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Comparative techno-environmental analysis of grey, blue, green/yellow and pale-blue hydrogen production

Riya Roy [a], Giorgio Antonini [a], Koami S. Hayibo [a], Md Motakabbir Rahman [a], Sara Khan [a], Wei Tian [b], Michael S.H. Boutilier [b], Wei Zhang [b], Ying Zheng [b], Amarjeet Bassi [b], Joshua M. Pearce [a,c,*]

[a] Department of Electrical & Computer Engineering, Western University, ON, Canada
[b] Department of Chemical and Biochemical Engineering, Western University, ON, Canada
[c] Ivey School of Business, Western University, ON, Canada

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ABSTRACT

Hydrogen holds immense potential to assist in the transition from fossil fuels to sustainable energy sources, but its environmental impact depends on how it is produced. This study introduces the pale-blue hydrogen production method, which is a hybrid approach, utilizing both carbon capture and bioenergy inputs. Comparative life cycle analysis is shown for grey, blue, green and pale-blue hydrogen using cumulative energy demand, carbon footprint (CF), and water footprint. Additionally, the integration of solar-powered production methods (ground-based photovoltaic and floating photovoltaic (FPV) systems) is examined. The results showed blue hydrogen [steam methane reforming (SMR) + 56% carbon capture storage (CCS)] was 72% less, green hydrogen gas membrane (GM) 75% less, blue hydrogen [SMR+90%CCS] 88% less, and green hydrogen FPV have 90% less CF compared to grey hydrogen. Pale-blue hydrogen [50%B-50%G], blue hydrogen (GM + plasma reactor(PR)) PV and blue hydrogen (GM + PR) FPV offset 26, 48 and 52 times the emissions of grey hydrogen.

1. Introduction

Hydrogen (H_2) is an odorless and colorless fuel [1] that holds immense potential as a cornerstone in the global transition from fossil fuels to cleaner, sustainable energy sources [2]. As hydrogen fuel has both high versatility and high energy density [3–5], its use is expected to rise across multiple industries, ranging from heavy industry and long-distance transport to electricity generation, making it an essential component of future clean energy systems [6]. Global initiatives aimed at H_2 development align with international climate goals, such as the Paris Agreement [7], which target significant reductions in carbon emissions. Hydrogen is projected to contribute to 6% of the total global emission reductions by 2050 [8], positioning it as a key enabler in the global decarbonization effort.

Hydrogen's environmental impact depends significantly on how it is produced. The categorization of H_2 into different "colors"—such as grey, blue, green, and turquoise—reflects both the energy source and production methods used [9]. Current H_2 production methods, however, are far from sustainable. Most of the world's hydrogen is produced from fossil fuels, primarily through natural gas steam reforming (76%) and coal gasification (23%) [10,11]. This method of production is known as *grey hydrogen*. Approximately 6% of the world's natural gas and 2% of coal are consumed annually to produce grey hydrogen, resulting in the emission of 830 million metric tons of CO_2 per year—representing 2.5% of global CO_2 emissions [12–15]. In total, hydrogen production globally emits about 900 million metric tons of CO_2 every year [11,12]. Despite the significant environmental costs, the global demand for hydrogen is expected to rise from 70 million tonnes (Mt) in 2019 to 120 Mt by 2024, with projections indicating a further increase to 530 Mt annually by 2050 [3,10,16,17]. This growth is driven largely by its use in critical industries: around 70 Mt of H_2 are consumed annually in oil refining (39 Mt/a) and ammonia (32 Mt H_2/a) production, while an additional 50 Mt are used in producing methanol, steel manufacturing, and power generation [6,7,13,15].

Despite the growing demand, the production of low-emission hydrogen is still in its infancy, accounting for only a small fraction of

* Corresponding author. Department of Electrical & Computer Engineering, Western University, ON, Canada.
E-mail addresses: rroy65@uwo.ca (R. Roy), gantonini@uwo.ca (G. Antonini), khayibo@uwo.ca (K.S. Hayibo), mrahm339@uwo.ca (M.M. Rahman), skha242@uwo.ca (S. Khan), joshua.pearce@uwo.ca (J.M. Pearce).

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total output [18]. The average emissions intensity of hydrogen production was around 12–13.5 kg CO_2-eq/kg H_2 in 2022, but it is expected to drop to 6–7.5 kg CO_2-eq/kg H_2 by 2030 in the Net Zero Emissions (NZE) scenario with further reductions below 1 kg CO_2-eq/kg H_2 by 2050 [19]. There is increasing momentum toward alternative hydrogen production methods that reduce carbon emissions. These include water electrolysis powered by renewable energy, methane pyrolysis, and natural gas steam reforming with carbon capture, utilization, and storage (CCUS) [20–25]. Electrolysis, which produces *green hydrogen*, is considered the cleanest but more costly [9,13] method, as it generates no direct emissions when powered by renewable electricity. Blue hydrogen, produced through steam methane reforming (SMR) combined with carbon capture and storage (CCS), reduces emissions compared to traditional grey hydrogen production, though it still relies on fossil fuels [20–27]. In 2030, annual low-emission H_2 production could reach 38 Mt, with 27 Mt expected to come from electrolysis and the remaining 10 Mt from fossil fuels with CCS [28].

Life cycle assessment (LCA) is a critical tool for evaluating the full environmental implications of hydrogen production, including energy demand and greenhouse gas (GHG) emissions [27,29]. By examining the entire production chain, LCA informs policymakers and stakeholders about the comparative sustainability of different hydrogen production technologies, helping guide decisions toward the most effective paths for reducing emissions and energy consumption [1,30,31]. The LCA of different hydrogen production methods shows vast disparities in their carbon emissions and energy consumption. For example, grey hydrogen production, which does not incorporate CCS, emits around 11 kg of CO_2 per kilogram of hydrogen, largely due to the process-related GHG emissions (77.75%) and the natural gas supply (22.13%) [10]. The International Energy Agency (IEA) reported that grey hydrogen production constituted approximately 6% of world carbon dioxide (CO_2) emissions in 2020 [32,33]. This underscores the importance of transitioning to cleaner H_2 production technologies.

Blue hydrogen production offers a lower emission alternative when CCS is employed. When 56% of the CO_2 is captured, the carbon intensity reduces to 6.87 kg of CO_2 per kg of H_2, with 60% of the emissions coming from the process itself [34,35]. At higher capture rates (90%), emissions can be further reduced to 3.97 kg of CO_2 per kg of H_2, lowering the process-related emissions contribution to 24.9% [34–36]. Despite CCS implementation, however, blue hydrogen still shows only an 18–25% reduction in GHG emissions compared to grey hydrogen, and it emits 20% more GHGs than natural gas or coal when used for heating [34,37]. This reveals the limitations of blue hydrogen as a sustainable alternative in the long term if it uses fossil fuel-based electricity. According to Howarth and Suer, using renewable energy during production can decrease the carbon footprint of blue hydrogen by 94% [14,37].

Water electrolysis, the core method for producing green hydrogen, is another alternative, but it is highly energy-intensive, requiring more than 55 kWh of electricity for every kg of H_2 produced [1,38]. In countries like Germany, where the electricity grid is not fully decarbonized, the global warming intensity (GWI) of green hydrogen can range from 3.94 to 34.85 kg CO_2-eq per kg of H_2, depending on the grid mix [10]. In the U.S., H_2 produced via electrolysis using the national electricity mix has been found to generate life cycle emissions as high as 27.3 kg of CO_2 per kg of H_2 [39]. Therefore, the sustainability of green hydrogen is directly tied to the carbon intensity of the electricity used in electrolysis. As renewable energy penetration increases, green hydrogen production can reduce lifecycle emissions by 60–90% compared to grey hydrogen [34].

Other production methods, such as methane pyrolysis, also referred to as methane “decomposition” and methane cracking (*turquoise hydrogen* production), show potential for reducing emissions. In this process, methane is split into hydrogen and solid carbon, avoiding the direct release of CO_2 [10]. The GWI for turquoise hydrogen varies depending on the energy source used for the process. For instance, methane pyrolysis can produce hydrogen with a GWI of 6.45 kg CO_2-eq per kilogram of hydrogen when natural gas is used as the heat source, and as low as 3.94 kg CO_2-eq per kilogram of hydrogen when hydrogen itself is used to power the process [10,37]. Coal gasification, which produces *brown hydrogen*, is particularly carbon-intensive, and can emit between 18 and 25 kg CO_2-eq per kg of H_2, making it one of the most polluting hydrogen production methods [34,40]. By contrast, *pink hydrogen* or *red hydrogen*, produced using nuclear energy, has minimal emissions, with a GWI as low as 0.1–0.6 kg CO_2-eq per kg of H_2 [19], however, it demands a massive public insurance liability [41]. *Yellow hydrogen*, produced using solar photovoltaic (PV) energy, and *white hydrogen*, a by-product of certain chemical processes, offer near-zero or very low emissions [10,42].

These vast differences in environmental impacts highlight the need for comprehensive LCA in evaluating hydrogen production technologies. LCA provides critical insights into not only the direct emissions from the hydrogen production process but also the indirect emissions associated with energy consumption, transportation, and material inputs. Table 1 represents a summary of LCA studies on different hydrogen production methods to date.

This study will introduce the pale-blue hydrogen production method, which is a novel hybrid approach, utilizing both carbon capture and bioenergy inputs, potentially achieving a carbon-negative outcome. Unlike traditional grey hydrogen methods, which emit large amounts of CO_2, and even standard blue hydrogen techniques that often require significant energy inputs for carbon capture, this innovative process integrates advanced catalytic systems and cutting-edge carbon capture technologies to drastically reduce emissions while enhancing efficiency. The pale-blue method not only minimizes the carbon footprint through a more effective integration of capture and conversion technologies but also offers significant scalability and economic advantages. The technical aspects of these processes, from methane reforming to electrolysis, involve differing energy demands, water usage, and GHG emissions, which require detailed analysis.

This study presents a comparative LCA of grey, blue, green and pale-blue hydrogen production methods, evaluating their cumulative energy demand (CED), carbon footprint (CF), and water footprint (WF). Additionally, the integration of solar-powered production methods, including ground-based photovoltaic systems and floating photovoltaic (FPV) systems, is examined. Emphasis is placed on pale-blue hydrogen's technical feasibility and its potential to serve as a carbon-negative energy source. Through this comparative analysis, the study aims to provide insights into which H_2 production pathway is the most sustainable and cost-effective for achieving long-term global decarbonization goals.

2. Methods

2.1. Technical description of different types of hydrogen production

2.1.1. Grey hydrogen

Grey hydrogen is produced primarily through the process of steam methane reforming (SMR), which remains the most common method of hydrogen generation today. In this process, natural gas—mainly composed of methane (CH_4)—is heated with steam (H_2O) at high temperatures ranging from 700 °C to 1000 °C, usually in the presence of a nickel-based catalyst [61,62]. The chemical reaction between methane and steam generates hydrogen (H_2) and carbon monoxide (CO). In a subsequent step known as the water-gas shift reaction, CO reacts with more steam to produce additional H_2 and carbon dioxide (CO_2) [63–66]. While the process results in a high yield of H_2, the lack of carbon capture mechanisms leads to the release of substantial amounts of CO_2. Despite its environmental impact, grey hydrogen is still widely used, approximately 62% of global H_2 production [28], due to the well-established infrastructure and low production costs, especially in sectors such as oil refining and ammonia synthesis.

Table 1
Summary of LCA studies for various types of hydrogen production.

Type of hydrogen	Hydrogen production technology	Primary input	Energy source	Carbon footprint kg $CO_{2eq.}$/kg H_2	References
Grey	SMR	Natural gas	Fossil fuel	11 to 13	[14,43–49]
Grey	SMR	Natural gas	Fossil fuel	10.84	[3,50]
Grey	SMR	LNG route	Fossil fuel	13.9	[51]
Grey	SMR	Pipeline route	Fossil fuel	12.3	[51]
Grey	SMR	Natural gas & coal	Fossil fuel	7.5 to 25	[42]
Grey	SMR	Natural gas	Fossil fuel	10.28	[3,52]
Brown	Gasification	Coal	Fossil fuel	19 to 24	[14,43–49]
Brown	Gasification	Coal	Fossil fuel	23.7	
Brown	Gasification	Coal	Fossil fuel	11.59	[14,43–49]
Brown	Chemical looping	Coal	Fossil fuel	9.54	
Green	PV electrolysis	Water	Solar	3.08	[14,43–49]
Green	Solar thermal electrolysis	Water	Solar	2.06	[14,43–49]
Turquoise	Pyrolysis + CCS	Methane	Fossil fuel	1.9 to 6.4	[3,50]
Turquoise	Pyrolysis + CCS	Methane	Fossil fuel	3.94-9.91	[42]
Biohydrogen	Gasification	Agricultural biowaste	Fossil fuel	−85 to 110	[3,53]
Green	Water electrolysis	Water	Fossil fuel	28.6	[3,39]
Brown	Gasification	Coal	Fossil fuel	23.7	[3,39]
Biohydrogen	Gasification	Biomass	Fossil fuel	4.4	[3,39]
Blue	SMR + CCS	Natural gas	Fossil fuel	12	[1,14,54]
Blue	SMR+ 56% CCS	Natural gas	Fossil fuel	6.87	[34,35]
Blue	SMR+ 90% CCS	Natural gas	Fossil fuel	3.97	[34–36]
Blue	SMR+ 55%–88% CCS	Natural gas	Fossil fuel	3.97 to 6.87	[42]
Blue	SMR+ 55%–88% CCS	Natural gas	Fossil fuel	11 to 22	[14,37]
Blue	SMR+ 55%–88% CCS	Natural gas	Renewable energy source (RES)	0.6 to 4.7	[14,37]
Green	Electrolysis	Water	RES	1.0 to 5.1	[14]
Green	Electrolysis	Water	U.S. grid mix	27.3	[39]
Green	Electrolysis	Water	Solar PV	2.73 to 4.34	[55]
Green	Electrolysis	Water	Solar PV	2.5	[51]
Green	Electrolysis	Water	Wind	0.6	[51]
Green	Electrolysis	Water	RES	~0	[42]
Green	High temperature water vapor electrolysis	Water	Nuclear reactors	2	[1,56]
Green	Alkaline electrolyzer	Water	Solar PV	2.3 to 4.3	[1,57]
Green	Wind fuel cell integrated system	Water	Wind	0.406	[1,58]
Green	Thermochemical water splitting	Water	Solar	1.02	[1,59]
Green	Electrolysis	Water	Wind	0.418	[1,44]
Green	Thermochemical water splitting	Water	Nuclear	2.027	[1,44]
Green	Electrolysis	Water	Solar	2 to 7	[1,60]
Pink/red	SMR + CSS	Natural gas	Nuclear	0.1-0.6	[42]
Yellow	SMR + CSS	Natural gas	Solar PV	~0	[42]
Bio hydrogen	Not specified	Biomass, biowaste	Fossil fuel	6.7–9.8	[42]
White hydrogen	Hydrogen produced as by-product	Not specified	Nuclear	0.87	[42]

2.1.2. Blue hydrogen

Blue hydrogen is produced through the same SMR process as grey hydrogen, but with the addition of CCS technologies to mitigate carbon emissions. After hydrogen is produced through SMR, the resulting CO_2 is captured, compressed, and either stored in geological formations or utilized in industrial processes. The CCS step significantly reduces the CO_2 emissions associated with hydrogen production, although the level of CO_2 reduction varies depending on the efficiency of the capture process.

Typical carbon capture rates for blue hydrogen range between 56% and 90%, depending on the technology and the production setup. For instance, with 56% carbon capture, the CO_2 emissions per kilogram of hydrogen can be reduced to approximately 6.87 kg, whereas with 90% capture, emissions drop further to about 3.97 kg CO_2 per kg of H_2 [34, 35]. While blue hydrogen reduces emissions compared to grey hydrogen, the reliance on natural gas and fossil fuel infrastructure still results in a residual carbon footprint. Therefore, blue hydrogen is considered a transitional solution on the path to fully decarbonized energy sources [67].

2.1.3. Green hydrogen

Green hydrogen is produced through water electrolysis, a process that uses electricity to split water into H_2 and oxygen [1]. When the electricity used for electrolysis is sourced from renewable energy, such as wind, solar, or hydropower, the entire process becomes nearly emission-free, making green hydrogen a highly sustainable option. The primary advantage of green hydrogen is the absence of direct CO_2 emissions, as no fossil fuels are involved in the production process [1]. The environmental impact of green hydrogen production is closely tied to the source of electricity, however. As green hydrogen technology evolves, it is increasingly seen as a critical component in the global transition to a low-carbon energy system.

2.1.4. Pale-blue hydrogen

Pale-blue hydrogen is an innovative production method that combines elements of both blue and green hydrogen production technologies. It leverages the carbon capture technologies used in blue hydrogen with the renewable energy-driven electrolysis of green hydrogen, aiming to produce hydrogen with a net carbon-negative footprint.

In this experimental setup presented in Fig. 2, the entire production process is powered by a solar photovoltaic system, designed to achieve carbon-negative H_2 production. Specifically the PV powered the open-source photobioreactor (MP), DC-DC converter based power supply (PS) for AEM electrolyzer [68], and a power supply for the plasma generator (PG). An alternating voltage is generated by the PG and then applied to the plasma reactor (PR), with the generation of plasma in the PR, where the interaction between plasma and CH_4 occurs to produce hydrogen gas. [69]. The components are thoroughly described in the literature on a small scale and then integrated to assess the system's synergy initially. The complete process is illustrated in Fig. 1, while the fully integrated system is demonstrated within a PV box in Fig. 2. The primary feedstock for the blue hydrogen component of this process is biogas, composed of 60% CH_4 and 40% CO_2. Initially, a gas membrane (GM) separates the CH_4 and CO_2. The separated CO_2 is directed into a

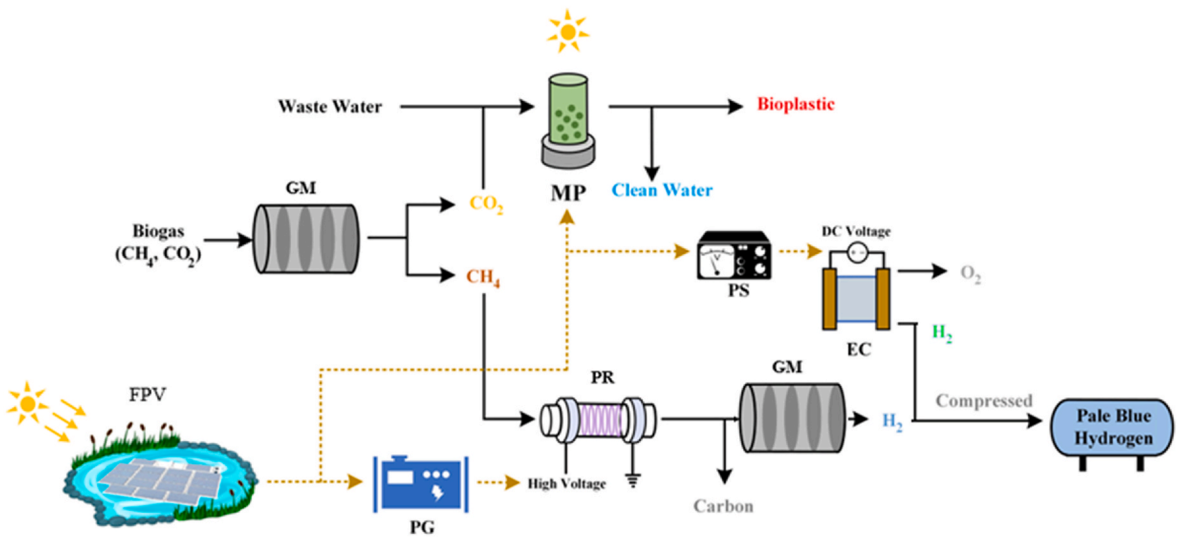

Fig. 1. Flow diagram of pale-blue hydrogen production. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

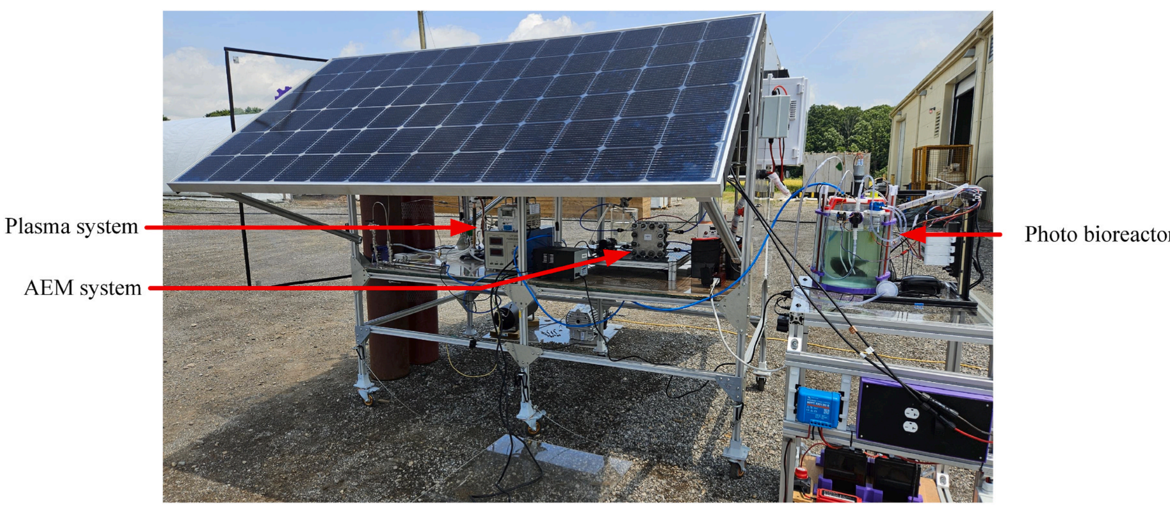

Fig. 2. Small scale integrated pale-blue hydrogen system. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

microalgae MP, while the CH_4 is sent to a PR, where it undergoes decomposition into H_2 and solid carbon (C). Any unreacted CH_4 exiting the plasma reactor is recycled through another GM, further increasing H_2 yield by converting additional methane into hydrogen. Simultaneously, the green hydrogen production process begins with the captured CO_2 from the biogas separation in the GM. This sequestered CO_2, along with the nutrients, is used to enhance microalgae growth in the MP [70]. Optimum growth condition such as adequate light exposure, pH level, temperature and agitation was maintained for microalgae growth which was later used for wastewater treatment [71]. After the treatment, the clean water produced is used for green hydrogen generation via electrolysis.

To scale up the hydrogen production, a 5-kW commercial anion exchange membrane (AEM) electrolyzer (EC) from Cipher Neutron [72] is employed in the next stage of this research. The AEM electrolyzer has a production capacity of 1200 L (108 g) of green hydrogen per hour [73]. To address the land-use concerns associated with large-scale PV installations, floating photovoltaic (FPV) technology was adopted to power the electrolyzer. FPV systems, particularly those using foam as the floating material, offer several advantages over conventional ground-based PV system, including reduced system costs [74], water conservation [75,76], and overall superior environmental impacts [77]. A 7 kWp FPV system, modeled on a previously reported FPV configuration [77], was deployed on a natural pond for the purposes of this project. The FPV modules are supported by foam-based racking systems made from polyethylene foam, marine sealant, and zip ties ensuring the modules' stability on the water surface. Further details regarding the foam-based FPV can be found in earlier studies [75–78].

A direct current (DC) to alternating current (AC) inverter (7.5 kW) equipped with a maximum power point tracking (MPPT) technology is used to condition the power from the FPV and supply the necessary electricity to the 5 kW electrolyzer. To prevent power fluctuations and provide backup during intermittent PV generation, a battery storage system is integrated into the setup. The primary goal of the plant, however, is to replace conventional battery storage with H_2-based energy solutions. Therefore, the battery is only intended to mitigate power variations during daylight hours. The sizing of the PV system is optimized based on the total load of the electrolyzer, and when sunlight is unavailable, the electrolyzer is deactivated to maximize energy efficiency. The 27-cell, 5 kW AEM stack is powered by an AC/DC power supply operating at 400 V, 3-phase, and capable of delivering DC power in the range of 0–50 V and 0–200 A.

2.2. Life cycle assessment of H_2 production

An LCA [79–84] provides a holistic view by assessing inputs like energy, materials, and emissions at each stage. According to ISO 14040, the LCA process consists of four key steps: defining the goal and scope, performing an inventory analysis, conducting an impact assessment, and interpreting the results [85–88]. This comprehensive evaluation helps identify areas for improvement and guides decision-making towards sustainability.

2.2.1. Goal and scope

This study conducts an LCA to compare the environmental impacts of various hydrogen production methods, including grey, blue, green, and pale-blue hydrogen. openLCA 2.1.0 [89], an open source LCA software by Green delta, was used for the study.

For this study, the well-to-gate system boundary was chosen. This means that the assessment includes all upstream processes such as the extraction of raw materials, their processing, and the hydrogen production itself. Downstream stages like hydrogen transport, storage, distribution, and end-use applications, however, are excluded from the analysis. This approach provides a focused view of the production-phase emissions and energy demands while excluding the complexities introduced by the logistics and final consumption phases.

The functional unit used in this study is 1 kg of H_2, which is standard practice for such analyses [3]. This unit allows for a consistent comparison of the environmental impacts associated with the production of each type of hydrogen. By narrowing the scope to well-to-gate, this study aims to provide a clearer understanding of the resource inputs, energy requirements, and emissions associated with the production phase of different H_2 types without the variability introduced by transport and end-use factors.

2.2.2. Life cycle inventory

The life cycle inventory (LCI) data for grey, blue, and green hydrogen production has been primarily sourced from existing literature [10,55], along with datasets from the USLCI database by NREL [90] and the ecoinvent database [91]. These sources provide comprehensive and widely accepted datasets for hydrogen production, capturing various inputs and emissions associated with different production methods.

The LCI for pale-blue hydrogen was developed directly from experimental data gathered during the experimental setup. In this experiment, inputs such as biogas feedstock, water, and electricity consumption were meticulously documented and used as the basis for the LCA analysis. Since pale-blue hydrogen production is a novel method, these real-time experimental data were essential to capturing the unique energy and material flows of the system accurately.

Additionally, the LCI data for FPV systems, large-scale solar PV installations, and the AEM electrolyzer have been sourced from relevant studies [29,55,77], respectively. These references provide details on the energy and material demands for these systems, which are critical for accurately modeling the renewable energy inputs into the pale-blue hydrogen production process. Furthermore, to assess the performance and optimal efficiency of the newly developed AEM electrolyzer by Cipher Neutron, specific operational data were directly obtained from the manufacturer.

Due to data limitations, the study excludes the manufacturing of balance of materials (BOM) for components like the gas membrane, plasma reactor, and microalgae photobioreactor. However, energy use, water consumption, biogas flow, and catalyst quantities were documented from the experimental setup.

The GM assembly for the system includes two pumps: a small DC pump consuming 2 W and a vacuum pump consuming 300 W. All energy consumed by these pumps is supplied entirely by the solar PV system, with no input from the grid. It is important to note that the vacuum pump is oversized for the current flow rate, as it can support a much larger system.

For the current small-scale experimental setup, the energy efficiency of blue hydrogen production may seem unfavorable, but this is only the case because some components are scaled up and others remain benchtop scale. Based on initial calculations, at a biogas flow rate of 64 sccm, it would take approximately 1.4 years of continuous operation to produce 1 kg of H_2. Over this period, both pumps would run continuously, leading to a significant power consumption of 302 W (combined for both pumps). This would result in the system consuming approximately 90 times more energy than the energy content of the H_2 produced. This highlights the need for more accurate estimates of energy consumption when the system is scaled up and optimized, which are provided below.

The plasma reactor currently operates at a flow rate of 64 sccm of biogas, converting 25% of the input CH_4 to H_2 at the outlet. In its present configuration, the reactor's production rate is low, and continuous operation over the mentioned time frame is necessary to produce 1 kg of H_2. The vacuum pump is capable of handling 4500 times the current H_2 flow rate, however, with only a $<1\%$ change in the pressure difference across the membrane, running at 200 W. At this optimized flow rate, the production of 1 kg of H_2 would take just 165 min.

For the membrane module in an optimized system, 22 DC pumps would be required running in parallel, although a larger and more efficient DC pump would significantly reduce energy consumption. This would bring the total power requirement for the membrane module to around 0.67 kWh/kg of H_2, when accounting for both the vacuum pump and the parallel DC pumps. Furthermore, in the scaled-up system, 4500 plasma reactors (or one larger, optimized reactor) would be needed to match the vacuum pump's capacity. The current DC pump is also significantly oversized, leading to unnecessary energy consumption. Table 2 outlines the key differences in energy requirements, flow rates, and overall efficiency between the experimental small-scale setup and a typical commercial H_2 production system.

In the production of green hydrogen, a comparative analysis between small-scale and commercial systems reveals notable differences in energy consumption and resource requirements. The AEM system operates with an energy consumption of 50 kWh to produce 1 kg of H_2, utilizing 12 kg of water and 1.2 kg of potassium hydroxide (KOH) as a catalyst. In contrast, the commercial AEM electrolyzer demonstrates a slightly higher energy demand, consuming 56.6 kWh for the same H_2 output. Additionally, experimental data shows that the commercial system requires significantly less KOH, at only 0.81 g, and a reduced water input of 9.12 kg [72].

Table 2
Comparison of energy consumption and efficiency metrics between small-scale and commercial hydrogen production systems.

Parameter	Small-Scale System	Optimized Industrial-scale System
Biogas flow rate	64 sccm	64 sccm
Hydrogen production rate	25% of CH_4 input	25% of CH_4 input
Time to produce 1 kg of H_2	1.4 years (continuous)	165 min
DC pump power rating	2 W	44 W
Number of DC pumps required	1 (oversized)	22 DC pumps (optimized)
Total pump power consumption	300 W (vacuum pump) + 2 W (DC pumps)	200 W (vacuum pump) + 44 W (DC pumps)
Energy consumption by GM (per kg of H_2)	60.3 kWh	0.67 kWh
Number of plasma reactors required	1	4500 plasma reactors (or optimized)
Energy consumption	1454 kWh	1454 kWh
Time required	1.4 years	165 min

2.2.3. Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase of an LCA, inventory data is translated into potential environmental impacts, assessing contributions to issues such as global warming, resource depletion, and pollution. Various LCIA methods are available in openLCA, with this study focusing on CED and the IPCC 100-year Global Warming Potential (GWP 100a) [92].

CED is commonly employed as a screening tool to assess environmental impacts based on energy consumption and compare LCA results with studies that report only primary energy demand. Furthermore, CED is effective for conducting plausibility checks, as deviations or errors in the life cycle results often become apparent through the analysis of total energy demand [92].

GWP is another important indicator, that measures the relative climate change impacts of greenhouse gas emissions over a specific period, using CO_2 as the reference. Direct GWPs provide a comparative measure of how much heat a given mass of gas will trap in the atmosphere relative to CO_2, thereby allowing emissions of different gases to be aggregated into a single impact category for climate change. The characterization factors for different gases vary, with fossil methane having a characterization factor of 30.5, while fossil CO_2 is set at 1 kg CO_2 equivalent per kg of CO_2 emitted [92,93]. Biogenic carbon emissions from renewable sources are considered neutral (factor of zero) as they do not contribute to long-term atmospheric carbon increases [94, 95].

2.2.4. Interpretation

The interpretation phase of an LCA is outlined in ISO 14044 and involves identifying significant findings from the inventory and impact assessment phases. It includes evaluating the completeness, sensitivity, and consistency of the data and methodology, followed by the formulation of conclusions, limitations, and recommendations for improving the system's sustainability [54].

In the context of LCAs, negative emissions can occur in two primary scenarios: (i) when emissions are removed from an environmental compartment, such as through CO_{2e} capture and storage, or (ii) when emissions are avoided due to more efficient or sustainable production processes [96]. In the first case, the physical removal of a specific emission from the environment results in a reduction of greenhouse gases or CO_2 equivalent (CO_2e), in the atmosphere [97]. For example, to achieve a net removal of 1 kg of CO_2e, a direct air capture and storage (DACS) system must capture and sequester 1.85 kg of atmospheric CO_2, as per the U.S. Department of Energy's guidelines [96]. This accounts for both the captured CO_2, and the emissions associated with running the system.

Additionally, GWPs for biogas production highlight increasing environmental impact over time, with values of 254 kg CO_2e (20 years), 281 kg CO_2e (100 years), and 312 kg CO_2e (500 years) [98]. This progressive increase is primarily due to the significant amounts of methane produced and the high electricity consumption required for biogas production. Methane's stronger greenhouse effect amplifies its long-term contribution to global warming [98]. Therefore, integrating methane from biogas into hydrogen production can enhance the system's environmental efficiency by mitigating methane emissions, lowers the overall carbon footprint, and improves sustainability by converting a potent greenhouse gas into a valuable energy carrier.Moreover, a lower CED value of the hydrogen production system indicates better energy performance and is often correlated with lower environmental impacts. Therefore, interpreting the CED can lead to actionable recommendations for improving energy efficiency, reducing resource consumption, and minimizing the environmental footprint. In the next section, the CF and CED of different hydrogen production will be described in detail.

3. Results

3.1. Environmental footprint of pale-blue hydrogen

3.1.1. LCA of pale-blue hydrogen

This study evaluates the CED and CF associated with the blue hydrogen component of pale-blue hydrogen production, based on the LCI outlined in Table 2. The blue hydrogen is produced from biogas in a closed-loop system, ensuring that no CO_2 is released into the atmosphere, thus resulting in zero direct emissions. In the LCA, biogas use is accounted for as the consumption of CH_4 and CO_2, effectively removing these gases from the atmosphere. Most emissions within this process are attributed to electricity consumption. Although the system is powered entirely by a solar PV array, which has a lower CF and carbon payback time (CPBT) compared to fossil fuel-based generation systems. This highlights that while solar PV systems contribute to reducing emissions, they are not inherently carbon-negative.

A cradle-to-grave LCA of both FPV systems and ground-mounted PV systems was undertaken. The CF and CED data for the ground-mounted system were sourced from Ref. [29], while the LCI for the FPV system was derived from Ref. [77].

3.1.1.1. Case 1: pale-blue hydrogen production powered by FPV. To produce 1 kg of blue hydrogen using an FPV system, the calculated CED was 32.18 kWh. The direct CF impact from biogas utilization and CO_2 capture resulted in −1,527.38 kg CO_2 eq./kg H_2, indicating a net removal of CO_2 from the atmosphere. The FPV system itself, however, contributed 9.08 kg CO_2 eq./kg H_2 in GHG emissions. As a result, the net CF for blue hydrogen production powered by FPV was calculated at −1,510.30 kg CO_2 eq./kg H_2.

The CED of the commercial AEM system's BOM is approximately 8.27×10^4 kWh, with a CF of 3.18×10^4 kg CO_2 eq. For simplicity, however, this data is excluded from the main analysis because this data is not available to allow equivalent comparisons to the other types of H_2. For green hydrogen production, the total CED is calculated at 1.08 kWh per kg of H_2 produced. The system emits 2.96 kg CO_2 eq. of GHGs per kg of H_2. Notably, 90% of these emissions are associated with the manufacturing of the catalyst, while the remaining emissions result from energy generation through the FPV system.

3.1.1.2. Case 2: blue hydrogen production powered by ground-mounted PV. In the case of H_2 production using a ground-mounted PV system, the total CED was significantly higher at 1.9×10^3 kWh per kg of H_2 produced. The net CF was found to be −1,412.42 kg CO_2 eq./kg H_2. Despite the removal of 1.52×10^3 kg CO_2 eq./kg H_2 from the atmosphere through biogas processing, the overall CF of the ground-mounted PV system remains high due to the emission from the ground-mount PV system which is approximately 1.14×10^2 kg CO_2 eq./kg H_2. The CPBT of the ground-mounted PV system is between 1.02 and 2.91 years. Beyond this period, the system would achieve a net-negative CF, ultimately leading to a reduction in carbon emissions.

The CED of the green hydrogen is 70.65 kWh and the CF is 7.19 kg CO_2 eq./kg H_2. 58.80% emission is related to the electricity generation and the rest of the process only emits 2.96 kg CO_2 eq./kg H_2. Table 3 represents the combined environmental analysis.

3.1.2. LCA of other hydrogen production

The production of grey hydrogen requires 91.12 kWh of energy and results in the emission of 29.14 kg CO_2 eq. of GHGs for each kilogram of hydrogen produced. Approximately 59% of the total CED is attributed to the processing of natural gas, and around 94% of the GHG emissions arise from the absence of carbon capture in the process.

In contrast, blue hydrogen production through SMR with CCS achieves a significant reduction in GHG emissions. With 56% CCS efficiency, the process emits 8.12 kg CO_2 eq. per kilogram of hydrogen. This

Table 3
Comparative analysis of blue hydrogen production powered by FPV and ground-mounted PV systems.

Parameter	FPV-powered blue H_2	Ground-mount PV-powered blue H_2	FPV-powered green H_2	Ground-mount PV-powered green H_2
CED (kWh/kg H_2)	32.18	1.9×10^3	1.08	70.65
Carbon footprint from biogas (kg CO_2eq/kg H_2)	−1527.38	−1,527.38	N/A	N/A
Emissions from PV system (kg CO_2eq/kg H_2)	9.08	114.95	0.30	4.22
Net carbon footprint (kg CO_2eq/kg H_2)	−1518.30	−1,412.42	2.96	7.19
CPBT (years)	0.67	1.02–2.91	0.67	1.02–2.91

emission is further reduced to 3.46 kg CO_2 eq. with 90% CCS efficiency. Despite these reductions in emissions, the CED remains almost identical for both grey and blue hydrogen production, as the core production methodology, SMR, remains largely the same. CED of blue hydrogen with 56% CCS and 90% CCS efficiency are 93 kWh/kg H_2 and 100 kWh/kg H_2, respectively. The primary difference lies in the implementation of carbon capture technologies, which lowers the CF without substantially impacting energy consumption.

3.1.3. Sensitivity analysis of pale-blue hydrogen

Finally, Fig. 3 illustrates the change in equivalent CO_2 savings from the environment based on the blue-to-green hydrogen ratio in the production of 1 kg of pale-blue hydrogen. As the percentage of blue hydrogen increases from 10% to 90%, the equivalent CO_2 savings rise significantly from 148.89 kg CO_2 eq. to 1,366.14 kg CO_2 eq. This trend underscores the importance of blue hydrogen in enhancing the environmental benefits of pale-blue hydrogen. The results suggest that while green hydrogen contributes positively to the overall reduction of carbon emissions, a higher proportion of blue hydrogen substantially increases the carbon savings from the atmosphere, reflecting its role in effective carbon management strategies.

4. Discussion

4.1. Comparative environmental impact assessment

Fig. 4 provides a comparative analysis of the CED associated with various hydrogen production methods, with grey hydrogen as the reference point, exhibiting a CED of 91.1 kWh per kilogram of hydrogen produced.

Blue hydrogen (GM + PR) produced using FPV system requires 32.2 kWh, resulting in a CED that is approximately 64.7% lower than that of grey hydrogen. This notable reduction indicates that blue hydrogen generated from FPV system is significantly less energy-intensive. Conversely, blue hydrogen (GM + PR) derived from ground-mounted PV systems demonstrates a substantially higher CED of 192 kWh. This production method is approximately 111.9% more energy-intensive than grey hydrogen, emphasizing its relatively higher energy demand.

In terms of green hydrogen production, the FPV method necessitates only 1.08 kWh, which represents a remarkable 98.8% reduction in CED compared to grey hydrogen. This showcases green hydrogen's efficiency in energy utilization. For green hydrogen produced via ground-mounted PV systems, the CED is reported at 70.7 kWh, which is not as good as FPV but still about 22.4% lower than grey hydrogen, reflecting a more favorable energy profile than traditional hydrogen production methods.

When examining blue hydrogen produced via SMR with 56% CCS, the CED is found to be 93.0 kWh, indicating a 2.1% increase compared to grey hydrogen. Meanwhile, blue hydrogen produced using SMR with 90% CCS requires 100 kWh, which represents an 8.8% increase in energy demand compared to grey hydrogen.

Lastly, the pale-blue hydrogen, comprising a 50% blend of blue and green hydrogen, exhibits a CED of 16.6 kWh. This production method results in a significant 81.8% reduction in energy demand compared to grey hydrogen, indicating a more energy-efficient approach to H_2 production.

While green hydrogen produced from FPV systems demonstrates the lowest cumulative energy demand, both blue hydrogen methods exhibit varying degrees of energy intensity when compared to grey hydrogen. Pale-blue hydrogen exhibits the second least energy-intense production

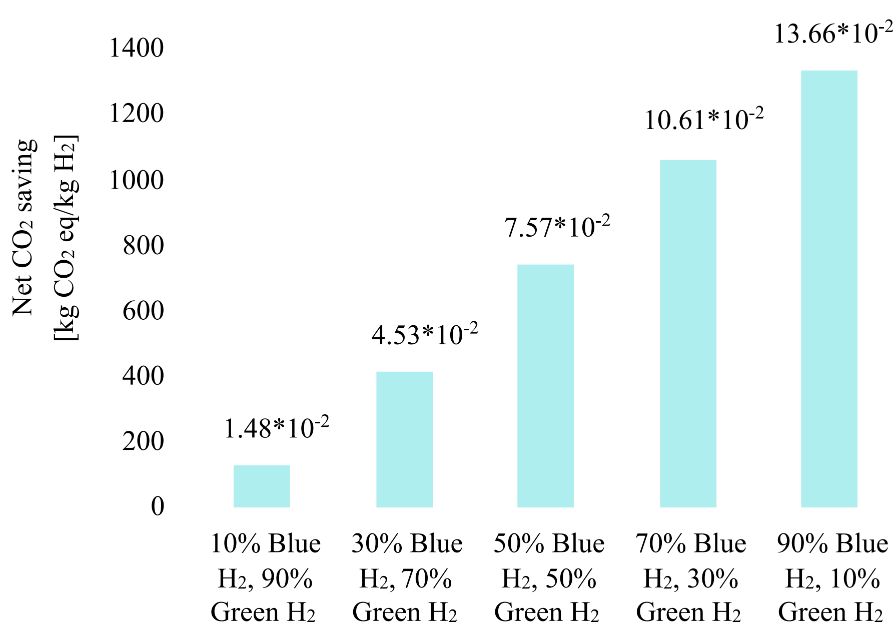

Fig. 3. Net carbon saving corresponding to different proportions of blue and green hydrogen in the production of pale-blue hydrogen. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

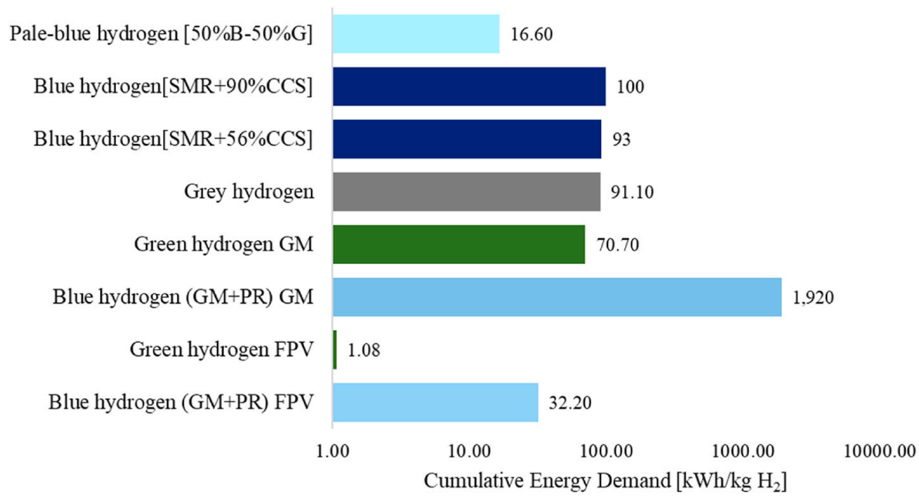

Fig. 4. Cumulative energy demand comparison of different hydrogen production methods.

method. This analysis underscores the importance of choosing efficient production methods to minimize energy consumption in hydrogen generation.

Fig. 5 presents a comparative CF analysis of various hydrogen production methods relative to grey hydrogen, which serves as the baseline for emissions quantified at 29.1 kg CO_2-eq. Blue hydrogen (GM + PR) produced using FPV systems demonstrates a substantial carbon elimination effect, reducing emissions by 1,510 kg CO_2 eq. This remarkable reduction indicates that blue hydrogen not only compensates for its own emissions but also offsets approximately 52 times the emissions generated by grey hydrogen. Similarly, blue hydrogen generated through ground-mounted PV systems achieves a significant reduction of 1,410 kg CO_2 eq. This compensatory effect translates to roughly 48 times more carbon offset compared to the emissions produced by grey hydrogen.

In contrast, green hydrogen produced from FPV, and ground-mounted systems shows also modest reductions, with emissions of 2.96 kg CO_2 eq. (representing about 90% less than grey hydrogen) and 7.19 kg CO_2 eq. (approximately 75% less), respectively. Blue hydrogen produced via SMR with 56% CCS results in carbon emission of 8.12 kg CO_2-eq., which is around 72% less than that of grey hydrogen. Meanwhile, the SMR process with 90% CCS yields 3.46 kg CO_2 eq., reflecting a reduction of approximately 88% compared to grey hydrogen.

Lastly, pale-blue hydrogen, consisting of a 50% blend of blue and green hydrogen, results in negative emissions of 758.0 kg CO_2-eq. This production method compensates for emissions at a rate of approximately 26 times more than grey hydrogen. This analysis highlights the superior carbon compensation capabilities of pale-blue hydrogen production methods compared to traditional grey hydrogen, emphasizing the significant role they can play in achieving net carbon neutrality and reducing overall greenhouse gas emissions.

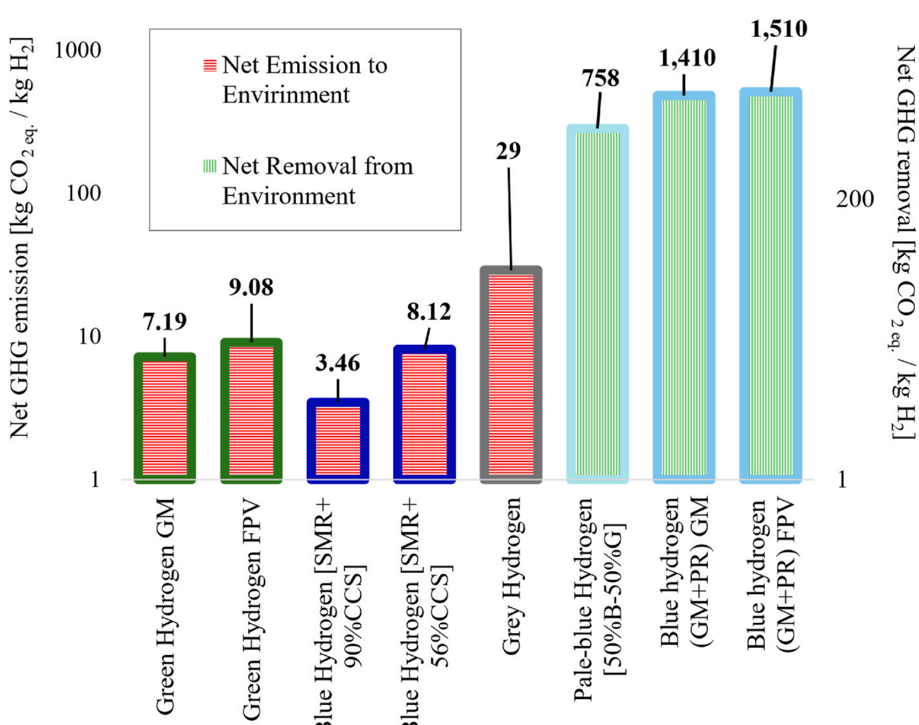

Fig. 5. Comparison of carbon footprint of different types of hydrogen production. Green value indicates the amount of CO_2 eq. removed from the environment, while red values are pollution. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.2. Global landscape of hydrogen production

China has rapidly positioned itself as a leader in green hydrogen production, particularly in the development of electrolyzer capacity. In 2020, China accounted for less than 10% of global electrolyzer capacity for dedicated hydrogen production [15,28]. Nevertheless, by 2022, China's installed capacity had surged to more than 200 MW, representing 30% of global capacity, including the world's largest electrolysis project at 150 MW [28]. By the end of 2023, China's electrolyzer capacity is expected to reach 1.2 GW, accounting for 50% of global capacity, with another world record-sized electrolysis project of 260 MW already in operation [28]. This rapid expansion underscores China's leadership in green hydrogen production and its commitment to developing clean energy technologies.

In contrast, North America and Europe have taken the lead in advancing low-emission hydrogen production through policy initiatives and investments. The G7 nations, including Canada, France, Germany, Italy, Japan, the United Kingdom, the United States, and the European Union, have been instrumental in scaling up hydrogen, ammonia, and hydrogen-based fuel production. Together, these countries account for roughly one-quarter of today's global hydrogen production and demand [28]. Canada is one of the world's largest hydrogen producers, generating approximately 3 million tonnes annually using SMR of natural gas [36,99]. Although Western Canada dominates in production by leveraging its vast fossil fuel resources, most of the plants operate without CCS, resulting in significant carbon emissions. [36,100]. Under the Paris Agreement, however, Canada has pledged to reduce methane emissions in the oil and gas sector by 40–45%, which could spur cleaner hydrogen production practices in the future [36]. This is also likely to radically transition the workforce [101].

Looking ahead, hydrogen is expected to have a broader application in industries that are currently underutilizing its potential. Novel uses of H_2 in heavy industry and long-distance transportation, for example, currently account for less than 0.1% of global demand [28]. By 2030, however, these sectors could represent one-third of global H_2 demand in a Net Zero by 2050 scenario [28]. This shift will be critical in driving the growth of low-emission H_2 production and in meeting the world's decarbonization goals. This study has shown several effective pathways to energy and carbon-efficient H_2, including the novel pale blue hydrogen route. The carbon emissions per kilogram of hydrogen vary significantly across different production methods. Previous studies presented in Table 1 show grey hydrogen generates between 7.5 and 25 kg CO_2 eq, blue hydrogen produces 0.6–22 kg CO_2 eq, and green hydrogen emits 0.6–7 kg CO_2 eq. In contrast, pale-blue hydrogen, as demonstrated in this study, removes 758 kg CO_2 eq from the environment for each kg H_2 produced, effectively resulting in a CO_2 offset. This represents a carbon reduction ranging from approximately 30 to 101 times more CO_2 removed compared to the emissions generated by grey hydrogen, and a CO_2 offset of 34 to 1263 times more than the emissions from blue and green hydrogen production methods.

5. Conclusions

This study highlights the significant advancements in hydrogen production methods, particularly focusing on the environmental implications of pale-blue hydrogen, which integrates both blue and green hydrogen components.

For the first time, the comparative analysis reveals that by CED, blue hydrogen (GM + PR) GM is 21 times more energy intensive, blue hydrogen [SMR+90% CCS] and blue hydrogen [SMR+ 56% CCS] has 10% and 2% higher energy demand, and green hydrogen GM, blue hydrogen (GM + PR) GM, pale-blue hydrogen [50%B - 50%G] and green hydrogen FPV have 22%, 65%, 82% and 99% lower energy intensity compared to grey hydrogen. On the other hand, blue hydrogen [SMR+ 56% CCS], green hydrogen GM, blue hydrogen [SMR+ 90% CCS], green hydrogen FPV have 72%, 75%, 88% and 90% less CF respectively compared to grey hydrogen. Notably, pale-blue hydrogen [50%B - 50% G], blue hydrogen (GM + PR) GM and blue hydrogen (GM + PR) FPV offset 26 times, 48 times and 52 times the emissions of grey hydrogen.

Blue hydrogen, produced from biogas in a closed-loop system, not only achieves net zero direct emissions, but also demonstrates substantial carbon footprint reductions when compared to grey hydrogen. Specifically, blue hydrogen produced via FPV systems achieves an impressive net carbon footprint reduction of approximately 1,510 kg CO_2 eq. per kilogram of hydrogen, effectively compensating for its emissions by offsetting over 52 times the emissions produced by grey hydrogen. Ground-mounted PV systems, while slightly less effective, still show a remarkable offset, reducing emissions by around 1,410 kg CO_2 eq., or approximately 48 times the emissions of grey hydrogen.

Pale-blue hydrogen, particularly with a 50% blue-to-green hydrogen ratio, further emphasizes the potential of this production method. It not only reduces emissions significantly, but also enhances overall carbon compensation capabilities, with a remarkable offset rate of approximately 26 times more than grey hydrogen. This positions pale-blue hydrogen as a crucial player in the transition towards NZE, underscoring its role in achieving net carbon neutrality and reducing greenhouse gas emissions. The findings of this study advocate for the increased adoption and scaling of pale-blue hydrogen production methods as an essential strategy in the global pursuit of sustainable energy solutions.

CRediT authorship contribution statement

Riya Roy: Writing – review & editing. **Giorgio Antonini:** Writing – review & editing. **Koami S. Hayibo:** Writing – review & editing. **Md Motakabbir Rahman:** Writing – review & editing. **Sara Khan:** Writing – review & editing. **Wei Tian:** Writing – review & editing. **Michael S.H. Boutilier:** Writing – review & editing. **Wei Zhang:** Writing – review & editing. **Ying Zheng:** Writing – review & editing. **Amarjeet Bassi:** Writing – review & editing. **Joshua M. Pearce:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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