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Review

A Review of Life Cycle Assessment of Carbon – Water – Energy of Hydrogen Production Systems

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Abstract: The hydrogen (H_2) economy is seen as a crucial pathway for decarbonizing the energy system, with green H_2 playing a key role as an energy carrier in this transition. The growing interest in H_2 comes from its versatility—it can serve as a raw material, and various technologies allow it to be produced from a wide range of resources. However, environmental impacts of H_2 production have primarily focused on greenhouse gas (GHG) emissions, despite other environmental aspects being equally relevant in the context of a sustainable energy transition. Recently, Life Cycle Assessment (LCA) studies of H_2 supply chains have become more common. This paper aims to contribute to developing a database by comparing different H_2 production pathways considering three environmental indicators: global warming potential, energy performance, and water consumption, from an LCA perspective.

Keywords: Hydrogen life cycle assessment; Water scarcity; Cumulative Energy; Global warming potential

1. Introduction

The rapid growth of cities and populations has led to a 38% increase in energy demands between 2000 and 2013 [1], raising concerns about our ongoing reliance on fossil fuels and the alarming rise in Earth's temperature, which is now more than 2.0 ºC above pre-industrial levels [2,3]. Local governments worldwide have pointed out energy security as a critical issue in ensuring a clean and reliable energy supply. In this context, a sustainable energy transition—driven by the increased use of renewable materials and the development of more efficient, sustainable processes—is therefore essential [4,5].

As concerns about climate change and energy security continue to grow [6], the development of renewable energy systems has become a key strategy [7]. The harmful effects of fossil fuel combustion on both the environment and human health highlight the urgent need to transition to a renewable energy system that reduces our dependence on fossil fuels. To meet environmental targets, it is estimated that by 2050, renewable energy must account for at least 12% of total energy consumption—six times the current global demand [3].

In this context, hydrogen (H_2) is emerging as a key component of a low-carbon, H_2-based economy, thanks to its diverse production methods and wide range of applications [8]. Greenhouse gas (GHG) emissions from human activities have been the primary driver of climate change since the mid-20th century. These emissions, primarily from the use of fossil fuels in electricity generation, industry, and heating, are the main contributors to changes in climate dynamics, as over 80% of global energy needs are met by fossil fuels, including oil, coal, and natural gas [9]. In 2020, GHG emissions from energy systems accounted for 73.3% of total global emissions [10]. It is clear, therefore, that the energy sector is the largest contributor to the increase GHG in the atmosphere [11]. Therefore, reduce them is global priority [12]. Developing renewable energy systems is, therefore, essential for shifting

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away from a fossil fuel-dependent economy and toward cleaner energy sources with lower environmental impacts [13].

According to the International Renewable Energy Agency (IRENA), renewable energy generation will play a crucial role in achieving GHG reductions by 2050, contributing 41% of the total reduction, while energy efficiency initiatives will account for 40% of decarbonization efforts [14]. With global energy needs projected to grow by 48% over the next 20 years due to population growth [15], the focus on alternative, clean, and renewable energy sources is intensifying [1].

In this context, H_2 could play a key role in transforming the current energy system [1]. H_2 is expected to significantly contribute to decarbonizing energy systems, especially in hard-to-abate sectors e.g., in cement production [16]. The H_2 energy system has the potential to reshape the energy landscape by driving market growth through competitive pricing, improved quality, enhanced energy security, and advancements in renewable energy technologies [17,18]. H_2 has been identified as a powerful catalyst for advancing toward a carbon-neutral society, thanks to its diverse applications and the fact that its combustion produces only water as a by-product [19,20].

However, it's important to note that H_2 is not readily available in its pure form and requires resources and technologies to produce [15]. Ensuring the efficiency and sustainability of H_2 production systems is essential [15].

Currently, most H_2 is produced from fossil fuels, e.g., natural gas and coal, through steam reforming and gasification processes, which account for 60% and 20% of global H_2 production, respectively [21]. By contrast, low-emission H_2 makes up less than 1% of global production [21]. This underscores the need to develop and scale up clean H_2 production systems. As for current H_2 applications, only a small proportion is used for energy purposes. The majority is consumed at production sites, primarily in the petrochemical sector (47%), and in ammonia manufacturing (45%), meaning over 90% of H_2 is used for traditional industrial purposes [22,23].

Additionally, H_2 can be synthesized from a variety of sources, including both fossil and renewable resources, providing multiple production pathways and ensuring a reliable and diverse energy supply [24]. Like electricity, H_2 acts as a secondary energy source, serving both as an energy carrier and a storage solution [25]. This makes H_2 systems particularly beneficial when integrated with renewable energy systems. H_2 can be converted into electricity, making it a highly versatile energy carrier [26]. It serves as a clean fuel for vehicles, offering an environmentally friendly alternative to conventional fossil fuels and significantly reducing GHG emissions [8]. Furthermore, H_2 plays a key role in stabilizing renewable energy systems by storing and releasing energy. This capability helps smooth out the variability of renewable energy sources, ensuring energy security, adaptability, and stability in these systems [9].

According to [8], H_2 usage can be categorized into three main areas: first, it is used as a reagent in hydrogenation processes, accounting for nearly 65% of H_2 consumption in the production of chemicals like ammonia, methanol, hydrochloric acid, hydrogen peroxide, and others; second, H_2 is applied in oil refining, petrochemical production, fertilizer hydrogenation, and metallurgical processes, making up 25% of the use cases; and finally, the remaining 10% of global H_2 supply is used as an oxygen removal agent, in internal combustion engines, and as a cooling refrigerant in electricity generation and weather balloons.

Historically, H_2 was not considered in energy system evaluation models due to its high production costs and the slow industrial response to climate change. However, this situation is changing. Technology costs are decreasing faster than anticipated, and the fossil fuel industry is shifting its approach, now able to harness resources to develop the primary and support infrastructures needed for this new H_2 resource [27].

Depending on the resources and technologies used for H_2 production, it can be categorized as gray, green, or blue energy [25,28,29]. Grey hydrogen is produced from fossil fuels (natural gas or coal) through steam methane reforming (SMR) and coal gasification (CG) [25]. SMR accounts for over 76% of global hydrogen production (IEA, 2019). It's a well-established, cost-effective method, but it comes with significant environmental concerns due to high GHG emissions [30,31]. Blue hydrogen is

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produced from fossil fuels with the addition of carbon capture and storage (CCS), while green hydrogen comes from renewable sources such as wind and solar energy [32]. However, it's important to note that these colors refer to energy sources and don't reflect the carbon intensity of each type.

As the development of renewable H_2 systems accelerates, assessing the potential environmental impacts of these systems has become crucial. Numerous studies have examined the environmental performance of H_2 systems, focusing on indicators such GHG emissions [27,30,33], water consumption (WC) [34–36], water scarcity footprint (WSF) [34,37], and energy efficiency [38–40]. In this context, Life Cycle Assessment (LCA) has been used as a comprehensive tool to evaluate the environmental impacts of processes or products throughout their life cycles. LCA helps improve product sustainability and inform environmental regulations [41]. However, most of these studies focus primarily on GHG emissions and energy efficiency. A few studies analyzed those indicators separately often overlooking factors like WC, and only a few have explored the effects of H_2 production on the WSF in specific regions [15,42–45]. Hydrogen-based energy systems are often evaluated solely from a GHG emissions perspective, as the main motivation for promoting H_2 is its potential to decarbonizing the economy [46,47].

This paper aims to contribute to the ongoing discussion on H_2 sustainability by emphasizing the importance of evaluating the environmental sustainability of H_2 production by considering factors such as water usage and energy requirements alongside GHG emissions assessments

2. Beyond GHG: Water and Energy as Strategic Aspects

Only a few studies have analyzed the water-energy-carbon nexus [48,49]. Given the strong and complex connection between the energy sector, water supply and carbon emissions [48], it's essential to consider this relationship when evaluating energy production, as water quality and availability directly influence energy supply [36].

This work provides an overview of H_2 production with respect to those indicators. GHG emissions are crucial for evaluating low-emission H_2 energy systems. Most global certification schemes use GHG intensity as a key criterion for certifying H_2 [21,50]. Energy efficiency is an important metric for assessing energy consumption (both fossil and renewable) throughout the life cycle of energy systems. It helps quantify how much H_2 production depends on fossil or renewable energy sources. Additionally, since H_2 systems require water as both a feedstock and for processing, evaluating water consumption is essential for assessing the availability and quality of water in H_2 production.

The evaluation of such indicators can be conducted by using LCA which is an effective and globally recognized method for analyzing the environmental aspects and potential impacts of a product or service throughout its life cycle [51]. As a standardized method, LCA can be employed for assessing the environmental performance of products or processes by identifying and analyzing potential environmental impacts across product life cycles.

Climate change, population growth, and pollution have all increased water demand, while many regions are experiencing water scarcity. As a result, countries may face significant challenges in water management if they aim to expand the industrial development of electrolytic hydrogen [52]. It is projected that global water demand could rise by 1.8% if electrolytic hydrogen were to replace all current fossil fuel usage [53]. Given that the energy sector relies heavily on the availability of water resources, assessing water availability and scarcity for green H_2 is crucial, as many green hydrogen facilities are located in areas with limited water resources [54]. Projections suggest that around 39% of hydrogen production capacity will be located in regions that face water scarcity [36]. Although various methods exist for evaluating water consumption and scarcity [55], this paper focuses primarily on studies that used the Available Water Remaining (AWARE) method, which aligns with LCA principles [56].

In LCA studies, the energy demand of a product serves as a broad indicator for evaluating primary energy consumption throughout its entire life cycle [57]. Cumulative Energy Demand (CED) is a valuable metric for assessing the energy required in the extraction, manufacturing, operation, and final disposal of resources used in the energy system [58]. However, CED should be considered alongside other environmental indicators, such as global warming potential (GWP), due to its interrelationship with these factors [59,60]. An indicator derived from CED is the Energy Return on Investment (EROI), which measures the energy profitability of an energy system [61]. EROI represents the ratio of useful energy produced by an energy system over its lifetime to the energy invested or consumed during its operation [62–64]. EROI is useful for evaluating energy performance and assessing the environmental impact of the energy system [61]. In addition to EROI, CED can be used to assess the Net Energy Ratio (NER), which estimates the renewability of an energy system by comparing the energy output to the fossil energy consumed throughout the product's life cycle [38].

Many studies have evaluated the environmental performance of H_2 systems, assessing various indicators such as GHG emissions, WC, WSF, and energy efficiency [6,8,46,65]. However, most of the studies analyzed such indicators separately, neglecting the existing nexus between water-carbon-energy in H_2 productions systems. Assessing resource consumption from a LCA perspective provides a comprehensive understanding of the environmental impacts associated with the H_2 production chain [42].

3. General Overview of H2 Production Pathways

As concern about climate issues and energy security, H_2 has been pointed out as a viable option for accelerating a sustainable energy transition. H_2 stands out due to its high energy storage capacity (**Error! Reference source not found.**), making it a viable solution for balancing energy supply and demand [66]. H_2, when combined with renewable energy systems, offers an effective way of balancing energy production and demand by generating H_2 during periods of excess electricity, which can then be stored for later use [9]. This approach ensures greater reliability and flexibility in electrical systems [67]. In addition, low-carbon H2 can help to achieving the economy decarbonization as well as reducing resources consumption as water and fuels.

Table 1. Energy content of different fuels per weight and per volume in LHV [68].

Fuel	Energy Content (MJ/kg fuel)	Energy Content (MJ/m³)
Diesel	42	38
Gasoline	43	35
Methane (liquid)	45	20
Ethanol	24	20
Methanol	20	18
H_2 (compressed, 1 bar)	120	-
H_2 (compressed, 350 bar)	120	4.5
H_2 (compressed, 700 bar)	120	7
H_2 (liquid, -253 ºC)	120	12
Ammonia (liquid)	20	18

At industrial level, H_2 can be produced from three main methods:

- Thermochemical
- Electrolytic and
- Photolytic

Each method uses different energy sources [31]. While interest in producing H_2 from renewable sources is growing, only a small fraction—just 1%—is currently produced using clean energy [23]. Various methods production exist (**Error! Reference source not found.**), but the most common focus on converting electricity into the desired energy resource, a process known as Power-to-X, where X represents the specific energy type or application [69]. Another method, Power-to-Gas, involves converting electricity into gaseous fuels like H_2 or synthetic fuels such as ammonia, methane, and aviation fuel.

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Additionally, Power-to-Power refers to converting the chemical energy in H_2 back into electricity [3,20]. Power-to-Gas methods are gaining popularity, as they offer a way to use existing natural gas infrastructure, reduce carbon emissions, and enhance energy security by integrating renewable sources.

Table 2. Hydrogen pathways.

Technology	Efficiency (%)	Price ($/kg H_2)	Energy demand (kWh/kg H_2)	Reference
Coal Gasification (CG)	45-65	2.0 - 2.8	63	[48,70]
Biomass Gasification (BG)	44-48	1.77 – 2.05	70	[48,70,71]
Electrolysis Photovoltaic (EL PV)	51-67	3.0 - 24.0	50	[70,71]
Electrolysis Wind (EL Wind)	51-67	3.0 - 9.0	50	[2,48,70]
Electrolysis Brazilian Grid (BR EL Grid)	51-67	1.27 – 1.64	50	[70,72]
Steam Reforming of Ethanol (SREtOH)	68-95	1.58	50	[70,73]
Steam Methane Reforming (SMR)	57-89	1.83 – 2.35	51	[71]

However, despite the variety of resources and technologies for H_2 production, its use faces significant energy inefficiencies throughout the supply chain. When it is used in fuel cells (FC), only 29% of the total energy invested is converted into useful energy [67]. In contrast, applications like combined heat and power can achieve higher efficiencies. For applications that burn H_2, the overall efficiency is much lower, with considerable energy losses occurring during transportation and distribution as well as in other stages of the supply chain. This underscores the importance of evaluating energy consumption across the entire life cycle of H_2 systems [67]. As can be seen from **Error! Reference source not found.** that summarizes the energy feedstock demand per H_2 route considered in this study, the energy demand exhibit a high degree of proximity, however, each feedstock production is associated with different levels on environmental impacts.

Table 3. Energy feedstock per H_2 route.

Technology	Feedstock	MJ feedstock/kg H_2	Reference
SMR	Natural Gas	174.0	[74]
SRBiogas	Biomethane	198.0	[74]
SREtOH	Ethanol	182.0	[75]
CG	Coal	218.0	[49]
EL	Electricity	180.0	[76]

H_2 can also be used to produce both electricity and heat. The re-electrification of hydrogen involves generating electricity from hydrogen in FCs. Another method is using hydrogen in internal combustion engines (gas turbines), but the efficiency is low—around 20 to 25%—which is less efficient than using gasoline in these engines [67]. This low efficiency is due to hydrogen's low volumetric energy density. As a result, fuel cells are more attractive for electricity generation, as they can achieve efficiencies between 60 and 80%, with their only byproducts being electricity and water [20].

Additionally, the infrastructure required for storing and transporting H_2 can lead to significant energy consumption. The main methods for storing and transporting H_2 involve both its gaseous and liquid states. Compressing H_2 to pressures ranging from 300 to 700 bar requires substantial energy and results in a gravimetric density of less than 40 kg/m^3. However, the energy spent on the compression process can account for 13–18% of the lower heating value (LHV) of the stored H_2, exceeding 2.21 kWh/kg H_2. On the other hand, liquefying H_2 requires energy for both compression and cooling to 20.15 K, which can consume up to 45% of the LHV of H_2, though it achieves a

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gravimetric density of 70.8 kg/m³ [62,68]. The next sections present the H_2 pathways selected for review analysis.

- Steam Reforming Process

Steam reforming of natural gas (SMR) is the most common and developed technique for producing H_2. In SMR, natural gas and other hydrocarbons are converted into synthesis gas through an endothermic process involving two main reactions: steam reforming and the water-gas shift reaction [8].

In the reformer unit, treated natural gas reacts with water to produce syngas, a gaseous mixture of H_2, CO, and CO_2. The CO in the syngas reacts with water in an exothermic water-gas shift (WGS) reaction, increasing the H_2 concentration and improving the overall efficiency of SMR [8,63,77]. To enhance the purity of the H_2 and remove other gases, the H_2 is directed to a pressure swing adsorption (PSA) unit, which separates it from CO_2, achieving H_2 purity levels of up to 99.95% [5,8,78]. Syngas, the precursor to H_2, can also be generated from renewable resources such as ethanol (EtOH), sugars [20] and biomethane. Typical natural gas reforming is shown as follows:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (2)$$

In this context, steam reforming can use ethanol (SREtOH) as both a raw material and an energy source for H_2 generation [79]. EtOH reacts with steam to produce syngas, and any remaining CO in the syngas is converted into CO_2 and more H_2 through the WGS reaction [49,80]. The equation below is the general reaction o EtOH reforming:

$$C_2H_5OH + H_2O \rightarrow 2C + 4H_2 \quad (3)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (4)$$

Several advantages exist for using EtOH as a feedstock for H_2 synthesis:

- Diverse biomass sources: EtOH can be produced from a variety of biomass sources [70].
- High H_2 content: EtOH has a high hydrogen-to-carbon ratio (3) [81].
- Extensive distribution network: An extensive distribution network for EtOH already exists.
- Convenient storage and low toxicity: EtOH is easily stored and has low toxicity [80].

Furthermore, converting EtOH to H_2 eliminates the need for the purification and dehydration steps required for certain ethanol applications, such as blending with gasoline. These processes can consume up to three-quarters of the energy used in EtOH production [80].

In addition to climate concerns, increases in solid waste generation constitute a significant challenge. Poor waste management practices negatively impact public health and contribute to soil and water pollution [82]. Using waste for energy provides a solution to both waste management issues and GHG emissions, which account for about 5% of global emissions [44].

Converting waste into biogas which is made up of methane (50 – 80%) and carbon dioxide (20 – 50%) with other trace gases [83] is one method for producing H_2 through steam reforming. Biogas can be derived from various waste sources, including organic waste, agricultural waste, landfill sites, and sewage treatment waste, as a byproduct of anaerobic digestion. Biogas serves as a viable alternative to fossil natural gas and results from the anaerobic breakdown of organic matter under specific conditions of temperature, acidity, and humidity. The process of generating H_2 from biogas is similar to that from natural gas, though it requires additional purification and treatment steps for biogas purification [84,85]. The equation below is a demonstration of the biomethane reforming process (SRBiogas):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (5)$$

- Coal Gasification Process

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Coal gasification (CG) is a widely used technology for producing inexpensive and efficient H_2. In this process, coal reacts with oxygen in low concentrations, combined with steam, under high temperature and pressure to produce syngas [49]. The gasification method has gained interest because it can employ both renewable and non-renewable materials [43]. The CO present in syngas can be converted to improve process efficiency through the WGS reaction, which increases the H_2 production rate [45]. Efficiency ranges between 74 – 85% [83]. Typical CG processes are shown below:

$$C + H_2O \rightarrow CO + H_2 \quad (6)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (7)$$

- Electrolysis Process

In addition to the thermochemical methods mentioned above, electrochemical methods that use water and electricity to produce H_2 are also noteworthy. These methods can reduce GHG emissions by nearly 90% compared to traditional fossil fuel-based methods [44]. Electrolysis (EL), an electrochemical method, involves converting electricity into H_2 by splitting water into H_2 and O_2 molecules when an electrical current is passed through water [16,86]. An ion-separating membrane is placed in the water to facilitate the separation of H_2 gas produced at the cathode from O_2 produced at the anode [60]. Efficiency ranges between 60 – 80% [87]. The equations below present the reactions that occur in the electrolysis process:

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \quad (8)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (9)$$

Currently, three main commercial methods for producing H_2 through electrochemistry are in use:

- Alkaline electrolysis (AEL), which leads the H_2 market and has been in development for several years [88];
- Solid oxide electrolysis (SOEC), which operates at high temperatures to break down water molecules without requiring significant electricity [20];
- Proton Exchange Membrane (PEM) electrolysis which offers greater operational flexibility and the ability to handle variable loads, making it ideal for systems that rely on intermittent energy sources [16].

A key consideration in EL systems is the potential market for the O_2 produced alongside H_2, which can yield approximately 8.0 kg of O_2 for every kg of H_2. This O_2 has applications across various sectors, including steel, pulp and paper, chemical, healthcare, and ozonation-based water treatments. However, with the expected increase in EL systems, the market for the generated O_2 may become insufficient [89].

The growing capacity of renewable energy sources like wind and solar is driven by lower costs and increasing demand, leading to reduced costs in the renewable sector [2]. EL systems powered by photovoltaic (PV) and wind energy offer several advantages, e.g., high purity (which eliminates the need for extra cleaning steps). These systems can also lower the costs of generating electricity or H_2 by using excess energy produced by these sources, which can be stored as H_2 for later use [90].

4. Life Cycle Assessment Review

This section presents the results of the literature review, comparing the findings from the authors with existing articles, reports, and documents. The review was conducted using the Scopus and ResearchGate websites, with key search terms including "hydrogen life cycle assessment," "hydrogen water footprint," "energy balance of hydrogen," "steam reforming of hydrogen," "carbon intensity of hydrogen pathways," and "hydrogen and energy transition." It was conducted a systematic exploration taken 2012 as cutoff year for the selected papers. It was selected 45 studies.

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Therefore, determining the sustainability of H_2 requires evaluating the resources and methods used for its production [24], along with other environmental factors and GHG emissions. The potential environmental impacts of the H_2 production chain can be assessed using LCA [88,90]. As interest in H_2 as an energy resource grows, research employing LCA is increasingly supporting decision-making about the best methods and resources for its production [9]. LCA outcomes can help: assess the impacts of producing and using a product or service; compare methods to aid in selecting the optimal approach; identify critical stages to reduce impacts throughout the production process; and guide planning and decision-making [91]. The next sections present the main findings for energy – water – carbon by using LCA approach.

4.1. Carbon Footprint

The next section provides a literature review on assessments of H_2 production. **Error! Reference source not found.** summarizes studies that analyzed the GWP of the H_2 supply chain using the LCA tool.

Table 4. GWP of H_2 production.

Route	GWP ($kg\ CO_{2eq}/kg\ H_2$)	Observations	Boundaries	References
SMR	11.2	-	Cradle-to-gate	[51]
	11.9	-	Not specified	[92]
	13.8	-	Well-to-pump	[93]
	10.8	Europe	Cradle-to-gate	[94]
	10.2	-	Cradle-to-grave	[95]
	10.4	-	Cradle-to-gate	[96]
	7	-	Cradle-to-gate	[8]
	12.6	-	Cradle-to-gate	[97]
	12.3	Finland	Cradle-to-gate	[65]
CGR	23.7	-	Well-to-pump	[93]
	11.59	Iran	Cradle-to-grave	[95]
	24.2	Country not specified	Cradle-to-grave	[49]
	26	-	Cradle-to-gate	[60]
	51.86	-	Cradle-to-distribution	[40]
	24.4	-	Well-to-wheel	[98]
	84.2	-	Not specified	[99]
	14.74	-	Cradle-to-gate	[100]
SRBiogas	9.2	Wheat grains EtOH from Swedish	Cradle-to-gate	[51]
	6.8	-	Cradle-to-gate	[101]
	7.27	Sugar beet EtOH from Tunisian	Cradle-to-gate	[102]
	0.25	Biogas supply from Germany	Cradle-to-gate	[103]
	12.2	US Corn EtOH	Well-to-pump	[93]
	-4.8	AD of waste in Europe Biogas supply and upgrading included	Cradle-to-gate	[94]
	4	Waste corn crops and pig manure	Cradle-to-distribution	[8]
	5.6	AD manure, cheese whey, maize silage and fodder beet	Cradle-to-gate	[101]
	10	Biomass collection in US	Well-to-pump	[93]
	3.9	Landfill gas in Korea	Well-to-wheel	[104]

Route	GWP ($kg\ CO_{2eq}/kg\ H_2$)	Observations	Boundaries	References
EL	-31,8	Residues from landfill bioreactor	Cradle-to-gate	[82]
	23	AEL Grid Italian Grid mix	Cradle-to-gate	[97]
	28.01	AEL Grid EU 80% fossil	Cradle-to-gate	[59]
	6.3	Grid BR	Cradle-to-gate	[72]
	28.6	Grid US	Well-to-pump	[93]
	31	PEM Grid US	Cradle-to-gate	[96]
	23	Grid UE 2019	Cradle-to-distribution	[8]
	5.7	AEL PV	Cradle-to-gate	[59]
	2.0	PV Canada	Cradle-to-grave	[6]
	0.37	PV	Not specified	[92]
	3.1	PV AEL Iran	Cradle-to-grave	[95]
	2.8	PEM PV	Cradle-to-gate	[96]
	0.5	AEL PV Switzerland	Cradle-to-gate	[60]
	2.5	PEM PV Finland	Cradle-to-gate	[65]
	2.5	AEL PV Australia	Cradle-to-gate	[16]
	1.9	Wind Germany	Cradle-to-grave	[57]
	9.7	Wind	Cradle-to-gate	[8]
	0.4	AEL Wind Europe	Well-to-tank	[60]
	3.4	Wind	Cradle-to-gate	[59]
	0.9	Wind Canada	Cradle-to-gate	[6]
	0.0325	Wind	Not specified	[92]
	1.8	PEM Wind	Cradle-to-gate	[96]
	0.6	PEM Wind Finland	Cradle-to-gate	[65]

SMR is often used as a benchmark for comparing other methods, as it is the primary technique for H_2 production, and renewable alternatives provide a pathway to transition away from fossil fuels. According to the studies reviewed, the GWP of the SMR method averages 11.4 kg CO_{2eq}/kg H_2. Emissions from the production phase are a key contributor to the GWP observed for the SMR pathway.

For example, [33] analyzed the GWP of SMR using the LCA approach, considering scenarios with efficiency improvements and a higher share of renewable energy in the electricity grid for 2030 and 2050. However, the study found that the GWP would remain around 10.0 kg CO_{2eq}/kg H_2 by 2050. Similarly, [95] used LCA to estimate a GWP of 10.3 kg CO_{2eq}/kg H_2, with 90% of greenhouse gas (GHG) emissions coming from natural gas consumption during operation, and only 1% attributed to the plant's construction and manufacturing.

In another study, [8] estimated a GWP of 7.0 kg CO_{2eq}/kg H_2 for the SMR method, noting operational phase contributed to 70% of total GHG emissions. They also pointed out that the compression stage could increase emissions by up to 0.64 kg CO_{2eq}/kg H_2 for gaseous compression and 3.0 kg CO_{2eq}/kg H_2 for liquefied transportation. Finally, [65] reported a GWP of 12.4 kg CO_{2eq}/kg H_2 for the SMR method, considering the extraction and transportation of natural gas by pipeline to the SMR facility, with the operation contributing around 66%, and natural gas transportation and extraction accounting for 25% of the GWP due to leaks considered by the authors. [93] reported a GWP of 28.6 for US grid mix (34% coal power, 32% natural gas and only a small percentage of renewable sources, 7%).

Studies on CG pathways show that they tend to have the highest GWP values among all the methods discussed in this report. For instance, [40] reported a GWP of 52 kg CO_{2eq}/kg H_2, with the operation phase being the largest contributor, accounting for about 60% of emissions. Coal production and extraction contributed 23%, while H_2 purification and transportation accounted for

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16%. Similarly, [49] noted that coal extraction and processing could account for up to 90% of emissions.

They also highlighted that CCS technologies could help reduce emissions for both SMR and CG methods. In particular, CCS could be more beneficial for the CG method, as it has a higher proportion of CO_2 available for capture compared to SMR, potentially leading to a 75% reduction in emissions [60]. Despite their high emissions, both SMR and CG methods could benefit from CCS technologies, which may help sustain these fossil fuel-dependent routes.

The EL process is recognized as a renewable and potential way of producing low-carbon H_2. However, as previously mentioned, the source of electricity significantly impacts the GHG emissions throughout the lifecycle of electrolytic H_2. If electricity is sourced from the grid, it can result in high emissions, especially when a substantial share of fossil fuels is used for electricity generation. [8] found a GWP of 23.0 kg CO_{2eq}/kg H_2 based on the average EU electricity mix in 2020, which included 44% fossil fuels. [97] reported a GWP of 4.3 kg CO_{2eq}/kg H_2 for alkaline electrolysis powered by PV energy and a fully renewable energy mix (45% hydro, 19% PV, and 15% wind). For electrolysis powered by PV and wind energy, most GHG emissions arise from the production of PV panels and wind turbines [45,65].

For the SREtOH, the average GWP was estimated at 8.0 kg CO_{2eq}/kg H_2. [51] found a GWP of 9.2 kg CO_{2eq}/kg H_2 for SREtOH from wheat grains, noting that 54% of the GWP came from wheat production and 45% from the ethanol distillery. Since animal feed is produced alongside ethanol, the authors expanded the system boundaries to offset the production of conventional animal feed. [102] reported a GWP of 7.26 kg CO_{2eq}/kg H_2 for beet ethanol, with 51% of GHG emissions attributed to the electricity used by the plant and 38% to ethanol distillery. By contrast, [93] reported a GWP of 12.2 kg CO_{2eq}/kg H_2 for ethanol reforming from corn under North American conditions.

Technologies that use biogas for H_2 production via steam reforming can have GWP values ranging from -32.0 to 3.9 kg CO_{2eq}/kg H_2. [82] reported a negative GWP of -31.8 kg CO_{2eq}/kg H_2 because renewable electricity (hydro) was used for the SRBiogas plant. This negative value is also attributed to the credit for biogas, as emissions that would have occurred if the waste had been sent to a landfill are offset. [103] found a GWP of 0.248 kg CO_{2eq}/kg H_2 (2.23E-02 CO_{2eq}/Nm^3 H_2) for SRBiogas from agro-industrial waste anaerobic digestion. The authors argued that this is the best method for biogas production due to its high CH_4/CO_2 ratio and the potential use of digestate as biofertilizer. In a Well-to-wheel assessment of H_2 production from landfill gas (LFG) in South Korea, [104] estimated a GWP of 3.9 kg CO_{2eq}/kg H_2. The upstream process received credit since GHG emissions from flaring are offset when biogas is produced from LFG. The total credit amounts to 68.2 kg CO_{2eq}/GJ H_2 linked to LFG recovery. The negative value found by [94] is due to the net carbon balance considered since CO_2 up taking from biomass growth was considered.

4.2. Water Consumption

Water is a strategic resource that is scarce in many regions, and climate change may further intensify this scarcity [105]. There are several methods to estimate the WF of a product, either based on the pressure on water resources (referred to as the Water Footprint Assessment) [106] or on the environmental impacts resulting from water consumption [56]. The first method focuses on the volumetric water demand for producing goods and services, while the Available Water Remaining (AWARE) method is an environmental impact indicator that estimates the amount of available water per area after human and ecosystem needs are met [107]. AWARE is recommended by the Life Cycle Initiative of the UN Environment Programme (UNEP) for calculating water scarcity [108]. This method considers both human and ecosystem water deprivation, assuming that the less water remaining per area, the more users in that area will experience freshwater shortages [109].

The energy industry consumes large amounts of water at various stages, from sourcing energy to generating electricity. In this sense, droughts, exacerbated by climate change, pose a significant threat to the energy supply system. Generating energy from renewable sources is one way to reduce WC.

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Electrochemical and thermochemical processes both use water for H_2 production, both as feedstock and for steam generation. In the context of H_2 energy systems, a study by [110] highlighted concerns about water availability. The study analyzed the pressure on water resources that could arise from establishing an H_2-based energy economy in 135 countries. The results showed that only 9 countries would need to increase their freshwater extraction by more than 10% to support an electrolytic H_2 energy system. A study by [52] concluded that the water required for a hypothetical volume of green H_2 production (400 Mt/year by 2050) would account for less than 3% of total water consumption for agriculture, industry, and municipalities. However, it is expected that about 40% of the production capacity for low-carbon electrolytic H_2 will be located in regions facing water scarcity [21].

Several studies have analyzed the WC and WSF of H_2 production systems (**Error! Reference source not found.**). However, since different methods and indicators were used, the results are not directly comparable.

Table 5. WC and WSF of H_2 production.

Route	Observations	Method	WF l water/kg H_2	WSF m³ water/kg H_2	Reference
SMR	US	LCA	15.8	-	[111]
	US	LCA	11.7	-	[112]
	-	AWARE	5.77	247.5	[49]
	-	WFN	52.4	-	[54]
	BR	LCA	257	-	[113]
CG	US	LCA	20.8	-	[111]
	-	AWARE	13.1	570.2	[49]
	US	LCA	28	-	[96]
	-	WFN	80	-	[54]
	CN	LCA	127.2	-	[35]
SREtOH	Maize ethanol	AWARE	2.24	91.61	[49]
	Wheat ethanol		3.87	149.4	[49]
	Brazil Sugarcane ethanol	LCA	9,600	-	[113]
BG	Waste corn crop	AWARE	4.94	212.4	[49]
	US	LCA	532		[96]
	-	WFN	7,467		[54]
BP	CN Wheat straw biomass	LCA	9,332.40	-	[35]
EL	PV	WFN	29	-	[54]
	Wind	WFN	9.2	-	[54]
	Nuclear	WFN	105	-	[54]
	PV/PEM US	LCA	15.5	-	[111]
	Wind/PEM US	LCA	15.5	-	[111]
	Grid not specified/PEM	AWARE	223.4	9,604.30	[49]
	Grid not specified /SOEC	AWARE	146.8	6,312.30	[49]
	Wind/SOEC	AWARE	9	379.3	[49]
	Wind/PEM	AWARE	16.40	629.8	[49]
	US Grid/PEM	LCA	280	-	[96]
	US PV/PEM	LCA	40	-	[96]
	US Wind/PEM	LCA	26	-	[96]
	US Grid/PEM	LCA	220	-	[96]
	US PV/SOEC	LCA	26	-	[96]
	US Wind/SOEC	LCA	25	-	[96]

Route	Observations	Method	WF l water/kg H_2	WSF m³ water/kg H_2	Reference
	Australia Grid/PEM	AWARE	200	3.0	[46]
	Australia PV/PEM	AWARE	40	1.0	[46]
	Australia Wind/PEM	AWARE	20	0.4	[46]
	CN PV/AEL	AWARE	66.6	915	[34]
	CN Wind/AEL	AWARE	36.4	1,700	[34]
	Wind/AEL US	LCA	30.2	-	[112]
	PV/AEL US	LCA	30.2	-	[112]

* Not specified.

As mentioned earlier, a fair comparison of WC across different methods can only be made if the results are standardized for alignment. However, all H_2 production methods require water, either directly or for cooling purposes [36]. For processes that rely on biomass for energy, most of the water use occurs during the growth or production of biomass [35,54,96]. The electrolysis method uses water directly to split the water molecules into H_2 and also for cooling. The source of electricity powering the electrolyzer has a significant impact on the water use for this method. Processes using PV and wind energy consume less water compared to those using grid electricity [46,49,96]. However, for PV and wind systems, most of the water is used in manufacturing of the equipment.

Using a WSF index for Australia, [46] found a water stress footprint (WSF) of 3.0, 1.0, and 0.4 m^3_{eq}/kg H_2 for electrolysis powered by the Australian grid, PV, and wind systems, respectively. WC during the life cycle of PV and wind systems is mainly attributed to equipment production. [54] highlighted that green H_2 from PV and wind energy results in a lower water footprint compared to coal gasification or natural gas reforming.

Biomass crop cultivation can result in higher WC compared to traditional methods like SMR [113]. For instance, sugarcane production for ethanol steam reforming leads to significant WC due to the water required for crop cultivation. Biomass crops need water for growth, which results in a high WC for hydrogen production via biomass gasification [54]. The researchers included the examination of contaminated water at various phases in the process of H_2 production.

[49] quantified the WSF using the AWARE indicator, which is distinct from the many environmental indicators assessed by the ReCiPe 2016 methodology. They conducted a comprehensive cradle-to-grave LCA of 9 hydrogen production routes. In terms of WC, they found that the WSF followed the same pattern as the WC indicator from ReCiPe, showing that technologies with a high WSF can significantly affect WC and other environmental indicators. They concluded that water scarcity is strongly influenced by the electricity source used in the studied routes, emphasizing the importance of combining technologies for both fuel and electricity production when assessing the water scarcity index. Another key trade-off they discovered was the correlation between WSF and global warming potential (GWP): routes with a high WSF impact generally tended to have a lower GWP.

[96] conducted an LCA of 11 hydrogen production pathways, estimating that WC ranged from 7–55 kg H_2O/kg H_2 for fossil resource-based routes, and from 530–3,400 kg H_2O/kg H_2 for biomass-based routes. They concluded that simultaneously reducing both GWP and WC is a significant challenge. Their analysis considered only surface and groundwater consumption, excluding the green (or rain) water used in biomass cultivation routes. It's important to note that although the cooling system operates as a closed loop, make-up water is still necessary to compensate for losses, such as blowdown losses and evaporation from cooling towers. Thus, the make-up water flow aligns with the calculated water consumption. They pointed out that biomass-based routes face a clear trade-off between reducing GWP and the WC needed for biomass cultivation.

In EL processes, the electricity source is crucial for accurately estimating both GWP and WC. [54] estimated the WF of EL powered by renewable energy compared to L resources, using the Water Footprint Network [106]. They found that routes powered by wind energy and PV systems had the lowest WF, while those using natural gas and coal had much higher WF due to significant blue water

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consumption associated with fossil fuel production. For biomass-based routes, the WF could rise as high as 5000 m³ H_2O/kg H_2 due to the inclusion of green water. They comprehensively evaluated the blue and grey water used for generating the primary energy resource, as well as water needed for process and operational uses (including feedstock and cooling water). Their findings showed that, while the WF across different routes can vary significantly, those using renewable resources (wind, PV) consistently demonstrated a lower WF compared to hydrogen produced from SMR and CGR, even when carbon capture and storage were applied.

[35] investigated the WF associated with hydrogen production from biomass and coal. They found that the WC for the wheat straw-based route reached 9,400 L H_2O/kg H_2 over its life cycle, which is in stark contrast to the fossil fuel route, which consumes only 130 L H_2O/kg H_2. They highlighted that water use for biomass cultivation accounts for around 99% of the total WC, whereas only 4.15% comes from coal production. The authors considered both green and blue water essential for the agricultural phase of biomass, along with the indirect WC from fertilizers, electricity, and fuels. They emphasized that improving fertilizer application efficiency and soil fertility could significantly reduce WC during the agricultural phase. In coal-based hydrogen production, WC is mainly driven by electricity use, which accounts for more than 50% of the total indirect water consumption.

[111] estimated the WC over the life cycle of seven hydrogen production routes. They found that renewable resource-based routes, such as electrolysis powered by wind and solar energy, consume significantly less water than conventional routes like CG and SMR.

Water use for electrolytic H_2 production is relatively small on a global scale [52]. However, [52] argue that assessing the availability and demand for water in electrolysis processes is important, as these factors vary by region. This means that certain areas may not have the capacity to produce sustainable H_2. They suggest that water usage in electrolysis systems powered by wind and PV technologies could be reduced by treating and recycling wastewater produced during the manufacturing of system components. Effective water management strategies and the selection of materials that r*eq*uire minimal water consumption could also help.

From a hydrological balance perspective, it's important to note that electrolytic H_2 should not be considered a major consumer of water resources. This is because green H_2, when oxidized (either through combustion or in a fuel cell), releases an amount of water *eq*ual to what was used in the electrolysis process. As a result, the water generated as a by-product of the H_2 reaction is released into the atmosphere as water vapor or condensate, which can then be recovered in liquid form. This creates a balance, leading to a neutral impact on water use and availability in green H_2 production [114].

Given that around 70% of planned electrolytic H_2 production for 2030 will be located within 100 km of the coast, this presents an ideal opportunity to use seawater through desalination. The cost of desalination plants is relatively low, accounting for less than 2% of H_2 production costs, with seawater reverse osmosis r*eq*uiring around 3–6 kWh/m³ of water [21,54].

The energy sector and water availability are closely linked, making it important to consider this relationship when evaluating energy production, as both water quality and quantity can significantly affect energy supply [36]. As such, the water issue has become a key consideration in planning H_2 plants, and it's essential to include water availability indicators in H_2 LCA studies.

4.3. Energy Performance

Multiple studies (**Error! Reference source not found.**) have highlighted the substantial use of fossil resources in renewable H_2 systems throughout their lifecycle, indicating that even green H_2 production relies on fossil fuels to some extent [82,97,101,115,116]. As a result, assessing the efficiency of the energy system has become crucial, with the goal of reducing dependence on fossil fuels while improving energy delivery.

Table 6. Cumulative Energy Demand and Energy Indicator (EI) of H_2 production.

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Technology	CED (MJ/kg H_2)	EI	References
SMR	216	0.6*	[60]
	-	2.44	[63]
		5.5	[97]
	-	0.7	[39]
CG	300	0.4*	[60]
	162	0.7*	[100]
	100	1.2	[100]
	-	1.47	[63]
	450	0.25*	[117]
	350	0.3*	[117]
SRBiogas	164	0.7*	[116]
	60	2.0*	[60]
EL PV	-	4.6	[16]
	-	7.22	[63]
	62	2.0*	[59]
		13.4	[97]
EL Wind	-	13.2	[38]
	30	4.0*	[60]
	34	4.1*	[57]
EL Grid EU	341	0.4*	[59]
EL Grid (45% NG and 20% Hydro)	-	14.3	[97]

*Estimated by the authors based on LHV H_2 (EROI = LHV H_2/fossil energy consumption).

The main goal of an energy system is to convert energy efficiently, and one way to measure this efficiency is through the "Cumulative Energy Demand" (CED), which compares the energy produced to the energy consumed by the system. Energy systems face a twofold challenge: they must reduce GHG emissions while increasing energy output. This can be achieved by increasing renewable energy production sixfold by 2050, using the current 12% renewable energy as a baseline [3]. In this context, assessing the energy efficiency of hydrogen (H_2) systems is essential. Several studies have evaluated the efficiency of H_2 production systems using the LCA approach. See Table 5.

For example, a Net Energy Ratio (NER) of 0.66 was found for the hydrogen SMR system, meaning that for every 1.0 MJ of fossil energy used, 0.66 MJ of H_2 is produced [39]. A life cycle efficiency of -39.6% was calculated, which comes from using natural gas (a non-renewable resource), and given the fact that the system consumes more energy than it produces [39]. NER is calculated by comparing the energy contained in H_2 to the fossil energy used by the system [39].

[117] estimated primary fossil energy consumption for deep coal gasification, CG with CO_2 removal and SMR. They found that deep coal gasification had a life cycle fossil energy consumption of 350 MJ/kg H_2, while CG and SMR consumed 450 MJ/kg H_2 and 250 MJ/kg H_2, respectively. Their findings indicated that deep coal gasification can reduce both coal and oil consumption compared to the traditional coal gasification process.

[100] assessed fossil primary energy use in H_2 generation through underground coal gasification and compared it with the traditional CG method. The results showed that the underground method required 61.2% of the energy of the traditional method. Fossil primary energy consumption was reported as being 100 MJ/kg H_2 for the underground method and 162 MJ/kg H_2 for CG.

[97] estimated the EROI for EL using PV and grid energy (56% fossil and 44% renewable), as well as for SMR. The EROI values, based on the higher heating value (HHV), were 13.4, 14.3, and 5.48 for PV electrolysis, grid energy, and the SMR process, respectively. According to the authors, the higher EROI for AEL compared to the SMR process is due to the high EROI of the fuels in the energy mix used for the AEL system.

A CED of 163.7 MJ/kg H_2 was found for H_2 production from biogas derived from the anaerobic digestion of cattle manure and corn silage (with digestate applied to the field). This value is lower

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than the estimated 185.1 MJ for the SMR route, but higher than the CED (8.8 - 54.5 MJ/kg H_2) reported for electrolysis systems [116]. The authors concluded that, from an energy perspective, the system is unsustainable due to the high natural gas consumption required to achieve the necessary temperature for the reforming process (with 20% of the total energy coming from biomethane and 80% from natural gas). They identified a significant energy deficit in the renovation facility, arising from the use of natural gas to reach the extreme temperatures essential for the steam reforming process.

A NER of 13.2 was estimated for AEL based on a wind power system [38]. This value reflects the renewable nature of the wind energy generation system. The total energy required by the system is approximately 9.1 MJ/kg H_2, with 72.6% attributed to the production of wind turbines, 31.6% to the gaseous hydrogen storage system, and 4.8% to the operation of the electrolysis facility.

A high fossil energy consumption was examined by [57] which estimated a total CED (including construction, operation, and decommissioning) of 34.3 MJ/kg H_2, with 82% of the CED attributed to fossil energy use, for wind energy-based electrolysis operation. Kinect energy of wind was not included in CED estimation.

[16] reported an EROI of 4.6 for H_2 produced through AEL powered by PV energy. They found that the PV modules have the largest impact, followed by the balance of system components (frames, hardware). The desalination facility has a minimal contribution in terms of built-in and consumed energy. It is important to note that the system's lifespan is a key factor for this indicator—plants with shorter lifespans tend to yield a lower EROI. The cited paper considered the solar energy for CED estimation.

[60] evaluated fossil energy consumption across various H_2 pathways throughout their life cycle. Their calculations revealed a CED, based on LHV, of 216 MJ/kg H_2 (0.6 EROI), 300 (0.4), 60 (2), and 30 (4) for the SMR, CG, AEL PV, and AEL Wind pathways, respectively.

[59] evaluated fossil resource consumption through CED for electrolytic routes powered by PV, wind, and grid energy (with only 14% of the energy being renewable). For wind power, a CED of 28 MJ/kg H_2 (2.5 MJ fossil/Nm^3 H_2) was reported; 62 MJ/kg H_2 (5.5 MJ fossil/Nm^3 H_2) for PV; and 341 MJ/kg H_2 (30 MJ fossil/Nm^3 H_2) for grid-based electrolysis. These figures clearly show that the grid-based system, with its high reliance on fossil energy, constitutes the most detrimental scenario due to the significant presence of non-renewable resources in the electricity mix.

[16] assessed the EROI associated with the generation of electrolytic H_2 using PV energy, referencing the higher heating value (HHV) of H_2. Their findings indicated that the longevity of the PV panels and the overall system lifespan significantly influence the EROI composition.

[63] conducted a comprehensive study that evaluated energy systems used for H_2 production to determine whether the energy output generated by the system exceeds the energy input required for its construction, operation, and maintenance. In general, they found that electrolysis-based methods (particularly those combining PV energy with a 100% grid energy source) exhibit a superior EROI compared to SMR technology. This is largely due to the higher EROI values of renewable energy resources compared to natural gas, a key input in the hydrogen production process via SMR. It is important to note that solar energy was included for EROI estimation.

5. Conclusions

Research highlights the urgent need to address the climate crisis and its harmful effects on the economy, environment, and society. The increasing demand for energy, potential shortages of fossil fuels, and environmental issues have driven initiatives to create sustainable energy solutions. In this scenario, H_2 is recognized as a key energy carrier and is emerging as a strong alternative among new energy options. Nevertheless, the current proportion of renewable H_2 production is still very low. To guarantee that H_2 production is environmentally sustainable throughout its supply chain, it is essential to evaluate the entire value chain, considering technical, economic, environmental, and social aspects. This thorough assessment will assist in pinpointing significant opportunities and challenges for all parties involved in the H_2 production process.

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H_2 is regarded as a crucial element in moving towards a sustainable energy future. Its benefits cover a variety of resources and raw materials that can be transformed into H_2, along with the application of proven and familiar technologies. The characteristics of H_2 and its diverse applications emphasize its vital position in reducing GHG, WC and improve energy efficiency of the energy sector. In this sense, choosing the right production method and energy sources is essential to guarantee the sustainability of H_2. This process requires analyzing a broad array of technical, environmental, economic, marketing, and theoretical considerations.

This study focused on three key aspects for evaluating the environmental performance of H_2 production systems as an energy carrier. Overall, it was found that renewable-based routes can help reduce GHG emissions, improve energy performance, and decrease WC compared to SMR and CGR routes. However, WC remains a significant challenge for renewable initiatives, particularly in regions where H_2 plants face droughts and water scarcity. A potential solution for these arid areas could be using seawater or reclaimed water to power water treatment facilities.

From an environmental approach, this research points out that renewable H_2 does have some negative environmental effects when evaluated throughout its life cycle. H_2 production through electrolysis, using renewable energy sources like wind and solar power, is considered a feasible option for the energy transition. Furthermore, research examining the use of grid electricity for electrolyzers suggests that GHG emissions and water usage could exceed those of traditional methods like steam methane reforming and coal gasification, depending on the grid's electricity based on hydraulic energy potential.

It's essential to understand that biomass-based methods can gain advantages from an energy source that absorbs carbon throughout its entire life cycle. Consequently, H_2 produced from biomass can result in neutral or even negative carbon emissions. First-generation ethanol from biomass has a lower GWP compared to traditional techniques. Nevertheless, the use of fossil fuels and nitrogen fertilizers in creating biomass and ethanol greatly adds to GHG emissions, water use for irrigation process, and energy consumption.

In contrast, routes based on waste may lead to negative GHG emissions since they are assigned to the biomass producer. However, because methane emissions are 28 times more potent than CO_2, any methane leaks during the upgrading of biogas can still influence the total emissions of SRBiogas.

The energy indicator showed that SMR and CG routes, which depend on fossil resources, yield an EROI less than 1, signifying high energy usage. Nonetheless, the different uses of H_2 may still warrant the ongoing application of these methods, particularly if technologies like CCS are adopted.

Overall, it was determined that renewable-based H_2 routes can aid in lowering GHG emissions, enhancing energy performance, and reducing water use compared to steam SMR and CG. However, water consumption continues to be a major hurdle for renewable projects, especially in areas where H_2 plants encounter drought and water shortages. A possible answer for these dry regions could involve utilizing seawater or recycled water to operate water treatment facilities.

Future studies could explore the interdependence of these three environmental indicators. Regions with abundant renewable energy may still face challenges related to water availability. It's crucial to assess both water and renewable energy sources, as these elements are interconnected and essential to the H_2 framework. Water quality can also increase energy consumption, as water treatment is necessary to achieve a high level of purity. In this context, all parameters considered during the construction and installation of hydrogen facilities should account for GHG emissions, as well as water and energy consumption during the operation of H_2 systems.

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Abbreviations

AD Anaerobic Digestion
AEL Alkaline Electrolysis
AWARE Available Water Remaining
BG Biomass Gasification Reforming
BP Biomass Pyrolysis
BR Brazil
CCS Carbon Capture and Storage
CED Cumulative Energy Demand
CG Coal Gasification
CN China
EL Electrolysis
EI Energy Indicator
EROI Energy Return on Investment
EtOH Ethanol
EU European
FC Fuel Cells
GHG Greenhouse gas
GWP Global Warming Potential
HHV High Heat Value
LCA Life Cycle Assessment
LFG Landfill Gas
LHV Low Heat Value
NER Net Energy Ratio
PEM Proton-Exchange Membrane
PV Photovoltaic
SMR Steam Methane Reforming
SOEC Solid Oxide Electrolyser Cell
SRBiogas Steam Reforming of Biomethane
SREtOH Steam Reforming of Ethanol
US United States
WC Water Consumption
WF Water Footprint
WFN Water Footprint Network
WGS Water Gas Shift
WSF Water Scarcity Footprint

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