

Hydrogen Futures for Malaysia: Techno-Economic, Environmental, and Policy Pathways through Sarawak's Renewable Transition

Michael Sillang George Albert^{1*}, Susie Patricia Bujang¹

¹Department of Electrical Engineering, Politeknik Mukah, KM 7.5 Jalan Oya, 96400, Mukah, Sarawak, Malaysia

*Corresponding author: michael@pmu.edu.my

Please provide an **official organisation email** of the corresponding author

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Abstract

This paper critically examines hydrogen development in Malaysia, focusing on Sarawak's renewable-electricity resources and the conditions required to establish a credible low-carbon hydrogen value chain. Rather than presenting an unreported computer simulation, the study uses a structured, literature-based comparative assessment of three pathways: hydropower-powered electrolysis, solar-powered electrolysis, and natural-gas reforming with carbon capture and storage (CCS). The assessment synthesises published techno-economic and life-cycle evidence with policy and infrastructure information to compare cost drivers, emissions boundaries, system requirements, and implementation risks. Malaysia's Hydrogen Economy & Technology Roadmap provides modelled 2030 cost benchmarks of USD 2.50/kg H₂ for mini-hydropower-powered PEM electrolysis, USD 3.03/kg H₂ for electrolysis using excess hydropower electricity, USD 1.72/kg H₂ for solar-PV-powered PEM electrolysis without incentives, USD 1.35/kg H₂ for the solar-PV pathway with incentives, and USD 3.71/kg H₂ for natural-gas steam methane reforming with carbon capture and storage (NG-SMR-CCUS). These are roadmap scenario projections, not observed market prices or calculations performed in this study. Published life-cycle studies also show that hydrogen carbon intensity varies with electricity source, methane leakage, capture performance, upstream emissions, and system boundary. The comparison therefore supports conditional rather than absolute conclusions: Sarawak's hydropower may provide an advantage where electricity is genuinely low-carbon and available at a competitive opportunity cost, while solar and blue-hydrogen pathways require transparent accounting of incentives, utilisation, methane, and residual emissions. The paper identifies priorities for cost-data disclosure, life-cycle certification, shared infrastructure, offtake development, and inclusive community governance. Its contribution is a transparent screening framework linking production pathways to environmental integrity and regional implementation conditions, while identifying the additional data required for a reproducible project-level assessment.

Keywords: - Green hydrogen, Sarawak, levelised cost of hydrogen, life-cycle assessment, carbon capture and storage, energy policy

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1. Introduction

Hydrogen is an energy carrier and industrial feedstock that may help reduce emissions in selected hard-to-abate applications, including primary steelmaking, chemicals, refining, shipping fuels, and some forms of long-duration energy storage. Its climate benefit, however, depends on how it is produced, the electricity and feedstocks used, and

the emissions included across the supply chain. Life-cycle assessment (LCA) research shows that hydrogen pathways can have markedly different greenhouse-gas (GHG) intensities and that results vary with modelling choices and system boundaries (Maniscalco et al., 2024 & Puig-Samper et al., 2024). Hydrogen should therefore not be treated as inherently low carbon simply because its use may produce no carbon dioxide at the point of use. (Staffell

et al., 2019; International Energy Agency [IEA], 2024, 2025 & Change, 2014).

Malaysia has begun to position hydrogen as part of its energy-transition and industrial-development agenda. Sarawak is a particularly relevant case because its electricity system has a substantial hydropower component and the state has announced projects involving hydrogen production, mobility, and potential export supply chains. Yet resource availability alone does not establish commercial viability. A credible hydrogen economy also requires competitive electricity, high electrolyser utilisation, water and land management, compression or conversion, storage and transport infrastructure, long-term buyers, and a certification system that verifies emissions intensity. The national roadmap explicitly identifies solar and hydropower as potential renewable inputs, while Sarawak's Hydrogen Economy Roadmap provides the state-level implementation context (Ministry of Science, Technology and Innovation [MOSTI], 2023 & Ministry of Energy and Environmental Sustainability Sarawak, 2025).

Recent peer-reviewed work illustrates both progress and remaining analytical needs. Yu et al. (2025) modelled green-hydrogen deployment for Malaysia's iron and steel sector using PyPSA-Earth and reported large electricity and investment requirements for full sectoral conversion. Rais et al. (2026) examined Sarawak's hydrogen ecosystem across production, storage, distribution, and end-use, highlighting infrastructure scale, cost competitiveness, and governance as connected constraints. At the wider methodological level, Puig-Samper et al. (2024) reviewed 100 LCA studies and found that differences in technology, electricity use, carbon capture, and methodological choices explain meaningful variation in reported emissions. These studies provide valuable contributions, but their analytical scopes differ in sector-specific energy modelling, system-level ecosystem assessment, and cross-pathway LCA synthesis, and do not necessarily provide a directly comparable screening of production costs, life-cycle emissions, and policy conditions across hydropower, solar, and blue hydrogen.

The research problem addressed here is that policy discussion about Sarawak's hydrogen opportunity can overstate the certainty of cost and environmental advantages when cost inputs, system boundaries, and upstream emissions are not made explicit. The study asks three questions: (1) how do the three selected pathways compare in terms of indicative production-cost drivers and life-cycle GHG considerations; (2) which technical, infrastructure, and policy conditions determine whether Sarawak's renewable-resource advantage translates into a viable hydrogen value chain; and (3) what evidence and governance measures are needed before regional investment or export claims can be substantiated? Comparable assessments should state the system boundary and emissions-accounting method explicitly, consistent with ISO/TS 19870:2023 and ISO 14044:2006 (International Organization for Standardization [ISO], 2006, 2023).

The study has three objectives: (i) to synthesise recent peer-reviewed evidence relevant to the techno-economic and environmental comparison of hydropower-based green hydrogen, solar-based green hydrogen, and blue hydrogen;

(ii) to establish a transparent screening framework that distinguishes literature-derived evidence from illustrative ranges inherited from the earlier manuscript; and (iii) to derive policy recommendations proportionate to the evidence and its limitations. The paper's contribution is not a claim of new validated simulation results. Instead, it provides a comparative screening assessment that links production pathways to the conditions required for credible cost, emissions, and regional-development claims.

2. Literature Review and Analytical Framework

2.1 Hydrogen Production Cost and Technology Choice

The levelised cost of hydrogen (LCOH) is commonly used to compare production pathways over a project's economic life. For electrolysis, major cost drivers include renewable-electricity price, electrolyser capital cost, annual operating hours, conversion efficiency, stack replacement, financing, water treatment, and compression. A low electricity price does not automatically produce low LCOH if the electrolyser operates at a low-capacity factor or requires substantial storage and balancing. Solar-powered electrolysis is particularly sensitive to the temporal match between photovoltaic output and electrolyser operation. Hydropower can offer a more dispatchable electricity profile in some settings, but its opportunity cost, seasonal availability, grid obligations, and the carbon and ecological implications of the reservoir must be considered. Cost studies consistently identify electricity price, electrolyser capital cost, utilisation, and financing as influential variables; the relative importance of each depends on system configuration and local conditions (Glenk & Reichelstein, 2019; Schmidt et al., 2017; International Renewable Energy Agency [IRENA], 2020 & IEA, 2024).

Blue hydrogen generally refers to hydrogen produced from fossil feedstocks, commonly natural gas through steam methane reforming, with carbon capture and storage applied to some process emissions. Its economic and environmental performance depends on gas price, plant configuration, capture rate, energy penalty, methane leakage, transport, and permanent storage. A high nominal capture rate at the process unit does not remove upstream methane emissions or necessarily capture all emissions associated with hydrogen production. As a result, a single cost or emissions value cannot be transferred between locations without documenting assumptions. Reviews and pathway-specific analyses caution that capture of process emissions alone does not determine the total climate footprint, because upstream methane and energy-related emissions can remain material (Howarth & Jacobson, 2021; Busch et al., 2023 & IEA, 2024).

2.2 Life-Cycle Greenhouse-Gas Evidence

Recent reviews reinforce the importance of harmonised life-cycle assessment (LCA). Maniscalco et al. (2024) reviewed hydrogen-production pathways and reported substantial differences in greenhouse-gas impacts across production routes. Puig-Samper et al. (2024), in a

systematic review and meta-regression analysis of 100 LCA studies, found that methodological choices and technology parameters help explain variability in reported hydrogen carbon footprints. Osman et al. (2024) further reviewed environmental considerations across hydrogen production, storage, and utilisation, underlining the importance of evaluating impacts beyond the production process alone. These findings caution against comparing emissions estimates that use different functional units, electricity mixes, allocation rules, or upstream boundaries. For this paper, the common functional unit is one kilogram of hydrogen at the production gate, and reported values are treated as literature benchmarks rather than results of a new, site-specific LCA. Similar concerns about methodological consistency and incomplete system boundaries have been identified in other systematic reviews and meta-analyses (Wilkinson et al., 2023; Busch et al., 2023 & ISO, 2023).

2.3 Malaysian and Sarawak Evidence

Malaysia-focused research is moving from broad resource and policy discussions toward sector-specific modelling. Yu et al. (2025) assessed hydrogen use in the iron and steel sector and estimated that full conversion would require substantial renewable electricity, hydrogen supply, and capital investment. This work demonstrates the importance of demand-side modelling and infrastructure costs, but its results relate to a particular industrial application and should not be interpreted as a general LCOH estimate for Sarawak. Rais et al. (2026) provides a

system-level assessment of Sarawak, connecting production, storage, distribution, end-use, and governance. Their regional framing is directly relevant, while the present paper focuses more narrowly on a comparative screening of three production pathways and the consistency between cost claims, LCA evidence, and policy recommendations. Broader international reviews also indicate that announced hydrogen supply can substantially exceed projects with firm investment decisions, while new demand and infrastructure remain key constraints (IEA, 2023, 2024, 2025).

2.4 Synthesis and Research Gap

Table 1 summarises the analytical relevance and limitations of selected recent studies. Taken together, the literature provides strong evidence that hydrogen outcomes are context-specific, but it also shows why a transparent, pathway-comparative framework is needed for policy discussions. The gap addressed here is not an absence of research on hydrogen in Malaysia or Sarawak; rather, it is the need to place pathway-level cost ranges, life-cycle emissions caveats, and ecosystem implementation requirements within one clearly bounded screening assessment. The analysis consequently avoids presenting a false precision or claiming that the estimates are validated project results. This interpretation is consistent with international assessments that emphasise harmonised emissions accounting, realistic cost assumptions, and demand-side readiness (IRENA, 2022a, 2022b & IEA, 2024).

Table 1: The analytical relevance and limitations of selected recent studies

Study	Method / Scope	Main Relevance	Limitation For The Present Comparison
Maniscalco et al. (2024)	Critical review of LCA pathways	Shows pathway-dependent GHG and wider environmental impacts	Not a Sarawak-specific project assessment
Puig-Samper et al. (2024)	Systematic review and meta-regression of 100 LCA studies	Explains variability in reported hydrogen carbon footprints	Cross-study evidence uses heterogeneous assumptions
Yu et al. (2025)	PyPSA-Earth techno-economic and energy modelling for Malaysian iron and steel	Quantifies sectoral electricity, hydrogen, and investment implications	Focused on industrial demand, not a universal production-cost benchmark
Rais et al. (2026)	System-level assessment of Sarawak's hydrogen ecosystem	Connects production to storage, distribution, end-use, and governance	The present paper uses a distinct three-pathway screening focus
Iyer et al. (2024)	Life-cycle analysis of SOEC, PEM, and alkaline electrolyzers under different energy sources	Reports 0.3–2.4 kg CO ₂ e/kg H ₂ for electrolysis using low-carbon energy in the study	International study: not a Sarawak-specific pathway estimates
MOSTI (2023)	National roadmap with modelled 2025–2050 LCOH scenarios	Provides traceable Malaysian scenario benchmarks for selected hydrogen pathways	Roadmap projections depend on technology and cost assumptions; not observed market prices

3. Methodology

3.1 Research Design and Source Selection

This study is a structured, literature-based comparative assessment and policy case study of Sarawak, Malaysia. It is not a process simulation and does not claim to have generated new project-level cost or LCA outputs. The evidence base combines peer-reviewed journal articles on hydrogen costs and life cycle impacts with selected

government, standards, and project sources used only to establish the policy and implementation context. Priority is given to peer-reviewed studies published from 2023 to 2026, including systematic reviews and Malaysia/Sarawak-focused analyses. Earlier foundational sources are retained where they define policy context or established methods. Sources are included when they report hydrogen production pathways, cost or GHG indicators, modelling assumptions, or regionally relevant infrastructure and policy information. News and company

webpages are treated as evidence of announcements, not as independent validation of project performance. The distinction between published scenario estimates and site-specific calculations follows good practice for transparent technology assessment (IRENA, 2020 & IEA, 2024).

The analysis proceeds in four steps: (1) classify the selected pathways and their main cost and emissions drivers; (2) extract published quantitative indicators where a traceable peer-reviewed source is available; (3) compare the pathways using a common qualitative framework while explicitly flagging values that are not independently reproducible from the original manuscript's source records; and (4) derive implementation implications from the combined cost, LCA, infrastructure, and policy evidence. Because this is a structured synthesis rather than a full systematic review, no claim is made that all relevant publications have been exhaustively identified.

3.2 Techno-Economic Assessment and LCOH Definition

For a project-level assessment, LCOH should be calculated as the discounted lifetime cost of hydrogen production divided by discounted lifetime hydrogen output. A general expression is: Discounted lifetime cost and output are standard elements of techno-economic comparison; assumptions should be disclosed to enable comparison across technologies and sites (Glenk & Reichelstein, 2019 & Schmidt et al., 2017).

$$\text{LCOH} = [\sum_t (I_t + \text{O\&M}_t + E_t + W_t + S_t + C_t) / (1 + r)^t] / [\sum_t H_2 / (1 + r)^t] \quad (1)$$

Where I_t is capital expenditure in year t , $\text{O\&M}_t$ is fixed and variable operation and maintenance, E_t is electricity or feedstock cost, W_t is water and treatment cost, S_t is storage/compression/other production-gate cost included in the chosen boundary, C_t is any carbon transport and storage cost included for the blue pathway, H_2 is hydrogen output, and r is the discount rate. The equation is a methodological specification; it has not been numerically evaluated in this study because the uploaded manuscript does not provide a complete, auditable set of project-specific capital costs, electricity tariffs, capacity factors, efficiency assumptions, financing parameters, plant lifetimes, replacement schedules, and annual output.

To avoid presenting unsupported figures as original calculations, the provisional ranges in the earlier manuscript are replaced with published Malaysian roadmap benchmarks. MOSTI's Hydrogen Economy & Technology Roadmap reports modelled 2030 LCOH values of USD 2.50/kg H_2 for mini-hydropower-powered PEM electrolysis, USD 3.03/kg H_2 for electrolysis using excess hydropower electricity, USD 1.72/kg H_2 for solar-PV-powered PEM electrolysis without incentives, USD 1.35/kg H_2 for the solar-PV pathway with incentives, and USD 3.71/kg H_2 for natural-gas steam methane reforming with carbon capture and storage (NG-SMR-CCUS) (Ministry of Science, Technology and Innovation [MOSTI], 2023). These are roadmap scenario outputs, not observed market prices or calculations performed in the present study. They should be interpreted within the roadmap's technology, cost, incentive, and learning

assumptions; they do not establish a universal ranking or directly represent delivered hydrogen cost in Sarawak.

3.3 Life-Cycle Assessment Approach

The environmental comparison adopts a cradle-to-production-gate perspective and the functional unit of 1 kg H_2 produced. Relevant stages include feedstock and electricity supply, production equipment where data are available, hydrogen conversion, and upstream emissions associated with natural gas and carbon capture. For blue hydrogen, the boundary should additionally identify methane leakage, process and energy-related emissions, capture rate, CO_2 transport, and storage. For hydropower, the boundary should state whether reservoir emissions and allocation of multipurpose reservoir impacts are included. For solar electrolysis, manufacturing and end-of-life treatment of photovoltaic and electrolyser equipment may affect the result. The boundary choices are aligned with product life-cycle assessment principles and hydrogen-specific guidance for accounting from production through conditioning and transport (ISO, 2006, 2023).

No new LCA inventory or impact-assessment model was available in the original manuscript, so the previously stated pathway values of approximately 0.8, 2.0, and 7.5 kg $\text{CO}_2\text{e/kg } H_2$ are removed rather than repeated as verified results. As an external benchmark, Iyer et al. (2024) report lifecycle greenhouse-gas emissions of 0.3–2.4 kg $\text{CO}_2\text{e/kg } H_2$ for electrolyser pathways supplied by low-carbon energy sources (nuclear, solar, or wind) in their study. This range is not a Sarawak-specific estimate and should not be directly assigned to hydropower or solar projects in Sarawak without matching the system boundary and inventory. Cross-study values are comparable only when electric carbon intensity, equipment manufacturing, methane leakage, capture rate, allocation, and lifecycle stages are aligned. The peer-reviewed reviews by Maniscalco et al. (2024) & Puig-Samper et al. (2024) support this caution.

3.4 Policy and Socio-Economic Assessment

Policy and socio-economic dimensions are assessed using a qualitative framework with five criteria: (i) regulatory clarity and certification of hydrogen carbon intensity; (ii) infrastructure readiness for storage, transport, conversion, and export; (iii) demand certainty through credible offtake agreements and domestic applications; (iv) local capability development, employment, and supply-chain participation; and (v) environmental and social safeguards, including water use, land access, biodiversity, and meaningful community engagement. The evidence is synthesised narratively. No quantified employment, export revenue, community benefit, or infrastructure-cost estimate is claimed because the source manuscript does not provide a dataset suitable for calculating those outcomes. Certification schemes differ in their thresholds and system boundaries, making internationally comparable emissions accounting important for cross-border trade (IEA, 2024; ISO, 2023 & European Commission, 2023).

3.5 Uncertainty, Sensitivity and Reproducibility

A numerical sensitivity analysis cannot be validly reported without a complete base-case model and input ranges. Instead, the assessment identifies variables most likely to change the pathway comparison: electricity price and carbon intensity; electrolyser capital cost, efficiency, and utilisation; financing and stack replacement; natural-gas price and methane leakage; CCS capture rate and storage cost; compression, conversion, and transport; and treatment of hydropower reservoir emissions. The provisional LCOH ranges in the earlier draft are excluded from the findings because their input assumptions and source trail could not be independently verified. Reproducibility would require a supplementary input table with source, year, currency basis, system boundary, and low/base/high values for each parameter. Electricity price and operating hours are particularly important sensitivities in electrolysis-based systems, while natural-gas supply emissions and capture configuration affect fossil-based pathways (Glenk & Reichelstein, 2019; Howarth & Jacobson, 2021 & IEA, 2024).

4. Findings

4.1 Indicative Techno-Economic Comparison

The MOSTI roadmap provides a traceable Malaysian benchmark for the production-cost discussion. Its 2030 scenarios report USD 2.50/kg H₂ for mini-hydropower-powered PEM electrolysis, USD 3.03/kg H₂ for PEM electrolysis using excess hydropower electricity, USD 1.72/kg H₂ for solar-PV-powered PEM electrolysis without incentives, USD 1.35/kg H₂ for the solar-PV pathway with incentives, and USD 3.71/kg H₂ for NG-SMR-CCUS (MOSTI, 2023). These values are modelled estimates under the roadmap's assumptions, not new calculations by the authors or observed commercial prices. The values represent specified technology configurations and should not be treated as fully harmonised project quotes.

Table 2: The MOSTI roadmap provides a traceable Malaysian benchmark for the production-cost discussion

Pathway	Published 2030 LCOH benchmark	Main cost drivers/scenario notes	Evidence status
Hydropower-based green H ₂	USD 2.50/kg H ₂ (mini hydro + PEM);	Electricity cost/opportunity cost; electrolyser CAPEX and utilisation; water; compression; financing	MOSTI (2023) roadmap model projections for 2030; not recalculated in this study
	USD 3.03/kg H ₂ (excess hydropower electricity + PEM)		
Solar-based green H ₂	USD 1.72/kg H ₂ (solar-PV + PEM),	PV and electrolyser CAPEX; variable output; utilisation;	MOSTI (2023) roadmap model

	without incentives); USD 1.35/kg H ₂ (with incentives)	balancing/storage; financing; incentives	projections for 2030; not recalculated in this study and not current market quotes
Blue H ₂ (natural gas + CCS)	USD 3.71/kg H ₂ (NG-SMR-CCUS)	Gas price; reformer efficiency; capture rate; methane leakage; CO ₂ transport/storage	MOSTI (2023) roadmap model projection for 2030; project-specific CCS assumptions matter

The roadmap's published 2030 scenarios do not show hydropower as the lowest-cost option in every configuration: the reported solar-PV electrolysis scenarios are USD 1.72/kg H₂ without incentives and USD 1.35/kg H₂ with incentives, compared with USD 2.50/kg H₂ for mini-hydropower-powered electrolysis and USD 3.03/kg H₂ using excess hydropower electricity. These scenario outputs should not be interpreted as a definitive ranking for Sarawak because the configurations and assumptions may differ, and the figures are not project-specific quotations. The comparison highlights the importance of incentives, electricity opportunity cost, electrolyser utilisation, capital cost, financing, and the inclusion of compression, storage, and delivery. Yu et al. (2025) demonstrate that electricity and infrastructure requirements can be substantial for large-scale Malaysian hydrogen deployment, while Rais et al. (2026) emphasise ecosystem-wide infrastructure and governance constraints in Sarawak. Production-gate LCOH alone is therefore insufficient for assessing delivered cost or export competitiveness. International cost assessments similarly caution that costs depend on regional electricity and gas prices, technology capital costs, utilisation, and the cost of capital, and that production-gate cost is not the same as delivered cost (IEA, 2024 & IRENA, 2020, 2022a).

4.2 Life-Cycle Emissions Comparison

The earlier manuscript's specific emissions values of approximately 0.8 kg CO₂e/kg H₂ for hydropower electrolysis, 2.0 kg CO₂e/kg H₂ for solar electrolysis, and 7.5 kg CO₂e/kg H₂ for blue hydrogen are removed because their source trail and harmonised boundaries were not documented. Iyer et al. (2024) provide a peer-reviewed benchmark of 0.3–2.4 kg CO₂e/kg H₂ for low-carbon-energy electrolyser pathways in their LCA, but this range is not a local estimate for Sarawak and should not be used as a direct pathway-specific value. The broader literature supports the conclusion that renewable-powered electrolysis can achieve low lifecycle emissions when electricity is genuinely low-carbon, while fossil-based hydrogen with CCS remains sensitive to upstream

methane, residual process emissions, and actual capture and storage performance (Maniscalco et al., 2024; Puig-Samper et al., 2024 & Iyer et al., 2024). The widespread published estimates are also documented in a systematic review of 85 studies, which found substantial variation by feedstock, electricity source, technology, and LCA choices (Busch et al., 2023).

For Sarawak, hydropower's climate advantage depends on the marginal electricity source and the emissions allocated to reservoirs and associated infrastructure. Solar-based hydrogen may reduce dependence on hydropower availability but needs a transparent account of photovoltaic manufacturing, electrolyser utilisation, and any balancing energy. Blue hydrogen could provide a dispatchable production option where gas and CCS infrastructure are available, but a low-carbon designation should depend on measured whole-chain intensity rather than the presence of capture equipment alone. Hydrogen's lifecycle footprint can also increase when conversion and transport require additional energy; therefore, export pathways should include carrier production, shipping, and reconversion where relevant (IEA, 2024; IRENA, 2022a; ISO, 2023).

4.3 Infrastructure, Markets and Socio-Economic Implications

The evidence points to a system-level constraint: low production cost does not itself create a viable hydrogen market. Hydrogen must be conditioned, stored, transported, and delivered in a form that meets buyer specifications. Conversion to ammonia or other carriers can improve handling for some trade routes but adds energy use, capital cost, and reconversion losses where hydrogen is required at destination. Shared infrastructure and coordinated setting may reduce duplication, yet they also require predictable demand and agreements on access, ownership, safety, and cost recovery. International assessments identify transport, storage, ports, and conversion infrastructure as major enabling requirements, while ammonia is prominent among announced seaborne hydrogen-carrier projects (IEA, 2019, 2024 & IRENA, 2022a).

The reviewed evidence supports the importance of domestic demand development alongside export ambitions. Malaysia's industrial decarbonisation requirements could create demand, but sectoral conversion entails large investments in renewable electricity, electrolysers, transport, and end-use equipment (Yu et al., 2025). Sarawak's emerging ecosystem similarly requires alignment between production, refuelling or industrial use, storage, logistics, and governance (Rais et al., 2026). The present paper does not quantify employment, export revenue, or distributional impacts; those outcomes require project-level data on procurement, local content, skills, workforce demand, and benefit-sharing. Current global demand remains concentrated in established industrial uses, and new low-emissions applications remain small; this supports sequencing new supply against credible offtake rather than announced capacity alone (IEA, 2024, 2025).

5. Discussion

The comparison suggests that Sarawak's hydropower resource is a strategic enabling condition, not proof that every hydrogen project will be cost-competitive or environmentally preferable. The advantage is strongest when renewable electricity can be contracted at a transparent price, the electrolyser operates at a sufficiently high utilisation rate, and the cost of compression and delivery does not erase the production-stage benefit. The opportunity cost of electricity must also be considered: electricity committed to hydrogen is not available for other industrial, household, or export uses unless additional supply is developed. The national and state roadmaps are useful policy signals, but international evidence indicates that project announcements alone do not establish commercial delivery or emissions performance (MOSTI, 2023; Ministry of Energy and Environmental Sustainability Sarawak, 2025 & IEA, 2024).

Solar electrolysis provides a complementary pathway and may diversify the renewable supply mix, but its economics depend on solar resources, plant configuration, utilisation, and the cost of flexibility. Comparing a solar system with a more continuously supplied hydropower system without equalising capacity factors and storage assumptions would produce a misleading cost ranking. A robust follow-up analysis should test low, central, and high cases for electricity prices, electrolyser capital cost, efficiency, utilisation, financing, and storage rather than report a single estimate. The importance of matching renewable generation profiles to electrolyser operation is consistent with techno-economic modelling of renewable electricity-to-hydrogen systems (Glenk & Reichelstein, 2019; Schmidt et al., 2017 & IRENA, 2020).

Blue hydrogen presents a different trade-off. It may use existing natural-gas infrastructure and provide relatively controllable production, but its environmental credibility depends on upstream methane control, the scope and rate of carbon capture, energy penalties, and secure long-term CO₂ storage. It should therefore be assessed using a whole-chain carbon-intensity metric and compared with renewable electrolysis under common system boundaries. The current evidence does not justify asserting that blue hydrogen is always more expensive or always more emissions-intensive than every renewable pathway; rather, it shows that performance is highly dependent on project conditions. Published blue-hydrogen analyses reach differing conclusions under different methane-leakage, capture-rate, and energy assumptions, reinforcing the need for transparent, project-specific accounting rather than a categorical label (Howarth & Jacobson, 2021; Busch et al., 2023 & IEA, 2024).

These findings lead to four evidence-based priorities. First, develop a transparent project-level cost model before making firm cost or export-competitiveness claims. Second, establish a lifecycle certification framework that specifies electricity sourcing, reservoir emissions treatment, methane leakage, CCS performance, and chain-of-custody rules. Third, sequence shared infrastructure against credible offtake commitments and demand forecasts rather than announced capacity alone. Fourth,

embed environmental and social safeguards early, including water planning, land and biodiversity assessment, community participation, workforce training, and local supplier development. These priorities follow from the identified uncertainties; they should be understood as strategic implications rather than quantified impacts demonstrated by this screening assessment. A harmonised emissions methodology can support this work: ISO/TS 19870:2023 addresses greenhouse-gas accounting for hydrogen production, conditioning, and transport, while the IEA highlights the need for consistent certification and stronger demand signals (ISO, 2023; IEA, 2024).

6. Limitations and Future Research

This study has important limitations. First, it is a structured literature-based screening assessment rather than a systematic review with exhaustive database searches or a new process simulation. Second, the LCOH figures are published Malaysian roadmap scenario estimates rather than values calculated by the authors; their assumptions are reported at the level available in the roadmap and are not re-modelled here. Third, the lifecycle emissions benchmark is drawn from international LCA literature and is not a Sarawak-specific inventory. Fourth, the policy and socio-economic assessment is qualitative; the study does not calculate jobs, export revenues, infrastructure costs, water demand, or community-level distributional effects. Finally, studies differ in year, technology maturity, system boundary, currency basis, and assumptions, limiting direct comparison.

Future work should develop a transparent, site-specific techno-economic model using verified Sarawak electricity tariffs and opportunity costs, electrolyser CAPEX and efficiency, operating profile, financing assumptions, stack replacement, water treatment, compression, storage, and transport. A harmonised LCA should use a clearly stated functional unit and cradle-to-gate boundary, and include sensitivity analysis for hydropower reservoir emissions, electricity sourcing, methane leakage, CCS capture rate, and CO₂ storage. Finally, a socio-economic assessment should quantify local employment, skills requirements, local procurement, water use, land-use impacts, and community benefit-sharing using project-level data. A future site-specific model should also distinguish plant-gate production costs from delivery-chain costs and use consistent lifecycle boundaries (IRENA, 2022a; ISO, 2023).

7. Conclusion

Hydrogen could contribute to Malaysia's industrial decarbonisation and energy-transition goals, and Sarawak has a potentially important enabling advantage through its renewable electricity resources and emerging hydrogen initiatives. However, the viability of a hydrogen economy depends on more than the nominal availability of hydropower. Production cost, lifecycle emissions, infrastructure, market demand, certification, and community outcomes must be assessed together. These

conditions align with Malaysia's national Hydrogen Economy & Technology Roadmap and Sarawak's state roadmap, while international evidence stresses that demand, infrastructure, and credible emissions accounting are necessary for implementation (MOSTI, 2023; Ministry of Energy and Environmental Sustainability Sarawak, 2025 & IEA, 2024).

The present screening assessment compares hydropower-based green hydrogen, solar-based green hydrogen, and blue hydrogen while making the evidence status of each claim explicit. Rather than retain unsupported original cost and emissions values, it uses the 2030 cost scenarios published in Malaysia's Hydrogen Economy & Technology Roadmap and an international lifecycle-emissions benchmark from peer-reviewed research. These are external literature values, not outputs of a new simulation or LCA conducted by the authors. The evidence indicates that Sarawak's hydropower resource is a potentially important enabling condition, but project viability still depends on electricity opportunity cost, electrolyser utilisation, lifecycle carbon accounting, infrastructure, market demand, certification, and community outcomes. The central contribution of this paper is a transparent analytical framework and a set of evidence-aligned priorities for future project assessment and policy design. Before strong investment or export claims are made, project-specific cost modelling, harmonised lifecycle accounting, credible offtake arrangements, and inclusive environmental and social governance are essential.

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