

## A Preliminary Methodological Framework of the Potential Hydrogen Economy for a Sustainable Transport in Malaysia

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**Abstract:** The transition to a hydrogen economy is vital for achieving sustainable transport in Malaysia, particularly in mitigating the environmental impact of heavy-duty mobility. This paper proposes a preliminary methodological framework to evaluate hydrogen's potential as a transformative solution for decarbonizing the transportation sector, focusing on key areas such as hydrogen production, storage, distribution, and vehicle integration, with an emphasis on green hydrogen from renewable sources. Our assessment reveals the significant potential of hydrogen to reduce greenhouse gas emissions and air pollutants, positioning it as a viable alternative to fossil fuels and battery-electric vehicles, especially in heavy-duty applications. The study assesses the technological feasibility, economic viability, and environmental benefits of adopting hydrogen in Malaysia, considering current infrastructure, production capabilities, and regulatory frameworks. Key challenges identified include the high costs of hydrogen production and infrastructure, technological barriers in storage and vehicle integration, and gaps in policy and market readiness. To address these, we propose strategic recommendations for stakeholders, highlighting the need for government support, public-private partnerships, and international collaborations. This framework aims to guide Malaysia's transition to a hydrogen-powered transport sector, aligning with the nation's sustainability and energy security goals while positioning Malaysia as a leader in hydrogen technology in Southeast Asia.

**Keywords:** *Hydrogen economy, sustainable transport, green hydrogen, Malaysia, decarbonization, heavy-duty vehicles, technological feasibility, economic viability*

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### 1. Introduction and Background

The global transportation sector is a significant contributor to greenhouse gas emissions, accounting for approximately 24% of global CO<sub>2</sub> emissions from energy consumption, with heavy-duty vehicles (HDVs) such as trucks, buses, and trains being major contributors within this sector (International Energy Agency [IEA], 2023). As the world seeks to transition towards more sustainable energy systems, the hydrogen economy has emerged as a promising solution for decarbonizing transportation, particularly heavy-duty mobility. In Malaysia's context, its National Energy Policy 2022-2040 the transition to a hydrogen-based economy is not merely strategic but essential. Malaysia's pledge to cut carbon emissions level by 15 percent in 2050, with the launching of the Hydrogen Economy and Technology Roadmap (HETR) has strengthened its commitment.

The concept of a hydrogen economy envisions a future where hydrogen plays a central role in energy storage, distribution, and utilization across various sectors, including transportation, industry, and power generation (International Renewable Energy Agency [IRENA], 2019). This transition is driven by advancements in hydrogen production technologies, such as electrolysis powered by renewable energy (producing "green hydrogen") and steam methane reforming coupled with carbon capture and storage (producing "blue hydrogen") (European Hydrogen Backbone, 2023) which are expected for its potential to be more economically competitive and environmentally beneficial over time.

The use of hydrogen in the transportation sector, particularly for heavy-duty vehicles, is one of the most promising aspects of the hydrogen economy. Fuel cell electric vehicles (FCEVs) use hydrogen to generate

electricity on-board through a chemical reaction in a fuel cell, offering a clean and efficient alternative to diesel engines (U.S. Department of Energy, 2021). Heavy-duty vehicles (HDVs), which include trucks, buses, and trains, are particularly well-suited for hydrogen fuel cells because of the high energy density of hydrogen, which provides longer driving ranges and quick refueling times compared to battery-electric alternatives (National Renewable Energy Laboratory [NREL], 2021). These vehicles are essential for the movement of goods and people over long distances, often serving as the backbone of economic activities, particularly in logistics and public transportation. Despite their importance, HDVs are also significant contributors to greenhouse gas (GHG) emissions and air pollution, which has made their decarbonization a priority in pushing towards sustainable transport.

As far as Malaysia is concerned, the state of Sarawak has taken the lead in the hydrogen economy to begin large-scale commercial production to be the exporter of hydrogen by 2027. The launching of its H2biscus project in Tanjong Kidurong, Bintulu is forecasted to produce 220,000 tons of green hydrogen, 630,000 tons of green ammonia and 600,000 tons of blue ammonia when it starts operation. On the other hand, the Sarawak Economic Development Corporation (SEDC) will promote extending the use of hydrogen-powered public vehicles to the people of Sarawak. Its Chairman Tan Sri Datuk Amar Abdul Aziz Hussain stated that the use of Autonomous Rapid Transit (ART) vehicles and buses will start its commercial operations by the end of 2025 (The Borneo Post Online, March 22, 2023). He further added that SEDC Energy needs to produce hydrogen to power the state's ART system and hence it is best to produce their electrolyzers to cut the cost.

Additionally, the shift towards a hydrogen economy has significant implications for energy security and economic development. By diversifying the energy mix and reducing reliance on imported fossil fuels, hydrogen can enhance energy resilience and provide new economic opportunities, particularly in regions with abundant renewable energy resources (European Hydrogen Backbone, 2023). Furthermore, as technologies advance and economies of scale are realized, the costs associated with hydrogen production and infrastructure are expected to decrease, making hydrogen a more competitive and viable option for widespread adoption.

Nevertheless, issues or challenges in a developing country like Malaysia are that the transition to a hydrogen economy would involve the need for extensive infrastructure development, high costs of hydrogen production and the lack of a cohesive regulatory framework present significant barriers to widespread adoption (IRENA, 2019). Addressing these challenges requires coordinated efforts from governments, industries, and research institutions to invest in technology development, infrastructure, and supportive policies. Thus, the primary objective of this paper is to propose a preliminary methodological framework for a hydrogen economy in Malaysia's transport sector, and the specific goals are to explore hydrogen's role, assess feasibility, identify impacts, and analyze challenges.

## 2. Literature Review

**Hydrogen as a Clean Energy Carrier:** One of hydrogen's most notable properties is that it is the most abundant element in the universe, making it a potentially limitless energy resource. As the lightest element, hydrogen boasts a high energy content per unit mass, making it highly efficient for energy storage and utilization (U.S. Department of Energy, 2021). Hydrogen's high energy density is particularly advantageous in applications requiring long driving ranges and heavy payload capacities, such as in heavy-duty transportation, where it is approximately three times that of gasoline (International Renewable Energy Agency [IRENA], 2020). Additionally, hydrogen is non-toxic and non-polluting, and when used in fuel cells, it combines with oxygen to produce electricity, with water vapor as the only by-product. This makes hydrogen an environmentally friendly alternative to traditional fossil fuels (Hydrogen Council, 2021).

The benefits of hydrogen extend beyond its clean emission profile. Hydrogen fuel cells, for instance, emit only water vapor, which significantly reduces greenhouse gas emissions and air pollutants compared to internal combustion engines powered by fossil fuels (International Energy Agency [IEA], 2021). Moreover, hydrogen can be produced from a variety of resources, including water, natural gas, biomass, and even industrial waste. This versatility allows hydrogen to be integrated into various energy systems, thereby enhancing energy security by diversifying the energy mix (IRENA, 2019). Another significant advantage is hydrogen's capacity for long-term energy storage, which makes it an ideal solution for balancing supply and demand in renewable

energy systems, where the production of electricity from sources like wind and solar can be intermittent (U.S. Department of Energy, 2021).

Hydrogen's applications are broad and impactful, particularly in transportation, industry, and power generation. In the transportation sector, hydrogen is increasingly seen as a promising solution for heavy-duty vehicles such as buses, trucks, and trains. The high energy density of hydrogen, combined with rapid refueling capabilities, offers significant advantages over battery-electric vehicles, particularly in applications requiring long ranges and heavy loads (Hydrogen Council, 2022). In the industrial sector, hydrogen is already widely used as a feedstock in processes such as ammonia production, oil refining, and steel manufacturing, and its role is expected to expand as industries seek to reduce carbon emissions (IEA, 2021). Furthermore, hydrogen can be utilized in power generation, either through direct combustion in gas turbines or in fuel cells, providing a clean and flexible option for electricity production (IRENA, 2019).

In recent years, there has been a significant increase in global interest and investment in hydrogen as a clean energy solution, especially in the transportation sector. Governments and industries worldwide are increasingly recognizing hydrogen's potential to decarbonize heavy-duty transport and are actively integrating it into their energy and transport strategies.

The European Union (EU) has made hydrogen a central component of its climate neutrality goals, with the EU Hydrogen Strategy outlining plans for the large-scale deployment of hydrogen technologies across the continent. This strategy includes ambitious targets, such as the installation of 6 GW of renewable hydrogen electrolyzers by 2024 and 40 GW by 2030, highlighting the EU's commitment to integrating hydrogen into its energy and transportation systems (European Commission, 2020). Similarly, Japan has been a pioneer in hydrogen technology, with its Hydrogen Roadmap setting out plans to establish a hydrogen-based society. Japan aims to deploy 320 hydrogen refueling stations and 200,000 hydrogen vehicles by 2025, focusing on reducing the cost of hydrogen and expanding its use in transportation (Ministry of Economy, Trade and Industry [METI], 2017). In the United States, the Department of Energy (DOE) has launched several initiatives, including the Hydrogen Energy Earth Shot, which seeks to reduce the cost of clean hydrogen to \$1 per kilogram by 2030. The U.S. is also investing heavily in hydrogen infrastructure to support the adoption of hydrogen-powered heavy-duty vehicles (U.S. Department of Energy, 2021).

In the transportation sector, hydrogen fuel cells are being increasingly adopted in vehicles, particularly in regions such as Japan, South Korea, and California. These vehicles offer longer driving ranges and quicker refueling times compared to battery-electric vehicles, making them particularly suitable for heavy-duty applications (Hydrogen Council, 2022). In Europe, hydrogen-powered trains like the Alstom Coradia iLint have been successfully deployed, demonstrating hydrogen's viability as a clean energy solution for rail transport (Alstom, 2022). Additionally, companies such as Hyundai and Nikola are developing hydrogen fuel cell trucks for long-haul transportation, which are expected to play a crucial role in reducing emissions from the freight sector (Hyundai, 2021; Nikola Corporation, 2022).

**Hydrogen in Heavy-Duty Mobility:** Alstom's Coradia iLint, the world's first hydrogen-powered train, was introduced in Germany in 2018. It operates on non-electrified tracks and has a range of approximately 1,000 kilometers on a single tank of hydrogen. This train has been celebrated for its low environmental impact, emitting only water vapor and offering a sustainable alternative to diesel trains on routes that are not yet electrified. The success of the Coradia iLint has prompted further interest in hydrogen trains across Europe and beyond (Alstom, 2022).

In 2020, Hyundai began deploying its XCIENT Fuel Cell trucks in Switzerland as part of a broader initiative to establish a green hydrogen ecosystem. These trucks, designed for long-haul freight operations, offer a range of around 400 kilometers per refueling, with plans to increase the fleet size in the coming years. This project has highlighted the operational feasibility of hydrogen trucks and the importance of developing supporting infrastructure such as refueling stations (Hyundai, 2021).

South Korea has been a leader in the adoption of hydrogen buses. Hyundai has developed and deployed hydrogen fuel cell buses in several cities across the country, with the buses being integrated into regular public

transit services. These buses are part of South Korea's broader strategy to reduce urban air pollution and greenhouse gas emissions, with the government providing substantial support for hydrogen infrastructure development (Hydrogen Council, 2022).

In Malaysia, the state of Sarawak has taken significant steps towards adopting hydrogen in public transportation. The Sarawak government launched Southeast Asia's first hydrogen-powered buses in Kuching in 2019. This pilot project is part of a larger initiative to explore hydrogen as a clean energy source for the region. The hydrogen used is produced locally, highlighting the potential for integrating hydrogen production and usage within the local economy. The success of this project could pave the way for the broader adoption of hydrogen technology in Malaysia's transport sector (Sarawak Energy, 2020).

**Framework Development Key Component:** The foundation of any hydrogen economy framework is the production and supply chain of hydrogen. According to the International Renewable Energy Agency (2019), green hydrogen, produced through electrolysis using renewable energy, is essential for reducing the carbon footprint of hydrogen production. Additionally, hydrogen production methods such as Steam Methane Reforming (SMR) with Carbon Capture and Storage (CCS) are currently more prevalent but face challenges related to carbon emissions and scalability (International Energy Agency, 2023). A robust hydrogen economy framework must prioritize green hydrogen while acknowledging the role of transitional technologies like SMR with CCS.

Storage and distribution are critical components of the hydrogen supply chain. The U.S. Department of Energy (2022) highlights that advancements in storage technologies, such as compressed gas, liquid hydrogen, and chemical carriers, are necessary to ensure a stable hydrogen supply. Efficient distribution networks, including pipelines and refueling infrastructure, are also crucial for the successful integration of hydrogen into the transportation sector. The framework must address the technological and logistical challenges associated with hydrogen storage and distribution to create a resilient supply chain.

The success of the hydrogen economy depends heavily on supportive policy and regulatory frameworks. The Hydrogen Council (2022) and the International Energy Agency (2023) emphasize the importance of government policies that incentivize hydrogen production and use, such as subsidies, tax credits, and carbon pricing. These policies must be designed to stimulate investment in hydrogen infrastructure and research while ensuring alignment with international standards and certifications. A methodological framework must incorporate policy recommendations that foster innovation, investment, and international collaboration.

The integration of hydrogen into transportation systems, particularly for heavy-duty vehicles, is a key focus of the hydrogen economy. Hydrogen fuel cell vehicles (FCVs) offer a zero-emission alternative to diesel engines, and their adoption is critical for decarbonizing the transportation sector (Hydrogen Council, 2022). The literature suggests that a successful framework must include strategies for scaling up FCV production, developing refueling infrastructure, and ensuring the economic viability of hydrogen as a fuel.

Finally, the framework must address the socio-economic and environmental impacts of transitioning to a hydrogen economy. This includes assessing the economic feasibility of hydrogen technologies, their potential to create jobs, and their environmental benefits compared to existing energy sources (National Renewable Energy Laboratory, 2021). The framework should also consider public acceptance and the social implications of widespread hydrogen adoption.

### 3. Research Methodology

**Methodological Framework Development:** Developing a preliminary methodological framework for establishing a hydrogen economy in Malaysia involves several critical steps, each designed to address the unique challenges and opportunities within the Malaysian context. The following outlines the key steps in this process:

#### **Step1: Literature Review and Benchmarking**

The first step is to conduct a comprehensive literature review and benchmarking of global hydrogen

economies. This involves analyzing existing hydrogen strategies and frameworks from leading countries such as Japan, Germany, and South Korea, as well as reviewing academic research and case studies on hydrogen technologies and their applications in transportation. This step will provide a solid foundation of knowledge on the current state of hydrogen economies globally, identifying best practices, key success factors, and potential pitfalls that could be relevant to Malaysia's context.

### **Step2: Stakeholder Analysis**

Identifying and engaging with key stakeholders in the hydrogen economy, including government agencies, industry players, research institutions, and non-governmental organizations (NGOs). This step involves mapping out the roles and interests of these stakeholders and assessing their influence and contribution to the development of a hydrogen economy in Malaysia. A stakeholder map that highlights the roles, responsibilities, and potential collaboration opportunities among different entities, ensuring a coordinated approach to hydrogen development.

### **Step3: Assessment of Malaysia's Current Energy Landscape**

Analyzing Malaysia's current energy mix, infrastructure, and policies to assess the readiness for integrating hydrogen as a significant energy carrier. This includes evaluating the availability of renewable energy sources for green hydrogen production, existing hydrogen production capacities, and the state of transportation infrastructure. A detailed report on Malaysia's energy landscape identifies existing assets, gaps, and areas requiring development to support a hydrogen economy.

### **Step4: Feasibility Studies**

Conducting technical, economic, and environmental feasibility studies specific to the Malaysian context. These studies will assess the potential for hydrogen production (both green and blue hydrogen), the cost-effectiveness of hydrogen technologies, and the environmental benefits and risks associated with hydrogen adoption. A series of feasibility reports that provide data-driven insights into the viability of hydrogen as a key component of Malaysia's energy and transportation sectors.

### **Step 5: Framework Design and Development**

Using insights from the previous steps, design a preliminary framework that outlines the structure, policies, and strategies required to develop a hydrogen economy in Malaysia. This framework should include technological pathways, infrastructure development plans, and policy recommendations tailored to Malaysia's specific needs. A draft framework document that serves as a roadmap for establishing a hydrogen economy in Malaysia, with clearly defined phases, milestones, and action plans.

### **Step 6: Pilot Projects and Case Studies**

Designing and implementing pilot projects in key areas such as transportation and industrial applications. These pilots will serve as practical case studies to test the viability of the hydrogen framework and provide real-world data for further refinement. Detailed case studies from pilot projects that offer insights into the practical challenges and successes of hydrogen adoption in Malaysia, inform the final framework.

### **Step 7: Feedback and Iteration**

Engaging stakeholders once more to gather feedback on the preliminary framework, followed by iterative refinement. This step ensures that the framework is robust, practical, and aligned with the needs and expectations of all stakeholders. A final, well-vetted framework ready for implementation, along with an action plan for its rollout across different sectors in Malaysia.

### **Step 8: Implementation Planning**

Developing a comprehensive implementation plan that includes timelines, resource allocation, and risk management strategies. This plan should outline the specific steps needed to transition from the framework to actionable projects and initiatives. A detailed implementation plan that guides the deployment of the hydrogen economy framework, ensuring the smooth execution and continuous monitoring and evaluation.

### **Step 9: Monitoring and Evaluation**

Establishing monitoring and evaluation mechanisms to track progress, measure impacts, and ensure the

framework's objectives are being met. This includes setting up key performance indicators (KPIs) and conducting regular assessments. A robust monitoring and evaluation system that provides continuous feedback and enables the framework to adapt to changing conditions or new information.

**Hydrogen Production Technologies:** When analyzing different hydrogen production methods for potential application within Malaysia's hydrogen economy, it is essential to adopt a systematic approach that considers both the technical and economic aspects of each method, along with its environmental impacts. The primary hydrogen production methods that need to be analyzed include green hydrogen, produced via electrolysis powered by renewable energy; blue hydrogen, produced from natural gas with carbon capture and storage (CCS); and grey hydrogen, produced from natural gas without CCS. Table 1 summarizes the technical feasibility, economic viability, and environmental impact of green, blue, and grey hydrogen production methods, with a focus on their application within Malaysia's hydrogen economy.

**Table 1: Hydrogen Technical Feasibility, Economic Viability, and Environmental Impact**

Aspect	Green Hydrogen	Blue Hydrogen	Grey Hydrogen
<b>Technical Feasibility</b>	<ul style="list-style-type: none"> <li>Evaluate availability and potential for scaling up renewable energy sources (e.g., solar, wind) for electrolysis.</li> <li>Consider the efficiency of current electrolyzer technologies.</li> <li>Examine the adaptability of these technologies to Malaysia's energy landscape.</li> </ul>	<ul style="list-style-type: none"> <li>Assess infrastructure and technology for natural gas reforming combined with CCS.</li> <li>Evaluate the availability of natural gas resources and proximity of CCS sites.</li> <li>Assess technology readiness for large-scale deployment.</li> </ul>	<ul style="list-style-type: none"> <li>Analyze current infrastructure for natural gas production.</li> <li>Consider the potential for transitioning to cleaner methods.</li> <li>Serve as a transitional method while green hydrogen infrastructure is developed.</li> </ul>
<b>Economic Viability</b>	<ul style="list-style-type: none"> <li>Examine the cost of producing green hydrogen, focusing on the cost of renewable energy, electrolyzers, and infrastructure.</li> <li>Factor in potential economies of scale and impact of government incentives or subsidies.</li> </ul>	<ul style="list-style-type: none"> <li>Analyze the costs associated with natural gas extraction, reforming technologies, and CCS.</li> <li>Evaluate the economic feasibility relative to other low-carbon options.</li> <li>Consider market demand and regulatory frameworks influencing costs.</li> </ul>	<ul style="list-style-type: none"> <li>Consider the current cost structure of grey hydrogen production.</li> <li>Assess potential economic shifts as Malaysia transitions to cleaner alternatives.</li> <li>Include an analysis of potential carbon pricing or taxes affecting long-term viability.</li> </ul>
<b>Environmental Impact</b>	<ul style="list-style-type: none"> <li>Evaluate lifecycle emissions, considering the carbon footprint of renewable energy sources.</li> <li>Assess the potential for near-zero emissions from green hydrogen production.</li> <li>Assess the environmental benefits of green hydrogen in reducing Malaysia's overall greenhouse gas emissions.</li> </ul>	<ul style="list-style-type: none"> <li>Analyze carbon capture efficiency and effectiveness in reducing emissions.</li> <li>Consider potential risks and environmental impacts associated with CCS technologies.</li> <li>Assess the role of blue hydrogen in achieving short-to-medium-term emissions reduction targets while green hydrogen infrastructure and technology continue to mature.</li> </ul>	<ul style="list-style-type: none"> <li>Assess environmental impact focusing on greenhouse gas emissions.</li> <li>Consider implications for Malaysia's climate goals and commitments under international agreements.</li> <li>Evaluate the environmental trade-offs of continued grey hydrogen production while transitioning towards more sustainable hydrogen production methods.</li> </ul>

**Hydrogen Storage and Distribution:** When developing a methodological framework for assessing the challenges and solutions associated with hydrogen storage and distribution in Malaysia, the following steps are critical:

**Step 1: Identification of Storage Methods**

Investigate the use of high-pressure tanks for storing hydrogen as a gas. Assess the technical feasibility, safety standards, and capacity limitations associated with compressed gas storage. Evaluate the viability of storing hydrogen in liquid form at cryogenic temperatures. Consider the energy requirements for liquefaction and the associated infrastructure needed for maintaining extremely low temperatures. Explore the potential for storing hydrogen in solid materials, such as metal hydrides, which can absorb and release hydrogen under certain conditions. Analyze the efficiency, scalability, and safety of these technologies in the context of Malaysia's energy landscape.

**Step 2: Technical and Economic Feasibility Assessment**

Conduct a technical assessment of the various storage methods, focusing on factors such as energy density, storage efficiency, material durability, and life cycle. Evaluate the adaptability of these methods to Malaysia's climate and existing infrastructure. Perform a cost analysis to determine the economic feasibility of each storage method. This includes calculating the initial capital costs, operating and maintenance expenses, and potential economies of scale. Consider the impact of government incentives and market demand on reducing these costs over time.

**Step 3: Safety and Regulatory Considerations**

Review existing safety standards and regulations for hydrogen storage in Malaysia and globally. Assess the risks associated with each storage method, including potential hazards such as leaks, explosions, and contamination. Analyze the current regulatory framework governing hydrogen storage in Malaysia. Identify gaps and propose necessary updates or new regulations to ensure safe and efficient hydrogen storage.

**Step 4: Infrastructure Assessment**

Assess the current state of infrastructure related to hydrogen storage and distribution in Malaysia. This includes existing storage facilities, pipelines, and transportation networks. Identify the infrastructure needed to support the large-scale deployment of hydrogen technologies. This involves planning for new storage facilities, distribution networks, and integration with existing energy systems.

**Step 5: Stakeholder Engagement**

Engage with key stakeholders, including government agencies, industry players, and research institutions, to gather input and support for developing and implementing storage solutions. Conduct workshops and consultations to ensure alignment and address concerns. Develop strategies to educate the public and relevant stakeholders about the importance of hydrogen storage and the safety measures in place. Public acceptance is crucial for the successful implementation of hydrogen storage infrastructure.

**Step 6: Pilot Projects and Case Studies**

Design and implement pilot projects to test various hydrogen storage methods in real-world scenarios. These projects will provide valuable data on the performance, costs, and challenges associated with each method. Conduct case studies on successful hydrogen storage projects in other countries, analyzing their strategies, challenges, and outcomes. Use these insights to refine the framework for Malaysia.

**Evaluation of Infrastructure Needs, Including Hydrogen Refueling Stations, and Logistics:** To support the widespread adoption of hydrogen as a sustainable fuel, Malaysia must develop an extensive infrastructure network. The evaluation of infrastructure needs involves the following key components:

**Hydrogen Refueling Stations**

Assess the current number and distribution of hydrogen refueling stations in Malaysia, if any. Identify areas where refueling infrastructure is most needed, such as urban centers, industrial zones, and major transportation corridors. Develop a strategic plan for the rollout of hydrogen refueling stations. This plan should consider the optimal locations for stations based on factors such as traffic density, proximity to

hydrogen production sites, and existing energy infrastructure. Evaluate the costs associated with building and operating hydrogen refueling stations, including land acquisition, construction, equipment, and maintenance. Identify potential funding sources, such as government subsidies, private investments, and public-private partnerships. Ensure that all hydrogen refueling stations comply with international safety standards and local regulations. This includes setting guidelines for station design, operation, and emergency response procedures.

### **Hydrogen Logistics and Distribution Networks**

Assess the feasibility of developing hydrogen pipelines for efficient transportation of hydrogen from production sites to storage facilities and refueling stations. Consider the costs, technical challenges, and regulatory requirements associated with pipeline construction. Evaluate the use of trucks and ships for transporting hydrogen, especially to regions not served by pipelines. Consider the safety and efficiency of different transport modes, as well as the need for specialized vehicles and containers designed for hydrogen transport. Analyze how hydrogen storage and distribution infrastructure can be integrated with Malaysia's existing energy systems, such as natural gas networks and electrical grids.

### **Long-term Infrastructure Planning**

Develop a scalable infrastructure plan that allows for gradual expansion as hydrogen demand grows. This plan should include provisions for upgrading and expanding storage facilities, refueling stations, and distribution networks as needed. Implement a monitoring system to track the performance of hydrogen infrastructure. Use this data to make informed decisions about future investments and adaptations to the infrastructure network.

### **International Collaboration**

Collaborate with countries that have advanced hydrogen infrastructure, such as Japan, Germany, and South Korea. Learn from their experiences and adapt their best practices to the Malaysian context. Explore the potential for cross-border hydrogen infrastructure projects with neighboring countries, which could enhance regional energy security and create new economic opportunities.

**Cost-Benefit Analysis of Hydrogen Use in Heavy-Duty Vehicles:** Conducting a cost-benefit analysis (CBA) of hydrogen use in heavy-duty vehicles requires a systematic approach to evaluate the financial viability and broader economic impacts of adopting hydrogen as a primary fuel source. The following steps outline the approach:

#### **Step 1: Define the Scope and Objectives**

Establish the scope of the analysis, including the types of heavy-duty vehicles (HDVs) to be considered. State the objectives, such as reducing greenhouse gas emissions, enhancing energy security, or achieving cost savings over the vehicle's lifecycle.

#### **Step 2: Identify and Quantify Costs**

Include the initial costs of purchasing hydrogen-powered vehicles, which may be higher than traditional vehicles due to the technology's current state. Account for the costs associated with developing the necessary hydrogen production, storage, and refueling infrastructure. This includes the construction of refueling stations and the modification of existing facilities to handle hydrogen. Assess the costs of hydrogen fuel, which depend on production methods. Include maintenance costs, which may differ from those of traditional vehicles due to the different technology used. Consider the potential costs associated with environmental impacts, such as the cost of carbon emissions if traditional fuels are used versus the near-zero emissions of hydrogen. These can be translated into financial terms through carbon pricing or emissions trading schemes.

#### **Step 3: Identify and Quantify Benefits**

Evaluate potential savings in fuel costs over the vehicle's operational life, particularly in regions where hydrogen may become cheaper than diesel or gasoline as production scales up. Quantify the reduction in greenhouse gas emissions and other pollutants, translating these into monetary terms where applicable. Assess the benefits of reduced reliance on imported fossil fuels, which may include enhanced energy independence and stability of fuel prices. Consider the broader economic impacts, such as job creation in the hydrogen sector and the potential for technological leadership and export opportunities.

**Step 4: Perform a Sensitivity Analysis**

Conduct sensitivity analyses to understand how changes in key variables impact the overall cost-benefit outcome. This helps in assessing the robustness of the conclusions under different scenarios.

**Step 5: Compare Net Present Value (NPV)**

Calculate the NPV of the costs and benefits over the vehicle's expected lifetime, using an appropriate discount rate. This will provide a clear picture of the economic feasibility of hydrogen-powered HDVs compared to traditional and alternative fuels.

**Step 6: Assess Non-Monetary Factors**

Consider qualitative factors such as the societal acceptance of hydrogen technology, the readiness of supporting infrastructure, and potential regulatory changes that could affect economic feasibility.

**Comparison of the Total Cost of Ownership:** The total cost of ownership (TCO) is a critical metric in comparing hydrogen-powered vehicles with traditional diesel or gasoline vehicles and alternative fuel vehicles such as battery-electric vehicles (BEVs). Table 2 provides a clear and concise comparison of the TCO for hydrogen-powered vehicles, traditional vehicles, and BEVs, highlighting the economic and environmental factors that influence the viability of each option in the context of the Malaysian transport sector.

**Table 2: TCO for Hydrogen-powered Vehicles, Traditional Vehicles, and BEVs**

Aspect	Hydrogen-Powered Vehicles	Traditional Vehicles (Diesel/Gasoline)	Battery-Electric Vehicles (BEVs)
<b>Vehicle Acquisition Costs</b>	Higher upfront costs due to fuel cell technology and lower production volumes.	Lower upfront costs due to economies of scale and established manufacturing processes.	Higher upfront costs due to battery technology, but costs are decreasing over time.
<b>Fuel Costs</b>	Higher fuel costs, especially for green hydrogen, but expected to decrease with advancements in renewable energy.	Lower fuel costs but subject to market fluctuations and geopolitical factors; higher emissions costs.	Lower fuel costs, particularly when charged during off-peak hours; are limited by long charging times.
<b>Maintenance Costs</b>	Potentially lower due to fewer moving parts in fuel cells; specialized maintenance skills required.	Predictable costs due to established services, though higher due to frequent parts replacement and emissions maintenance.	Lower due to fewer moving parts and no oil changes; significant battery replacement costs.
<b>Lifespan and Residual Value</b>	Long fuel cell lifespan; residual value depends on hydrogen adoption and secondary market development.	An established market for used vehicles helps maintain residual value.	Residual value linked to battery life and rapid tech advancements; potential for depreciation.
<b>Environmental and Regulatory Costs</b>	Benefit from low or zero emissions; lower environmental costs, especially with increasing carbon taxes.	Increasing costs due to stricter emissions regulations and potential carbon pricing.	Zero tailpipe emissions; environmental impact tied to electricity mix; benefits of incentives.
<b>Incentives and Subsidies</b>	Government incentives/subsidies can significantly reduce TCO, making hydrogen more competitive.	Fewer incentives; are subject to increasing regulations and carbon pricing.	Often eligible for significant incentives, subsidies, and tax benefits.

#### 4. Comprehensive Assessment of Hydrogen's Environmental, Technological, and Economic Feasibility for Sustainable Transport in Malaysia

**Environmental Impact Analysis:** The transition towards a hydrogen economy in Malaysia, particularly within the transportation sector, holds significant promise for reducing greenhouse gas (GHG) emissions and enhancing environmental sustainability. However, to ensure that the adoption of hydrogen technologies contributes positively to Malaysia's environmental goals, a comprehensive Environmental Impact Assessment (EIA) is essential. This section introduces the role of EIA in evaluating the environmental implications of developing a hydrogen economy, specifically focusing on the sustainable transport sector. Table 3 shows the comparative assessment of the greenhouse Gas Emissions and Environmental Impact of FCVs, Gasoline vehicles, BEVs and biofuels.

**Table 3: Comparative Assessment of The Greenhouse Gas Emissions And Environmental Impact**

Aspect	Hydrogen Fuel Cell Vehicles (FCVs)	Diesel and Gasoline Vehicles	Battery-Electric Vehicles (BEVs)	Biofuels
<b>Tailpipe Emissions</b>	Zero tailpipe emissions; no CO <sub>2</sub> , NO <sub>x</sub> , or PM. Only water vapor as a by-product.	Significant tailpipe emissions: CO <sub>2</sub> , NO <sub>x</sub> , and PM. Diesel: approx. 94 g CO <sub>2</sub> e/MJ	Zero tailpipe emissions; similar to hydrogen FCVs.	Produces CO <sub>2</sub> when burned, though generally less than fossil fuels.
<b>Lifecycle Emissions</b>	1-4 g CO <sub>2</sub> e/MJ for green hydrogen produced via renewable energy.	High lifecycle emissions due to extraction, refining, and combustion of fossil fuels.	Lifecycle emissions depend on the electricity mix; 50-100 g CO <sub>2</sub> e/MJ in fossil-fuel-heavy grids.	Varies widely; generally lower than fossil fuels but still significant.
<b>Air Pollutants</b>	No NO <sub>x</sub> or PM emissions; significant reduction in air pollutants.	High emissions of NO <sub>x</sub> and PM, contribute to air quality degradation.	No NO <sub>x</sub> or PM emissions; dependent on the electricity grid for overall impact.	Emits pollutants when burned; production can impact land and water resources.
<b>Environmental Impact of Production</b>	Minimal if produced from renewable energy; higher if from fossil fuels.	High environmental impact due to extraction and refining processes.	Significant due to raw material extraction (lithium, cobalt) and electricity generation.	Can impact land use and water resources; and potential competition with food production.

**Technological Feasibility:** The development of a hydrogen economy for sustainable transport in Malaysia hinges on the technological feasibility of hydrogen production, storage, distribution, and utilization in the transportation sector. Technological feasibility refers to the practical capability of deploying hydrogen technologies on a large scale, considering the current state of technology, infrastructure, and the readiness of these systems to meet the demands of a hydrogen-based transport network. This section introduces the key aspects of technological feasibility that need to be addressed to realize the potential of hydrogen as a sustainable energy solution for Malaysia's transportation sector. Table 4 shows the hydrogen production, storage, and vehicle integration in Malaysia.

**Table 4: Hydrogen Production, Storage, and Vehicle Integration in Malaysia**

Aspect	Current Status	Statistics	Potential for Improvement
<b>Hydrogen Production</b>	Focused on grey hydrogen, primarily for industrial use. Green hydrogen production is in the early stages of	<ul style="list-style-type: none"> <li>Annual Production: 60,000 tonnes of hydrogen, mostly grey (Petronas, 2022).</li> <li>Renewable Energy</li> </ul>	<ul style="list-style-type: none"> <li>Capitalize on solar and hydropower resources.</li> <li>Improve electrolyzer efficiency and scale renewable energy.</li> <li>Implement CCS for grey</li> </ul>

	pilot projects.	Contribution: 23% of electricity in 2023, targeted to increase to 31% by 2025 (Ministry of Energy, 2023).	hydrogen to transition to blue hydrogen.
<b>Hydrogen Storage</b>	Mainly through compressed gas storage. Research is ongoing into liquid hydrogen and solid-state storage but not commercially deployed.	<ul style="list-style-type: none"> <li>• Green Hydrogen Costs: \$4-6/kg (IRENA, 2020).</li> <li>• Storage Infrastructure: Limited to a few industrial sites with no large-scale storage facilities (Petronas, 2022).</li> <li>• Energy Efficiency: Compression can consume up to 15% of hydrogen's energy content (U.S. Department of Energy, 2021).</li> </ul>	Develop advanced storage technologies such as solid-state and liquid hydrogen. Build a standardized regulatory framework for safe storage and scaling up infrastructure.
<b>Vehicle Integration</b>	Early-stage integration with pilot projects like the Sarawak Hydrogen Bus Project. Limited refueling infrastructure and high costs.	<ul style="list-style-type: none"> <li>• Hydrogen Refueling Stations: Only two operational stations, both in Sarawak (Sarawak Energy, 2023).</li> <li>• Hydrogen Vehicles: Fewer than 100 in operation, mainly buses (Sarawak Metro, 2023).</li> <li>• Vehicle Costs: \$750,000 per bus (Hydrogen Council, 2022).</li> </ul>	Invest in expanding refueling infrastructure in urban areas and major routes. Reduce vehicle costs through economies of scale and technological advancements. Government incentives and subsidies are needed.

**Economic Assessment:** The economic assessment of the potential hydrogen economy for sustainable transport in Malaysia is a critical component of the overall feasibility study. This section aims to assess the financial viability and economic impact of adopting hydrogen as a key energy source for the transportation sector. By assessing costs, benefits, market dynamics, and potential economic outcomes, the economic assessment provides a comprehensive understanding of the financial implications of transitioning to hydrogen-powered transportation. Table 5 shows the cost factors associated with hydrogen production, storage, and distribution while Table 6 shows the economic considerations for hydrogen-powered heavy vehicles.

**Table 5: Cost Factors Associated with Hydrogen Production, Storage, and Distribution**

Category	Type	Cost	Description
<b>Hydrogen Production Costs</b>	Green Hydrogen	\$4-6 per kilogram	Produced through electrolysis powered by renewable energy sources such as solar or wind. Costs are high due to renewable energy and electrolyzer technology (International Renewable Energy Agency [IRENA], 2020)
	Blue Hydrogen	\$2-3 per kilogram	Produced from natural gas through SMR combined with carbon capture and storage (CCS). Lower cost than green hydrogen but includes CCS technology expenses (Petronas, 2022)

<b>Hydrogen Storage Costs</b>	Grey Hydrogen	\$1-2 per kilogram	The most common and cheapest form is produced from natural gas without carbon capture. Environmentally unfriendly due to high CO <sub>2</sub> emissions (U.S. Department of Energy, 2021)
	Compressed Gas Storage	\$15-20 per kilogram	Stored as a compressed gas at high pressures (350-700 bar). Costs include compression energy and high-pressure storage tanks (International Energy Agency [IEA], 2021)
	Liquid Hydrogen Storage	\$30-50 per kilogram	Stored as a liquid at cryogenic temperatures (-253°C). More expensive due to the energy-intensive liquefaction process but allows higher energy density (U.S. Department of Energy, 2021)
<b>Hydrogen Distribution Costs</b>	Solid-state Storage	Higher and varies depending on the materials	Involves storing hydrogen in metal hydrides or other solid materials. Technology is still in development with potential safety and efficiency benefits (International Renewable Energy Agency [IRENA], 2020)
	Pipeline Distribution	\$1-2 per kilogram per 100 kilometers	Cost depends on distance and pipeline material. Higher costs due to limited infrastructure in Malaysia, requiring new pipelines or retrofitting existing ones. (Petronas, 2022)
	Transport by Road	\$2-4 per kilogram	Transported by road using high-pressure tube trailers or cryogenic liquid tankers. Costs are higher than pipeline transport, depending on distance and mode (U.S. Department of Energy, 2021)
	Shipping	\$3-6 per kilogram	Shipped as a liquid or in chemical carriers like ammonia. Significant costs due to the need for specialized ships and additional conversion processes (International Energy Agency [IEA], 2021)

**Table 6: Economic Considerations For Hydrogen-Powered Heavy Vehicles**

Aspect	Hydrogen-Powered Vehicles (FCVs)	Diesel Vehicles	Battery-Electric Vehicles (BEVs)
<b>Vehicle Acquisition</b>	\$300,000-\$500,000 per vehicle (High due to fuel cell tech)	\$200,000-\$300,000 per vehicle (Lower due to mature technology)	Higher costs due to battery technology, but decreasing over time (BloombergNEF, 2021)
<b>Fuel Costs</b>	\$10-15 per kilogram of hydrogen (High)	\$0.60 per liter of diesel (Lower fuel costs in the short term)	Lower electricity costs, but dependent on charging infrastructure availability
<b>Maintenance Costs</b>	Lower due to fewer moving parts; specialized skills required	Higher due to more frequent wear and tear	Lower maintenance costs, but battery replacement is significant
<b>Short-term Economic Viability</b>	High costs; less economically viable currently	Most economically viable in the short term due to lower costs	Economically viable for short-range applications, but less so for long-haul due to battery constraints

<b>Long-term Economic Viability</b>	Expected to improve with decreasing hydrogen production costs	Increasing costs due to carbon taxes and emissions regulations	Expected to improve as battery technology advances and costs decrease
<b>Suitability for Heavy-Duty and Long-Haul Applications</b>	High stability due to long-range and quick refueling	High suitability currently, but facing future regulatory pressures	Less suitable due to battery constraints (range and charging time)

**Discussion**

**Environment, Technology and Economic Impacts:** The adoption of hydrogen as a fuel source for heavy transport in Malaysia presents significant environmental benefits, particularly in reducing greenhouse gas (GHG) emissions and improving air quality. Hydrogen fuel cell vehicles (FCVs), when powered by green hydrogen, produce zero tailpipe emissions, emitting only water vapor as a by-product. This stands in stark contrast to traditional diesel vehicles, which are major contributors to CO<sub>2</sub>, NO<sub>x</sub>, and particulate matter (PM) emissions. The potential for reducing lifecycle emissions to as low as 1-4 grams of CO<sub>2</sub>-equivalent per megajoule (g CO<sub>2</sub>e/MJ) with green hydrogen underscores the transformative impact hydrogen can have on Malaysia’s carbon footprint, especially in the transportation sector, which is one of the largest sources of GHG emissions in the country.

The environmental significance is further emphasized when considering Malaysia's commitments under international agreements, such as the Paris Agreement, and its national goals for reducing carbon emissions. By transitioning to hydrogen, Malaysia can make substantial progress toward its climate targets while simultaneously addressing the pressing issue of urban air pollution, which has direct health implications for its population. Moreover, the use of green hydrogen aligns with Malaysia’s renewable energy ambitions. As the country increases its capacity for solar and hydropower, there is a growing opportunity to produce hydrogen sustainably, thus reinforcing the environmental credentials of hydrogen technology. This transition not only supports global climate objectives but also enhances local air quality, contributing to the overall health and well-being of Malaysian citizens.

The economic assessment of hydrogen adoption in Malaysia reveals both challenges and opportunities. Currently, the costs associated with hydrogen production, storage, and distribution are relatively high compared to traditional fossil fuels and even some renewable alternatives like battery-electric vehicles (BEVs). For example, the production cost of green hydrogen in Malaysia ranges from \$4-6 per kilogram, which is significantly higher than the cost of producing grey hydrogen or conventional fuels like diesel. Additionally, the infrastructure required for hydrogen storage and distribution, including pipelines and refueling stations, demands substantial upfront investment.

However, the long-term economic viability of hydrogen looks promising, especially as technology matures and economies of scale are realized. As Malaysia continues to invest in renewable energy infrastructure, the cost of green hydrogen is expected to decrease, making it more competitive with traditional fuels. Furthermore, hydrogen’s potential to serve as a "future-proof" fuel—capable of powering heavy-duty vehicles with longer ranges and quick refueling times—positions it as a strategic investment in the country’s transport sector.

The broader economic implications include the potential for hydrogen to catalyze new industries and job creation within Malaysia. By becoming an early adopter and leader in hydrogen technology, Malaysia could develop a competitive edge in the global clean energy market, attracting international investment and fostering innovation. Additionally, the reduction in dependency on imported fossil fuels could enhance Malaysia’s energy security, providing greater price stability and resilience against global energy market fluctuations.

The integration of hydrogen into Malaysia’s transport sector has far-reaching implications for the country’s sustainability and energy security. Environmentally, the shift to hydrogen supports Malaysia’s efforts to decarbonize its economy, reducing reliance on fossil fuels and mitigating the adverse effects of climate change. Economically, the transition could drive growth in new sectors, from hydrogen production and distribution to

fuel cell manufacturing and related technologies. From an energy security perspective, hydrogen offers a pathway to diversify Malaysia's energy mix, reducing vulnerability to global oil price fluctuations and supply disruptions. By producing hydrogen domestically, particularly through green methods, Malaysia can leverage its abundant renewable resources, thus decreasing the need for energy imports and enhancing self-sufficiency.

**Challenges and Barriers:** The adoption of hydrogen in heavy-duty mobility in Malaysia faces several key challenges, particularly in technology, infrastructure, regulation, and economics. One of the primary technological hurdles is the high cost and efficiency of green hydrogen production, driven by expensive renewable energy and electrolyzer technology. Current production methods, like steam methane reforming (SMR) and electrolysis, are either carbon-intensive or costly, making large-scale adoption difficult. Hydrogen fuel cells, while offering longer ranges and faster refueling than battery-electric vehicles (BEVs), are less efficient in energy conversion and require significant advancements to improve durability and reduce costs for mass-market adoption.

Infrastructure challenges are also significant, with Malaysia currently lacking sufficient hydrogen refueling stations and the necessary production, storage, and distribution facilities. Building this infrastructure demands substantial investment in new pipelines, storage facilities, and refueling stations, as well as the integration of hydrogen into the existing energy grid, which poses technical and safety challenges due to hydrogen's highly flammable nature.

Regulatory barriers further complicate hydrogen adoption. Malaysia's regulatory framework is underdeveloped, with gaps in safety standards, certification processes, and regulatory oversight. Without clear regulations and supportive policies, industry investment in hydrogen technologies and infrastructure remains limited. Existing energy policies do not sufficiently incentivize the transition to hydrogen, particularly when compared to other clean energy technologies like BEVs.

Economically, hydrogen for heavy-duty vehicles is challenged by high production and infrastructure costs. Green hydrogen remains significantly more expensive than conventional fuels, making it less competitive without substantial subsidies. The total cost of ownership for hydrogen vehicles is also higher than for diesel or BEV alternatives, due to higher initial costs and fuel prices. Additionally, the immature market for hydrogen technologies limits economies of scale, further keeping prices high and deterring private investment.

Finally, the market for hydrogen-powered heavy vehicles in Malaysia is still in its early stages, with limited consumer awareness and acceptance. The underdeveloped supply chain for hydrogen production and distribution exacerbates these challenges, limiting the availability and affordability of hydrogen fuel and slowing adoption.

**Proposed Preliminary Framework:** The proposed preliminary framework for a hydrogen economy in Malaysia outlines a comprehensive strategy for transitioning to a sustainable energy future through the adoption of hydrogen technologies. This framework focuses on key components such as hydrogen production, storage, distribution, and vehicle integration, supported by a robust regulatory and policy environment.

Hydrogen production is a central element of the framework, emphasizing the development of green hydrogen through renewable energy sources like solar and wind. Malaysia's abundant solar potential makes it an ideal candidate for large-scale photovoltaic systems integrated with electrolysis units, which are critical for reducing carbon emissions and aligning with global decarbonization trends. While green hydrogen is the ultimate goal, the framework also acknowledges the role of blue hydrogen as a transitional solution. This involves producing hydrogen from natural gas combined with carbon capture and storage (CCS) technology, serving as a bridge while green hydrogen infrastructure matures. Additionally, the establishment of regional hydrogen production hubs is proposed, particularly in areas with high renewable energy potential and proximity to industrial centers. These hubs would centralize hydrogen production, storage, and distribution, thereby reducing transportation costs and enhancing supply chain efficiency.

In terms of hydrogen storage and distribution, the framework calls for significant investment in advanced storage technologies, including compressed gas, liquid hydrogen, and solid-state storage. Each storage method

offers distinct advantages, and a diversified approach would address the specific needs of different sectors. Developing a dedicated hydrogen pipeline network, initially connecting production hubs with major industrial and transportation corridors, is also identified as a key infrastructural goal. In regions where pipeline construction is impractical, the use of cryogenic tankers and tube trailers for hydrogen transport is recommended.

For Vehicle Integration and Infrastructure, the framework proposes the phased deployment of hydrogen refueling stations across key transportation routes and urban centers. This infrastructure is essential to support the adoption of hydrogen-powered heavy-duty vehicles in Malaysia. The framework also encourages the development of hydrogen fuel cell vehicles (FCVs) tailored to Malaysia's heavy-duty transport needs, such as buses, trucks, and rail. Collaborations with international manufacturers and local technology firms will be crucial to reduce costs and enhance vehicle performance.

Regulations and Policy Support is a crucial pillar of the framework. The framework includes various financial incentives to stimulate hydrogen adoption, such as subsidies for hydrogen production and infrastructure development, tax rebates for hydrogen vehicles, and grants for research and development. Establishing clear safety standards and regulations for hydrogen production, storage, and transport is emphasized, along with advocating for the integration of hydrogen into Malaysia's broader energy and environmental policies to ensure alignment with national decarbonization goals.

The implementation strategy is phased over short, medium, and long terms. In the short term (1-3 years), the focus will be on launching pilot projects in hydrogen production, storage, and vehicle integration, establishing a regulatory framework, and engaging stakeholders across government, industry, and academia. In the medium term (3-7 years), the strategy shifts to scaling up infrastructure, fostering market development through targeted investments, and increasing research and innovation to improve hydrogen production efficiency, storage solutions, and vehicle technology. The long-term strategy (7+ years) aims for the mass adoption of hydrogen across multiple sectors, including heavy-duty transport, industry, and power generation. This phase also includes ensuring that hydrogen is fully integrated into Malaysia's long-term energy strategy and strengthening international partnerships for technology transfer, joint ventures, and access to global markets. The role of stakeholders in supporting this transition is critical.

The Malaysian government plays a pivotal role in setting strategic direction, establishing regulatory frameworks, and providing financial incentives. Government agencies are responsible for coordinating infrastructure development and ensuring that hydrogen policies align with national energy and environmental goals. The private sector is essential for deploying hydrogen technologies and infrastructure, with companies in the energy, transportation, and manufacturing sectors expected to invest in hydrogen production, storage, and distribution. Industry players will also be key in scaling up hydrogen vehicle production and establishing supply chains, with collaboration with international companies bringing in the necessary technology and expertise. Academia contributes by advancing hydrogen technology through research and the development and training of the workforce required to support the hydrogen economy. Academic institutions also provide the data and analysis necessary to inform policy decisions and guide technological innovation.

## 5. Managerial Implications and Recommendations

**Strategic Recommendations for Stakeholders:** As Malaysia strives to establish a hydrogen economy to support sustainable transport, coordinated actions by the government, industry, and research institutions are critical to driving the adoption of hydrogen technologies. These recommendations aim to align the efforts of all parties toward a low-carbon, hydrogen-powered future, ensuring Malaysia's competitiveness in the global energy transition. The government plays a central role in creating a supportive environment for hydrogen adoption. This includes developing and implementing a comprehensive national hydrogen strategy that sets clear goals for hydrogen production, infrastructure development, and vehicle integration. Policies should incentivize hydrogen adoption through subsidies, tax breaks, and carbon pricing mechanisms, creating financial incentives for industries to transition from fossil fuels to hydrogen.

Infrastructure development is another key area where government action is necessary. Prioritizing funding for

hydrogen refueling stations and storage facilities, particularly in strategic locations like industrial zones and transportation corridors, is essential. Supporting the expansion of renewable energy infrastructure, crucial for green hydrogen production, will further drive sustainability.

Public awareness and education are also vital. The government should launch campaigns to increase public understanding and acceptance of hydrogen as a clean fuel alternative. Additionally, collaborating with educational institutions to develop specialized training programs will ensure a skilled workforce is ready to support the growing hydrogen economy.

For the industry, investment in research and development (R&D) is paramount. Companies should focus on reducing the costs of hydrogen production, especially green hydrogen, and improving the efficiency of storage and fuel cell technologies. Developing hydrogen-powered vehicles, particularly for heavy-duty transport, is another critical area where industry collaboration can accelerate commercialization.

Public-private partnerships (PPPs) offer a strategic avenue for co-financing and building hydrogen infrastructure, such as refueling stations and production facilities. These partnerships can mitigate financial risks and ensure efficient infrastructure development. Furthermore, engaging in international collaborations will allow companies to access advanced hydrogen technologies, expand into global markets, and position Malaysia as a regional leader in hydrogen.

Research institutions have a crucial role in advancing hydrogen technology through focused research initiatives. Prioritizing studies to improve the efficiency and cost-effectiveness of green hydrogen production and exploring advanced storage solutions is essential. Collaborating with industry to test and refine these technologies in real-world settings will bridge the gap between research and commercialization. Additionally, research institutions should support policy development by providing data-driven insights and recommendations to guide government strategies. Developing specialized educational programs to train professionals in hydrogen technologies will also be critical to sustaining the growth of the hydrogen sector.

**Public-Private Partnerships and International Collaborations:** Public-private partnerships are vital for leveraging government support with private-sector innovation and investment. These partnerships can accelerate the development of hydrogen infrastructure, reduce costs, and ensure projects are completed efficiently. In the context of hydrogen adoption, PPPs are particularly effective in developing refueling infrastructure, establishing hydrogen production hubs, and launching large-scale demonstration projects.

International collaborations are equally important. Forming alliances with countries and companies that lead in hydrogen innovation will facilitate technology transfer, joint research initiatives, and shared knowledge. These partnerships can also open new markets for Malaysian hydrogen products and services, contributing to the country's economic growth.

**Policy and Regulatory Recommendations:** Developing supportive policies and regulations is crucial for facilitating hydrogen adoption in Malaysia's transport sector. The government should establish a comprehensive national hydrogen strategy that outlines long-term goals and a roadmap for hydrogen integration. This strategy should align with broader climate and energy policies to ensure hydrogen contributes effectively to national decarbonization efforts.

Integrating hydrogen into existing energy and transport policies is essential, with mandates for hydrogen blending, support for hydrogen in public transport, and the development of hydrogen corridors. A clear regulatory framework addressing safety, quality, and operational standards will reduce investment risks and promote confidence in the hydrogen sector. Financial incentives, such as grants, subsidies, and tax breaks, are necessary to reduce the costs of hydrogen production, storage, and infrastructure development. These incentives will lower entry barriers for private investors and encourage greater participation in the hydrogen economy.

**Investment and Funding Strategies:** Substantial investment and strategic funding are required to develop Malaysia's hydrogen economy, particularly in the transport sector. Government-backed initiatives, including

national budgets, dedicated grants, and green financing programs, will be primary funding sources for hydrogen projects. Public-private partnerships offer a robust mechanism for financing large-scale hydrogen projects by combining public and private resources. Malaysia can also tap into multilateral development banks and international climate funds for additional financing.

Innovative funding mechanisms, such as green bonds and sustainability-linked loans, can raise capital for hydrogen infrastructure projects. Attracting venture capital and private equity is crucial for fostering innovation and scaling hydrogen technologies, with the government providing a conducive environment through tax incentives and reduced regulatory barriers. A stable regulatory framework is essential to attract private and international investment. By offering financial incentives and establishing international partnerships, Malaysia can position itself as a regional hub for hydrogen technology and innovation.

This paper has presented a comprehensive framework for establishing a hydrogen economy in Malaysia's transport sector. The key findings emphasize the significant potential of hydrogen as a clean energy carrier, capable of driving Malaysia's decarbonization efforts while positioning the country as a regional leader in hydrogen technology. However, achieving this potential requires overcoming challenges related to cost, infrastructure, and technology. By aligning the efforts of government, industry, and research institutions, and fostering strong public-private partnerships and international collaborations, Malaysia can successfully transition to a hydrogen-powered future. Continued research, strategic policy development, and stakeholder collaboration are crucial to navigating the opportunities and challenges ahead, ensuring that hydrogen plays a central role in Malaysia's sustainable energy future.

### **Conclusion**

This paper has proposed a preliminary methodological framework for establishing a hydrogen economy to support sustainable transport in Malaysia, highlighting both the potential and challenges associated with adopting hydrogen technologies, particularly for heavy-duty mobility.

Hydrogen, especially when produced from renewable sources (green hydrogen), offers significant potential as a clean energy carrier that can decarbonize Malaysia's transport sector. It provides a viable pathway to achieving near-zero emissions in heavy-duty vehicles such as trucks, buses, and trains. Higher energy density, rapid refueling capabilities, and suitability for long-range applications make hydrogen a competitive alternative to fossil fuels and battery-electric vehicles in specific transport segments. However, the adoption of hydrogen technologies faces substantial challenges, including high production costs, lack of infrastructure, and technological barriers related to storage and vehicle integration. The current cost of green hydrogen production is particularly high, and the necessary infrastructure—such as refueling stations and distribution networks—is still underdeveloped. Additionally, the regulatory framework needed to ensure the safety and standardization of hydrogen technologies requires significant attention.

Hydrogen is crucial for achieving Malaysia's decarbonization goals. The integration of hydrogen into the country's energy and transport systems aligns with broader sustainability objectives, contributing to reduced greenhouse gas emissions and improved air quality. Malaysia's abundant renewable energy resources, particularly solar and hydropower, position the country well to scale up green hydrogen production, not only to meet domestic energy needs but also to become a regional leader in hydrogen technology. Beyond environmental benefits, hydrogen presents an economic opportunity for Malaysia to establish itself as a hub for hydrogen innovation and deployment in Southeast Asia. By investing in hydrogen production, storage, and distribution infrastructure, Malaysia can attract international investment, create new jobs, and foster economic growth. This leadership could also enhance Malaysia's geopolitical influence by providing an alternative energy source to neighboring countries.

While the path to a hydrogen-powered future presents formidable challenges, the rewards are significant. Overcoming these challenges requires a coordinated effort from all stakeholders, including government, industry, and academia. Continued research, innovation, and strategic policy development are essential to reduce costs, improve technology, and build the necessary infrastructure. Public-private partnerships and international collaborations will be vital in accelerating hydrogen adoption and ensuring Malaysia's leadership in the global transition to clean energy.

In conclusion, embracing hydrogen as a central component of Malaysia's sustainable transport strategy offers substantial environmental, economic, and social benefits. Success depends on unified efforts, ongoing research, and strong stakeholder collaboration. The framework and the recommendations outlined in this paper provide a roadmap for guiding Malaysia towards a sustainable and prosperous hydrogen economy.

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