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Benchmarking Hydrogen Life Cycle Assessments: A Review of Methodologies and Result

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Hydrogen plays a crucial role in the global transition to cleaner energy, offering a path to reduce carbon emissions in industries, transportation, and energy storage. To assess its environmental impact, life cycle assessment (LCA) is a vital tool. However, the application of LCA varies significantly across countries, leading to differences in methods, results, and standards. These inconsistencies make it challenging to establish a unified approach for assessing hydrogen's contribution to global sustainability. This study benchmarks global hydrogen LCAs by analysing methodologies, functional units, system boundaries, and impact categories, drawing insights from the latest published studies and government reports. Key findings reveal how regional energy mixes, production technologies, and policy incentives influence the carbon emissions associated with hydrogen production. The review highlights challenges such as methodological inconsistencies and the absence of standardized frameworks. This work provides a foundation for enhancing hydrogen sustainability assessments and offers strategic insights for the global hydrogen economy.

1. Introduction

The global pursuit of carbon neutrality has intensified efforts to transition towards cleaner energy systems. Among emerging energy carriers, hydrogen has garnered significant attention due to its potential to decarbonize various sectors, including industry, transportation, and energy storage (Bicer and Dincer, 2017). Hydrogen can be produced through a range of pathways; each with varying environmental impacts depending on the feedstock, energy source, and technology used. Life Cycle Assessment (LCA) serves as a critical tool for evaluating the environmental impacts associated with various hydrogen production pathways. However, despite its robustness, the application of LCA in the hydrogen sector remains fragmented. Different countries and organizations adopt diverse methodological approaches, functional units, system boundaries, and impact categories, often influenced by regional policies, data availability, and technological maturity (Quarton and Samsatli, 2020). This inconsistency creates three major barriers to a functional global hydrogen market: (1) trade inefficiencies, as buyers cannot reliably compare emissions across suppliers; (2) regulatory misalignment, where conflicting LCA standards may lead to subsidies supporting that are not truly clean in the long run; and (3) greenwashing risks, where carbon accounting methods could allow high-carbon hydrogen to be mislabelled as 'clean.' Without harmonized LCA frameworks, the hydrogen economy risks fragmentation, delayed investment, and compromised climate benefits, making standardization not just beneficial, but essential for credible decarbonization.

2. Benchmarking Global Hydrogen Life Cycle Assessments

For the benchmarking analysis, studies were retrieved from the ScienceDirect database, covering publications from January 2024 to March 2025 to capture the latest developments in hydrogen production. Unlike earlier reviews focusing on pre-2023 LCAs (Wilkinson et al., 2023), this work examines recent studies across multiple

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production pathways. The search, using combinations of keywords such as “hydrogen production,” “life cycle assessment,” “LCA,” “functional unit,” and “system boundary,” yielded 352 articles. Screening was conducted in two stages: first, titles and abstracts were reviewed to exclude non-peer-reviewed sources, conference papers, and studies outside the production scope, reducing the pool to 196; second, full-text assessments were performed based on predefined inclusion criteria:

a) Clear definition of system boundaries and functional units.
b) Explicit description of the Life Cycle Impact Assessment (LCIA) method and LCA software used.
c) Quantitative reporting of at least one midpoint or endpoint environmental impact category, with global warming potential (GWP) as a minimum.
d) Geographic scope is identifiable at the country or regional level.
e) Studies were excluded if they (i) lacked sufficient methodological detail for replication, (ii) used outdated datasets without justification, or (iii) were purely conceptual without quantitative LCA results.

Table 1: Hydrogen LCA studies reviewed

No.	Authors	Hydrogen production technology	Region	Methodology			Impact Assessment		GWP (kg CO_2/FU)
				Functional unit (FU)	System boundaries	Method/LCA software	Mid-point	End-point	
1.	Al-Ghussain et al. (2024)	Electrolysis (Wind & PV, PEM)	US	1 kg of hydrogen produced	Cradle-to-gate	GREET	√		0.35-1.9 (Wind) 1.8-2.95 (PV)
2.	Armando et al. (2024)	Aqueous phase reforming (APR) of glycerol	Mexico	1 kg of hydrogen produced	Gate-to-gate	SimaPro, ReCiPe 2016	√	√	4.84
3.	Guven (2024)	Electrolysis (Wind, PEM)	Turkey	1 kg of hydrogen produced	Cradle-to-gate	GREET, ReCiPe 2016	√		0.7
4.	Hincapié-Ossa and Gingerich (2024)	Coal gasification	US	1 MJ of hydrogen produced	Cradle-to-gate	OpenLCA,	√		0.216
5.	Li et al. (2024)	Electrolysis (Nuclear, SOE)	China	1 kg of hydrogen produced	Cradle-to-gate (included transportation)	SimaPro, CML	√		2.18
6.	Rangel et al. (2024)	Electrolysis (Wind & PV, PEM)	Portugal	1 kg of hydrogen produced	Cradle-to-gate	SimaPro, ReCiPe	√		1.38-2.45
7.	Rey et al. (2024)	Electrolysis (Wind, PEM)	Spain	1 kg of hydrogen produced	Cradle-to-gate (including cond. And recond.; transportation forth and back;	OpenLCA, EFv 3.1	√	√	4.12
8.	Oburoh et al. (2025)	Autothermal Reforming	UK	144 t/day of hydrogen produced	Gate-to-gate (including CCS)	SimaPro, ReCiPe 2016	√		233941
9.	Tahir et al. (2025)	Electrolysis (PV, AE)	Pakistan	1 kg of hydrogen produced	Cradle-to-grave	SimaPro, CML-IA	√		9.92
10.	Zhang et al. (2025)	Plasma co-gasification of coal and biomass	China	500 kg of biomass	Cradle-to-gate (included transportation)	SimaPro, CML	√		5507.43

This process resulted in a final selection of 10 studies, covering major hydrogen production pathways (electrolysis, gasification, biomass-based) and a range of geographic regions. The selection prioritized methodological completeness and transparency over quantity to ensure that each study could be critically compared on an equal footing. Table 1 summarizes the reviewed studies and their key parameters.

2.1 Hydrogen Production Technology

Table 2 below is a summary table presenting the Technology Maturity Level (TML) of hydrogen production technologies reviewed in the literature (Dawood et al., 2020), spanning a TML range from Level 1, representing basic research, to Level 10, indicating a fully bankable asset. Relating hydrogen production methods to their TML is important for assessing both technological readiness and environmental viability in the energy transition. Over half of the reviewed studies (6 of 10) examined electrolysis pathways, generally associated with lower Global Warming Potential (GWP) than conventional methods such as Steam Methane Reforming (SMR) and coal gasification. Wind-powered electrolysis, featured in four studies, emerged as a particularly promising option. Among electrolysis types, Proton Exchange Membrane (PEM) technology was the most common (4 of 6 studies), valued for its compatibility with variable renewable energy, high efficiency, and fast response times compared to other electrolysis methods while lowering carbon emissions (Guven, 2024).

While TML and LCA performance are not strictly correlated, higher maturity can lead to improved outcomes through process optimization and supply chain stability. However, maturity alone does not determine environmental impact, where coal gasification (TML 10) can yield higher GWP than PEM electrolysis (TML 7–9) when the latter is powered by renewable energy. This highlights that factors such as energy source and system design often outweigh maturity in influencing life cycle results.

Table 2: Technology Maturity Level (TML) of Hydrogen Production Technology (Dawood et al., 2020)

Production Technology	Technology Maturity Level
Steam Methane Reforming (SMR)	10
Partial Oxidation	7-9
Autothermal Reforming (ATR)	6-8
Coal Gasification	10
Biomass Gasification	10
Alkaline Electrolysis (AE)	9-10
Proton Exchange Membrane Electrolysis (PEM)	7-9
Solid Oxide Electrolyser Cell Electrolysis (SOE)	3-5

2.2 Functional Unit (FU)

The reviewed studies demonstrate significant variation in the selection of functional units (FU) for hydrogen production, with choices based on mass, feedstock, or energy. A majority (8 out of 10) adopted a mass-based FU (1 kg of hydrogen or 144 t/day), making it the most common approach. This was followed by feedstock-based FUs, used in one study, which measured input materials such as 500 kg of biomass, and one study utilized an energy-based FU (1 MJ of hydrogen), which, similar to the mass-based FU, offers clarity and ease of comparison. The energy-based FU is particularly suitable when the study includes the end-use of hydrogen for energy generation (Hincapié-Ossa and Gingerich, 2024). Based on this, 1 kg of hydrogen is the most suitable functional unit (FU) as it provides a consistent basis for comparing environmental impacts across different hydrogen production pathways. It aligns with standard Life Cycle Assessment (LCA) and techno-economic practices, enabling uniform evaluation of emissions, energy use, and system efficiency.

2.3 System Boundary

Figure 1 presents the system boundaries considered in past studies. The majority (8 out of 10) employed a cradle-to-gate system boundary, focusing on the environmental impacts from raw material extraction to hydrogen production while excluding downstream processes such as storage, transportation, distribution, usage, and end-of-life stages. Only a few studies accounted for transportation emissions or included the conditioning phase for storage, contributing to inconsistencies and a lack of transparency in system boundary definitions. This variability presents a major challenge in comparing results across studies, highlighting the need for standardized and well-defined system boundaries to ensure methodological consistency and accurate assessment of environmental impacts.

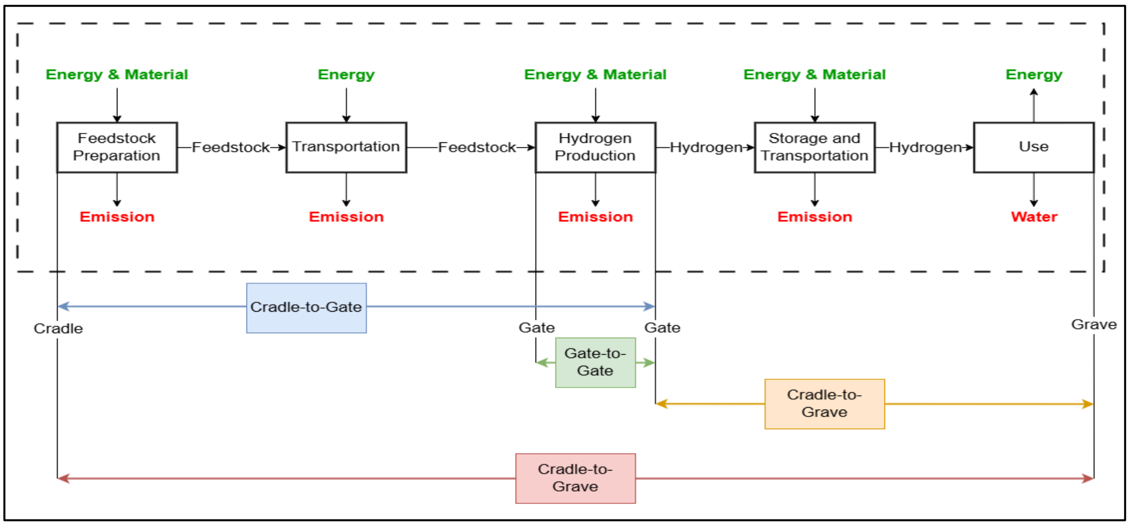

Figure 1: System Boundary

2.4 Software/Method and Impact Assessment

Various software such as SimaPro, GREET, and OpenLCA have been used in the study. It was found that SimaPro has been used most (by six studies). SimaPro is a commercial software used for LCA, while OpenLCA is the most common open-source software used for LCA. The results obtained from the software should be interpreted with caution, as variations may result not only from differences in database content but also from divergent model parameterization, default settings, and background scenario assumptions (e.g., regional electricity mixes, allocation methods, transport distances). Herrmann and Moltesen (2014) found that even when applying the same LCA method, tools such as SimaPro and GaBi can produce differing results due to both database discrepancies and implementation choices, underscoring the need for careful interpretation and methodological transparency. The most commonly used impact assessment methods are ReCiPe (four studies), followed by CML (three studies). All the studies have assessed the midpoint impact, and only 2 studies have endpoint categories. The most widely utilized midpoint impact indicators were global warming potential (GWP), and the endpoint categories were human health, ecosystem, and resources.

3. Influence of Energy Mix on Carbon Emissions

Siddiqui and Dincer (2019) clearly demonstrate that the carbon emissions associated with hydrogen production via electrolysis are heavily influenced by the electricity mix used to power the process. When water electrolysis is powered by the U.S. electricity grid, which consists of 34.2 % coal, 31.6 % natural gas, 20.3 % nuclear, and smaller portions of hydro, wind, solar, and other sources. The global warming potential (GWP) for this pathway is 28.6 kg CO_2-equivalent per kg of hydrogen, the highest among all hydrogen production methods assessed in the study due to the significant share of fossil fuels, especially coal and natural gas, in the electricity mix. The findings emphasize that even though electrolysis does not emit greenhouse gases during the actual splitting of water, the upstream emissions from electricity generation can significantly raise the overall carbon footprint. As such, hydrogen from electrolysis using a fossil-heavy grid can be less environmentally sustainable, undermining its classification as “green” hydrogen.

A similar study by Vilbergsson et al. (2023) underscores that the Global Warming Potential (GWP) of electrolytic hydrogen is largely dictated by the carbon intensity of the electricity mix. The hydrogen produced in Iceland, where electricity is sourced from geothermal and hydropower, demonstrates a 13–21 times lower carbon footprint compared to production in Austria or Belgium. For instance, hydrogen produced in Iceland via Polymer Electrolyte Membrane (PEM) electrolysis emits just 1.01 kg CO_2-eq/kg H_2, whereas Austrian and Belgian grid-powered electrolysis emit 13.33 kg CO_2-eq/kg H_2 and 21.18 kg CO_2-eq/kg H_2. This stark contrast highlights how decarbonized grids enable truly green hydrogen, while fossil-heavy grids negate electrolysis’s environmental benefits.

Although using renewable energy reduces carbon emissions, in some cases it might be the opposite. Vilbergsson et al. (2023) also highlight that low full-load hours (FLH) significantly contribute to increased carbon emissions in hydrogen production systems, even when powered by renewable energy sources. In regions with limited renewable availability or intermittent supply, electrolysers operate below their optimal capacity for much of the time, leading to inefficient use of capital-intensive infrastructure. Additionally, to maintain a consistent hydrogen output during periods of low renewable generation, electricity is often supplemented from the grid, which may contain carbon-intensive sources. As a result, low FLH not only reduces the overall system efficiency but also undermines the environmental advantages of green hydrogen by increasing reliance on higher-emission backup electricity. From this, the energy mix for electrolysis heavily impacts the carbon emissions of hydrogen production, as energy input is a part of the system boundary for LCA (cradle-to-gate).

4. Influence of Policy Incentives on Carbon Emissions

Policy incentives significantly influence the carbon emissions from renewable hydrogen production. A study by Alonso et al. (2025) shows that different regulatory frameworks affect both the environmental impact and economic feasibility of hydrogen projects. For example, carbon intensity limits, like Japan's threshold of 3.4 kg CO_2 per kg of hydrogen, push producers to use cleaner energy sources such as wind and solar instead of grid electricity, which often relies on fossil fuels. The impact of these policies depends on how strict and well-enforced they are. The study also highlights that temporal correlation rules play a crucial role: stricter hourly matching, where hydrogen production must align in real time with renewable generation, which can reduce emissions by up to 51 % compared to more flexible approaches. On the other hand, yearly matching allows producers to use an annual average of renewable generation, offering lower costs and greater flexibility but with a higher risk of emissions, especially when gaps are filled by fossil-based grid electricity. This trade-off underscores the need to carefully design temporal rules that balance environmental goals with economic and technical feasibility.

Power Purchase Agreements (PPAs) originated as contractual mechanisms in liberalized electricity markets, designed to provide renewable energy developers with long-term revenue certainty. Their role as a policy-driven force has grown as governments and regulatory bodies have introduced measures such as renewable portfolio standards, corporate renewable energy procurement mandates, and auction-based renewable tenders, all of which create stable demand for clean electricity contracts. In the context of renewable hydrogen, PPAs help reduce carbon emissions by securing a steady supply of wind or solar power and minimizing dependence on fossil fuel-based grid electricity, which is an essential factor for meeting strict carbon limits like Japan's 3.4 kg CO_2/kg H_2 threshold. The study shows that hydrogen produced under wind PPAs can emit as little as 0.749 kg CO_2/kg H_2, compared to over 25 kg CO_2/kg H_2 in grid-reliant scenarios during low renewable periods. However, Japan's low PPA adoption (less than 1 % of global volumes) limits this potential due to weak policy support. These findings highlight the importance of not only promoting PPA uptake through enabling legislation and market reforms but also pairing them with additionality and temporal matching rules to achieve truly low-carbon hydrogen at scale.

An Italian case study by Stolte et al. (2025) demonstrates both the challenges and opportunities of green hydrogen production. While current solar PV-based production costs remain high at 7.7 EUR/kg compared to fossil alternatives, national incentives targeting abandoned industrial areas can reduce costs to 3.3-3.5 EUR/kg. These incentives not only improve economic viability but also yield significant environmental benefits, enabling 85 % emission reductions by encouraging larger PV systems with hydrogen storage that minimize grid electricity dependence. However, a critical limitation emerges in land requirements, which is that the larger, more efficient systems demand substantial space for PV panels. Where land availability near industrial sites is constrained, this force compromises in system design that both increase costs by 15-20 % and significantly raise emissions due to greater grid electricity reliance. This indicates that when governments provide subsidies and policy incentives, hydrogen producers are more likely to use greener energy sources to power their electrolysers, reducing carbon emissions in Life Cycle Assessment (LCA) calculations.

5. Conclusions

This study underscores the critical role of standardized methodologies in assessing the environmental impact of hydrogen production across diverse global contexts. The benchmarking analysis reveals significant variations in LCA practices, particularly in system boundaries and functional units, which hinder the development of a unified sustainability framework. Key findings highlight that electrolysis, especially when powered by wind energy, offers the lowest carbon footprint, but its environmental benefits are heavily dependent on regional energy mixes and policy incentives. Stricter temporal correlation can drastically reduce emissions, though they often increase costs, emphasizing the need for balanced policy design. This review identifies three priority measures to address current inconsistencies: (1) universal adoption of cradle-to-gate system boundaries to capture full upstream impacts, (2) strict renewable energy requirements for green hydrogen production, and (3) implementation of audited certification schemes such as CertifHy and the EU Renewable Energy Directive. Together, these would enhance comparability while ensuring the climate benefits of hydrogen are not overstated.

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