applied sciences

MDPI

Article

A Comparative Science-Based Viability Assessment Among Current and Emerging Hydrogen Production Technologies

Yehia F. Khalil

Chemical & Environmental Engineering Department, School of Engineering & Applied Science (SEAS), Yale University, New Haven, CT 06520, USA; yehia.khalil@yale.edu

Featured Application: Advancing environmental sustainability and the circular economy through the production of clean and green hydrogen as a promising energy carrier of the future.

Abstract: This research undertakes a comparative analysis of current and emerging hydrogen (H_2) production technologies, evaluating them based on quantitative and qualitative decision criteria. The quantitative criteria include cost of H_2 production (USD/kg H_2), energy consumption (MJ/kg H_2), global warming potential (kg CO_2-eq/kg H_2), and technology energy efficiency (%). The qualitative criteria encompass technology readiness level (TRL) and availability of supply chain materials (classified as low, medium, or high). To achieve these objectives, an extensive literature review has been conducted, systematically assessing the selected H_2 production technologies against the aforementioned criteria. The insights synthesized from the literature provide a foundation for an informed, science-based evaluation of the potentials and techno-economic challenges that these technologies face in achieving the 1-1-1 goal set by the U.S. Department of Energy (DOE) in 2021. This target aims for a H_2 production cost of USD 1/kg H_2 within one decade (by 2031), including costs associated with production, delivery, and dispensing at H_2 fueling stations (HRSs). Also, the DOE established an interim goal of USD 2/kg H_2 by 2026. This research concludes that among the examined H_2 production technologies, water electrolysis and biomass waste valorization emerge as the most promising near-term solutions to meet the DOE's goal.

Keywords: hydrogen production; clean hydrogen; sustainable hydrogen; waste valorization; bio-based waste upcycling; DOE 1-1-1 goal; clean hydrogen; circular economy

check for updates

Academic Editor: Andrea Frazzica

Received: 25 November 2024
Revised: 14 December 2024
Accepted: 26 December 2024
Published: 7 January 2025

Citation: Khalil, Y.F. A Comparative Science-Based Viability Assessment Among Current and Emerging Hydrogen Production Technologies. *Appl. Sci.* **2025**, *15*, 497. https://doi.org/10.3390/app15020497

Copyright: © 2025 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Hydrogen is a major contributor to the global effort to achieve the net-positive environmental goal that goes beyond the net-zero goal that focuses only on offsetting CO_2 emissions. The net-positive goal reenforces the overarching intent of circular economy bio-based waste valorization for H_2 production as one of the key technology pathways for sustainable H_2 production [1]. However, the energy transition from the current fossil-based technologies to sustainable H_2 production is a physical transformation in its early stages, and there are many technical, economic, and supply-chain logistics challenges that need to be sorted before at-scale adoption of H_2-based technologies can be realized [2–4]. Accordingly, the present research aims to improve the current state of knowledge about these challenges by conducting a comparative science-based and data-driven viability assessment among current and emerging hydrogen production technologies. The assessment evaluates the selected technologies against specific quantitative and qualitative decision

criteria. Based on the insights generated from the comparative assessment, conclusions are made about the most promising H_2 production technologies that could meet the U.S. DOE 1-1-1 clean energy goal described in its 2021 "Hydrogen Shot" conference. In addition, techno-economic challenges of the selected H_2 production pathways are highlighted.

The academic merit of this contribution lies in advancing our understanding of the present and future cost competitiveness of key hydrogen production technologies. Additionally, it elucidates the anticipated role of hydrogen as a promising energy carrier and a crucial enabler in achieving net-zero emissions.

The remainder of this manuscript is organized as follows: Section 2 outlines the research methodology employed, Section 3 presents the results, Section 4 discusses the findings, and Section 5 summarizes the conclusions of the comparative assessment. Additionally, Appendix A provides the list of acronyms used in this manuscript.

2. Research Method

To achieve the objectives of this research, extensive literature reviews [*using the following research query: Hydrogen production technologies (All Fields) OR Green hydrogen production (All Fields) AND Hydrogen production cost (All Fields) OR Hydrogen carbon footprint (All Fields) AND Technoeconomic Analysis OR Environmental Impact Assessment AND 2000–2024 (Publication Years)*] were conducted to assemble the relevant quantitative and qualitative data. Section 2.1 highlights the key findings of the literature reviews. The collated information was mapped to specific decision criteria that support the comparative assessment. In addition, the steam-methane reforming (SMR) technology, with and without carbon capture and storage (CCS), was used as the benchmark H_2 production technology.

2.1. Literature Reviews and Key Findings

As an introduction to this subsection, it is worth noting that by 2050, the global energy demand is anticipated to be around 30 terawatts (TW), which is double that of 2011 [5]. Hydrogen is specifically being considered as an alternative fuel in the transportation sector to power fuel cell electric vehicles [6] and for electrifying the commercial aviation (viz., hybrid-electric and all-electric aircraft). The U.S. DOE projected that clean H_2 could be produced for USD 2/kg H_2 by 2025 (*H_2New*, 2021), and in its 2021 "Hydrogen Shot" conference, the DOE drafted its long-term goal to reduce the cost of clean H_2 production to USD 1 per kg H_2 in one decade.

Herein, a literature review of 75 published sources was conducted on various H_2 production technologies, specifically the most prominent conventional technologies and the most promising greener technologies. With a couple exceptions, only papers and reports published in the last decade (2013–2024) were consulted, with an effort to rely on publications from the past 5 years whenever possible, in order to ensure the comparative analysis contained the most updated information. From these sources, both quantitative and qualitative data were extracted to support the comparative assessment of H_2 production technologies.

The conventional methods of H_2 production provide either "gray" or "blue" hydrogen. Steam-methane reforming (SMR) is widely acknowledged as the most well-established method [3], and it is often used as a point of reference to analyze and compare the performance and feasibility of non-conventional methods. Because SMR is a very mature technology, it is thoroughly studied and produces low-cost hydrogen, but it also has low potential for technical improvements that will improve efficiency or performance [7,8]. Several papers studying the conventional methods of producing blue H_2 discuss how CCS reduces emissions significantly but also increases production cost and decreases energy efficiency [8–12].

Waste valorization was evaluated as a more sustainable H_2 production technology. Utilizing waste streams eliminates both the polluting effects of waste build-up and the need for energy-intensive and high-emitting waste incineration. Biomass is a broad term and can be prepared as a feedstock from organic sources, such as grass, wood, agricultural products, animal waste, food scraps, municipal solid waste, and algae, and it can be valorized by methods such as gasification, pyrolysis, supercritical water gasification, and dark fermentation [11,13]. One study noted that food waste is specifically suitable for H_2 production for a number of reasons, such as its carbohydrate richness, wide availability, and low cost [14]. Another study explained that converting food waste to H_2 via dark fermentation is energetically advantageous because it can be achieved under ambient temperature and pressure with low chemical energy requirements, but it must be performed onsite to be feasible due to the high water content and biodegradability of food waste [15]. Even more so than food waste fermentation, gasification of biomass is a highly studied process due to its convenient utilization of diverse waste streams and production of clean biohydrogen. Biomass gasification is currently faced with low conversion and thermal efficiencies, but they can be improved with the optimization of the process temperature, the catalyst used, and the biomass content [16].

Glycerol is another promising waste stream to utilize for H_2 generation, as it is produced abundantly as a byproduct of the transesterification of biomass to biodiesel. By strategically incorporating H_2 production plants into existing biodiesel production plants, glycerol could even become a free material stream. A simulation-based life cycle assessment (LCA) compared the environmental and health impacts of several glycerol-based hydrogen production technologies—ATR, APR, and SCWR—versus those of the conventional method of SMR [17,18]. A techno-economic analysis (TEA) compared the cost of hydrogen produced from APR and steam reforming of glycerol, revealing that APR is slightly less expensive but still not competitive with SMR [18]. Another report on pathways to producing H_2 from biomass provided H_2 production costs and TRLs of SCWR, APR, and SR of glycerol [16].

Water electrolysis is widely considered a promising method of sustainably producing H_2 due to fairly negligent carbon emissions [19–21]. A number of sources compared powering electrolyzers with the local electricity grid mix versus renewables. Because the grid mix varies so widely, a wide range of H_2 cost values were reported, but in general, it is agreed that costs could be reduced by strategically utilizing renewable power sources rather than relying on the grid mix [22–26]. Research has recently explored utilizing wind power and solar PV power to produce green H_2 by electrolysis [20]. While discussed to a lesser extent, other renewables like hydropower and nuclear power are also contenders for more sustainable electrolysis power sources [27–29]. While hydropower is a well-established renewable electricity source, one report noted that it will be overtaken by solar PV power due to its lower levelized cost of electricity (LCOE) and higher energy capacity [30]. Nuclear energy is also a firmly established renewable energy source, but still, setbacks such as social apprehension keep it from becoming the focus of green H_2 research [28]. Different renewable energy sources make more sense for different areas, depending on which natural resources are most abundant and consistent in a given region [25]. Therefore, cost and energy efficiency analyses [31] are further complicated with the additional variable of energy source.

The TRL of water electrolysis varies depending on the technology and the energy source utilized. However, as explored in a variety of reports, electrolysis is a fairly well-developed technology, particularly AKE, PEM, and SOE—more so than AEM [9,16,22,32–35]. In addition to its nearly negligible global warming impact, its high TRL makes electrolysis an attractive green H_2 production technology. However, high H_2 production costs and high energy require-

ments are setbacks that are keeping electrolysis from replacing the conventional methods. One paper noted that despite its low GWP and high technological readiness, solar PV-powered electrolysis will only be able to take the forefront as a potential option for H_2 production when its energy efficiency is improved, which will also subsequently lower its high production costs [5,36].

Electrolyzers are oftentimes divided into two classes: low-temperature electrolyzers (LTEs) and high-temperature electrolyzers (HTEs). The U.S. DOE has invested R&D funding into these two types of electrolysis in order to promote the most durable, effective, and efficient system of green H_2 production. The characteristics of LTE, such as PEM, is that it is commercially available, but it is not durable, efficient, or affordable enough, while the characteristics of HTE, such as SOE, are that it is less mature but has potential for higher efficiency and a longer lifespan [37]. According to one paper, SOEs are advantageous because of their ability to co-electrolyze steam and carbon dioxide in a single step and, thus, eliminate the need for expensive and maintenance-intensive water–gas shift reactors [38]. SOEs operate at high temperatures, meaning that they require greater energy input, but also that they can utilize low-cost active metals rather than expensive noble metals [38]. The Global Hydrogen Review claims that AEME electrolysis combines the benefits of PEME and AKE, since it does not require expensive platinum utilized by PEME nor the corrosive electrolytes used in AKE, but it is a less mature technology [22].

Emerging technologies for clean H_2 production are also evaluated in this research. Because of the novelty of these technologies, they will not have very high TRLs, with most still being in the research and early development stages [16,22,39]. Several studies of thermochemical decomposition via both solar and nuclear power demonstrate that these technologies are far from being commercially mature [9,34]. However, even though the technologies are immature, their TEA reveals that several of the emerging technologies, like bio-photolysis, biomethane pyrolysis, and ESMR, are potentially able to produce H_2 for competitive prices [11,28,40,41]. ESMR is especially attractive when considered as an easily implemented technology to help aid in the transition from gray to cleaner H_2. It utilizes the same natural gas feedstock but incorporates renewable electricity to lower emissions, resulting in a system that is more sustainable than the conventional methods and more economically and technically feasible than the other emerging technologies [41]. Among the emerging H_2 production technologies is the so-called white color, of natural origin; however, due to its rare occurrence in the Earth's rock, there is no commercial interest at this point in time [42]. This geologic H_2 (aka., white, gold, or natural H_2) is found beneath the Earth's surface and is postulated to be produced by high-temperature reactions between water and iron-rich minerals.

Most of the other emerging technologies still require more technological development to compete with standard hydrogen prices [24,43]. Strategic plant optimization can help lower production costs. For example, H_2 costs from ammonia thermal decomposition via fixed-bed reactors and PSA membranes are expected to decrease if plants are built to be larger and centralized, which would lead to economies of scale and less expensive ammonia costs [44,45]. One article discussed how the fluctuations in H_2 production costs via thermochemical processes are mainly due to variable electricity prices, but the utilization of reliable green electricity from renewable sources like solar PV and wind turbines can greatly reduce production costs [11]. The lack of comprehensive studies of promising emerging technology, like biomethane pyrolysis and SMC, has been called out and discussed. These turquoise H_2 production technologies [46] are preferable to SMR due to their lower emissions and energy requirements, but the information on them is still sparse and the data are often conflicting and inconsistent [47]. There tends to be a disproportionate focus on green H_2 production technologies, particularly water electrolysis,

despite other promising candidates. Further analysis of these emerging technologies will open up a slew of diverse avenues for clean hydrogen production.

Another reason to invest more resources in a wider range of promising clean H_2 production technologies is their potential to be combined and integrated into hybrid systems. This integration process can strategically lower H_2 production cost, decrease energy requirements and carbon emissions, increase efficiency, and utilize waste to make useful products. A well-established example of technology integration is the addition of CCS to gray H_2 production technology, a method that succeeds in reducing emissions but also tends to increase production cost and energy consumption while reducing process efficiency [7,8,10,17,47]. More technically advanced and economically and energetically efficient combinations can be devised. One paper performed an energy analysis of an integrated system with SMC and SOE for the production of turquoise H_2 and clean methanol [38]. Another paper examined hybrid wind and solar PV energy systems, finding that the combination of power sources meets the load demand and minimizes emissions and system costs [48]. A study reported that the energy output of FWF can be increased by 7–9 times with a 2-stage fermentation process that results in H_2 produced via dark fermentation and methane produced via anaerobic digestion [15]. This methane could then be utilized as renewable natural gas to be injected into the existing natural grid infrastructure.

The major challenges for H_2 production include high costs, infrastructure development, carbon sequestration, and efficiency issues. Key research priorities should focus on improving technological efficiency, developing cost-effective distributed generation systems, enhancing CCS, and exploring novel catalytic processes. The potential prospects are substantial, with H_2 poised to power vehicles, balance energy grids, decarbonize industries, and meet a significant portion of global energy needs by 2050, thereby aiding in GHG reduction.

2.2. Quantitative and Qualitative Decision Criteria

The following set of decision criteria were used as the framework by which the selected H_2 production technologies were compared, as discussed in the results in Section 3.

2.2.1. Quantitative Decision Criteria

- Cost of hydrogen production (USD/kg H_2)

This criterion represents the cost to produce one kilogram of H_2 from the given technology. It is an indicator of the economic viability of each technology. To account for the time–value of money, H_2 production costs that are collected from the published literature are adjusted to the 2024 USD using the Chemical Engineering Plant Cost Index, or CEPCI [11]. To adjust H_2 product cost from a previous year to 2024, Equation (1) is applied:

$$H_2\ \text{Cost}_{2024} = H_2\ \text{Cost}_{\text{YOP}} \left(\frac{\text{CEPCI}_{2024}}{\text{CEPCI}_{\text{YOP}}} \right) \quad (1)$$

where the subscript YOP signifies the year of publication of the H_2 production cost.

- Energy consumption (MJ/kg H_2)

This quantitative criterion represents the amount of energy (MJ) required to produce one kilogram of H_2 from the given technology.

- Global warming impact (Kg CO_2-eq/kg H_2)

This quantitative criterion represents the global warming potential (GWP) of the H_2 production technology and shows how many kilograms of CO_2 are emitted per kilogram of H_2 produced.

- Technology energy efficiency

The energy efficiency of a technology is defined as the ratio of the lower heating value (LHV) of produced H_2 to total energy supplied to the H_2 production process. This efficiency is expressed as a percentage value. Some publications reported this process energy efficiency in terms of high heating value (HHV), and in order to keep comparisons between the production technologies consistent, these values are converted herein to be in terms of LHV by multiplying the reported value by the ratio of H_2 LHV to HHV, as shown in Equation (2).

$$\frac{(\text{LHV})_{\text{H2}}}{(\text{HHV})_{\text{H2}}} = \frac{120\ \text{MJ/kg}}{142\ \text{MJ/kg}} = 0.8451 \quad (2)$$

In addition to creating consistency in this comparative assessment, evaluating the technology energy efficiency in terms of LHV rather than HHV is more conservative, as it gives the lower bound of the efficiency and, therefore, does not overestimate this efficiency value.

2.2.2. Qualitative Decision Criteria

- Technology readiness level (TRL)

Technology readiness level is a qualitative criterion that reflects the maturity of a given technology on a nine-point scale (1–9). A higher number indicates greater maturity and readiness for commercialization. The following color-coded chart depicts the TRL scale as technologies advance from research to development (R&D) to deployment (Figure 1).



Figure 1. Technology readiness levels (TRL).

- Supply chain material availability

Supply chain material availability is reflective of the availability and ease of accessibility of raw materials, energy, and equipment for the given H_2 production technology. This criterion assesses the technologies on a three-point scale: low, medium, and high. Due to the qualitative and broad nature of this criterion, a simple three-point scale prevents the need for tedious analysis and difficult rankings. However, in order to avoid oversimplification, a comment section is provided to provide clarity on ratings if deemed necessary.

2.3. Hydrogen Production Technologies Being Evaluated

The production technologies being evaluated are as follows:

- Conventional via steam-methane reforming (SMR)

The conventional method for H_2 production is steam-methane reforming (SMR), which accounts for around 50% of H_2 production [5]. This method converts natural gas (primarily methane) and steam to H_2 and CO_2, a byproduct that contributes to global warming. The second conventional method of producing gray hydrogen is coal gasification, but it is not included in this research because it is less common than SMR. Autothermal reforming (ATR) of natural gas is yet another conventional technology for H_2 production. ATR is similar to SMR in that it produces H_2 and CO_2, but it has the advantage of producing more exothermic reactions from the partial oxidation that occurs [8]. The H_2 produced from SMR, coal gasification, and ATR is denoted as "gray" H_2. The integration of carbon capture and storage (CCS) with any of these conventional technologies produces the so-called "blue" H_2. While integration with CCS results in CO_2 emissions reduction, both production cost and energy consumption are shown to increase compared to the case without CCS.

- Hydrogen production by waste valorization

The utilization of various waste streams for hydrogen production is examined in food waste fermentation (FWF), waste plastics gasification (wPG), and biomass gasification with and without CCS. The valorization of biodegradable food waste by dark fermentation can help alleviate the waste management crisis and reduce the production of carbon emissions and toxic pollutants in overcrowded landfills, while also producing more eco-friendly H_2 [49–51]. Data-driven interpretation, comparison, and optimization of H_2 production from supercritical water gasification of biomass has been carried out. Gasification is the high-temperature partial oxidation of waste feedstocks, like plastics or biomass, to produces syngas, which is a mixture of CO and H_2. Syngas can be further converted to make other useful chemicals using the Fischer–Tropsch (FT) process or combusted to generate steam for electricity generation [52].

- Waste byproduct reforming (glycerol from biodiesel production)

A promising waste stream to utilize for H_2 production is the glycerol byproduct that results from biodiesel production via the transesterification of agricultural crops [17]. The technologies studied that convert glycerol into hydrogen are supercritical water reforming (SCWR), aqueous-phase reforming (APR), autothermal reforming, and steam reforming (SR).

- Greener hydrogen production via water electrolysis

The water electrolysis technologies considered herein are alkaline electrolyzer (AKE), proton exchange membrane electrolyzer (PEME), anion exchange membrane electrolyzer (AEME), and solid oxide electrolyzer (SOE) via solar photovoltaic (PV) power, wind power, hydropower, grid mix electricity, and nuclear power. Hydrogen produced via water electrolysis with renewable energy is called green H_2 and is characterized by its low global warming impact. Electrolysis powered by grid mix electricity does not produce green H_2, but it benefits from utilizing the current electricity grid. The US grid electricity mix is roughly as follows: 38% natural gas, 17% coal, 20% nuclear, 11% wind, 7% hydropower, 5% solar, and 2% other [53].

- Emerging hydrogen production technologies

Various emerging clean H_2 production technologies were evaluated in this comparative analysis. The high-temperature processes of biomethane pyrolysis and solar methane cracking (SMC) produce the so-called "turquoise" H_2 and carbon black. SMC utilizes concentrated solar energy to power the high-temperature process, resulting in even cleaner hydrogen [38]. Biophotolysis, electrified steam-methane reforming (ESMR), and ammonia (NH3) thermal decomposition via fixed-bed reactor and via PSA-membrane technology were also evaluated in this research. Biophotolysis utilizes sunlight energy to convert water to hydrogen through biological systems [40]. ESMR combines traditional SMR with renewable electricity. Both solar thermal-powered thermochemical decomposition of water and nuclear-powered thermochemical decomposition of water were researched. There are many variations in nuclear-powered thermochemical decomposition, but only four of the most promising cycles were included in this study. These are the three-step sulfur–iodine (S-I) cycle, the two-step hybrid sulfur (HyS) cycle, the four-step copper–chlorine (Cu-Cl) cycle, and the three-step magnesium–chlorine (Mg-Cl) cycle.

3. Results

The sources introduced in the literature review in Section 2.1 were examined to perform a comparative analysis among the H_2 production technologies for the decision criteria introduced in Section 2.2. The quantitative and qualitative results of the comparative analysis are organized in Tables 1–9. As shown below, Tables 1–3 give the cost of H_2, energy consumption, and global warming impact of the technologies. Tables 4–6 provide the energy efficiencies in terms of the $(LHV)_{H_2}$ of the technologies. Tables 7–9 show the TRL and supply chain material availability of the technologies.

It should be noted that for most decision criteria, the results are recorded as a range of values. This is because multiple sources were cross-referenced in order to provide the most accurate data. For each technology, there are a variety of conditions, such as plant size and local electricity cost, that can vary widely. Therefore, a technology's performance for a given criterion cannot be given in a single value without being very specific about plant specifications (viz., technology type, production capacity, etc.). Providing a range of values from multiple sources is less limiting to the overarching objective of the comparative assessment. It is important to note that for waste plastic gasification [54] with CCS and biomass gasification with CCS (Table 1), as well as biomethane pyrolysis (Table 3), certain papers reported their global warming impact as a negative value. These scenarios imply that net carbon emissions are negative based on utilizing waste streams that would have emitted more carbon otherwise and also due to capturing the carbon emissions associated with gasification.

Table 1. Cost of H_2 (USD/kg H_2), energy consumption (MJ/kg H_2), and GWP (kg CO_2/kg H_2) of conventional production technologies and waste valorization technologies.

Hydrogen Production Technology	Cost of Hydrogen ($/kg H_2) (All in 2024 U.S. $)	Energy Consumption (MJ/kg H_2)	Global Warming Impact (kg CO_2/kg H_2)
• **Conventional H_2 production with natural gas**			
• Gray H_2 Production (SMR without carbon capture)	1.19–2.40 [8,19]	183.2 [18]	9.89–11.9 [18,48]
• Blue H_2 Production (SMR with carbon capture)	1.64–2.29 [8,12]	224.75–265.91 [8]	3.32–8.20 [8,48]
• Blue H_2 Production (ATR with carbon capture)	1.44–1.7 [8,9,12]	162.92 [8]	2–4 [8,9]
• **H_2 production by waste valorization (cleaner & sustainable)**			
• Waste plastics gasification (wPG)	2.23–3.41 [53,55]	20.8–25.3 [53]	12.8–15.6 [53], 8.46–5.94(CCS) [9]
• Food waste fermentation (FWF)	2.57–2.88 [9,17]	120–180 [56]	6.6–9.5 [57]
• Biomass gasification	1.72–4.1 [9,12]	115–180 [9,58]	1.9–18 [9]
• Biomass gasification w/CCS	3.7 [9]	180–240 [9]	−15–13 [9]
• Waste byproduct reforming (glycerol from biodiesel production):			
➢ Supercritical water reforming (SCWR) of glycerol	1.69–4.36 [17]	33.17 [18]	51.9 [18]
➢ Aqueous-phase reforming (APR) of glycerol	4.48–9.92 [17,19]	23.76 [18]	4.11 [18]
➢ Autothermal reforming (ATR) of glycerol	1.20 [8]	121.15 [18]	87.2 [18]
➢ Steam reforming (SR) of glycerol	2.03–2.63 [17], 4.86–9.67 [19]	40–60 [19]	4–18 [9]

The key insights to be drawn from the data reported in Table 1 are as follows:

(a) For conventional H_2 production from natural gas: (a.1) Due to the exothermic heat generation, the ATR technology has the lowest energy consumption (MJ/kg H_2); (a.2) without CCS, SMR technology has the highest CO_2 emissions (kg CO_2/kg H_2); and (a.3) as expected, integrating CCS with the conventional H_2 production technology increases the cost of H_2 production (USD/kg H_2). However, this cost increase is impacted

by other location-dependent externalities, such as cost of energy, cost of electricity, labor cost, etc.

(b) For H_2 production via waste valorization: (b.1) Biomass gasification with CCS technology has the highest energy consumption (MJ/kg H_2), (b.2) aqueous-phase reforming (APR) of glycerol has the lowest CO_2 emissions (kg CO_2/kg H_2), and (b.3) cost of H_2 production (USD/kg H_2) using ATR of glycerol seems to be the lowest compared to the other waste valorization technologies.

Table 2. Cost of H_2 (USD/kg H_2), energy consumption (MJ/kg H_2), and GWP (kg CO_2/kg H_2) of various water electrolysis technologies with different energy sources.

	Hydrogen Production Technology	Cost of Hydrogen ($/kg H_2) (All in 2024 U.S. $)	Energy Consumption (MJ/kg H_2)	Global Warming Impact (Kg CO_2/Kg H_2)
•	**Greener H_2 production via water electrolysis**			
•	Wind + Alkaline Electrolysers (AKE)	5.25–11.92 [29,33,59]	180–280 [60]	0.0325–4.45 [9,61]
•	Wind + Proton Exchange Membrane Electrolysers (PEME)	4–12.27 [26,29,62]	180–280 [60]	0.0325–3.69 [9,61]
•	Wind + Solix oxide Electrolysers (SOE)	6.72–7.77 [60,63]	165.6–184 [60,64]	0.0325 [61]
•	Wind + Anion Exchange Membrane (AEM) Electrolyzer	4.48–8.96 [23]	185–237 [60]	0.0325 [61]
•	Solar PV + Alkaline Electrolysers (AKE)	7.00–9.86 [33]	180–280 [60]	0.37–8.78 [9,61]
•	Solar PV + Proton Exchange Membrane Electrolysers (PEME)	10.13–16.51 [29,33]	184–280 [60]	0.37–7.79 [9,61]
•	Solar PV + Solix oxide Electrolysers (SOE)	3.36–8.96 [23]	165.6–174.2 [64]	0.37–2.3 [9,61]
•	Solar PV + Anion Exchange Membrane Electrolyzer (AEME)	3.36–8.96 [23]	185–237 [60]	0.37 [61]
•	Hydro Power + Electrolyzers (AKE, PEME, OXE, AEME)	2.70 [65]	180-216 [48]	0.72-1.75 [9,28]
•	Grid Mix + Electrolysers	4.00–8.81 [23–26,66]	180–216 [48]	1–30 [9,25]
•	Nuclear power + PEM	4.66–7.15 [29]	180–280 [60]	1.1 [9]
•	Nuclear power + SOE	3.79–5 [9,29]	165–180 [64]	0.67–2.1 [9]

The data summarized in Table 2 show that:

- PEME technology that uses solar PV electricity tends to have the highest cost of H_2 production (USD/kg H_2) compared to the other technologies.
- Water electrolyzers that use electricity from the grid mix tend to have the highest CO_2 emissions (kg CO_2/kg H_2).

For the data shown in Table 3 for the emerging H_2 production technologies, the following observations can be derived:

- Thermochemical decomposition integrated with solar thermal as well as ammonia thermal decomposition with PSA membrane separation seem to have the highest cost of H_2 production ($/kg H_2).
- Electrified steam-methane reforming (ESMR) has the lowest energy consumption (MJ/kg H_2).
- CO_2 emissions (kg CO_2/kg H_2) from the evaluated emerging H_2 production technologies seem to be low, with biomethane pyrolysis emerging as the most environmentally friendly, followed by thermochemical decomposition integrated with solar thermal technology.

Table 3. Cost of H_2 production (USD/kg H_2), energy consumption (MJ/kg H_2), and GWP (kg CO_2/kg H_2) of emerging clean H_2 technologies.

Hydrogen Production Technology	Cost of Hydrogen ($/kg H_2) (All in 2024 U.S. $)	Energy Consumption (MJ/kg H_2)	Global Warming Impact (Kg CO_2/Kg H_2)
• **Emerging H_2 production technologies**			
• Turquoise H_2 produced from biomethane pyrolysis	1.36–3.37 [12,17,29]	36–108 [48]	−10.4 to −4.09 [48]
• Electrified steam methane reforming (ESMR)	1.53 [42]	28.8 [23]	5–6 [23]
• Solar methane cracking (SMC)	2.9 [9]	180 [9]	1.9 [9]
• Solar thermal + thermochemical decomposition	7.74–12.22 [12,25,29]	110–150 [29]	0 [25]
• Nuclear + thermochemical decomposition			
• S-I	2.66–7.5 [44,67]	159–223 [67]	0.0–0.5 [25,44]
• HyS	2.39–8.34 [44,67]	116–128 [67]	0.0–0.48 [25,44]
• Cu-Cl	2.24–4.79 [44,64,67]	111 [67]	0.0–1 [25,64]
• Mg-Cl	4.11–5.15 [44,67]	169 [67]	0.0–1 [25,44]
• Bio-photolysis	1.42–7.27 [57]	110–160 [67]	7.5 [57]
• Ammonia thermal decomposition via fixed bed reactor	4.24–11.36 [45]	100–150 [45]	0.0–1 [46]
• Ammonia thermal decomposition with PSA-membrane separation	5.98–11 [45]	100–150 [45]	0.0–1 [46]
• Integration of biomass gasification (BG) with chemical looping hydrogen production (CLHP). • Source: Wu, D. et al. (2024) [68]	For the Air case and O_2 case, the costs are 3.05 and 2.82 $/kg H_2, respectively	n/a	−15.13 to −17.00

Table 4. Energy efficiencies (%) of conventional H_2 production technologies and waste valorization H_2 production technologies.

Hydrogen Production Technology	Energy Efficiency (%) *
• **Conventional with natural gas (NG)**	
• SMR	65–75 [7]
• SMR w/CCS	54 [10]
• ATR w/NG & CCS	45–56 [8,10]
• **Waste valorization**	
• wPG	40–50 [69]
• FWF	57–80 [17,50]
• Biomass gasification	40–50 [29,69]
• Biomass gasification w/CCS	40 [29]
• Glycerol-based:	
➢ SCWR	55–60 [17]
➢ ATR	71–74 [69]
➢ APR	45–55 [69]
➢ Steam reforming (SR)	60–70 [69]

* Efficiency is defined as the ratio of lower heating value (LHV) of hydrogen in product gas to total energy supplied to the process.

Table 5 shows that SMR and steam reforming (SR) of glycerol feedstock have the highest energy efficiency. Biomass gasification technology integrated with CCS has the

lowest energy efficiency. Carbon capture and storage (CCS) tends to increase the energy consumption and, hence, lowers the energy efficiency of the technology being evaluated.

Table 5. Energy efficiencies (%) of H_2 production via various water electrolysis technologies with different energy sources.

Hydrogen Production Technology	Energy Efficiency (%) *
▪ **Greener H_2 (water electrolysis)**	
• Wind + AKE	59–70 [24,33,70,71]
• Wind + PEME	58–74 [24,33,70]
• Wind + SOE	71–84 [23,24,72]
• Wind + AEME	69 [9]
• Solar PV + AKE	59–70 [24,33,71]
• Solar PV + PEME	60–68 [24,33,73]
• Solar PV + SOE	69–84 [23,24,26,72]
• Solar PV + AEME	69 [9]
• Hydropower + electrolyzers	61.6–66.10 [34,74]
• Grid mix + electrolyzers	60–84 [23,75]
• Nuclear + SOE	71–81 [24,29,72]
• Nuclear power + PEME	60–65 [24]

* Efficiency is defined as the ratio of lower heating value (LHV) of hydrogen in product gas to total energy supplied to the process.

Table 5 shows that solid oxide electrolyzers (SOEs) using electricity from wind turbines, solar PV, and nuclear power seem to have the highest energy efficiency.

Table 6. Energy efficiencies (%) of emerging clean H_2 production technologies.

Hydrogen Production Technology	Energy Efficiency (%) *
▪ **Emerging technologies**	
• Biomethane pyrolysis	40–56 [23,69]
• ESMR	70 [42]
• SMC	49.4–82.2 [26]
• Solar thermal + thermochemical decomposition	20 [29]
• Nuclear + thermochemical decomposition	
➢ S-I	42–52 [25,44]
➢ HyS	49 [25]
➢ Cu-Cl	43 [44]
➢ Mg-Cl	45 [25]
• Bio-photolysis	10–15 [41,56,57]
• Ammonia thermal decomposition via fixed bed reactor	78–80 [45]
• Ammonia thermal decomposition with PSA-membrane separation	87–90 [45]

* Efficiency is defined as the ratio of lower heating value (LHV) of hydrogen in product gas to total energy supplied to the process.

Table 6 shows that, among the evaluated emerging H_2 production technologies, ammonia thermal decomposition integrated with PSA membrane separation is the most energy-efficient technology and bio-photolysis is the least energy-efficient technology.

Table 7. Color-coded technology readiness level (TRL) and supply chain material availability of conventional and waste valorization H_2 production technologies.

Hydrogen Production Technology	TRL	Supply Chain Material Availability			Feedstock Type
		L	M	H	
▪ **Conventional using NG:**					
• **SMR**	9 [17]		✔		methane
• SMR w/CCS	8 [9]		✔		methane
• ATR w/CCS	5 [9]		✔		methane
▪ **Waste valorization**					
• wPG	7 [17]			✔	Waste plastics
• FWF	2–5 [9,17]			✔	Food waste
• Biomass gasification	7–9 [9,17]			✔	biomass
• Biomass gasification w/CCS	5 [9]			✔	biomass
• Glycerol-based					
➢ SCWR	4 [17]			✔	Glycerol waste
➢ ATR	7 [9]			✔	Glycerol waste
➢ APR	4–5 [17]			✔	Glycerol waste
➢ SR	8 [75]			✔	Glycerol waste
1 **2** **3**	**4**	**5**	**6**	**7** **8** **9**	

As shown in Table 7, SMR is the most mature and commercial-scale technology, and thus has a TRL of 9. Food waste fermentation (FWF) technology is the least mature and thus has the lowest TRL, in the 2 to 5 range. Steam reforming of glycerol has a high TRL of 8. Glycerol supercritical water reforming (SCWR) and aqueous-phase reforming (APR) have a lower TRL compared to more mature ATR technology. With respect to supply chain feedstock availability, glycerol waste, biomass, waste plastic, and food waste are more available compared to natural gas (primarily methane).

As displayed in Table 8, the alkaline electrolyzer (AKE) is the most mature technology, with a TRL of 9, and the least mature electrolyzer technology is the anode exchange membrane electrolyzer type, with a TRL as low as 2 or 3. Supply chain availability of metals used in the electrolyzer electrodes are, for the most part, location-dependent.

From Table 9, it can be seen that ammonia thermal decomposition via fixed-bed reactors seems to have the highest TRL of 9 tables. All other H_2 production technologies have lower TRLs, which are indicative that these technologies did not achieve the required maturity level to be commercialized at scale. Once again, supply chain material availability is highly location-dependent, among other externalities.

Table 8. Color-coded technology readiness level (TRL) and supply chain material availability of H_2 production via various water electrolysis technologies with different energy sources.

Hydrogen Production Technology	TRL	Supply Chain Material Availability			Comments
		L	M	H	
■ **Greener H_2 (water electrolysis):**					
• **Wind + AKE**	9 [9,35]			✔	Nickel, Cupper
• Wind + PEME	6–8 [9,33], 9 [17,35]	✔			Platinum, Iridium, titanium
• Wind + SOE	5 [9], 6–7 [23], 8 [35]			✔	Scandium
• Wind + AEME	2–3 [9], 4–5 [23], 6 [35]			✔	Platinum, Nickel, Transition Metal Catalysts (CeO_2–La_2O)*
• Solar PV + AKE	9 [9,35]			✔	Nickel, Cupper
• Solar PV + PEME	6–8 [9,33], 9 [17,35]	✔			Platinum, Iridium, titanium
• Solar PV + SOE	5 [9], 6–7 [23], 8 [35]			✔	Scandium
• Solar PV + AEME	2–3 [9], 4–5 [23], 6 [35]		✔		Platinum, Nickel, Transition Metal Catalysts (CeO_2–La_2O)*
• Hydropower + electrolyzers	9 [34]		✔		
• Grid mix + electrolyzers	9 [17]		✔		
• Nuclear + SOE	5 [9], 8 [35]			✔	Scandium
• Nuclear power + PEME	6–8 [9], 9 [35]	✔			Platinum, Iridium, titanium
1 2 3 4		5	6	7 8 9	

Table 9. Color-coded technology readiness level (TRL) and supply chain material availability of emerging clean H_2 production technologies.

Hydrogen Production Technology	TRL	Supply Chain Material Availability			Comments
		L	M	H	
■ **Emerging technologies**					
• Biomethane pyrolysis	3–7 [17,71]			✔	
• ESMR	4 [23]		✔		
• SMC	3–5 [9]			✔	
• Solar thermal + thermochemical decomposition	3–4 [9,35]		✔		ZnO/Zn cycle
• Nuclear + thermochemical decomposition					
➢ S-I	3–4 [9,35]		✔		
➢ HyS	3–4 [9,35]		✔		
➢ Cu-Cl	3–4 [9,35]		✔		
➢ Mg-Cl	3–4 [9,35]		✔		
• Bio-photolysis	4 [57]		✔		
• Ammonia thermal decomposition via fixed bed reactors	9 [45]		✔		Precious metal catalyst
• Ammonia thermal decomposition with PSA-membrane separation	4 [45]		✔		
1 2 3	4 5	6	7	8	9

4. Discussion

Based on the results presented (Tables 1–9) in Section 3, the following discission and insights can be synthesized:

- Conventional H_2 production via SMR has the advantage of being low-cost (around USD 1–2/kg H_2) and having a high TRL. However, SMR technology without CCS suffers from a high global warming impact of around 11 kg CO_2/kg H_2, as well as its nonrenewable feedstock requirement of natural gas.
- SMR with CCS and ATR with CCS result in lower global warming impacts, but they still produce around 2–8 kg CO_2/kg H_2, which is higher than the emissions of the majority of H_2 production via water electrolysis. Also, the energy requirements (MJ/kg H_2) of blue H_2 production technologies are generally higher than those of gray

H_2 production technologies. The emerging carbon capture, utilization, and storage (CCUS) is expected to add additional environmental and economic values that go beyond CCS only.

- Assessment of waste valorization as an alternative to the conventional methods for H_2 production reveals that its most robust advantage is its high supply chain material availability due to using waste as the feedstock. The various methods utilize different waste streams that would otherwise contribute to costly waste management and environmental issues like toxic leaching and emission of air pollutants from landfills and waste incineration.
- In terms of GWP, waste valorization methods that are integrated with CCS can produce negative carbon emissions with the utilization of waste that otherwise would have been incinerated. Otherwise, when only considering carbon emissions, these technologies are not necessarily more sustainable than the conventional methods, with the exception of APR, with a promising GWP of 4.11 kg CO_2/kg H_2 [18]. Therefore, incorporating CCS technology into waste valorization technologies will enhance their environmental benefits.
- Waste plastics gasification (wPG), food waste fermentation (FWF), and biomass gasification with and without CCS are somewhat more expensive than the conventional methods (around USD 2–4/kg H_2), but not so expensive as to be uncompetitive, particularly when potential for technological improvements and economies of scale are taken into consideration. The energy requirements of the processes range significantly, from 20 to 240 MJ/kg H_2, but as noted earlier, these values vary widely with plant location, energy sources, and many other externalities. Therefore, it is perhaps more meaningful to examine energy efficiency, which is fairly average for wPG and biomass gasification (40–50%) and slightly higher for FWF. Improvements in technology will improve energy efficiency and subsequently further decrease production costs.
- Examining the four methods of glycerol conversion (data in Table 1) reveals that APR is more attractive than both ATR and SCWR, not only due to its lower carbon emissions but also due to its lower energy consumption [17]. Therefore, APR outperforms its glycerol-based counterparts in sustainability and energy consumption, but with a TRL of 4–5, APR is not a mature technology yet and is therefore currently the most expensive, followed by steam reforming (SR), then SCWR, and finally ATR [17]. Also, the energy efficiencies of the four technologies range from 45 to 74, with APR performing the least efficiently. Considering all factors, APR is the most worthwhile technology of the four glycerol-based hydrogen production processes to improve upon.
- The compiled literature data about water electrolysis reveal that it is a very promising technology for green H_2 production, producing close-to-zero carbon emissions. The performance of electrolysis varies depending on the specific technology and electricity source. First examining costs in Table 2, it can be seen that hydropower and nuclear power currently produce the least expensive H_2, at around USD 2.7/kg H_2. The grid mix, wind power, and solar PV power are slightly more expensive, with wind generally being less expensive than solar PV. In terms of the types of electrolyzer, SOE and AEME are more cost-effective than PEME and AKE. For wind and solar PV power, the most optimal costs for SOE and AEME are USD 3.36–6.72/kg H_2, and for PEME and AKE, the most optimal costs are USD 4–10.13/kg H_2. The energy requirements for the various technologies and power sources are comparable to one another, ranging from 165 to 280 MJ/kg H_2. However, energy efficiency does differ, with wind-powered electrolysis being slightly more efficient than solar PV, and with SOE being the most efficient type of electrolyzer.
- Examining the TRLs of water electrolysis technologies in Table 8, it can be seen that PEME and AKE are the most technologically mature, but their material supply chain

availabilities are not very high in terms of availability. PEME specifically has a lower material supply chain availability score because it requires a rare metal (platinum) catalyst. Taking all of the criteria into consideration, a case could be made for any of the water electrolysis processes, but SOE powered by renewable electricity appears to be an especially worthwhile technology to focus on in the future. The source of renewable electricity that should be utilized depends on the characteristics of the region in which the electrolyzer is built. While wind energy showed greater energy efficiency and lower production cost in the literature review, this does not necessarily mean it is the most optimal option everywhere. Also, an important alternative that was not in the scope of this research is the possibility of utilizing multiple sources of renewable electricity in conjunction with, or integrating them into, the electricity grid mix. A hybrid configuration can ensure a more stable and reliable electricity supply, particularly in the case of wind and solar PV, which are known to be intermittent sources.

- The literature review also revealed some encouraging data about the emerging H_2 production technologies. Biomethane pyrolysis, ESMR, supercritical water gasification of sewage sludge [76], industrial CO-to-H_2 via water–gas shift reaction [77], solar thermal thermochemical decomposition, nuclear thermochemical decomposition, bio-photolysis, and ammonia thermal decomposition were herein investigated, all of which are in the late research and early development stages, except for ammonia thermal decomposition via fixed-bed reactors, which exhibits a TRL of 9. Because these technologies are mostly laboratory-scale or small-scale, data rely heavily on simulations and models. Out of the emerging technologies, currently biomethane pyrolysis, ESMR, and bio-photolysis predict the lowest hydrogen costs, with minimum costs of USD 1.36–1.53 per kg H_2. Nuclear thermochemical decomposition is not far behind, at USD 2.24–4.11/kg H_2, with the price varying by almost USD 2 depending on the cycle type. Solar thermal thermochemical decomposition and ammonia thermal decomposition are currently not competitive and will need a lot of technological development and improvements to become viable options for hydrogen production. However, ammonia decomposition via fixed-bed reactors or PSA membranes can produce H_2 at a high energy efficiency with close-to-zero carbon emissions while utilizing ammonia as a renewable feedstock. Therefore, more so than solar thermal decomposition, which has a low energy efficiency, the strategic integration of ammonia thermal decomposition technologies has fairly high prospects as long as production costs are lowered [56–58,60,62,64,67,70,71,73,74,76,77].
- Out of the rest of the H_2 production technologies, nuclear thermal thermochemical decomposition and biomethane pyrolysis appear to be the most promising. The production of "turquoise" H_2 via biomethane pyrolysis has low energy requirements and has a negative global warming potential due to utilizing an otherwise high-emitting feedstock. Thermochemical decomposition with nuclear power has an energy demand similar to that of SMR and produces zero carbon emissions. The most promising cycles are S-I, HyS, and Cu-Cl. The energy efficiencies of the two technologies are 40–56%, which could be improved upon with more research and design optimization. The other technologies exhibit some advantages, such as ESMR's high energy efficiency and the potentially low production cost of bio-photolysis, but due to their higher GWPs, they are more practical as transitional technologies rather than as long-term solutions [75,78].

5. Conclusions and Recommendations

This research evaluated various H_2 production technologies based on cost (USD/kg H_2), energy consumption (MJ/kg H_2), technology efficiency (%), and carbon emissions (kg CO_2-

eq/kg H_2). Steam-methane reforming (SMR) with and without carbon capture and storage (CCS) served as the benchmark H_2 production technology. Despite its low cost, SMR without CCS has high carbon emissions. Water electrolysis, hindered by high energy demands (kWh/kg H_2) and high costs (USD/kg H_2), shows promise, with advancements in renewable energy sources for green electricity production. Waste valorization methods such as biomass gasification or reforming and food waste fermentation offer dual benefits of waste management and sustainable H_2 production, albeit at higher costs at this early stage of development. Emerging technologies like biomethane pyrolysis and nuclear-powered thermochemical cycles also present promising avenues for achieving clean and sustainable H_2 production with minimal environmental impact.

Future research should focus on enhancing the technological maturity, scalability, and cost-efficiency of promising yet underdeveloped H_2 production technologies, such as biomass waste valorization via gasification (or reforming) and water electrolysis using low-cost green electricity, to achieve low carbon emissions and competitive production costs. Additionally, the impact of governmental policies and incentives on H_2 economics should be rigorously analyzed to provide a comprehensive techno-economic framework for sustainable H_2 production. Emphasizing the environmental impacts of these technologies and conducting comparative life cycle assessments along their supply chains can further elucidate the global benefits of green H_2 initiatives.

Funding: This research received no external funding.

Institutional Review Board Statement: Not relevant to this study.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the research are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The author of this research is grateful for the valuable comments and reviews provided by his colleagues from the University of Oxford, University of Cambridge, and Imperial College of London, in the United Kingdom, as well as by Harvard University, in the U.S.

Conflicts of Interest: The author declares no conflicts of interest.

Appendix A. Acronyms

AEME	Anion exchange membrane electrolyzer
AKE	Alkaline electrolyzer
APR	Aqueous-phase reforming
ATR	Autothermal reforming
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
Cu-Cl	Copper–chlorine
ESMR	Electrified steam-methane reforming
FWF	Food waste fermentation
HRS	Hydrogen refueling station
HyS	Hybrid sulfur
Mg-Cl	Magnesium–chloride
PEM	Proton exchange membrane electrolyzer
SCWR	Super-critical water reforming
S-I	Sulfur–iodine
SMR	Steam-methane reforming
SOE	Solid oxide electrolyzer
TEA	Techno-economic analysis

TRL	Technology readiness level
wPG	Waste plastic gasification

References

1. Lui, J.; Paul, M.C.; Sloan, W.; You, S. Techno-economic feasibility of distributed waste-to-hydrogen systems to support green transport in Glasgow. *Int. J. Hydrogen Energy* **2022**, *47*, 13532–13551. [CrossRef]
2. The Paris Agreement | UNFCCC. 2020. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement (accessed on 9 March 2024).
3. Frueh, S. Can Hydrogen Help the Energy Transition? Panel Explores the Benefits and Challenges. National Academies of Science, Engineering, and Medicine. 23 August 2024. Available online: https://www.nationalacademies.org/news/2024/08/can-hydrogen-help-the-energy-transition-panel-explores-the-benefits-and-challenges-of-developing-more-clean-hydrogen-for-fuel (accessed on 25 December 2024).
4. Ghasemi, A.; Rad, H.N.; Akrami, M. Biomass-to-Green Hydrogen: A Review of Techno-Economic-Enviro Assessment of Various Production Methods. *Hydrogen* **2024**, *5*, 474–493. [CrossRef]
5. Dincer, I.; Acar, C. Review and evaluation of hydrogen production methods for better sustainability. *Int. J. Hydrogen Energy* **2015**, *40*, 11094–11111. [CrossRef]
6. Alternative Fuels Data Center: Hydrogen. Energy.gov. 2023. Available online: https://afdc.energy.gov/fuels/hydrogen_basics.html#:~:text=The%20energy%20in%202.2%20pounds,driving%20range%20of%20conventional%20vehicles (accessed on 9 March 2024).
7. IRJET Journal. IRJET-review paper on hydrogen: The fuel of future. *IRJET* **2020**, *7*, 2978–2981. Available online: https://www.academia.edu/44307163/IRJET_REVIEW_PAPER_ON_HYDROGEN_THE_FUEL_OF_FUTURE?amp;swp=rr-rw-wc-57873971&nav_from=7992dc07-7621-4e2d-a8a1-1ed8ca920f22&rw_pos=17 (accessed on 11 March 2024).
8. Oni, A.O.; Anaya, K.; Giwa, T.; Di Lullo, G.; Kumar, A. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Convers. Manag.* **2022**, *254*, 115245. [CrossRef]
9. Wilkinson, J.; Mays, T.J.; McManus, M. Review and meta-analysis of recent life cycle assessments of hydrogen production. *Clean. Environ. Syst.* **2023**, *9*, 100116. [CrossRef]
10. Martínez-Rodríguez, A.; Abánades, A. Comparative Analysis of Energy and Exergy Performance of Hydrogen Production Methods. *Entropy* **2020**, *22*, 1286. [CrossRef]
11. Maxwell, C. Cost Indices—Towering Skills. Toweringskills.com. 2020. Available online: https://toweringskills.com/financial-analysis/cost-indices/ (accessed on 25 December 2024).
12. Yousefi Rizi, H.A.; Shin, D. Green Hydrogen Production Technologies from Ammonia Cracking. *Energies* **2022**, *15*, 8246. [CrossRef]
13. Patel, S.K.S.; Gupta, R.K.; Rohit, M.V.; Lee, J.-K. Recent developments in hydrogen production, storage, and transportation: Challenges, opportunities, and perspectives. *Fire* **2024**, *7*, 233. [CrossRef]
14. Hosseinzadeh, A.; Zhou, J.L.; Li, X.; Afsari, M.; Altaee, A. Techno-economic and environmental impact assessment of hydrogen production processes using bio-waste as renewable energy resource. *Renew. Sustain. Energy Rev.* **2022**, *156*, 111991. [CrossRef]
15. Cudjoe, D.; Chen, W.M.; Zhu, B. Valorization of food waste into hydrogen: Energy potential, economic feasibility and environmental impact analysis. *Fuel* **2022**, *324*, 124476. [CrossRef]
16. Jarunglumlert, T.; Prommuak, C.; Putmai, N.; Pavasant, P. Scaling-up bio-hydrogen production from food waste: Feasibilities and challenges. *Int. J. Hydrogen Energy* **2018**, *43*, 634–648. [CrossRef]
17. Lepage, T.; Kammoun, M.; Schmetz, Q.; Richel, A. Biomass-to-hydrogen: A review of main routes production, processes evaluation and techno-economical assessment. *Biomass Bioenergy* **2021**, *144*, 105920. [CrossRef]
18. Khalil, Y. Simulation-based environmental-impact assessment of glycerol-to-hydrogen conversion technologies. *Clean Energy* **2021**, *5*, 387–402. [CrossRef]
19. Khodabandehloo, M.; Larimi, A.; Khorasheh, F. Comparative process modeling and techno-economic evaluation of renewable hydrogen production by glycerol reforming in aqueous and gaseous phases. *Energy Convers. Manag.* **2020**, *225*, 113483. [CrossRef]
20. Ashwath, J.; Kanishka, S.; Jannan, B.; Janardhan, A.; Shailesh, A.; Rathore, S. Life Cycle Analysis of Hydrogen. *AIP Conf. Proc.* **2021**, *2396*, 020008. [CrossRef]
21. Sapnken, F.E.; Posso, F.; Kibong, M.T.; Noumo, P.G.; Fantah, A.C.; Tamba, J.G. Green hydrogen demand in Cameroon's energy sectors by 2040. *Renew. Sustain. Energy Rev.* **2024**, *205*, 114834. [CrossRef]
22. Ajeeb, A.; Neto, R.C.; Baptista, P. Life cycle assessment of green hydrogen production through electrolysis: A literature review. *Sustain. Energy Technol. Assess.* **2024**, *69*, 103923. [CrossRef]
23. IEA. *Global Hydrogen Review 2021*; IEA: Paris, France, 2021. Available online: https://www.iea.org/reports/global-hydrogen-review-2021 (accessed on 17 April 2024).

24. Christensen, A. *Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe*; International Council on Clean Transport: Washington, DC, USA, 2020. Available online: https://theicct.org/wp-content/uploads/2021/06/final_icct2020_assessment_of-_hydrogen_production_costs-v2.pdf (accessed on 15 April 2024).
25. Edvan, F. Multiple criteria evaluation of hydrogen production processes for use in automotive sector. *Int. J. Hydrogen Energy* **2023**, *49*, 843–861. [CrossRef]
26. Clark, C.E.; Barker, A.; Brunik, K.; Kotarbinski, M.; Grant, E.; Roberts, O.; King, J.; Andrew Bhaskar, P.; Bay, C.J. Opportunities for green hydrogen production with land-based wind in the United States. *Energy Convers. Manag.* **2023**, *296*, 117595. [CrossRef]
27. Lima, T.M.; Lima, C.G.S.; da Costa Madriaga, V.G.; Vasconcelos, S.C.; Quatrocciochi, D.G.; Ferreira, P.G.; de C. da Silva, F.; da S. M. Forezi, L.; Ferreira, V.F. An Overview of Hydrogen Production from Renewable Sources and Its Main Applications. *ChemistrySelect* **2024**, *9*, e202401237. [CrossRef]
28. Koroneos, C.; Dompros, A.; Roumbas, G.; Moussiopoulos, N. Life cycle assessment of hydrogen fuel production processes. *Int. J. Hydrogen Energy* **2004**, *29*, 1443–1450. [CrossRef]
29. El-Emam, R.S.; Özcan, H. Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. *J. Clean. Prod.* **2019**, *220*, 593–609. [CrossRef]
30. Gerhardt-Morsdorf, J.; Incer-Valverde, J.; Morosuk, T.; Minke, C. Exergetic life cycle assessment for green hydrogen production. *Energy* **2024**, *299*, 131553. [CrossRef]
31. Lee, B.; Choe, C.; Kim, H.; Kim, A.; Shin, Y.-U.; Haider, J.; Lim, H. Economic Parity Analysis of Green Methanol Synthesis Using Water Electrolysis Based on Renewable Energy. *ACS Sustain. Chem. Eng.* **2021**, *9*, 15807–15818. [CrossRef]
32. Sharma, M.; Pramanik, A.; Bhowmick, G.D.; Tripathi, A.; Ghangrekar, M.M.; Pandey, C.; Kim, B.-S. Premier, Progress and Prospects in Renewable Hydrogen Generation: A Review. *Fermentation* **2023**, *9*, 537. [CrossRef]
33. Schnuelle, C.; Wassermann, T.; Fuhrlaender, D.; Zondervan, E. Dynamic hydrogen production from PV & wind direct electricity supply—Modeling and techno-economic assessment. *Int. J. Hydrogen Energy* **2020**, *45*, 29938–29952. [CrossRef]
34. Altayib, K.; Dinçer, I. Development of an integrated hydropower system with hydrogen and methanol production. *Energy* **2022**, *240*, 122780. [CrossRef]
35. Guide, T. *ETP Clean Energy Technology Guide—Data Tools—IEA*; IEA: Paris, France, 2023. Available online: https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide (accessed on 10 February 2024).
36. Li, J.; Xie, W.; Zhou, H.; Li, Z.; Shao, M. Techno-economic analysis of electrochemical hydrogen production coupled with alternative oxidation. *Chem. Eng. Sci.* **2024**, *298*, 120322. [CrossRef]
37. Naqvi, S.R.; Kazmi, B.; Taqvi, S.A.A.; Chen, W.-H.; Juchelková, D. Techno economic analysis for advanced methods of green hydrogen production. *Curr. Opin. Green Sustain. Chem.* **2024**, *48*, 100939. [CrossRef]
38. H_2NEW: Hydrogen (H_2) from Next-Generation Electrolyzers of Water LTE Task 3c: System and Technoeconomic Analysis. DOE Hydrogen Program. 2021. Available online: https://www.nrel.gov/docs/fy21osti/79835.pdf (accessed on 25 December 2024).
39. Banu, A.; Biçer, Y. Energy and exergy analysis of an integrated system with solar methane cracking and co-electrolysis of CO_2/H_2O for efficient carbon management. *Int. J. Hydrogen Energy* **2023**, *52*, 580–593. [CrossRef]
40. Mersbet, N.H.; Kerboua, K.; Hoinkis, J. Hydrogen production from wastewater: A comprehensive review of conventional and solar powered technologies. *Renew. Energy* **2024**, *226*, 120412. [CrossRef]
41. Nagarajan, D.; Lee, D.H.; Kondo, A.; Chang, J.S. Recent insights into biohydrogen production by microalgae—From biophotolysis to dark fermentation. *Bioresour. Technol.* **2017**, *227*, 373–387. [CrossRef]
42. Mehanovic, D.; Al-Haiek, A.; Leclerc, P.; Rancourt, D.; Fréchette, L.; Picard, M. Energetic, GHG, and economic analyses of electrified steam methane reforming using conventional reformer tubes. *Energy Convers. Manag.* **2023**, *276*, 116549. [CrossRef]
43. Germscheidt, R.L.; Moreira, D.E.B.; Yoshimura, R.G.; Gasbarro, N.P.; Datti, E.; dos Santos, P.L.; Bonacin, J.A. Hydrogen Environmental Benefits Depend on the Way of Production: An Overview of the Main Processes Production and Challenges by 2050. *Adv. Energy Sustain. Res.* **2021**, *2*, 2100093. [CrossRef]
44. Safari, F.; Dinçer, I. A review and comparative evaluation of thermochemical water splitting cycles for hydrogen production. *Energy Convers. Manag.* **2020**, *205*, 112182. [CrossRef]
45. Kanaan, R.; Henrique, P.; Achard, P.; Beauger, C. Economical assessment comparison for hydrogen reconversion from ammonia using thermal decomposition and electrolysis. *Renew. Sustain. Energy Rev.* **2023**, *188*, 113784. [CrossRef]
46. Cha, J.; Park, Y.; Brigljević, B.; Lee, B.; Lim, D.; Lee, T.; Jeong, H.; Kim, Y.; Sohn, H.; Mikulčić, H.; et al. An efficient process for sustainable and scalable hydrogen production from green ammonia. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111562. [CrossRef]
47. Pashchenko, D. Green hydrogen as a power plant fuel: What is energy efficiency from production to utilization? *Renew. Energy* **2024**, *223*, 120033. [CrossRef]
48. Diab, J.; Fulcheri, L.; Hessel, V.; Rohani, V.; Frenklach, M. Why turquoise hydrogen will Be a game changer for the energy transition. *Int. J. Hydrogen Energy* **2022**, *47*, 25831–25848. [CrossRef]
49. Abdin, Z.; Mérida, W. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: A techno-economic analysis. *Energy Convers. Manag.* **2019**, *196*, 1068–1079. [CrossRef]

50. Mohanakrishna, G.; Sneha, N.P.; Rafi, S.M.; Sarkar, O. Dark fermentative hydrogen production: Potential of food waste as future energy needs. *Sci. Total Environ.* **2023**, *888*, 163801. [CrossRef]
51. Chen, Z.; Wei, W.; Chen, X.; Liu, Y.; Shen, Y.; Ni, B.-J. Upcycling of plastic wastes for hydrogen production: Advances and perspectives. *Renew. Sustain. Energy Rev.* **2024**, *195*, 114333. [CrossRef]
52. Azadvar, S.; Tavakoli, O. Data-driven interpretation, comparison and optimization of hydrogen production from supercritical water gasification of biomass and polymer waste: Applying ensemble and differential evolution in machine learning algorithms. *Int. J. Hydrogen Energy* **2024**, *85*, 511–525. [CrossRef]
53. Afzal, S.; Singh, A.; Nicholson, S.; Uekert, T.; DesVeaux, J.S.; Eric Dutta, A.; Carpenter, A.; Baldwin, R.M.; Beckham, G.T. Techno-economic analysis and life cycle assessment of mixed plastic waste gasification for production of methanol and hydrogen. *Green Chem.* **2023**, *25*, 5068–5085. [CrossRef]
54. Short-Term Energy, Outlook—U.S. Energy Information Administration (EIA). Eia.gov. 2023. Available online: https://www.eia.gov/outlooks/steo/report/BTL/2023/02-genmix/article.php (accessed on 11 January 2024).
55. Lan, K.; Yao, Y. Feasibility of gasifying mixed plastic waste for hydrogen production and carbon capture and storage. *Commun. Earth Environ.* **2022**, *3*, 300. [CrossRef]
56. Nikolaidis, P.; Poullikkas, A. A comparative overview of hydrogen production processes. *Renew. Sustain. Energy Rev.* **2017**, *67*, 597–611. [CrossRef]
57. Acar, C.; Dincer, I. Review and evaluation of hydrogen production options for better environment. *J. Clean. Prod.* **2019**, *218*, 835–849. [CrossRef]
58. Yakaboylu, O.; Harinck, J.; Smit, K.G.; De Jong, W. Supercritical Water Gasification of Biomass: A Literature and Technology Overview. *Energies* **2015**, *8*, 859–894. [CrossRef]
59. Webinar: Wind-to-Hydrogen Cost Modeling and Project Findings. Energy.gov. 2013. Available online: https://www.energy.gov/eere/fuelcells/webinar-wind-hydrogen-cost-modeling-and-project-findings (accessed on 25 December 2024).
60. IRENA. *Making the Breakthrough: Green Hydrogen Policies and Technology Costs*; International Renewable Energy Agency: Masdar City, Abu Dhabi, 2021. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6 (accessed on 25 December 2024).
61. Suleman, F.; Dinçer, I.; Agelin-Chaab, M. Comparative impact assessment study of various hydrogen production methods in terms of emissions. *Int. J. Hydrogen Energy* **2016**, *41*, 8364–8375. [CrossRef]
62. Jang, D.; Kim, K.; Kim, K.H.; Kang, S. Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant. *Energy Convers. Manag.* **2022**, *263*, 115695. [CrossRef]
63. Lamagna, M.; Ferrario, A.M.; Garcia, D.A.; McPhail, S.J.; Comodi, G. Reversible solid oxide cell coupled to an offshore wind turbine as a poly-generation energy system for auxiliary backup generation and hydrogen production. *Energy Rep.* **2022**, *8*, 14259–14273. [CrossRef]
64. Saeedmanesh, A. Solid Oxide Electrolysis Cell (SOEC) and System Technology for Widespread Use with Renewable Energy. Escholarship.org. 2021. Available online: https://escholarship.org/uc/item/6x19c8wf (accessed on 25 December 2024).
65. Karayel, G.K.; Javanı, N.; Dinçer, I. Hydropower for green hydrogen production in Turkey. *Int. J. Hydrogen Energy* **2023**, *48*, 22806–22817. [CrossRef]
66. IEA. *Energy Technology Perspectives 2023*; IEA: Paris, France, 2023. Available online: https://www.iea.org/reports/energy-technology-perspectives-2023 (accessed on 25 December 2024).
67. El-Emam, R.S.; Özcan, H.; Zamfirescu, C. Updates on promising thermochemical cycles for clean hydrogen production using nuclear energy. *J. Clean. Prod.* **2020**, *262*, 121424. [CrossRef]
68. Wu, D.; Gao, Z.; Wu, S.; Xiao, R. Negative net global warming potential hydrogen production through biomass gasification combined with chemical looping: Environmental and economic assessments. *Int. J. Hydrogen Energy* **2024**, *66*, 24–32. [CrossRef]
69. Parthasarathy, P.; Narayanan, K.S. Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield—A review. *Renew. Energy* **2014**, *66*, 570–579. [CrossRef]
70. Tebibel, H. Methodology for multi-objective optimization of wind turbine/battery/electrolyzer system for decentralized clean hydrogen production using an adapted power management strategy for low wind speed conditions. *Energy Convers. Manag.* **2021**, *238*, 114125. [CrossRef]
71. Ursúa, A.; Marroyo, L.; Gubía, E.; Gandía, L.; Diéguez, P.M.; Sanchis, P. Influence of the power supply on the energy efficiency of an alkaline water electrolyser. *Int. J. Hydrogen Energy* **2009**, *34*, 3221–3233. [CrossRef]
72. Technical Targets for High Temperature Electrolysis. 2022. Available online: https://www.energy.gov/eere/fuelcells/technical-targets-high-temperature-electrolysis (accessed on 25 December 2024).
73. Li, G.; Cui, P.; Wang, Y.; Liu, Z.; Zhu, Z.; Yang, S. Life cycle energy consumption and GHG emissions of biomass-to-hydrogen process in comparison with coal-to-hydrogen process. *Energy* **2020**, *191*, 116588. [CrossRef]

74. Nnabuife, S.G.; Ugbeh-Johnson, J.; Okeke, N.E.; Ogbonnaya, C. Present and Projected Developments in Hydrogen Production: A Technological Review. *Carbon Capture Sci. Technol.* **2022**, *3*, 100042. [CrossRef]
75. Li, Z.; Brouwer, J. Dynamic operation and feasibility study of a self-sustainable hydrogen fueling station using renewable energy sources. *Int. J. Hydrogen Energy* **2015**, *40*, 3822–3837. [CrossRef]
76. Fatimah, M.; Qyyum, M.A.; Lee, M.; Alshareef, R.S.; Aslam, M.; Saeed, B.; Dai, L.; Gilani, M.A.; Bazmi, A.A.; Chang, I.S.; et al. Industrial waste gases as a resource for sustainable hydrogen production—Resource availability, production potential, challenges, and prospects. *Carbon Capture Sci. Technol.* **2024**, *12*, 100228. [CrossRef]
77. Hu, D.; Ren, C.; Zhang, S.; Ma, M.; Chen, Y.; Chen, B.; Guo, L. Thermodynamic and environmental analysis of integrated supercritical water gasification of sewage sludge for power and hydrogen production. *Energy* **2024**, *299*, 131568. [CrossRef]
78. Frowijn, L.S.F.; van Sark, W.G.J.H.M. Analysis of photon-driven solar-to-hydrogen production methods in the Netherlands. *Sustain. Energy Technol. Assess.* **2021**, *48*, 101631. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.