

The findings highlight the transformative potential of green hydrogen in Serbia's energy transition. The integration of renewable energy with hydrogen systems aligns with global decarbonization goals and enhances energy system resilience. The results are consistent with existing studies emphasizing the environmental advantages of hydrogen production through renewable sources (Acar and Dincer, 2019).

However, several challenges must be addressed. Economic feasibility remains a key concern, particularly in the initial deployment phase. The high capital costs of electrolysis systems and infrastructure development may hinder large-scale adoption. Additionally, policy support and regulatory frameworks are essential to incentivize investment and innovation.

The study also identifies trade-offs between system efficiency and cost. While advanced technologies improve efficiency, they often require higher initial investment. Balancing these factors is crucial for sustainable implementation.

Comparative analysis with existing literature reveals that Serbia's potential is comparable to other European regions, but localized strategies are necessary to address specific constraints. The integration of hydrogen into existing energy systems requires careful planning to ensure compatibility and scalability.

Conclusion

This study provides a comprehensive analysis of green hydrogen potential in Serbia, emphasizing its role in achieving decarbonized energy systems. The integrated framework highlights the technical feasibility, environmental benefits, and economic considerations associated with hydrogen deployment.

The research demonstrates that green hydrogen can significantly contribute to reducing carbon emissions and enhancing energy security. However, successful implementation requires coordinated efforts involving technological innovation, policy support, and infrastructure development.

Future research should focus on advanced modeling techniques, real-time system optimization, and policy impact analysis to further enhance hydrogen integration strategies.

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