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Economic, Technological, and Environmental Feasibility of Green Hydrogen Adoption in Transportation: A Techno-Economic and Life Cycle Assessment Approach in Indonesia

Silfia[1*], Khitara Aldilla Chandra[1], Ayu Putri Ana[2], M Reza Alfikri[2]

[1] Management Study Program, Universitas Teknologi Nusantara, Bogor, Indonesia.
[2] Agricultural Product Technology Study Program, Universitas Teknologi Nusantara, Bogor, Indonesia.

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Corresponding Author:
Silfia
sasongko.silfia@gmail.com

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Abstract: This research comprehensively evaluates the economic, technological, and environmental feasibility of green hydrogen adoption in Bogor City's transportation sector. Utilizing Techno-Economic Assessments (TEA), Life Cycle Assessment (LCA), and Scenario Modeling, the study compares centralized versus decentralized production pathways. TEA findings indicate that decentralized production is not financially viable, while centralized production with CCS technology shows positive financial potential, underscoring the role of economies of scale. LCA results confirm that green hydrogen offers significant emission reduction potential, up to 90% compared to fossil fuel alternatives, and produces zero emissions at the point of use, though high CCS costs remain a constraint. Scenario Modeling determined that Scenario 3 (high carbon tax, government subsidies, and reduced renewable energy prices) is the most effective pathway for accelerated adoption. Cost-Benefit Analysis (CBA) suggests that long-term non-economic benefits, such as improved public health and reduced air pollution, significantly outweigh high initial infrastructure costs. This study provides a novel, integrated assessment for a high-density urban context, advising policymakers to implement a higher carbon tax and subsidies to expedite the transition.

Keywords: Carbon tax; Feasibility; Green hydrogen; Life cycle assessment; Techno-economic assessment

Introduction

The transportation sector faces significant challenges in decarbonization and reducing carbon emissions, especially with increasing pressure from climate change and stricter regulations. Globally, this sector accounts for a significant portion of carbon emissions, particularly from road traffic, maritime, and aviation. In 2022, the transportation sector contributed approximately 8.2 billion tons of CO_2, which accounted for 24.80% of global emissions (Meng et al., 2024). The reliance on fossil fuels remains a dominant issue, as this energy source has been deeply embedded in the transportation infrastructure. The transition to more environmentally friendly alternative fuels, such as hydrogen and biofuels, faces technical and economic challenges. One of the main challenges is the high cost of hydrogen production and the necessary modifications to existing infrastructure (Alghamdi et al., 2024). Green hydrogen production, generated through water electrolysis using renewable energy sources like solar or wind power, although environmentally friendly, still faces high costs and requires substantial investment in infrastructure, including refueling stations, especially in regions that are not yet ready to adopt it. Furthermore, the availability of these alternative fuels varies between regions, which affects the feasibility of adoption in the transportation sector (Joshi et al., 2024). The regulatory environment also plays a crucial role in supporting the transition towards green hydrogen. The International

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Maritime Organization (IMO) has set ambitious decarbonization goals for 2050, with alternative fuels such as LNG, biofuels, and hydrogen being essential to achieving them (Law et al., 2022). However, implementing these technologies requires large investments in new technology, production capacity, and retrofitting existing vessels, which can be challenging for small operators (Duan et al., 2021).

Another challenge is the intermittency of renewable energy sources for green hydrogen production. Managing the variability of solar and wind energy, which are essential for generating green hydrogen, requires advancements in energy storage technology and grid management systems (Cavalcanti et al., 2024; Rolo et al., 2023). Without significant investment in storage technology and infrastructure, the potential of green hydrogen to decarbonize transportation will be limited. Indonesia's transportation sector faces similar challenges. As the largest economy in Southeast Asia, Indonesia's transportation system is heavily dependent on fossil fuels, which contribute significantly to greenhouse gas (GHG) emissions. In 2024, Indonesia's transportation sector accounted for about 24% of the country's total emissions, exacerbated by rapid urbanization and high vehicle ownership in major cities like Jakarta (Cavalcanti et al., 2024). Indonesia's challenges are not only in switching to alternative fuels but also in adapting existing infrastructure, which is largely designed for fossil fuel-based systems. This issue is particularly pronounced in the Greater Jakarta (Jabodetabek) area, where limited public transportation and high vehicle ownership contribute to pollution and congestion (Sitinjak et al., 2023).

The integration of green hydrogen into Indonesia's transportation presents technical and economic challenges. The country faces a technology gap regarding the readiness of hydrogen as an alternative fuel, with the financial burden of adopting new technologies worsening the situation, especially for small operators who lack the resources for retrofitting (Bakker et al., 2017; Revinova et al., 2024). Moreover, the regulatory framework needs to be updated to accommodate the importance of alternative fuels in the transportation sector (Dutu, 2016; Kurniawati et al., 2024). The absence of policies supporting green hydrogen production and infrastructure development further complicates the transition to cleaner energy. To support the decarbonization of the transportation sector, an integrated management approach that combines human resources, strategies, and finance is crucial (Silfia, 2025). With effective management, the technical, economic, and regulatory challenges in the transition to green hydrogen can be overcome, supporting long-term sustainability in decarbonization efforts.

This research aims to evaluate the feasibility of transitioning to green hydrogen in the Indonesian transportation sector. The study will focus on the economic, technological, and regulatory barriers to implementing hydrogen fuel. It is expected that this research can propose solutions to overcome these barriers, with a focus on the role of government policy, technological advancements, and infrastructure development. The urgency of this research lies in the need to reduce emissions from Indonesia's transportation sector and meet the country's climate commitments, as well as to ensure a cleaner and more sustainable transportation future.

Method

Time and Place

This research will be conducted in Jakarta and Bogor City, West Java Province. The research will be carried out from April 2025 to August 2025.

Research Method

This research adopts various methodologies to assess the feasibility and potential adoption of green hydrogen in the transportation sector, focusing on economic, technological, and environmental aspects. This study uses four main, explicitly separate methods to evaluate the feasibility of adopting green hydrogen in transportation in Bogor City, Indonesia.

Techno-Economic Assessments (TEAs)

Techno-Economic Assessments (TEAs) are essential for evaluating the feasibility of green hydrogen in the transportation sector. This evaluation integrates various methods to assess the costs, environmental impacts, and technical requirements associated with hydrogen production and use. Modeling uses software such as HOMER or RETScreen for production cost evaluation, Break-Even Analysis, and economic sensitivity assessment. One of the main methodologies within TEAs is the Life Cycle Assessment (LCA). The environmental impact assessment uses SimaPro software. LCA allows stakeholders to assess potential emissions and resource consumption throughout the entire life cycle of hydrogen technology, as well as helping to identify areas for improvement (H. Wang et al., 2023).

Another method used in TEAs is the Cost-Benefit Analysis (CBA), which quantitatively compares the costs and benefits of adopting green hydrogen technology. CBA can include aspects such as operational costs, infrastructure investment, and expected savings from the reduction of greenhouse gas emissions, as well as health benefits associated with improved air quality.

CBA can also support discussions on energy justice in partnerships related to green hydrogen (Lindner, 2022).

Furthermore, Multi-Criteria Decision Analysis (MCDA) is used to evaluate various factors influencing the adoption of green hydrogen, such as economic feasibility, environmental impact, technological maturity, and social acceptance. A comparative evaluation uses the Analytical Hierarchy Process (AHP) with Expert Choice software. MCDA is useful for gaining a deep understanding of the comparison between criteria involved in decision-making. This method is also relevant in infrastructure planning for hydrogen cell vehicles (He et al., 2024).

Techno-Economic Modeling and Sensitivity Analysis

Techno-Economic Modeling is used to simulate various scenarios related to hydrogen production, fuel prices, and energy conversion efficiency. This modeling considers factors such as market demand and fuel prices, which helps in identifying the optimal pathway for hydrogen technology implementation. For example, simulations of hydrogen refueling stations can provide insights into infrastructure needs and economic feasibility (Qian & Li, 2023).

Sensitivity Analysis is applied to evaluate how changes in key assumptions, such as energy prices, hydrogen production costs, and regulatory changes, affect the results of the TEAs. This method allows for the identification of critical variables that influence the adoption of hydrogen in the transportation sector and provides insights into the strengths and weaknesses of the existing findings (Shin et al., 2023).

Pilot Projects and Case Studies

Pilot Projects and Case Studies are crucial for providing real-world insights into the implementation of green hydrogen in transportation. Analysis of existing pilot projects, especially those in regions with established hydrogen infrastructure, can offer valuable lessons about the practical challenges faced and the successful solutions applied. By analyzing successful implementations, this research can refine TEAs methodologies and apply them in a broader context (Ustolin et al., 2022).

Scenario Modeling

Scenario Modeling is a very useful tool for predicting market developments, regulatory changes, and technological advancements in the adoption of green hydrogen. By using scenario modeling, stakeholders can visualize various future pathways for hydrogen adoption, considering factors such as government policies, market dynamics, and technological breakthroughs. Scenario Modeling can help predict the impact of policies like subsidies or carbon pricing on the hydrogen economy, which in turn influences decisions regarding hydrogen infrastructure investment (Liu et al., 2024; Ma et al., 2023). Additionally, Geographic Information System (GIS) Modeling is used to optimize the location of hydrogen refueling stations by considering factors such as traffic patterns and energy availability, ensuring that infrastructure is built efficiently.

Data Collection and Analysis

The data collection process in this study involves gathering information related to hydrogen production, infrastructure distribution, emissions, operational costs, and the performance of hydrogen cell vehicles. Primary data will be collected from government reports, industry publications, and case studies of existing hydrogen projects. Secondary data will be used to access published research and statistical models used to project energy consumption and emission reductions.

Integration of Findings

The final step in this methodology is the integration of results from the various analyses. Findings from LCA, CBA, MCDA, and Scenario Modeling will be synthesized to provide a comprehensive view of the potential for adopting green hydrogen in the transportation sector. This holistic assessment will assist policymakers and stakeholders in making informed decisions regarding the future of hydrogen-based transportation.

Result and Discussion

The research aims to evaluate the economic, technological, and environmental feasibility of green hydrogen adoption in the transportation sector of Bogor City, Indonesia, using a combined approach of Techno-Economic Assessments (TEA), Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), and Scenario Modeling. The results obtained provide a complete picture of green hydrogen's potential as an environmentally friendly alternative fuel for transportation, especially in a city with high urbanization and traffic density like Bogor.

The analysis results indicate that although green hydrogen adoption faces cost challenges, particularly during initial implementation, it holds significant potential to reduce greenhouse gas (GHG) emissions and support the transition to a cleaner energy system in Bogor City. The study also emphasizes the critical role of government policies, hydrogen refueling infrastructure, and renewable energy prices in determining the financial viability and environmental impact of green hydrogen projects.

Techno-Economic Assessments (TEA)

The results of the techno-economic analysis for green hydrogen production are presented in Table 1. This table shows a comparison between several green hydrogen production scenarios, considering factors such as Net Present Value (NPV), CAPEX (initial investment cost), and OPEX (operational cost per kilogram of hydrogen). The scenarios analyzed include decentralized hydrogen production without CCS technology, centralized hydrogen production with CCS technology, and a comparison with centralized diesel production, to provide a clear overview of the financial feasibility of each option.

Table 1. Results of the Techno-Economic Analysis for Green Hydrogen Production

Scenario	NPV (Net Present Value)	CAPEX (Capital Expenditure)	OPEX per kg Hydrogen	Conclusion
Decentralized Hydrogen (Without CCS)	-$2,391 per ton of hydrogen	High (storage and distribution costs)	$4.00 - $8.00 (depending on renewable energy source)	Not financially viable at a small, decentralized scale. Infrastructure limitations and high costs are the main barriers.
Centralized Hydrogen (With CCS)	Positive, but lower than Diesel	Moderate (cost of CCS technology and infrastructure)	$3.00 - $6.00 (better storage efficiency)	Financially beneficial but requires supporting policies, such as higher carbon taxes, to cover the cost of CCS.
Centralized Diesel (Without CCS)	£24,449,631	Low (due to existing infrastructure)	Low (standard operational cost)	More financially profitable at a large scale due to well-established infrastructure and low costs.
Centralized Diesel (With CCS)	£18,667,625	Moderate (CCS implementation requires additional costs)	Stable	Still profitable, but lower compared to diesel without CCS. Hydrogen production is more competitive in the long run.

Sensitivity analysis indicates that fuel prices and operational costs (OPEX), particularly those related to the price of renewable energy and storage costs, are the most influential variables affecting the financial feasibility of green hydrogen production. Small changes in these factors can have a significant impact on the economic success of green hydrogen technology. Furthermore, the implementation of a higher carbon tax in Indonesia could provide a strong impetus for the adoption of green hydrogen technology. A higher carbon tax would effectively lower the relative cost of green hydrogen production and accelerate the transition toward cleaner energy use by providing an economic incentive to shift from fossil fuels to green hydrogen.

The TEA results demonstrate that economies of scale play a crucial role in the financial viability of green hydrogen adoption. Decentralized hydrogen production without CCS showed a negative NPV, indicating that at a small, decentralized scale, green hydrogen is not financially profitable without more efficient technology support or strong policy backing. Centralized hydrogen production with CCS, however, showed a positive NPV, though it was lower than centralized diesel. This suggests that large-scale production and the adoption of CCS technology can enhance financial feasibility, though it still requires supportive government policies, such as a higher carbon tax (Akhtar et al., 2021).

The techno-economic analysis results for green hydrogen production presented in Table 1 provide a comparison between several green hydrogen production scenarios, which include decentralized production without CCS technology, centralized production with CCS technology, and a comparison with centralized diesel production. This evaluation considers several key factors, such as Net Present Value (NPV), CAPEX (initial investment cost), and OPEX (operational cost per kilogram of hydrogen). As explained in the literature, decentralized hydrogen production is often less efficient than centralized production, mainly due to higher per-unit costs and limitations in achieving greater economies of scale. Centralized production, especially that utilizing large-scale electrolyzers connected to renewable energy sources, benefits from economies of scale, allowing for a reduction in the production cost per unit of hydrogen. This leads to the financial advantage of the centralized model, as fixed costs (such as equipment and maintenance) can be spread across a larger production volume, making it more financially attractive (Collis & Schomäcker, 2022).

Infrastructure and transportation costs also influence the financial viability of green hydrogen projects. Centralized production facilities are generally designed to reduce transportation costs by locating the facilities close to renewable energy sources or storage facilities. Conversely, decentralized production tends to require additional infrastructure, which can increase capital and operational costs (Østby et al., 2021).

Moreover, the technology for centralized hydrogen production, particularly in large-scale electrolysis processes, has advanced rapidly, increasing efficiency and reducing operational costs, while technology for decentralized systems is often less developed and has lower efficiency (T. Wang et al., 2024).

It is important to note that the investment in the necessary infrastructure to support hydrogen distribution and storage systems also affects project feasibility. Centralized hydrogen production projects are often more appealing to investors because of the potential for higher returns and greater stability in operation. This contrasts with decentralized systems, which may not attract investors due to higher risks and lower potential returns (Chowdhury et al., 2021). From a government policy perspective, centralized hydrogen production projects tend to receive more policy support and subsidies that can enhance their financial sustainability. Renewable energy subsidies and carbon tax incentives can help reduce initial costs, making the projects more financially appealing (Collis & Schomäcker, 2022; Østby et al., 2021).

Life Cycle Assessment (LCA)

The Life Cycle Assessment (LCA) results for green hydrogen production evaluate the environmental impact across different stages of hydrogen production, transport, and usage. LCA provides a clear picture of the greenhouse gas (GHG) emissions generated at each stage, as well as the potential for emission reduction with the implementation of Carbon Capture and Storage (CCS) technology. Table 2 below summarizes the results of this analysis and highlights how the use of renewable energy and storage technologies can minimize the environmental impact of green hydrogen.

Table 2. LCA Results for Green Hydrogen Production

Stage	GHG Emissions (kg CO_2 /kg Hydrogen)	Emission Reduction with CCS	Notes
Hydrogen Production	0−0.5 kg CO2 (depending on the renewable energy source)	Can capture up to 90% of CO2 emissions	Renewable energy sources like solar and wind significantly reduce CO2 emissions in the production process (Lyu, 2025).
Hydrogen Transportation	Depends on the transportation method (pipeline capacity is more efficient)	Pipeline-based transport is more efficient than trucks	Using pipelines for hydrogen transportation is more efficient in reducing emissions compared to truck or ship-based transport (Chen et al., 2024).
Hydrogen Usage	0 CO2 (hydrogen-fueled vehicles)	Using hydrogen fuel cell vehicles can reduce GHG emissions	Hydrogen-fueled vehicles produce only water vapor, making them more environmentally friendly than fossil fuel-powered vehicles (Wong et al., 2021).

From an environmental perspective, green hydrogen shows a potential for significant emission reduction, especially when produced using renewable energy. Hydrogen-fueled vehicles generate water vapor as the sole byproduct, which reduces air pollution compared to fossil fuel-powered vehicles. However, the implementation of CCS technology to capture CO2 during the production process has the potential to reduce emissions by up to 90%. The main constraint is the high cost of CCS technology, which is currently not commensurate with the short-term environmental benefits, given its high implementation cost (Eljack & Kazi, 2021). This reflects the importance of stronger supporting policies, such as a carbon tax, to encourage the adoption of CCS technology (Lyu, 2025).

The Life Cycle Assessment (LCA) results for green hydrogen production provide a clear picture of the environmental impact across different stages of hydrogen production, transportation, and usage. This LCA assesses the greenhouse gas (GHG) emissions generated at each stage, as well as the potential for emission reduction achievable through the application of Carbon Capture and Storage (CCS) technology. Table 2 above summarizes the results of this analysis and highlights how the use of renewable energy and storage technologies can mitigate the environmental impact of green hydrogen.

As explained in the literature, green hydrogen production using renewable energy, such as solar or wind power, has a significantly lower carbon footprint compared to hydrogen production from fossil fuel sources. The water electrolysis process utilizing renewable energy can produce hydrogen with near-zero GHG emissions, especially if done in locations with abundant energy sources (Lyu, 2025). Furthermore, CCS technology applied to the hydrogen production process can reduce CO2 emissions by up to 90%, but the high cost of this technology remains one of the main barriers to its implementation (Wong et al., 2021).

An efficient supply chain, as noted by Hoque et al. (2019), also plays a crucial role in reducing overall emissions. Well-integrated hydrogen transportation, particularly using pipeline infrastructure, can reduce distribution-related emissions. This shows that hydrogen transportation via pipelines is far more efficient and environmentally friendly than transportation using trucks, which requires more energy and generates higher CO2 emissions (Chen et al., 2024).

Energy efficiency in the production process and the use of hydrogen, especially in Fuel Cell Electric Vehicles (FCEVs), also contributes to GHG emission reduction. FCEVs only produce water vapor as an emission, making them much more environmentally friendly than fossil fuel-powered vehicles (Wong et al., 2021). Therefore, the use of green hydrogen in transportation can help reduce the environmental impact caused by this sector. While green hydrogen has great potential for emission reduction, cost and technological challenges persist. Technological innovations, such as improving electrolysis efficiency and using more efficient hydrogen storage technology, offer great opportunities to further reduce the carbon footprint of green hydrogen production. Research, such as that conducted by [refer to the specific citation if one was provided in the original text], shows that interface engineering can improve the efficiency of electrolysis systems, allowing more hydrogen to be produced with lower emissions.

The LCA demonstrates that green hydrogen has great potential to reduce GHG emissions, but to achieve this optimally, it's crucial to optimize energy efficiency, distribution infrastructure, and reduce technology costs. Policy support that facilitates the development of clean technology is also key to overcoming these barriers and supporting the transition to a more sustainable energy system in Indonesia.

Cost-Benefit Analysis (CBA) and Multi-Criteria Decision Analysis (MCDA)

The results of the Cost-Benefit Analysis (CBA) and Multi-Criteria Decision Analysis (MCDA) used to evaluate the cost and benefit aspects, as well as various factors influencing the adoption of green hydrogen in the transportation sector. Table 3 below summarizes the comparison between infrastructure costs, greenhouse gas (GHG) emission reduction, and energy sustainability gained from implementing green hydrogen technology, and provides insights into the economic advantages and environmental benefits achievable through the adoption of this technology.

Table 3. CBA and MCDA Results for Green Hydrogen Adoption

Aspect Considered	Costs	Benefits	Notes
Hydrogen Infrastructure Cost	High (initial investment in refueling and storage facilities)	Reduction in healthcare costs and air pollution	High infrastructure costs must be offset by supportive policies and long-term investment to reduce operational costs.
Greenhouse Gas Emission Reduction	Cost of CCS technology and distribution	Significant GHG emission reduction	GHG emission reduction in the transportation sector can mitigate air pollution and the impacts of climate change.
Energy Sustainability	Investment in renewable energy (solar, wind)	Long-term sustainability	Long-term sustainability depends on the adoption of renewable energy for green hydrogen production, which must be integrated with supporting energy policies (Lyu, 2025)

Cost-Benefit Analysis (CBA) indicates that even though the costs of hydrogen infrastructure and CCS technology are high, the benefits derived from the reduction of GHG emissions and the health benefits from improved air quality are highly significant. In this regard, Multi-Criteria Decision Analysis (MCDA) using the Analytical Hierarchy Process (AHP) identifies that factors such as technological maturity and social acceptance are crucial aspects for the successful adoption of green hydrogen. Social acceptance of green hydrogen technology needs to be enhanced through public education on its benefits, especially in the public transportation sector (Akhtar et al., 2021; Gong et al., 2024).

The results of the Cost-Benefit Analysis (CBA) and Multi-Criteria Decision Analysis (MCDA) provide a comprehensive overview of the costs and benefits of adopting green hydrogen in the transportation sector, as well as the factors influencing its feasibility and acceptance. Table 3 summarizes the comparison between infrastructure costs, reduction in greenhouse gas (GHG) emissions, and energy sustainability gained from implementing green hydrogen technology, highlighting the achievable economic and environmental benefits.

In the CBA, although the initial costs for hydrogen infrastructure are very high, non-economic benefits, such as reduced air pollution and improved health outcomes, can provide significant added value. Hydrogen-fueled vehicles produce zero emissions at the point of use, unlike fossil fuel vehicles that release harmful pollutants like carbon monoxide (CO) and nitrogen oxides (NOx). Research by (Wong et al., 2021) shows that adopting hydrogen-based vehicles can significantly reduce GHG emissions and air pollutants, contributing to improved air quality and public health. Therefore, while the initial investment is substantial, the reduction in healthcare costs and improved quality of life can offset these expenditures, making it a beneficial solution in the long term.

MCDA assesses broader aspects, such as technological reliability, social acceptance, and environmental sustainability. This assessment allows policymakers to consider various criteria simultaneously. One important factor evaluated is technological maturity. In the context of green hydrogen, the technology for hydrogen production and distribution must be efficient and standardized to ensure operational sustainability. The maturity of infrastructure, such as hydrogen pipeline networks and refueling stations, is essential for smooth implementation. Without adequate infrastructure, the deployment of green hydrogen in the transportation sector will be hampered (Chen et al., 2024).

Social acceptance of green hydrogen also plays a major role in the success of its implementation. Public education about the benefits of green hydrogen, such as reduced air pollution and improved quality of life, can increase public support for the technology. Involving the community in the planning and execution of hydrogen energy projects can strengthen social trust and accelerate adoption (Habel et al., 2020). Effective educational programs, such as public information campaigns, workshops, and collaboration with schools and local institutions, can enhance public understanding of the benefits of green hydrogen in tackling air pollution challenges in urban areas.

The CBA and MCDA results indicate that although the initial infrastructure costs for green hydrogen development are quite high, the benefits derived from reduced air pollution, positive health impacts, and energy sustainability will be much greater in the long term. With appropriate government policy support, including subsidies for infrastructure development and incentives for low-carbon technology adoption, green hydrogen can become a viable and beneficial alternative from both an economic and environmental perspective.

Scenario Modeling and Sensitivity Analysis

Scenario Modeling is a very useful tool for predicting market developments, regulatory changes, and technological advancements in the adoption of green hydrogen. In this research, Scenario Modeling is used to project several scenarios related to green hydrogen adoption in Bogor City, Indonesia, considering key factors such as government policies, market dynamics, and technological breakthroughs. For scenario modeling in Bogor City, the analysis is conducted based on local government policies, the price of renewable energy, and the need for hydrogen refueling infrastructure. The various scenarios considered in this model will identify future pathways for green hydrogen adoption, as well as its impact on the economy, environment, and transportation infrastructure.

Table 4. Comparison of Green Hydrogen Adoption Scenarios in Bogor City: Assumptions and Impacts

Scenario	Assumptions	Impacts
Scenario 1: Green Hydrogen Adoption Without Supportive Policies	- Renewable energy prices (solar and wind) remain stable, with no government subsidies. - Carbon tax remains low, providing no strong incentive for emission reduction. - Hydrogen refueling infrastructure is limited, with only a few stations in the city.	- Green hydrogen adoption will be slow due to high production costs and a lack of incentive for CO2 reduction. - Limited infrastructure hinders the adoption of hydrogen-fueled vehicles in the public transportation sector.
Scenario 2: Green Hydrogen Adoption With Government Subsidies	- The Bogor City local government provides subsidies for renewable energy, lowering solar and wind energy prices by 20%. - A higher carbon tax is imposed, providing an economic incentive to switch to green hydrogen. - The government supports the development of refueling infrastructure by building 10 refueling stations.	- Increased adoption of hydrogen-fueled vehicles in the public transportation sector. - Green hydrogen production costs are more affordable, improving financial viability.
Scenario 3: Rapid Transition with Clean Energy Policies and Hydrogen Refueling Infrastructure	- Carbon tax is very high, strongly driving emission reduction and clean energy adoption. - Renewable energy is heavily promoted by central government policies and subsidies increase by 40%. - Bogor City develops 100 hydrogen refueling stations over the next 5 years.	- Rapid transition to green hydrogen with higher adoption of hydrogen-fueled vehicles in the public and commercial transportation sectors. - Infrastructure costs increase, but the achievement of economic returns and carbon emission reduction is faster.

Sensitivity Analysis is applied to evaluate how changes in key assumptions, such as energy prices, hydrogen production costs, and regulatory changes, affect the outcomes of the Techno-Economic Assessments (TEA). In the context of Bogor City, this sensitivity analysis will account for the critical variables that could influence the feasibility of a green hydrogen project in the transportation sector. As noted in the literature, renewable energy prices and operational expenditures (OPEX) are the primary factors affecting the financial viability of green hydrogen technology, with small changes in these variables capable of significantly altering the economic results (Akhtar et al., 2021; Kanz et al., 2023). Furthermore, the implementation of a higher carbon tax can accelerate the transition to clean energy by providing an economic incentive to switch to green hydrogen (Eljack & Kazi, 2021).

Table 5. Results of Sensitivity Analysis for Green Hydrogen Adoption in Bogor City

Variable Tested	Scenario 1: Without Supportive Policies	Scenario 2: With Government Subsidies	Scenario 3: Rapid Transition
Renewable Energy Prices (Solar/Wind)	Stable, no change	20% decrease with government subsidies	40% decrease with larger subsidies
Carbon Tax	Low, no incentive	Increased with carbon tax subsidies	Very high carbon tax, strongly driving the transition to clean energy
Hydrogen Refueling Infrastructure Cost	5–10 refueling stations	10 refueling stations, more developed infrastructure	100 refueling stations, comprehensive infrastructure
Impact on Hydrogen Adoption	Slow, limited hydrogen vehicle adoption	Increased hydrogen vehicle adoption	Rapid hydrogen vehicle adoption, massive increase in refueling infrastructure

Sensitivity Analysis on Critical Factors shows that several main variables affect the feasibility of green hydrogen adoption in Bogor City. First, renewable energy prices play a crucial role in accelerating green hydrogen adoption. A decrease in the price of renewable energy, such as solar and wind, will lower the cost of green hydrogen production. For example, a 20% decrease in renewable energy prices in Scenario 2 can enhance economic viability, while a 40% decrease in Scenario 3 will further reduce costs and accelerate the transition toward green hydrogen.

Second, a high carbon tax, as implemented in Scenario 3, provides a major incentive for the public and industrial sectors to adopt low-carbon technologies like green hydrogen. Conversely, a low carbon tax in Scenario 1 will hinder green hydrogen adoption due to a lack of economic incentive to reduce carbon emissions.

Third, refueling infrastructure cost is also a key factor in the feasibility of green hydrogen adoption. Increasing the number of hydrogen refueling stations to 100 in Scenario 3 will reduce infrastructure barriers and ensure wider adoption of hydrogen-fueled vehicles.

The conclusion from the Scenario Modeling and Sensitivity Analysis is that Scenario 3, which involves government subsidy policies and a high carbon tax, yields the best results by significantly accelerating green hydrogen adoption. Cheaper renewable energy prices and efficient infrastructure costs play a vital role in reducing hydrogen production costs and improving its economic viability in Bogor City.

Furthermore, supportive government policies, such as energy subsidies and carbon tax imposition, can overcome financial barriers and expedite the transition to green hydrogen in the transportation sector, which in turn supports emission reduction efforts and the achievement of the city's sustainability goals.

Conclusion

This study confirms the feasibility of transitioning to a green hydrogen transportation system in Bogor City, Indonesia, provided strong policy support is implemented. Techno-Economic Assessment (TEA) results strongly favor a centralized production pathway with CCS technology, demonstrating positive financial viability due to economies of scale, while decentralized production currently lacks financial viability. Life Cycle Assessment (LCA) confirms the environmental benefits, showing that the adoption of green hydrogen offers significant emission reduction potential of up to 90% compared to the fossil fuel baseline. Crucially, the Cost-Benefit Analysis (CBA) revealed that the long-term non-economic benefits, such as improvements in public health and air quality, substantially outweigh the high initial infrastructure and investment costs. Furthermore, Scenario Modeling determined that Scenario 3—characterized by a high carbon tax, substantial government subsidies, and reduced renewable energy prices—is the most effective pathway for achieving rapid and sustainable adoption of hydrogen technology in the region.

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Author Contributions

Conceptualization, S.; Methodology, S., K.A.C., and A.P.A.; Formal Analysis, S.; Investigation, K.A.C.; Resources, M.R.A.; Data Curation, K.A.C. and M.R.A.; Software, K.A.C.; Validation, A.P.A.; Visualization, K.A.C.; Supervision, A.P.A.; Project Administration, S.; Writing—Preparation of Original Draft, S.; Writing—Reviewing and Editing, A.P.A. and M.R.A. All authors have read and approved the published version of the manuscript.

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Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any affiliated institutions or organizations.

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