

How does techno-economic analysis and lifecycle assessment help in commercializing the biohydrogen supply chain?

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ABSTRACT

Hydrogen is considered as the fuel of the future not only because of its high energy density but also due to its zero-carbon emission potential during combustion. However, to achieve sustainable growth, the hydrogen generation process must be techno-economically feasible and have minimum carbon footprint. The techno-economic analysis (TEA) of various hydrogen generation process aids in identifying the effective bio-hydrogen generation process at minimal cost thereby aiding in faster dissemination of the system by attracting investors. Among the various techniques available for bio-hydrogen production, gasification was found to be most economical (\$1.2/kg H₂) followed by anaerobic digestion process (\$1.25/kg H₂). Meanwhile, after carrying out the life cycle analysis (LCA) of the different bio-hydrogen generation process, it was found that generation of bio-hydrogen by gasification of eucalyptus wood produced least carbon foot of -1.6 kg CO_{2eq}/kg H₂. Thus, the TEA and LCA of different biohydrogen production process also helps to identify the bottlenecks haunting the penetration of hydrogen in energy market which can be overcome by framing effective policies by the governing agencies.

1. Introduction

The transportation sector is one of the major consumers of energy worldwide, and a major fraction of this energy is derived from petroleum. In some countries, like Portugal, the fraction of energy consumed in the transportation sector is as high as 38%, leading to 31% of carbon dioxide emissions [1]. In the United States also, the transportation sector is the largest end-use consuming sector accounting for about 37 % of total energy consumption. Due to diminishing fossil fuel reserves, petroleum production might not be sufficient to meet increasing energy demand for a long time. This energy insecurity, along with the growing

environmental concerns and regulations with the use of fossil fuel have generated a great interest in identifying renewable transportation fuel.

In this regard, hydrogen is considered an important fuel, as it can be produced with minimal carbon emission and can be transported by adopting different storage techniques (liquefied, compressed, or adsorbed in metal hydrides) [2]. With the low heating value (LHV) of 120 MJ/kg and high energy density (0.0899 kg/m³), hydrogen is also known as an energy carrier of the future. As it has many applications, including transportation fuel, chemical industry, and cogeneration [3,4]. Currently, most of the industrial hydrogen is produced by using fossil fuels as energy source [5]. The conventional methods include coal

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gasification, steam reforming of methane, water electrolysis [3,6]. Most of these methods are energy intensive, expensive, and negatively impact the environment [3,6]. Biohydrogen, the hydrogen produced from renewable sources, can address these limitations, and can aid in meeting the increasing fuel demand. In this connection, biohydrogen production technologies from different biomass sources (agricultural waste, forest residues, food processing wastes, algae) have been developed and investigated. Thermochemical gasification of lignocellulosic biomass and biological fermentation of sugars obtained from hydrolysis of storage carbohydrates (starch) or structural carbohydrates (cellulose, hemicellulose) are the most common and promising methods to produce biohydrogen [7]. Sugars obtained from hydrolysis of starch or cellulose and hemicellulose are fermented to produce H₂.

However, to achieve a sustainable hydrogen economy, it is important to develop a hydrogen production system which is highly efficient, economically feasible, and environmentally friendly. TEA and LCA are the common approaches used to determine the technical feasibility, economic viability, and environmental sustainability of the technologies/processes in the developmental stage. This paper attempts to review and understand the outcomes of TEA and LCA of the biohydrogen production from various feedstocks using different production pathways. While there are some reviews in literature focusing on the various aspects of biohydrogen processes [8–11]. This is the first comprehensive review that specifically focuses on the economic and environmental sustainability metrics which are critical to identify challenges and opportunities and understand the feasibility of commercialization of the

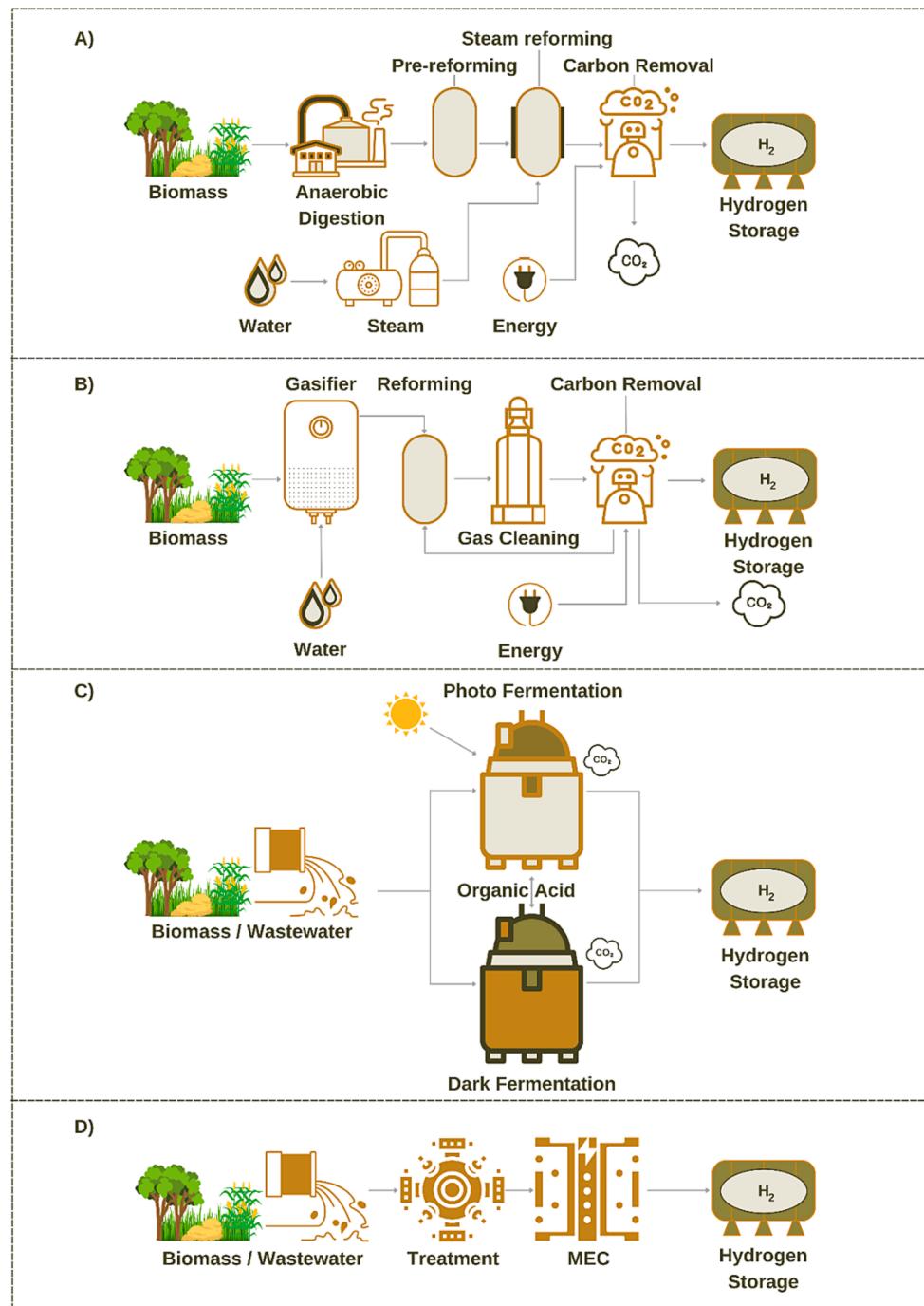


Fig. 1. Schematic representation of biohydrogen production; A) Anaerobic digestion; B) Gasification; C) Fermentation; D) Microbial electrolysis cell.

process. In addition, the policies on green hydrogen formulated by various nations across the world is also summarized in this manuscript.

2. Hydrogen production

Hydrogen can be generated by three different pathways namely, thermo-chemical, bio-chemical, and electro-chemical. However, generating biohydrogen by using biomass feedstock is gaining prominence in the recent days as it abets in converting agricultural waste, forest residues, and municipal solid waste to fuel which is one among the major source of GHG emissions. The different methodologies adopted to generate biohydrogen is illustrated in Fig. 1.

2.1. Anaerobic digestion

Hydrogen can be produced by anaerobic digestion of organic materials by either reforming hydrogen from methane present in biogas. Meanwhile, hydrogen production by anaerobic process can also be achieved through selecting appropriate feedstocks and modifying the process parameters to maximize hydrogen production by minimizing methane and carbon dioxide formation [12]. The hydrogen production is generally enhanced in anaerobic process by inhibiting the microbes involved in methanogenesis process through pre-treatment (heating, acidification, ultra-sonification, and alkalisation) thereby preventing conversion of H₂ to CH₄ [13].

The pre-treatment methodology adopted for hydrogen generation form anaerobic process depends on the feedstock fed to the digester. For instance, the maximum H₂ production of 13.8 mL/g of volatile suspended solids was achieved when the feedstocks (sewage sludge and food waste) were pre-treated by ultra-sonification and alkali treatment while the pH of the digester was maintained around 5–5.5 [14]. On the other hand, when sludge of wastewater treatment plant was used as feedstock, acidification coupled with thermal treatment was found to be an effective pre-treatment mechanism [15]. Meanwhile, it is necessary to ensure that the partial pressure of H₂ is maintained by removing the generated hydrogen from the digester. As increment in concentration of H₂ is toxic to acetogenic bacteria which is responsible for hydrogen production from small organic materials [14].

2.2. Thermo-chemical process

Pyrolysis and gasification techniques are predominantly used to convert bioenergy resources into biofuel such as hydrogen. Pyrolysis takes place under the absence of oxygen whereas gasification happens when only 33% of stoichiometric oxygen is supplied. The syngas formed during these processes are reformed to hydrogen.

During gasification process, air, steam, and oxygen are used as gasifying agents to convert biomass into hydrogen (H), carbon monoxide (CO), and carbon dioxide (CO₂) at temperature >700 °C [16]. The CO produced during the process generates hydrogen on reacting with water (Water-gas shift reaction) [17]. Finally, the hydrogen is separated from other gases through adsorption and/or membrane techniques. There is diverse variety of gasifiers which includes updraft fixed bed, downdraft fixed bed, bubbling fluidized bed, circulating fluidized bed, dual stage fluidized bed, and entrained flow gasifier [18]. Among these fluidized bed reactors (FBRs) (Bubbling and Circulating) are highly preferred for hydrogen production due to their advantages like direct/indirect heating, higher heating value, controlling over temperature application. Hydrogen yield of 49 – 79 g H₂/kg of biomass is observed when the gasifier is operated at 800 – 950 °C [19]. However, FBRs has disadvantages such as medium tar yield and higher particle loading.

On the other hand, during fast pyrolysis process the biomass is heated for less than a minute at a temperature ranging from 500 to 1000 °C with a heating rate of 300 °C/minute [20]. However, the composition of syngas generated during fast pyrolysis process is like the producer gas generated during gasification process. Hence, CO present

in the syngas is converted to hydrogen by employing water gas shift reaction. The hydrogen produced from pyrolysis process is about 112 g H₂/kg biomass. However, the amount of biomass which gets converted into syngas is 13% while the rest is converted into biochar and bio-oil (75% and 12%) which necessitates further processing of these co-products to hydrogen [21].

2.3. Fermentation

Biological hydrogen is produced through two different processes namely; photo fermentation and dark fermentation [11]. Though the yield of bio-hydrogen by employing fermentation process is lower it can be enhanced with the aid of organic and inorganic nanomaterials [22].

Dark fermentation is one of the old methods to produce hydrogen. H₂ producing bacteria such as *Enterobacter* sp. and *Clostridium* sp. are employed during dark fermentation process for hydrogen production. Several studies have used these bacteria to produce hydrogen from simple and waste organic feedstocks, including agricultural waste, industrial processing wastewater, and municipal waste. The bacteria's involved in fermentation process make use of protons as electron acceptors to release H₂, which is required for Adenosine Triphosphate (ATP) generation to maintain the cells' energy. Meanwhile, the molecular techniques adopted to identify the microbial strain for enhancing biohydrogen production by employing dark fermentation process was characterized by Kumar et al. [23].

Several parameters influence the yield of hydrogen during the dark fermentation process, it is necessary to control such parameters specifically including, pH, micro and macro nutrition's, temperature, and solids retention time affects the hydrogen yield and need to be carefully controlled. However, among these parameters pH is considered as the most critical parameter which depends on both substrate and microorganism involved in the process. Hence, it is necessary to maintain the pH at 5 to 7 for better yield [24]. Guo et al. [25] reported that the optimal pH range for livestock waste, food waste, and crop waste are 6.5 – 7.5, 5 – 6, and 6.5 – 7, respectively.

In case of photo fermentation process, microbes (photosynthetic bacterial species) use sunlight as the energy source to for consuming organic matter to produce hydrogen. These bacteria involved in photo fermentation process mostly belongs to the purple non-sulphur bacteria class, i.e., *Rhodospirillum*, *Rhodopseudomonas*, and *Rhodobacter*. During the photo fermentation process, the inoculum requires less nitrogen with a high carbon-to-nitrogen ratio to develop the free energy for hydrogen production [26]. Nitrogenase, uptake hydrogenase, fermentative [NiFe]-hydrogenase, and the CO-dehydrogenase/hydrogenase are the four major enzymes which control the metabolism of bacteria involved in hydrogen production by photo fermentation process.

2.4. Microbial electrolysis cell (MEC)

In the microbial electrochemical system, the microbes catalyse the process by converting organic substances into hydrogen in the presence of an external energy source, electricity. Microbial fuel cells (MFC) and microbial electrolysis cells (MEC) are methods used in this approach. Among these, the microbial electrolysis cells produce the hydrogen gas by electro-hydrogenation process under anaerobic condition. During this process, hydrogen is produced by oxidising the organic matter at the anode with the aid of electrochemical active bacteria and reducing the electrons at the cathode. The efficiency of hydrogen production by adopting MEC technology (75%) is higher than that of water electrolysis [27]. As the theoretical voltage required for hydrogen evolution reaction by the microbial electrochemical cell (-0.11 V) is 11 times lower than and water electrolysis process (-1.22 V). Thus, MEC technology not only aids in water treatment but also abets in hydrogen production. However, the high cost of membrane and catalyst (platinum) utilized in MEC increases the capital cost of the system.

3. Hydrogen storage technologies

The storage and transportation of hydrogen have some challenges due to low volumetric density, which needs compact, safe, and economic storage solution. Efforts are made by researchers to overcome the above bottleneck by storing hydrogen in compressed, cryo-compressed, liquefied, and in materials as depicted in Fig. 2. However, among these techniques only compressed hydrogen storage has achieved commercial scalability.

3.1. Compressed hydrogen gas

During this physical storage method, the hydrogen is compressed and stored at a pressure ranging from 20 to 70 MPa in specially designed vessels [28,29]. But the compression process is energy intensive and effective thermal management of the storage tank is needed to ensure hydrogen is stored safely. However, the following safety measures must be considered while selecting compressed gaseous hydrogen (cGH₂) [30].

- The cGH₂ storage containers must be made of durable materials and which is capable of withstanding high pressures without leakage.
- The effects of oxidisation and hydrogen penetration should also be considered while selecting the material for container.
- The vessels must meet the regulations, codes, and standards (RSC) developed by ISO and ASME which is regulated by government organisations.
- All the cGH₂ storage tanks should undergo the following tests namely, bonfire test, hydrostatic burst test, ambient pressure cycling test, penetration test, leak before break test as per RSC.
- Pressure relief devices (PRDs) must be incorporated in hydrogen storage vessels to ensure safety.
- Resealing and depressurization of the cGH₂ storage vessels are not permitted.

3.2. Liquefied hydrogen

This storage technology delves into liquefying the hydrogen before storing. Meanwhile, to ensure the hydrogen remains in liquid state, it

must be maintained at 21.2 K at ambient pressure, due to its extremely low critical temperature of 33 K [31]. Despite its promising performance, the boil-off losses happening during this process inhibit them from wider dissemination. Moreover, the theoretically high energy consumption (3.91 kWh/kg) of the liquefaction process adds to its complexity [32].

3.3. Cryo-compressed hydrogen

This technology synergies the advantages of compressed and liquefied hydrogen storage thereby enabling its storage at a temperature and pressure of 20 K as 35 MPa; respectively which is discharged around 0.4 MPa during its end use. Though hydrogen storage by cryo-compressed technology was successfully demonstrated by prototype, which was able to store 5.6 kg of hydrogen, this technology requires further investigation for it to be commercially viable [33].

3.4. Material based storage

All the above-discussed technologies, alters the physical characteristics of hydrogen to enable effective storage. But when the molecular forces of attraction [34] are instrumental in storing the hydrogen, then they are termed as material-based storage methods. During physisorption, porous materials with high surface area and an affinity towards hydrogen have been identified as potential adsorption storage materials. They include Metal-Organic Frameworks (MOF), carbon-based materials, zeolites, microspheres. Since physisorption is a surface phenomenon, the hydrogen binding energy is comparatively low, which facilitates faster reaction kinetics and does not require complex auxiliary thermal management systems [35]. The other advantages are the low-pressure requirement, cheaper adsorbent materials, low susceptibility to impurities, and simplistic system design. On the other hand, during chemisorption, intermetallic hydrides which are reversible are formed by hydrogen when it reacts with metals or metalloids. While absorption of hydrogen is an exothermic reaction and the release of hydrogen is an endothermic reaction. LaNi₅ is the most widely investigated metal hydride alloy, which forms hydride LaNi₅H₆ at 0.37 MPa and 313 K [36]. However, the hydrogen storage capacity by metal-based storage needs to be improved to make commercially viable. Table 1

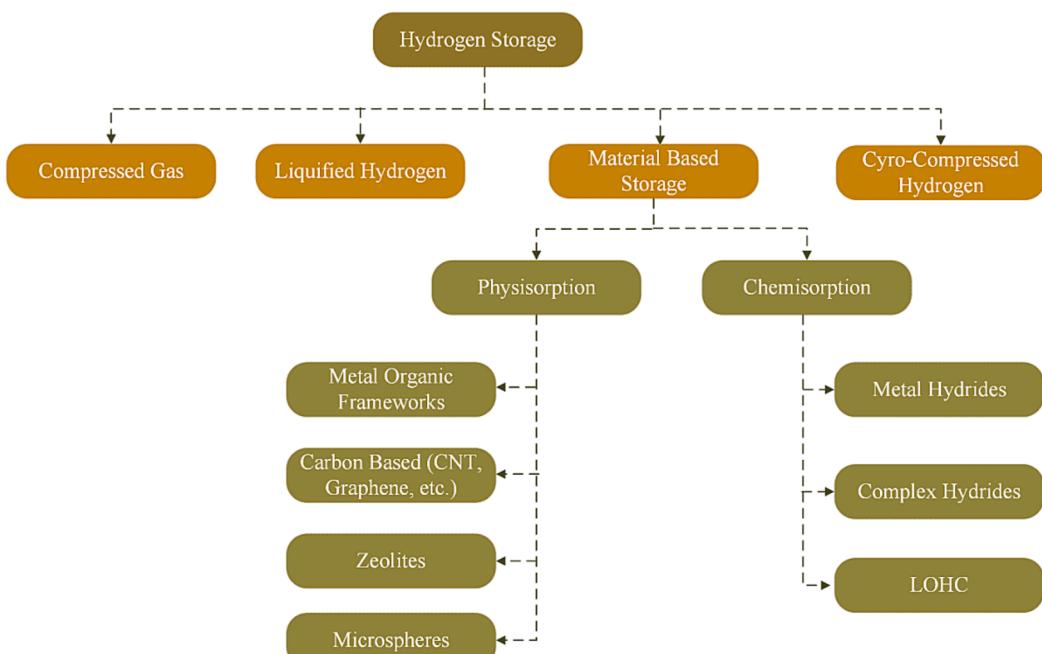


Fig. 2. Hydrogen storage methods.

Table 1

Summary of various hydrogen storage methods and their capacities.

Storage System	Storage Type	Storage Condition	Gravimetric Capacity (wt%)	Volumetric Capacity (g/L)	Reference
Type IV composite vessel 35 MPa	Compressed hydrogen gas	298 K and 35 MPa	5.5	17.6	[29]
Type IV composite vessel 70 MPa	Compressed hydrogen gas	298 K and 70 MPa	5.2–5.7	26.3	[37]
Low temperature vacuum super insulated double walled metal vessel	Liquid hydrogen	21.2 K and 0.1 MPa	–	70	[38]
Generation 2 prototype of cryogenic pressure vessel	Cryo-compressed hydrogen	20 – 260 K and 35 MPa	5.73	33.16	[39]
Generation 3 prototype of cryogenic pressure vessel	Cryo-compressed hydrogen	25 – 200 K and 27 – 30 MPa	6.5	47.8	[33]
Composite double walled vessel with vacuum superinsulation	Cryo-compressed hydrogen	20 – 180 K and 25 – 35 MPa	7 – 7.4	40.5	[40]
Metal organic framework, MOF-177	Physisorption based storage	77 K and 7 MPa	7.5	47	[41]
PCN-610/NU-100 (type of MOF)	Physisorption based storage	77 K and 5.6 MPa	9.95	28	[42]
MOF-5 with multiwalled carbon nanotubes	Physisorption based storage	77 K and 0.1 MPa	2	–	[43]
Carbon nanotubes (CNT) – Armchair (5,5) structure	Physisorption based storage	77 K and 10 MPa	19	–	[44]
Pristine graphene sheets	Physisorption based storage	77 K and 1 MPa	1.2	–	[45]
Al and Ni doped graphene sheets	Physisorption based storage	473 K and 5 MPa	5.7	–	[46]
Activated carbon from Tamarind seeds	Physisorption based storage	303 K and 4 MPa	4.73	–	[47]
Activated carbon from Melaleuca bark – SPK6	Physisorption based storage	77 K and 1 MPa	4.08	–	[48]
Zeolite template carbon (ZTC) – CB850h	Physisorption based storage	77 K and 2 MPa	6.9	–	[49]
ZTC derivative of Zeolite X	Physisorption based storage	77 K and 0.1 MPa	2.4	–	[50]
2 % Co loaded hollow glass microsphere	Physisorption based storage	473 K and 1 MPa	3.31	–	[51]
Metal hydride (MH) – LaNi ₅	Chemisorption based storage	313 K and 0.37 MPa	1.6	115	[36]
MH – Mg	Chemisorption based storage	620 K and 0.5 MPa	7.6	–	[52]
MH – Mg ₂ Ni	Chemisorption based storage	573 K and 2 MPa	3.8	–	[53]
Complex hydride – LiNH ₂ (TiCl ₃ as catalyst)	Chemisorption based storage	423 – 523 K and 3 MPa	5.5	–	[54]
Complex hydride – Ca(BH ₄) ₂	Chemisorption based storage	673 – 713 K and 70 MPa	9.6	–	[55]
Complex hydride – Li ₃ BN ₂ H ₈	Chemisorption based storage	523 K	10	–	[56]
LOHC – N-ethylcarbazole (1 g of Ru/Al ₂ O ₃ as catalyst)	Chemisorption based storage	413 K and 6 MPa	5.6	–	[57]
LOHC – 1-methylindole (5 wt% Pd/Al ₂ O ₃ as catalyst)	Chemisorption based storage	433 – 463 K	5.76	59	[58]

summarizes the various hydrogen storage methods and along with their capacities.

4. Techno-economic analysis

A technically proven technology must be economically feasible to attract investors. In this regard, TEA is a valuable tool to analyze the commercial feasibility of any technology or product. TEA involves the use of comprehensive process simulation models to design the complete production process, achieve mass and energy balance, and determine detailed process economics and profitability. The TEA provides insights on the process feasibility and helps in identifying the bottlenecks/hot spots in the entire process that pose technical challenges and are extremely critical to achieving economic viability.

4.1. TEA of bio-hydrogen production from different feedstock

Sarkar and Kumar [59] used biomass-derived bio-oil as a feedstock for producing bio-hydrogen. Bio-oil was produced through fast pyrolysis

of biomass, which was subsequently steam reformed to produce hydrogen fuel. The cost of hydrogen production from whole-tree-based biomass (\$2.40/kg of H₂) was observed to be lower than that from forest residue and agricultural residue [59]. Zhang et al. [60] performed a comprehensive techno-economic analysis to evaluate the economic feasibility of a commercial hydrogen production facility (2000 t/d) using two pathways: bio-oil gasification and bio-oil reforming. The analysis revealed that bio-oil reforming pathways is effective technology and have advantages like higher yield hydrogen production and lower TCI.

In another study, Galera and Gutiérrez [61] compared hydrogen and electricity production from glycerol through two different process namely supercritical water reforming (SCWR) and autothermal supercritical water reforming (ASCWR). The minimum selling price (MSP) of hydrogen generated at a feed rate of 1000 kg/h was found to be \$5.36/kg and \$5.75/kg (assuming discount rate = 10% and Net Present Value = 0) for SCWR and ASCWR technique, respectively. Despite the increment in production of hydrogen by about 1.54% during ASCWR process when compared to SCWR process, the MSP of hydrogen generated from

ASCWR process was higher, due to the increment in its investment cost and operating cost by about 8.5% and 7.6%, respectively, when compared to SCWR process.

Yao et al. [62] reviewed carbon neutral hydrogen production through various routes: dual fluidized bed (DFB) biomass steam gasification, alkaline electrolysis (AEL) and biogas steam reforming (BSR). The H₂ fuel production efficiencies of the DFB, AEL, and BSR was observed as 38.9%, 66%, and 47%, respectively. However, DFB process was found to be generate hydrogen at the minimum breakeven price of €0.148/kWh. The techno-economic and environmental analysis of bio-hydrogen generation from corn straw by adopting gasification technology incorporated with and without methane tri-reforming (MTR) was done by Li et al. [63]. Though the presence of MTR increased the total capital investment (TCI) of gasification system (GS) by 10.97%, the energy consumption and production cost (PC) decreased by 3.09% and 10.12%, respectively, when compared GS without MTR. Meanwhile, the presence of MTR also aided in increasing the energy efficiency of GS with MCR by 17.08 %. The payback period of GS with and without MCR was 4.72 years, respectively. Nevertheless, the carbon emission from GS with MCR was 4.96 kg CO_{2eq}/kg of H₂ which is lower than the carbon emitted from GS without MCR by 7.85%. The bio-hydrogen production from soybean straw was assessed by Okolie et al. [64] by employing catalytic supercritical water gasification process.

The TEA of gasification system capable of processing 170 MTPD feedstock was found to be economically feasible provided the MSP of hydrogen generated was \$1.94/kg. Meanwhile, the net return rate (NRR) of the system was 37.1%. Nouwe Edou et al. [65] evaluated the potential of generating 22,032 t/y of bio-hydrogen using four different thermo-chemical process to satisfy the fuel demand of 2300 public transport buses. Wood pellets were used as feedstock while employing direct thermo-chemical process namely, fluidised bed gasification (FBG), fast pyrolysis-FBG (FPFBG), and fast pyrolysis-steam reforming (FPSR) whereas in case of steam reforming of biogas (SRB) process the anaerobic digestor made used of food waste to generate biogas. The techno-economic modelling of the four processes were carried out by incorporating carbon capture and storage (CCS) system and assuming the CO₂ market price as \$120/t.

The capital cost and the operating cost of SRB process was the least at \$101.24 million and \$80, respectively. However, the minimum selling price of hydrogen generated by FBG was the least at \$3.40/kg as the system captured 3 times more CO₂ when compared to SRB. Yet all the systems were found to be economically viable as the payback period of these systems ranging between 5.10 and 7.18 years. The impact of incorporating a CCS system with a GS which uses corn straw to generate bio-hydrogen was evaluated by Ma et al. [66]. The incorporation of CCS system aided in reducing the CO₂ emission by about 0.94–1.49 kg CO_{2eq}/kg of H₂ generated. But the TCI and PC of the GS incorporated with CCS increased by 1.3 % and 14.6 %-19.6 %, respectively. Furthermore, the payback period of the bio-hydrogen generation system with and without CCS was found to be about 4.5 years and 5–6 years, respectively. The results stated that the TCI, PC, energy consumption, and payback period of the GS with CCS increased with increment in its CCS potential.

Reactive flash volatilisation (RFV) of micro algae which is considered as the 4th generation feedstock was investigated by Ghokar et al. [67]. RFV of microalgae in the presence of steam as gasifying agent aided in eliminating tar formation during hydrogen generation. Meanwhile, Ni-Rh/alumina catalyst was used for promoting hydrogen production. On evaluating the techno-economic feasibility of the bio-hydrogen plant which generated 1239 kg/h of H₂ on feeding 12790 kg/h of microalgae, it was found that the plant was economically feasible. As the payback period and IRR was 3.78 years with 22%, respectively.

Khamhaeng et al. [68] evaluated the techno-economic potential of generating hydrogen from ethanol via two different processes namely, steam reforming and dehydrogenation. The production cost of hydrogen

was minimum at \$1.58/kg while adopting steam reforming process. Yet when hydrogen was generated using steam reformation of ethanol it resulted in positive carbon emission, despite the usage of CO₂ for methanol production. On the other hand, dehydrogenation of ethanol not only produced hydrogen with zero carbon emission but also produced ethyl acetate or acetaldehyde as by-products which has market value.

Vatsala et al. [69] investigated the economics of hydrogen production from sugarcane distillery effluent and estimated the hydrogen production cost of \$35.44/100 m³. Meanwhile, the bio-hydrogen production system was found to be economically feasible, as it returned a net profit of about \$37070/year. The techno-economic analysis of bio-hydrogen generation by continuous mixed immobilized sludge reactor of various capacities were evaluated by Han et al. [24]. Molasses collected from sugar refining industry was used to produce hydrogen by dark fermentation process and it was found that the system became more feasible with the increment in plant capacity. However, hydrogen plants below 30-m³ was found to be economically non-viable. But the return on investment of 40-m³ and 50-m³ plants were found to be 0.63% and 9.25%, respectively, while its payback period was 9.7 years and 6.9 years, respectively.

Efforts were made by Ljunggren et al. [70] to enhance the productivity of bio-hydrogen from barley straw by combining dark fermentation and photo fermentation process. Nevertheless, the production cost of hydrogen was €421.7/GJ which is 20 times higher than cost required to generate ethanol from the same feedstock. Thus, making bio-hydrogen production from barley straw a least preferred option from investor perspective. On the other hand, a study investigated by Dasgupta et al. [71] compared the generation of hydrogen through photo-fermentation process from micro algae namely, *Scenedesmus* sp. NBRI012 and *Chlorella* sp. NBRI029. Among these two microalgae, *Scenedesmus* sp. NBRI012 was observed to produce highest amount of hydrogen (17.72% v/v H₂ of total gases). Meanwhile, production of H₂ in sulphur deprived environment aided in incrementing the lipid content of residual micro algae which was used as feedstock for biodiesel production.

Mahmod et al. [72] studied the performance of hydrogen and methane generation from two stage anaerobic system of capacity 204,750 MT_{POME}/year by using Palm oil mill effluent (POME) rich in fermentable sugars as feedstocks. Furthermore, the two-stage anaerobic system was found to be economically viable with the net present value (NPV), internal return rate (IRR), dynamic payback period and return on investment (ROI) of \$4624705, 21.48%, 8.01 years, and 19.87% respectively. Meanwhile, it was reported that the quality of POME and market price of products had an enormous impact on the economic viability of the two-stage anaerobic system. Tawfik et al. [73] evaluated the performance of hydrogen and methane generation from wastewater of biscuit industry by employing up-flow anaerobic hybrid reactor (UAHR). The hydrogen yield and the payback period of the system was found to be 118.6 ± 22.3 mL/g COD_{removed} and 7.1 years, respectively. However, the hydrogen yield of the system was incremented to 414.2 ± 38.1 mL/g COD_{removed} when a mixture of biscuit industry wastewater and domestic sewage was used as feedstock in the ratio of 3:1, respectively. Thus, the increase in hydrogen productivity aided in decreasing the payback period of the anaerobic system to 5.7 years. Table 2 and 3 summarises the production of hydrogen from bio feedstocks and non-bio feedstocks, respectively by adopting different process along with its yield. Fig. 3 represents the biohydrogen production cost from different methods.

4.2. Factors influencing the Bio-hydrogen production

Bio-hydrogen production can be centralized or decentralized or a combination of both. The choice would be highly influenced by the type of source and feedstock used. The centralized system would be preferred for the plants producing exceptionally large volumes at high production

Table 2

Summary of Hydrogen production from Bio feedstock with various process conditions and its yields.

Feedstock	Process	Reactor	Organism or enzymes	T(°C)	P	pH	Software	Capacity	Production	Yield (H ₂ & Price)	CAPEX (\$)	Efficiency (%)	IRR (%)	Ref.
Corn straw	Gasification	Circulating fluidized bed reactor	NA	1300 °C	3 Mpa	Aspen Plus 8.8	0.27 MTD	NA	1004.5 kg/h	CNY 1,178 M/a	37.8 %	NA	[63]	
Corn straw	Gasification with methane tri-reforming catalytic supercritical water gasification	Circulating fluidized bed reactor	NA	1300 °C	3 Mpa	Aspen Plus 8.8	0.23 MTD	NA	1004.5 kg/h	CNY 1,307 M/a	44.4 %	NA	[63]	
Soybean straw				500 °C	25 Mpa	Aspen Plus v7.3	170 MTD	110 t/d	\$1.94/kg	6.25 M	NA	10 %	[64]	
Wood chips and wood pellets	Gasification	Circulating FB reactor		850 °C	NA	ASPEN plus v9	2,181 t/d	62.1 t/d	\$2.84/kg	118.56 M		15 %	[65]	
Wood chips and wood pellets	FPPBG	Circulating FB reactor fast pyrolysis reactor followed by FBG reactor		500 °C & 850 °C	NA	ASPEN plus v9	1.22 MTD	62.1 t/d	\$7.49/kg	219.8 M		15 %	[65]	
Wood chips and wood pellets	Fast pyrolysis-steam reforming	FB fast pyrolysis reactor followed by catalytic steam reformer		500 °C & 900 °C	NA	ASPEN plus v9	0.7 MTD	62.1 t/d	\$6.58/kg	178.5 M		15 %	[65]	
Food and agricultural wastes	SRB	AD followed by catalytic steam reformer		atmospheric & 850 °C	NA	ASPEN plus v9	1.68 MTD	62.1 t/d	\$3.67/kg	101.24 M		15 %	[65]	
Bio-oil	Gasification	Fluidized bed reactor	NA	500 °C & 900 °C	20 atm	NA	ASPEN PLUS	2000 MTD	147 MTD	NA	374 M	47 (EE)	8.4	[60]
Microalgae	Reforming pathways Fermentation method	NA	Scenedesmus sp	27 °C ± 0.5 °C	NA	NA	7.2	NA	160 MTD	NA	374 M	84 (EE)	18.6	[71]
Waste bread	Dark fermentation& Anaerobic sludge	CSTR	Aspergillus awamori & Aspergillus oryzae	55 °C (enzymatic hydrolysis)	NA	NA	ASPEN PLUS	58.8 m ³ (waste capacity)	353.9 mL/h/1 H ₂	37.6 % (Biogas content) & \$14.9/kg H ₂	0.9 M	61 (HE)	21.7	[74]
Food waste	Solid-state Fermentation method & Anaerobic sludge	NA	Aspergillus awamori & Aspergillus oryzae	55 °C (enzymatic hydrolysis)	NA	4–4.6	ASPEN PLUS	3-ton waste food/day	42,858 m ³ H ₂ /year	39.14 mL H ₂ /g food waste & \$1.02/m ³	0.58 M	82.8–87.2 (SCE)	24.7	[75]
Beverage water Agricultural waste	Dark fermentation	Batch fermenter	NA	37 °C (optimal condition)	NA	5.5	ASPEN PLUS	10 m ³	NA	27.37 L/d/L & \$2.7/m ³	0.16 M	NA	NA	[76]
Biomass	Dark fermentation	Hydrogen fermenter	NA	70 °C	NA	NA	ASPEN PLUS	32.3 metric ton	21.2 kg/h	45.75 mmol H ₂ /L/h	€12.6 M	NA	NA	[77]
Barely straw	Dark fermentation	NA	Caldicellulosiruptor saccharolyticus	70 °C	NA	6.5	ASPEN PLUS	0.2 MT dry straw per year	1243 kg/h	20 mmol H ₂ /L/h & €51.0/kg H ₂	€ 225.6 M/y	NA	NA	[70]
Bio-oil	Steam Reforming	NA	NA	850 °C	0.17 MPa	NA	ASPEN PLUS	2000 dry tones/day	NA	9.8 % wt & \$2.42/kg H ₂	0.05 M	NA	NA	[59]
Microalgae	Gasification (RVF)	NA	NA	NA	NA	NA	ASPEN PLUS	NA	NA	1239 kg/d H ₂ & ₹650/kg H ₂	144.6 M	NA	22	[67]
Methanol Ethanol	Reforming (SMR)	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	36.6 (EE)	NA	[78]

T-Temperature; p-Pressure; CAPEX-Capital expenditure; η-Efficiency; IRR-Internal rate of return.

Table 3

Summary of Hydrogen production non-bio feedstock with various process conditions and its yields.

Feedstock	Method	Process	Software	Best scenario	Efficiency (%)	H ₂ Market price	H ₂ output	Emissions	CAPEX (\$)	Plant life (Y)	Payback period (Y)	IRR (%)	Ref.
Natural gas	i) SMR ii) ATR iii) SCL iv) CLR	Reforming	ASPEN Plus V8.6	CLR consumes least natural gas for hydrogen production	84 (TE)	\$0.98/kg H ₂	18.9 t H ₂ /h	8.8 kg CO ₂ /kg H ₂ (CLR)	570 M	30	NA	12	[79]
Natural gas	SE-SMR configuration	Reforming	ASPEN Plus	SE-SMR with indirect air-natural gas combustion calciner	82.6 (NE)	€2.20–3.00/kg H ₂	19.5 t H ₂ /h	5.5 kg CO ₂ /kg H ₂	€264.9 M	30	5	NA	[80]
Natural gas	i) ICLWS ii) SMR	Reforming	ASPEN Plus V8.8	ICLWS having higher hydrogen efficiency	79.3 (TE)	\$1.41–1.62/kg H ₂	0.24 MT/y	0.84 kg CO ₂ /kg H ₂	\$369.6 M	25	NA	NA	[81]
Natural gas	SMR	Reforming	NA	Steam reforming of Natural gas having less payback period and higher ROI	70–80 (FCE)	\$1.48/kg H ₂	1500/kg	NA	\$1514322	20	6–7	31	[82]
Water	Three different hypotheses	Electrolyser	NA	The power to a gas concept is introduced based on water electrolysis	70 (ELE)	€20.3/kg H ₂	12.7 kg H ₂ /d	NA	€542.75 k	20	12	9.8	[83]
Water	Four different configurations of a hybrid system	Electrolyser	HOMER	Grid-connected system having less cost to energy	NA	COE- \$0.096 to 0.125/kWh.	NA	30591 kg/y	\$173570	25	NA	NA	[84]
Natural gas and biomass	i) Biomass EF ii) Biomass FB iii) SMR iv) NTR	Reforming and Gasification	ASPEN PLUS Model	EF based having higher thermal efficiency	56 (TE)	\$3.1/kg H ₂	18.9 kg H ₂ /h	11.4 kg CO ₂ /kg H ₂	\$1229 M	30	NA	12	[85]
Water	Various aspects of decentralized water electrolysis are investigated	Electrolyser	NA	This study identifies the competitive decentralized hydrogen is evaluated	80 (EE)	\$2.57/kg H ₂	NA	86 g CO _{2eq} /km	NA	25	NA	NA	[86]
Natural gas and biomass	i) BTH ii) MTR	Reforming and Gasification	ASPEN Plus V8.8	Both BTH and MTR contribute to solving environmental problem without considering the natural carbon cycle	36.6 (EE)	NA	1004.5 kg H ₂ /h	4985.1 kg CO _{2eq} /1004.5 kg H ₂	115 × 10 ⁷ CNY	20	4.5	NA	[87]
Water	Solar Thermochemical System	Electrolyser		Concentrating solar plant with multiple towers to split water	54 (SFE)	\$2.57/kg H ₂	1431 kg/d H ₂	NA	\$34141704	25	NA	NA	[23]
Water	i) PEC ii) PV-E	Electrolyser	HOMER	The base case PEC system having advantages over other five cases	61 (PE)	\$1.39/kg H ₂	10000 kg/d H ₂	NA	NA	20	NA	NA	[88]
Coal and Biomass	i) BTH ii) CTH	Reforming and Gasification	ASPEN PLUS	This study evaluates the hydrogen production from BTH & CTH	37.82 (EE)	0.62 CNY/Nm ³ H ₂	NA	15 kg CO ₂ /kg H ₂ –BTH	NA	20	NA	NA	[89]

PEC- Photo electrochemical; MTR-Methane Tri Reforming; PV-E- Photovoltaic-electrolytic; CTH- Coal to hydrogen; BTH- Biomass to Hydrogen; SMR- Steam Methane Reforming; ATR- Auto Thermal Reforming; SCL- Syn gas Chemical lopping; CLR- Chemical Looping Reforming; ICLWS- Integrated Chemical Lopping Water Splitting; ROI- Rate of Investment; COE – Cost of Energy; FB- Fluidized bed; EF- Entrained flow; NA-Data Not Available.

Feedstock



Production Method

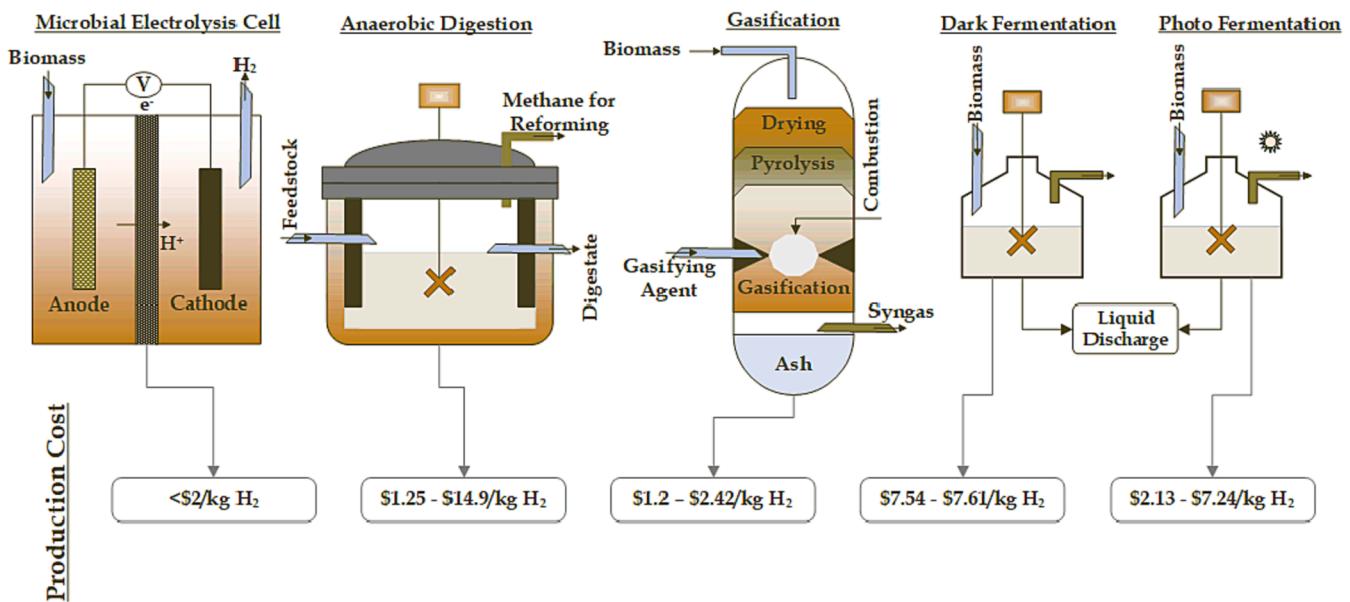


Fig. 3. Hydrogen production cost of different methods [19,90,91].

efficiency. From this facility, the bio-hydrogen could be disturbed to long range for the electricity production. Meanwhile, hydrogen produced by an electrolyser energized by biomass resource becomes feasible only when the cost of electricity generated is less than €60/MWh and the operating hours of the centralised plant is greater than 6500 h/a. Furthermore, the hydrogen production cost decreases when the electrolyser capacity increases from 2 MW to 10 MW [92]. Furthermore, the demand for the hydrogen in the market should also be analysed before setting up centralised bio-hydrogen plants because the maximum amount of hydrogen that can be blended with natural gas is 25% [93].

On the other hand, the decentralized bio-hydrogen production system is used for the local fuelling. However, when the electrolyser is used for hydrogen generation to supply local fuelling station the decentralized facilities connected to the grid deliver hydrogen at lower price (€2.2–3.3/kg H₂) when compared to decentralized unit connected dedicated wind and/or solar PV systems (€2.5–6.7/kg H₂) [94]. The improper balance between the centralized and decentralized system for bio-hydrogen production highly affects the hydrogen economy [95].

Another major issue is transportation and storage infrastructure which will affect the supply and demand of the bio-hydrogen. The suitable technology for transportation must be identified and stored based on production and its usage. Meanwhile, the cost of hydrogen is highly affected by feedstock cost and its quality. Though the cost of feedstock can be reduced by making use of waste from wood, ethanol and MSW (Municipal Solid Waste). Sustainable supply chain of feedstock with homogenous quality is needed for continuous operation of large-scale hydrogen generation plant. The installation of large-scale hydrogen generation plant helps in reducing the high capital cost needed for bio-chemical and thermo-chemical plants. The high market value for hydrogen can also help in attracting investors thereby enabling faster dissemination of technology.

In addition, the low utility cost of electricity generated from low carbon source not only aid in making the system economically feasible by reducing its operating cost but also aids in reducing the carbon emitted during hydrogen generation. At the same time, researchers must focus on identifying a low-cost anode and current collector material for generating hydrogen using microbial electrolytic cell (MBC). As these material account for 94% of the total material cost in MBC. Above all implementation of strong policies supporting hydrogen generation from biomass by governing bodies is necessary for faster dissemination of hydrogen production technologies. Since, the cost hydrogen generated from biomass is higher than cost of H₂ generated from conventional fossil fuel sources.

5. Life cycle assessments of biohydrogen production

LCA is a well-established approach to comprehensively analyze the environmental impact of a product at various stages of its life, including raw material acquisition, production, utilization, and recycling [1]. Several studies quantified the environmental impacts in terms of fossil energy use, GHG (Green House Gases) emissions, and other environmental categories, of biohydrogen production using LCA approaches. Due to the non-existence of commercial biohydrogen production, most of these LCA studies have been performed using primary data from lab-scale/pilot-scale experiments and process simulation models. The primary materials to produce biohydrogen are lignocellulosic biomass. Most of the LCA studies on biohydrogen production evaluated the global warming potential (GWP) only by using the system boundary provided in Fig. 4.

Wulf and Kaltschmitt [4], compared LCA results from six biohydrogen pathways, including gasification of softwood and short rotation coppice (SRC), steam reforming of biomethane from two feedstocks,

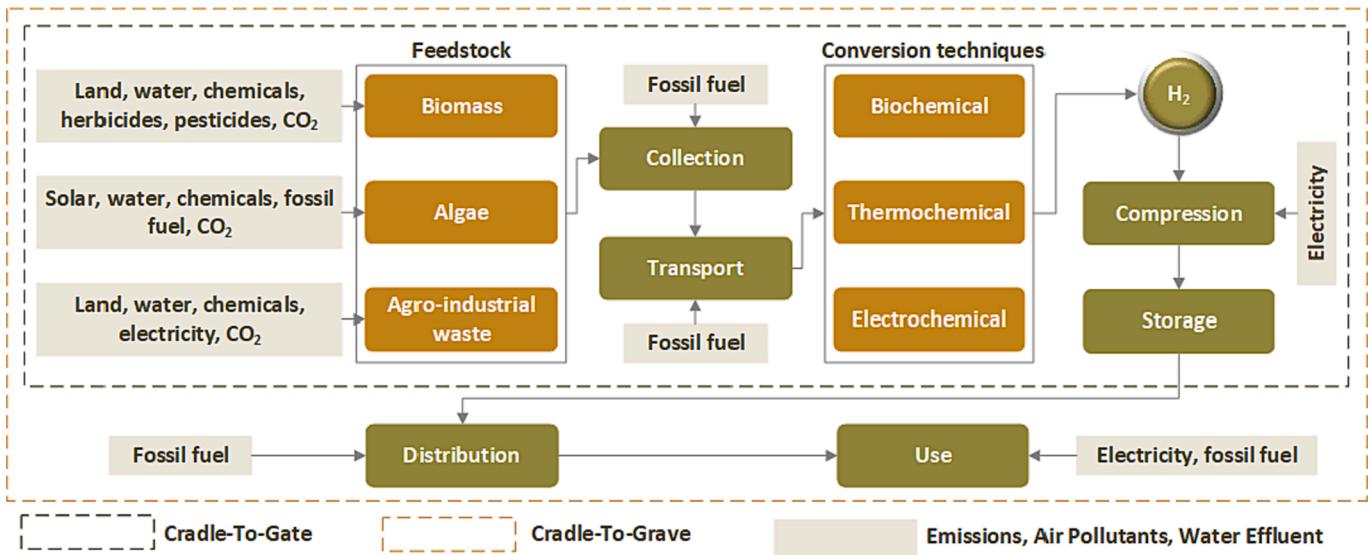


Fig. 4. Hydrogen production system boundary conditions.

pyro reforming of glycerol (by-product from biodiesel), and alkaline water electrolysis using electricity produced from burning straw. The pyro reforming process resulted in the highest GHG emissions among all production pathways, followed by the electrolysis process. This was due to high emissions associated with glycerol production and lower electrical power efficiency. The GHG emissions from the hydrogen production from gasification of forest residues (28.3–29.7 g $CO_{2eq}/MJ H_2$ or 3.4–3.6 kg $CO_{2eq}/kg H_2$) were minimum among all pathways. As it does not need fertilizers and pesticides for its growth. Similar observations were made by Moreno et al. [96], who concluded that GHG emissions

during H_2 production from gasification of forest waste from pine and eucalyptus were lower than using vine and almond pruning as feedstocks. In their study, the total CO_2 emissions were found to be negative for eucalyptus due to its ability to fix highest amount of carbon during its growth [96]. Siddiqui and Dincer, (2019a) [97] also observed that among six production pathways (Water electrolysis, corn stover gasification, coal gasification, steam methane reforming, natural gas-based methanol-reforming, corn ethanol reforming), hydrogen production through the gasification of corn stover resulted in the least GHG emissions (4.4 kg $CO_{2eq}/kg H_2$ vs 12.2–28.6 kg $CO_{2eq}/kg H_2$).

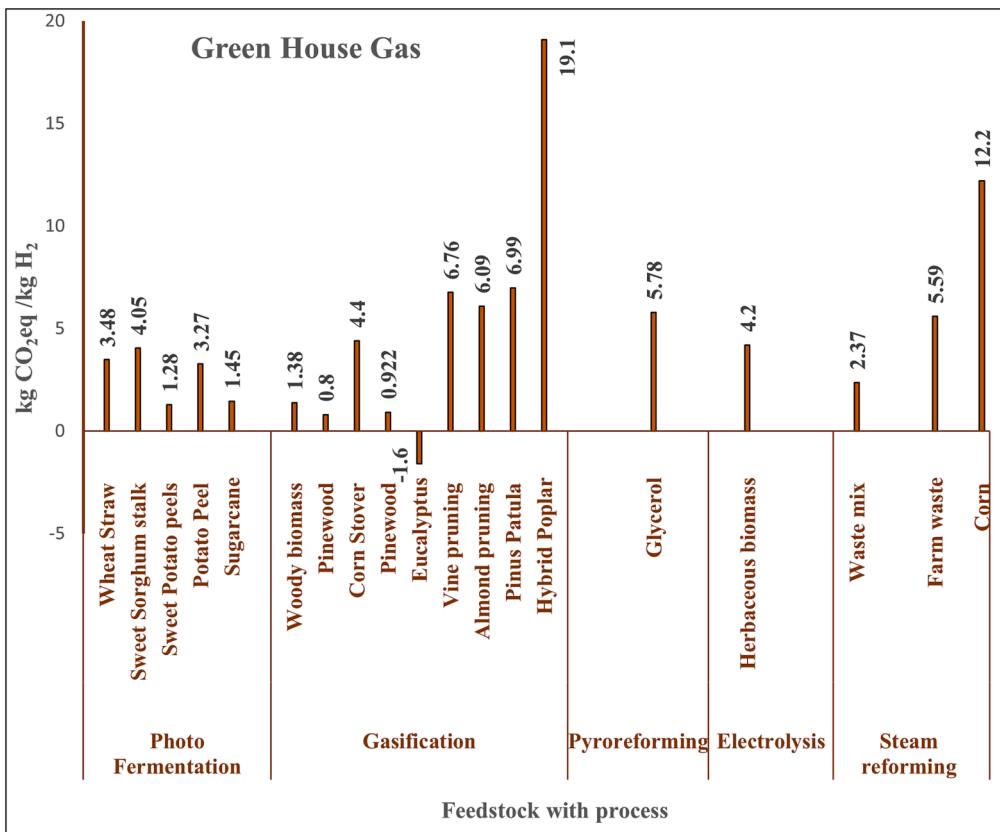


Fig. 5. Environmental effects from various biohydrogen production methods.

Hydrogen production through the gasification of biomass has been found to be promising and environmentally friendly approach [6]. Susmozas et al. [6] determined the environmental impact of hydrogen production from hybrid poplar through gasification route and found that its GWP (0.41 kg CO_{2eq}/kg H₂) was several folds lower compared to hydrogen production from natural gas using steam reforming (10.56 kg CO_{2eq}/kg H₂). However, the poplar growth requires huge land area thereby making its land competition (LC) impact higher. It is interesting to note that although fossil energy input was observed lower compared to the conventional process (natural gas-based steam reforming), the total energy input was higher, leading to low lifecycle energy efficiency (19 % vs 65 %). This trend was also observed during LCA of other renewable transportation fuels, such as lignocellulosic ethanol [98]. The emissions reported by Susmozas et al. [6] were significantly lower compared to Wulf and Kaltschmitt [4] because of the assumption of in-house electricity production (instead of electricity from the local grid) by burning all by-product gases (after hydrogen separation). Due to the same assumption, Kalinci et al. [99] also reported lower GHG emissions (0.75–2.06 kg CO_{2eq}/kg H₂) during the lifecycle of biohydrogen production from gasification of pinewood (Fig. 5).

Hajjaji et al. [100] conducted LCA of biohydrogen production by reforming biogas produced from anaerobic digestion (AD) of farm waste and found its GHG emissions were (5.59 kg CO_{2eq}/kg H₂) about 50 % lower compared to steam reforming process. The emissions reported in this study were similar to the biohydrogen production from reforming of biogas produced from AD of German substrate mix and non-food substances (5.9–6.1 kg CO_{2eq}/kg H₂), reported by Wulf and Kaltschmitt [4]. The emissions from reforming of methane produced from typical German mix and German mix including non-food mix were similar. Although maize (major fraction of German mix) production cause significantly high GHG emissions compared to waste, the high methane yield (almost 4 times than waste) compensate the net GHG emission in the overall life cycle of H₂ production process [4]. The net energy ratio (NER) of 28.88 calculated by Hajjaji et al. [100] was about 50 time higher compared to NER for natural gas reforming (0.57).

Njakou and Blumberga [3] compared the energy use and environmental impact results from LCA of biohydrogen production using sugar fermentation pathway for three feedstocks namely: wheat straw (WS), sweet sorghum (SS) stalk, and sweet potato peels (SPP). The agricultural residues (WS and SS) required an energy-intensive pre-treatment process before hydrolysis of sugars, whereas SPP can be directly hydrolysed. Though, the remaining unit processes were same, the amounts of enzymes and chemicals involved varied due to the different chemical compositions of the feedstocks. The results were highly impacted by including the co-product credit (using the system expansion approach). The SPP remained the most environmentally friendly feedstock with minimum environmental impact followed by WS and SS. A similar trend was observed for the resource depletion and GHG emissions, with SPP identified as the best feedstock for hydrogen production (Table 4). The emissions from using hydrogen produced from these three feedstocks were 52 to 56% and 54 to 57% lower compared to diesel and methane reforming, respectively. The energy ratio was also found maximum for SPP among three feedstocks (2.67 compared to 1.54 and 1.4 for WS and SS) as it does not require any pre-treatment. Among the various stages of hydrogen production, the fermentation process contributed the maximum in the GHG emissions due to high electricity demand in the bioreactors. Ferreira et al. [1] conducted an energy and environmental impact analysis of biohydrogen production from sugarcane and potato peels. The CO₂ emissions for hydrogen production from potato peel were 35 % and 67 % lower than hydrogen produced using natural gas reforming and hydrogen electrolysis processes, respectively. The emissions reduction was lower compared to the values (54 % reduction compared to reforming) reported by Njakou and Blumberga [3] for biohydrogen production from sweet potato peels. This could be explained by the exclusion of co-product credit in the current study [1].

The emission reduction values were even lower for sugarcane

(23.74–31.06 g CO_{2eq}/MJ H₂; 74 and 87% lower). Due to the assumption of sugarcane transportation from Brazil, the distribution system was a major contributor to the energy use and GHG emissions compared to the farming process in the case of potato peels. Since, peels are considered as waste, it aided in decrementing the emissions by 7%. However, a LCA study on hydrogen production from steam potato peels through the fermentation route reported the process being highly inefficient and produce worse environmental impact when compared to the steam reforming process [101]. The inputs (mainly phosphorous) used during the fermentation process were found responsible for these results. Meanwhile, the hydrogen yield in this study was almost one-third of that reported by Njakou and Blumberga [3], thus, indicating the significance of assumption used in the process simulations and calculations. The GHG emissions during hydrogen production from dark fermentation of microalgae were high and unsustainable (5–6 kg CO_{2eq}/MJ). Most of these emissions (more than 50%) were contributed by microalgae culturing and cultivation [104]. Meanwhile, the emissions were found extremely sensitive to the type of energy mix used for electricity production. Also, in the scale-up scenarios, considering optimized cultivation using advanced techniques, the emissions were reduced by 14%. Further, on accounting the CO₂ absorbed, the total emissions were found to be negative (-584 to -406 g CO_{2eq}/MJ H₂). These results further indicate and emphasize the importance of choosing the appropriate assumptions, the scale of operation, and data while performing an LCA.

6. Hindrance and status of commercialization

Biohydrogen production technologies have seen more advancement the last decade with inventions of new materials for efficient storage, transportation, supply chain establishment, strategies for pre-treatment of raw materials, and development of automobiles whose engines are compatible with using hydrogen as a fuel. Despite these advances, certain hindrances challenge the use of hydrogen on a large scale. Some of them are as follows.

- The generation of oxygen during hydrogen production via fermentation process acts as strong repressors of enzymes (hydrogenases, nitrogenases) involved in hydrogen production [105].
- When multiple reactions are combined for efficient utilization of feedstock, it requires the engineering of multiple reactors with distinct experimental conditions and process controls thereby incrementing the overall cost [106].
- Storage and supply of hydrogen is still an issue owing to the low volumetric density of hydrogen [107]. The existing amenities lack safe, compact, low-weight, and cost-effective infrastructure for the ease of transportation.
- The reactor of hydrogen production system requires control of operating parameters that are specific to the method of synthesis, raw materials used, and microbial strain cultivated.
- The pre-treatment techniques involving thermal, electrical, and enzymatic agents are likely to add up to the overall cost of the process and should be carefully chosen prioritizing the properties and composition of the feedstock.
- In the case of microbial electrolysis, the choice of electrodes and membranes should be economical, efficient, and eco-friendly.
- The risk of handling high compression energy of hydrogen gas poses a threat to the labor and energy consumed. Also, the targeted volumetric capacity of Type IV tanks has not yet been achieved despite improvement in system gravimetric capacity [29].
- High storage capacity can be attained with liquified hydrogen; however, the temperature must be maintained at 21.2 K at atmospheric pressure. Also, the power consumed during the process of liquefaction is significantly high [108].
- The present techniques lack proper management of the thermal build-up of gas in storage tanks during fast-filling which can be unsafe [109].

Table 4

Environmental impacts of biohydrogen production using various feedstocks and production pathways.

Substrate/Study location	Production Pathway	System Boundary	Allocation Type	Impact categories	Results	Database	Notes	Reference
Wheat Straw (Belgium)	Consecutive thermophilic & photo fermentation of sugars obtained from hydrolysis	well-to-tank	System expansion (protein residue replaces animal feed)	human health, ecosystem quality, climate change, and resources	GHG: 3.48 kg CO _{2eq.} /kg H ₂ Resources: 79.09 MJ/kg H ₂ Human health impact: -8×10^{-7} DALY/kg H ₂	Pilot plant, literature, Ecoinvent database	Alkali pre-treatment The results mentioned here are including co-product credits	[3]
Sweet Sorghum stalk (Belgium)	Consecutive thermophilic & photo fermentation of sugars obtained from hydrolysis	well-to-tank	System expansion (protein residue replaces animal feed)	human health, ecosystem quality, climate change, and resources	GHG: 4.05 kg CO _{2eq.} /kg H ₂ Resources: 87.3 MJ/kg H ₂ Human health impact: -2.54×10^{-8} DALY/kg H ₂	Pilot plant, literature, Ecoinvent database	Alkali pre-treatment The results mentioned here are including co-product credits	[3]
Sweet Potato peels (Belgium)	Consecutive thermophilic & photo fermentation of sugars obtained from hydrolysis	well-to-tank	System expansion (protein residue replaces animal feed)	human health, ecosystem quality, climate change, and resources	GHG: 1.28 kg CO _{2eq.} /kg H ₂ Resources: 45.7 MJ/kg H ₂ Human health impact: -24×10^{-6} DALY/kg H ₂	Pilot plant, literature, Ecoinvent database	No pre-treatment The results mentioned here are including co-product credits	[3]
Potato Peel (Portugal)	Consecutive thermophilic & photo fermentation of sugars obtained from hydrolysis	well-to-tank		GHG emissions, energy use	GHG: 59.78–70.39 g CO _{2eq.} /MJ H ₂ Energy use: 0.49–0.61 MJ/MJ H ₂	SimaPro 7.1, Greet 1.7	Co-product (protein rich residue) credits were not considered Range in the results is due to uncertainty in electricity production	[1]
Sugarcane (Portugal)	Consecutive thermophilic & photo fermentation of sugars obtained from hydrolysis	well-to-tank	Not allocated	GHG emissions, energy use	GHG: 23.74–31.06 g CO _{2eq.} /MJ H ₂ Energy use: 0.3–0.34 MJ/MJ H ₂	SimaPro 7.1, Greet 1.7	Sugarcane imported from Brazil; Co-product (bagasse) credits were not considered Range in the results is due to uncertainty in electricity production	[1]
Potato steam peels (Austria)	Consecutive thermophilic & photo fermentation of sugars obtained from hydrolysis	Well-to-gate	–	acidification, arcinogens, climate change, ecotoxicity, fossil fuel, respiratory inorganics, respiratory organics, radiation, ozone layer, land use, minerals and	Environmental impact: 4.3 pts/kg H ₂	Aspen Plus, SimaPro, Ecoinvent database	Results of impact categories were expressed in points	[101]
Algae (Portugal)	Dark fermentation	well-to-gate	–		GHG: 5119–6268 g CO _{2eq.} /MJ H ₂	SimaPro 7.1, Ecoinvent database	Algae production in outdoor raceway pond	[102]
Woody biomass (forest residues and short rotation coppice) (Germany)	Gasification	Well-to-gate	Mass and volume-based allocation for wood residue production	GHG emissions, AP, fossil energy demand	GHG: 28.3–29.7 g CO _{2eq.} /MJ H ₂ AP: 71 mg SO _{2eq.} /MJ H ₂	Ecoinvent database		[4]
Pinewood (Turkey)	Gasification	Well-to-wheel	–	Fossil energy use, GHG emissions	GHG: 6.27–17.13 g CO _{2eq.} /MJ H ₂ H ₂ Energy ratio (output/input) : 5.71 – 11.36	–	Two types of gasifiers: Downdraft and Fluidized Bed; Energy ratio include only fossil energy input	[99]
Corn Stover (Canada)	Gasification	Well-to-pump	–	AP, GWP, HTP, POFP, EP	GWP: 4.4 kg CO _{2eq.} /kg H ₂ AP: 0.016 kg SO _{2eq.} /kg H ₂ POFP: 0.0015 kg-ethene eq./kg H ₂ EP: 0.00086 kg PO _{4eq.} /kg H ₂	Greet	–	[97]

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Table 4 (continued)

Substrate/Study location	Production Pathway	System Boundary	Allocation Type	Impact categories	Results	Database	Notes	Reference
Pinewood (Spain)	Gasification	Well-to-gate	–	GHG, acidification and eutrophication	GHG: 0.922 kg CO _{2eq} /kg H ₂ Net energy ratio: 0.47	Ecoinvent database	Fix bed gasifier; Net energy ratio did not account energy in biomass and co-products	[96] **
Eucalyptus (Spain)	Gasification	Well-to-gate	–	GHG, acidification and eutrophication	GHG: –1.6 kg CO _{2eq} /kg H ₂ Net energy ratio: 0.52		Fix bed gasifier; Net energy ratio did not account energy in biomass and co-products	[96] **
Vine pruning (Spain)	Gasification	Well-to-gate	Mass based allocation between fruits and waste	GHG, acidification and eutrophication	GHG: 6.76 kg CO _{2eq} /kg H ₂ Net energy ratio: 0.41		Fix bed gasifier; Net energy ratio did not account energy in biomass and co-products	[96] **
Almond pruning (Spain)	Gasification	Well-to-gate	Mass based allocation between fruits and waste	GHG, acidification and eutrophication	GHG: 6.09 kg CO _{2eq} /kg H ₂ Net energy ratio: 0.37		Fix bed gasifier; Net energy ratio did not account energy in biomass and co-products	[96] **
<i>Pinus Patula</i> (Colombia)	Gasification	Well-to-gate		GWP, ODP, TA, FE, ME, POFP, HT, TET, FET, MET, WD, FD	GHG: 0.15 kg CO _{2eq} /MJ H ₂ ODP: 1.52 × 10 ⁻⁶ g CFC-11 eq./MJ H ₂ TA: 3.41 × 10 ⁻⁴ kg SO _{2eq} /MJ H ₂ FE: 0.01 kg P eq./MJ H ₂ ME: 4.29 × 10 ⁻⁵ kg N eq./MJ H ₂	Aspen plus model, literature, SimaPro	–	[103] ***
Hybrid Poplar	Gasification	Well-to-gate	Economic allocation	GWP, ADP, ODP, AP, EP, POFP, LC	GHG: 0.41 kg CO _{2eq} /kg H ₂ ADP: 8.57 × 10 ⁻³ kg Sb eq./kg H ₂ ODP: 1.62 × 10 ⁻⁷ kg CFC-11 eq./kg H ₂ POFP: 44 × 10 ⁻³ kg C ₂ H _{2eq} /kg H ₂ LC: 13.43 m ² a/kg H ₂ AP: 11.9 × 10 ⁻³ kg SO _{2eq} /kg H ₂ EP: 2.85 × 10 ⁻³ kg PO ₄ ³⁻ eq./kg H ₂	Aspen Plus model, Ecoinvent database	Economic allocation: 0.95 for hydrogen and 0.05 for electricity	[6]
Glycerol (by-product from biodiesel) (Germany)	Pyroreforming	Well-to-gate	–	GHG emissions, AP, fossil energy demand	GHG: 124.1 g CO _{2eq} /MJ H ₂	Ecoinvent database		[4]
HerbaceousBiomass (Germany)	Electrolysis of water using electricity produced from burning straw	Well-to-gate	–	GHG emissions, AP, fossil energy demand	GHG: 90 g CO _{2eq} /MJ H ₂	Ecoinvent database	Assumed electrical efficiency 33.5 %; electrolyser efficiency 60 %	[4]
Waste mix (Germany)	Steam reforming of methane produced from anaerobic fermentation of organics	Well-to-gate	–	GHG emissions, AP, fossil energy demand	GHG: 48.7–50.7 g CO _{2eq} /MJ H ₂ AP: 751–969 mg SO _{2eq} /MJ H ₂	Ecoinvent database	German substrate mix (mostly maize silage) and non-foodSubstances (mostly kitchen and garden residues)	[4]
Farm waste (Mix of manure, cheese whey, maize silage, and fodder beet)	Steam reforming of biogas produced from anaerobic fermentation of organics	Well-to-gate	System expansion (digestate replaces mineral fertilizers)	ADP, GWP, ODP, AP, HTPce, HTPnce, IRP, POCP	GHG: 5.59 kg CO _{2eq} /kg H ₂ ADP: –1.20 × 10 ⁻⁴ kg Sb eq./kg H ₂ ODP: 1.53 × 10 ⁻⁵ g CFC-11 eq./kg H ₂ AP: 0.29 mol H ⁺ eq./kg H ₂	Ecoinvent database		[100] ***

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Table 4 (continued)

Substrate/Study location	Production Pathway	System Boundary	Allocation Type	Impact categories	Results	Database	Notes	Reference
Corn	Reforming of ethanol from corn	Well-to-pump	–	AP, GWP, HTP, POFP, EP	GWP: 12.2 kg CO _{2eq.} /kg H ₂ AP: 0.032 kg SO _{2eq.} /kg H ₂ POFP: 0.0045 kg-ethene eq./kg H ₂ EP: 0.0043 kg-PO _{4eq.} /kg H ₂	Greet		[97]

AP: Acidification potential; ADP: abiotic depletion, GWP: Global warming potential; POCP: Photochemical oxidant formation potential; EP: Eutrophication potential; FE: freshwater eutrophication; FET: fresh-water ecotoxicity; HT: human toxicity; HTPce: Human Toxicity with cancer effects; HTPnce: Human Toxicity without cancer effects; IRP: Ionising Radiation; LC: land competition; ME: marine ecotoxicity; MET: Marine ecotoxicity; WD: water depletion.

** Some of the results (data) was extracted from figures.

*** Results of some selected categories are reported; please refer to the paper for complete result.

- Another unavoidable issue is the evaporation of hydrogen due to boil-off losses. This loss is higher in smaller storage tanks [110].

The commercial viability of hydrogen production is steadily pacing up with the involvement of major automobile companies like BMW, Toyota, Hyundai, and Honda. Toyota Mirai is the first-ever mass-produced vehicle with a hydrogen storage capacity of 112.4 L [37]. Similarly, Hyundai Tuscon, Hyundai Nexo, and Honda Clarity were also fuel cell electric vehicles (FCEVs). Yet, research is still under the pipeline to further reduce the cost of hydrogen production, material handling, and portability. Liquefaction and cryo-compressed hydrogen technique have reported high storage capabilities. Optimization of the liquefaction cycles and process has shown to reduce energy consumption [111]. However, the commercialization of cryo-compressed hydrogen requires more research for the development of storage devices. Studies show that the price of hydrogen production is expected to drop at least 10 times by 2025 considering the growth of this field [112]. Meanwhile, the automobiles sectors must ensure the availability of refueling stations at certain distances if this technology must be brought into regular use.

7. Policies on biohydrogen across the world

Hydrogen generated using renewable energy sources can act as clean energy carrier, energy storage medium, and raw materials for chemical industries (methanol, ammonia, etc.). Meanwhile, it can also abet in decarbonising energy intensive industries like iron and steel industry where renewable electricity cannot be used directly, thus acting as sector couplers. Nations across the globe have also identified the potential of green hydrogen and have enacted policies to promote green hydrogen usage and production which in turn aids them in achieving their climate targets.

Japan was the first country to adopt hydrogen strategy in December 2017 [113]. The “Basic Hydrogen Strategy” of Japan aims to establish the supply chain for production, storage, transportation, and consumption of hydrogen by 2030. The policy aims to deliver hydrogen at JPY 30/Nm³ by 2030. In this regard, Japan plans to import blue hydrogen and green hydrogen from global low-cost and stable producers. Meanwhile, Japan also plans to improve the contribution of Hydrogen/ammonia to its energy mix to 1% by 2030. Japan plans to achieve the above target by decarbonizing its coal and gas power plant by co-firing them using 20% ammonia and 30% H₂, respectively. To achieve its hydrogen production target, the Fukushima Hydrogen Energy Research Field started conducting demonstration of 10 MW electrolyser energized by 20 MW solar PV system in the year 2020. The electrolyser is capable of generating 1,200 Nm³/h of hydrogen [113].

At the same time, to promote hydrogen usage in automobile sector the Japan government formulated a ‘Strategy for Developing Hydrogen and Fuel-Cell Technologies’ which intends increase the fleet of fuel cell vehicles to 0.2 million and 12.8 million by the end of 2025 and 2030,

respectively. In connection to this, the Ministry of the Environment and the Ministry of Economy, Trade and Industry of Japan has together planned to invest JPY76.58 billion and JPY77.28 billion in the year 2020 and 2021, respectively to develop and demonstrate hydrogen utilization by various industries [114].

The European Union (EU) Hydrogen strategy adopted in 2020, aims to accelerate the deployment of clean hydrogen in three phases [115]. During the first phase (until 2024) it aims to create infrastructure for generating, transporting, and storing green hydrogen. At the same time, it also plans to decarbonise the existing hydrogen industry during this period. Thus, aiming to generate 1 MT of green hydrogen during this span. Between 2024 and 2030 (phase II), the EU aims not only upscale the generating facilities to 10 MT of green hydrogen but also plans to promote green hydrogen usage in industries, transport sector, and in households to satisfy the thermal demand. To enable it, EU plans to create hydrogen refuelling stations, storage plants, and retrofitting the existing gas network for hydrogen supply. Finally, in phase III, it aims to install 80 GW renewable hydrogen capacity of which half will be installed in EU and the rest in Ukraine and North Africa. The EU has emphasised its commitment to hydrogen energy by approving €5.4 billion for hydrogen subsidies in July 2022 which aided in unveiling 41 projects on hydrogen technology in 15 nations [116]. Amazon (e-commerce company) has aimed to achieve net zero emission operations by 2040. Hence, Amazon has vowed to devote \$2 billion as a part of its climate pledge fund. In this regard, the Amazon has invested (amount undisclosed) in Sunfire, an electrolyser manufacturing company in Germany to generate green hydrogen [117].

Germany plans to achieve net zero emission by 2045 and has adopted its hydrogen strategy in 2020 [118]. In this regard, it plans to generate green hydrogen by installing 5 GW of renewable energy capacity by 2030 and double it before 2040. It also plans to import hydrogen from other countries and has already signed agreement with numerous countries and the Federal Ministry for Economic Affairs and Climate Action has approved €900 million on December 2021 to import green hydrogen [119]. Meanwhile, to import green hydrogen derivative (ammonia) from Saudi Arabia, Germany’s Trade & Invest has started constructing import terminal at Homberg along with two private companies [120].

The National Hydrogen Mission of India, launched during its 75th Independence Day, aims at generating 5 MT of Green hydrogen by 2030 [121]. The policy makes renewable power purchase hassle free by providing open access in 15 days from the receipt of application and waiver of inter-state transmission charges for 25 years. Meanwhile, green hydrogen and ammonia producers can bank the unconsumed renewable energy generated by them for 30 days with the distribution company. The policy also facilitates setting up of storage facilities near ports while the land required for it will be provided by the corresponding Port Authorities at applicable charges. India’s first green hydrogen production plant (10 kg/day) was installed at Jorhat, Assam in

April 2022 by Oil India Limited [122]. The anion exchange membrane electrolyser was powered by 50 kW solar PV power plant, and it aims to increase its production capacity to 30 mg/day in the coming days. Meanwhile, Gas Authority of India Limited which blends 2 % (by volume) of H₂ with natural gas has offered a contract to a domestic vendor for generating 4.3 MT of H₂ per day by utilizing photon exchange membrane electrolyser at Vijaipur Complex, Madhya Pradesh [123].

The National Clean Hydrogen Strategy and Roadmap released by the US Department of Energy (DOE) in 2021, aims to produce 1 kg of clean hydrogen at a cost of \$1 by 2031 [124]. It also plans to generate 10 MT of clean hydrogen per year by 2030 and plans to double it by 2040 and finally 50 MT of clean hydrogen per year by 2050. Meanwhile, the CO_{2eq} emitted during clean hydrogen generation should not exceed 4 kg/kg H₂. Industries aiming to decarbonize their sector has identified hydrogen as clean energy source and have started investing in green hydrogen production. For instance, the e-commerce giant Amazon has raised \$198 million for Boston based start-up named electric hydrogen as a part of its climate pledge funds [117].

The medium and long-term plan for the development of hydrogen energy industry in China was announced by National Energy Administration and National Development and Reform Commission on March 2022. It aims to generate around 0.1–0.2 MT of green hydrogen by 2025 thereby mitigating CO₂ emission of about 1–2 MT. Meanwhile, it also intends to increase the number of fuel cell vehicles energised by hydrogen to 50,000 by 2025 [125]. In this regard, China Petroleum & Chemical Corporation (Sinopec) has stated constructing a water electrolysis based green hydrogen plant of capacity 20000 t/a at Xinjiang. The H₂ production cost is expected to be around \$2.67/kg and it is estimated to mitigate about 485000 t/a [126].

At the same time, countries like Chile who contribute to just 0.3 % of global GHG emission but blessed with renewable energy potential aims to produce 160 MT of green hydrogen per year by 2040 thereby planning to position themselves as low-cost hydrogen exporters [127]. About 117 countries have adopted policies to promote hydrogen production. The outcome of these policies and their effectiveness will be seen in the

upcoming years. For instance, green hydrogen plants of capacity 900 t/a and 0.6 MT/a are being constructed in Egypt and Brazil, respectively [128,129]. A timeline on various policies adopted by nations across the world for faster dissipation of green hydrogen-based energy source is depicted in Fig. 6.

8. Conclusion and perspectives

Hydrogen is a clean energy and its production from renewable resources makes it sustainable and environmentally friendly. This manuscript briefs the different methods available for biohydrogen generation, storage, and the economic and environmental perspective through various techno-economic and life-cycle assessments performed for efficient production of hydrogen. The following are some of the key findings that were addressed in this review and future perspectives in biohydrogen synthesis:

- Bio-hydrogen production by employing gasification technique was found to be most economical (\$1.2/kg H₂) followed by anaerobic digestion process (\$1.25/kg H₂).
- Generation of bio-hydrogen by gasification of eucalyptus wood produced the least carbon foot of -1.6 kg CO_{2eq}/kg H₂.
- Bio-H₂ produced by an electrolyzer energized by biomass resource becomes feasible only when the cost of electricity generated is less than €60/MWh and the operating hours of the centralized plant is greater than 6500 h/a.
- The green hydrogen plants installed and under commissioning are predominantly energized by solar and wind energy systems.
- The cost of biohydrogen produced from gasification and anaerobic digestion of biomass is cost competitive with green hydrogen produced from solar and wind energy systems. Hence, policies must be drafted by nations targeting hydrogen generation from bioenergy resources to enable its faster dissemination in the energy market.

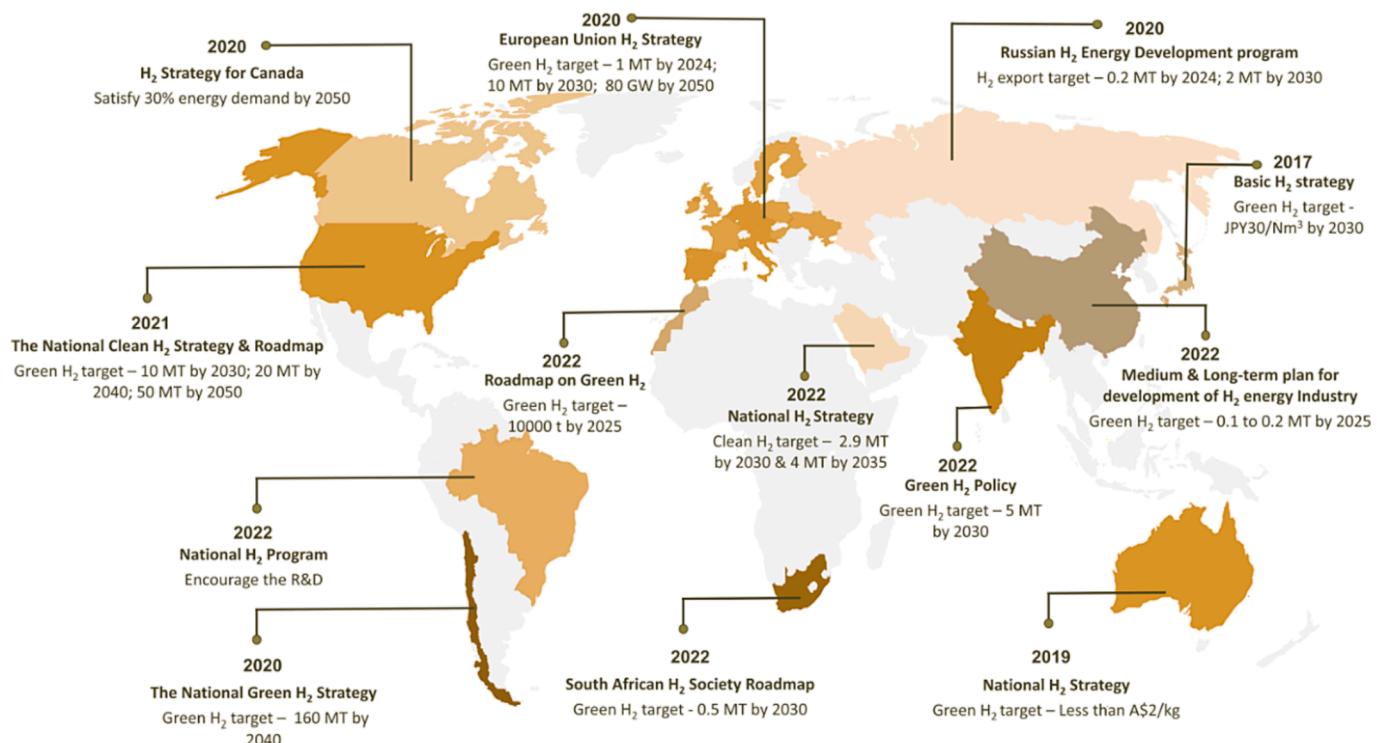


Fig. 6. Timeline of the hydrogen policies adopted across the world.

CRediT authorship contribution statement

Prabakaran Ganeshan: Conceptualization, Writing – review & editing. **V.S. Vigneswaran:** Writing – review & editing. **Sarath C. Gowd:** Writing – review & editing. **Dhamodharan Konduusamy:** Writing – review & editing. **C. Sanjay kumar:** Writing – review & editing. **Nageshwari Krishnamoorthy:** Writing – review & editing. **Deepak Kumar:** Writing – review & editing. **Ankita Juneja:** Writing – review & editing. **Balasubramanian Paramasivan:** Writing – review & editing. **Nithin N Raju:** Writing – review & editing. **Karthik Rajendran:** Conceptualization, Writing – review & editing, Supervision. **Ariavalagan Pugazhendhi:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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References

- [1] Ferreira AF, Ribau JP, Silva CM. Energy consumption and CO₂ emissions of potato peel and sugarcane biohydrogen production pathways, applied to Portuguese road transportation. *Int J Hydrogen Energy* 2011;36:13547–58. <https://doi.org/10.1016/j.ijhydene.2011.08.008>.
- [2] Valente A, Iribarren D, Dufour J. Life cycle assessment of hydrogen energy systems: a review of methodological choices. *Int J Life Cycle Assess* 2017;22: 346–63. <https://doi.org/10.1007/s11367-016-1156-z>.
- [3] Njakou S, Blumberga D. Bioresource Technology Comparative life cycle assessment of three biohydrogen pathways. *Bioresour Technol* 2011;102: 2684–94. <https://doi.org/10.1016/j.biortech.2010.10.139>.
- [4] Wulf C, Kaltschmitt M. Life cycle assessment of biohydrogen production as a transportation fuel in Germany. *Bioresour Technol* 2013;150:466–75. <https://doi.org/10.1016/j.biortech.2013.08.127>.
- [5] Bhandari R, Trudewind CA, Zapp P. Life cycle assessment of hydrogen production via electrolysis - A review. *J Clean Prod* 2014;85:151–63. <https://doi.org/10.1016/j.jclepro.2013.07.048>.
- [6] Susmozas A, Iribarren D, Dufour J. Life-cycle performance of indirect biomass gasification as a green alternative to steam methane reforming for hydrogen production. *Int J Hydrogen Energy* 2013;38:9961–72. <https://doi.org/10.1016/j.ijhydene.2013.06.012>.
- [7] Tian H, Li J, Yan M, Tong YW, Wang CH, Wang X. Organic waste to biohydrogen: A critical review from technological development and environmental impact analysis perspective. *Appl Energy* 2019;256:113961. <https://doi.org/10.1016/j.apenergy.2019.113961>.
- [8] Ghimire A, Frunzo L, Pirozzi F, Trably E, Escudie R, Lens PNL, et al. A review on dark fermentative biohydrogen production from organic biomass: Process parameters and use of by-products. *Appl Energy* 2015;144:73–95. <https://doi.org/10.1016/j.apenergy.2015.01.045>.
- [9] Kumar G, Sivagurunathan P, Sen B, Mudhoo A, Davila-Vazquez G, Wang G, et al. Research and development perspectives of lignocellulose-based biohydrogen production. *Int Biodeterior Biodegrad* 2017;119:225–38. <https://doi.org/10.1016/j.ibio.2016.10.030>.
- [10] Mudhoo A, Forster-Carneiro T, Sánchez A. Biohydrogen production and bioprocess enhancement: A review. *Crit Rev Biotechnol* 2011;31:250–63. <https://doi.org/10.3109/07388551.2010.525497>.
- [11] Nagarajan D, Lee DJ, Kondo A, Chang JS. Recent insights into biohydrogen production by microalgae – From biophotolysis to dark fermentation. *Bioresour Technol* 2017;227:373–87. <https://doi.org/10.1016/j.biortech.2016.12.104>.
- [12] Lim X. Turning organic waste into hydrogen. *Chem Eng News* 2019;97:26–9. <https://doi.org/10.1021/CEN-09714-FEATURE3>.
- [13] Zappi A, Hernandez R, Holmes WE. A review of hydrogen production from anaerobic digestion. *Int J Environ Sci Technol* 2021;18:4075–90. <https://doi.org/10.1007/s13762-020-03117-w>.
- [14] Kim S, Choi K, Kim JO, Chung J. Biological hydrogen production by anaerobic digestion of food waste and sewage sludge treated using various pretreatment technologies. *Biodegradation* 2013;24:753–64. <https://doi.org/10.1007/S10532-013-9623-8/FIGURES/7>.
- [15] Peña Muñoz K, Steinmetz H. Evaluation of pre-treatment on the first stage of an anaerobic digester for enhancing bio-hydrogen production and its associated energy balance. *Energy Procedia* 2012;29:469–79. <https://doi.org/10.1016/j.egypro.2012.09.055>.
- [16] Krishna, B.B., Biswas, B., Bhaskar, T., 2019. Gasification of lignocellulosic biomass, 2nd ed. Biomass, Biofuels, Biochemicals: Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels. Elsevier Inc. <https://doi.org/10.1016/B978-0-12-816856-1.00012-9>.
- [17] Narinawar SL, Panwar NL. Biomass gasification for climate change mitigation and policy framework in India: A review. *Bioresour Technol Reports* 2022;17: 100892. <https://doi.org/10.1016/j.biteb.2021.100892>.
- [18] Alauddin ZABZ, Lahijani P, Mohammadi M, Mohamed AR. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review. *Renew Sustain Energy Rev* 2010;14:2852–62. <https://doi.org/10.1016/j.rser.2010.07.026>.
- [19] Parthasarathy P, Narayanan KS. Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield - A review. *Renew Energy* 2014;66:570–9. <https://doi.org/10.1016/j.renene.2013.12.025>.
- [20] Al Arni S. Comparison of slow and fast pyrolysis for converting biomass into fuel. *Renew Energy* 2018;124:197–201. <https://doi.org/10.1016/j.renene.2017.04.060>.
- [21] Yaashikaa PR, Kumar PS, Varjani S, Saravanan A. A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. *Biotechnol Reports* 2020;28:e00570.
- [22] Shanmugam S, Hari A, Pandey A, Mathimani T, Felix LO, Pugazhendhi A. Comprehensive review on the application of inorganic and organic nanoparticles for enhancing biohydrogen production. *Fuel* 2020;270:117453. <https://doi.org/10.1016/J.FUEL.2020.117453>.
- [23] Kumar G, Mathimani T, Sivaramakrishnan R, Shanmugam S, Bhatia SK, Pugazhendhi A. Application of molecular techniques in biohydrogen production as a clean fuel. *Sci Total Environ* 2020;722:137795. <https://doi.org/10.1016/J.SCITOTENV.2020.137795>.
- [24] Han W, Liu Z, Fang J, Huang J, Zhao H, Li Y. Techno-economic analysis of dark fermentative hydrogen production from molasses in a continuous mixed immobilized sludge reactor. *J Clean Prod* 2016;127:567–72. <https://doi.org/10.1016/J.JCLEPRO.2016.04.055>.
- [25] Guo XM, Trably E, Latrille E, Carré H, Steyer JP. Hydrogen production from agricultural waste by dark fermentation: A review. *Int J Hydrogen Energy* 2010; 35:10660–73. <https://doi.org/10.1016/J.IJHYDENE.2010.03.008>.
- [26] Cao X, Wu X, Ji C, Yao C, Chen Z, Li G, et al. Comparative transcriptional study on the hydrogen evolution of marine microalga *Tetraselmis subcordiformis*. *Int J Hydrogen Energy* 2014;39:18235–46. <https://doi.org/10.1016/J.IJHYDENE.2014.09.037>.
- [27] Kundu A, Sahu JN, Redzwan G, Hashim MA. An overview of cathode material and catalysts suitable for generating hydrogen in microbial electrolysis cell. *Int J Hydrogen Energy* 2013;38:1745–57. <https://doi.org/10.1016/J.IJHYDENE.2012.11.031>.
- [28] Barthelemy H, Weber M, Barbier F. Hydrogen storage: Recent improvements and industrial perspectives. *Int J Hydrogen Energy* 2017;42:7254–62. <https://doi.org/10.1016/J.IJHYDENE.2016.03.178>.
- [29] Hua TQ, Ahluwalia RK, Peng JK, Kromer M, Lasher S, McKenney K, et al. Technical assessment of compressed hydrogen storage tank systems for automotive applications. *Int J Hydrogen Energy* 2011;36:3037–49. <https://doi.org/10.1016/J.IJHYDENE.2010.11.090>.
- [30] Tretyakova-McNally, 2015. Safety of hydrogen Storage. http://www.hyresponse.eu/files/Lectures/Safety_of_hydrogen_storage_notes.pdf.
- [31] Rivkin C, Burgess R, Buttner W. Hydrogen Technologies Safety Guide. Nrel 2015; 67. <https://www.nrel.gov/docs/fy15osti/60948.pdf>.
- [32] Jensen JO, Vestbø AP, Li Q, Bjerrum NJ. The energy efficiency of onboard hydrogen storage. *J Alloys Compd* 2007;446–447:723–8. <https://doi.org/10.1016/j.jallcom.2007.04.051>.
- [33] Ahluwalia RK, Hua TQ, Peng JK, Lasher S, McKenney K, Sinha J, et al. Technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications. *Int J. Hydrogen Energy* 2010;35:4171–84. <https://doi.org/10.1016/J.IJHYDENE.2010.02.074>.
- [34] Torres FG, Díosas-Salinas DC, Pizarro-Ortega CI, De-la-Torre GE. Sorption of chemical contaminants on degradable and non-degradable microplastics: Recent progress and research trends. *Sci Total Environ* 2021;757:143875. <https://doi.org/10.1016/J.SCITOTENV.2020.143875>.
- [35] Zhang F, Zhao P, Niu M, Maddy J. The survey of key technologies in hydrogen energy storage. *Int J Hydrogen Energy* 2016;41:14535–52. <https://doi.org/10.1016/J.IJHYDENE.2016.05.293>.
- [36] Nazir H, Muthuswamy N, Louis C, Jose S, Prakash J, Buan ME, et al. Is the H₂ economy realizable in the foreseeable future? Part II: H₂ storage, transportation, and distribution. *Int. J. Hydrogen Energy*. 2020. <https://doi.org/10.1016/J.IJHYDENE.2020.05.241>.
- [37] Nonobe Y. Development of the fuel cell vehicle mirai. *IEEJ Trans Electr Electron Eng* 2017;12:5–9. <https://doi.org/10.1002/tee.22328>.
- [38] Wallner T, Lohse-Busch H, Gurski S, Duoba M, Thiel W, Martin D, et al. Fuel economy and emissions evaluation of BMW Hydrogen 7 Mono-Fuel demonstration vehicles. *Int. J. Hydrogen Energy* 2008;33:7607–18. <https://doi.org/10.1016/J.IJHYDENE.2008.08.067>.

- [39] Aceves SM, Espinosa-Loza F, Ledesma-Orozco E, Ross TO, Weisberg AH, Brunner TC, et al. High-density automotive hydrogen storage with cryogenic capable pressure vessels. *Int. J. Hydrogen Energy* 2010;35:1219–26. <https://doi.org/10.1016/j.ijhydene.2009.11.069>.
- [40] Moreno-Blanco J, Petitpas G, Espinosa-Loza F, Elizalde-Blancas F, Martinez-Frias J, Aceves SM. The storage performance of automotive cryo-compressed hydrogen vessels. *Int. J. Hydrogen Energy* 2019;44:16841–51. <https://doi.org/10.1016/j.ijhydene.2019.04.189>.
- [41] Wong-Foy AG, Matzger AJ, Yaghi OM. Exceptional H₂ saturation uptake in microporous metal-organic frameworks. *J. Am. Chem. Soc.* 2006;128:3494–5. <https://doi.org/10.1021/ja058213h>.
- [42] Farha OK, Yazaydin AÖ, Eryazici I, Mallikas CD, Hauser BG, Kanatzidis MG, et al. De novo synthesis of a metal-organic framework material featuring ultrahigh surface area and gas storage capacities. *Nat. Chem.* 2010;2:944–8. <https://doi.org/10.1038/nchem.834>.
- [43] Yang SJ, Jung H, Kim T, Im JH, Park CR. Effects of structural modifications on the hydrogen storage capacity of MOF-5. *Int. J. Hydrogen Energy* 2012;37:5777–83. <https://doi.org/10.1016/j.ijhydene.2011.12.163>.
- [44] Assfour B, Leoni S, Seifert G, Baburin IA. Packings of carbon nanotubes - New materials for hydrogen storage. *Adv. Mater.* 2011;23:1237–41. <https://doi.org/10.1002/adma.201003669>.
- [45] Jain V, Kandasubramanian B. Functionalized graphene materials for hydrogen storage. *J. Mater. Sci.* 2020;55:1865–903. <https://doi.org/10.1007/s10853-019-04150-y>.
- [46] Gu J, Zhang X, Fu L, Pang A. Study on the hydrogen storage properties of the dual active metals Ni and Al doped graphene composites. *Int. J. Hydrogen Energy* 2019;44:6036–44. <https://doi.org/10.1016/j.ijhydene.2019.01.057>.
- [47] Ramesh T, Rajalakshmi N, Dhatathreyan KS. Activated carbons derived from tamarind seeds for hydrogen storage. *J. Energy Storage* 2015;4:89–95. <https://doi.org/10.1016/j.est.2015.09.005>.
- [48] Xiao Y, Dong H, Long C, Zheng M, Lei B, Zhang H, et al. Melaleuca bark based porous carbons for hydrogen storage. *Int. J. Hydrogen Energy* 2014;39:11661–7. <https://doi.org/10.1016/j.ijhydene.2014.05.134>.
- [49] Yang Z, Xia Y, Mokaya R. Enhanced hydrogen storage capacity of high surface area zeolite-like carbon materials. *J. Am. Chem. Soc.* 2007;129:1673–9. <https://doi.org/10.1021/ja067114g>.
- [50] Musyoka NM, Ren J, Langmi HW, North BC, Mathe M. A comparison of hydrogen storage capacity of commercial and fly ash-derived zeolite X together with their respective templated carbon derivatives. *Int. J. Hydrogen Energy* 2015;40:12705–12. <https://doi.org/10.1016/j.ijhydene.2015.07.085>.
- [51] Dalai S, Savithri V, Sharma P. Investigating the effect of cobalt loading on thermal conductivity and hydrogen storage capacity of hollow glass microspheres (HGMs). *Mater. Today Proc.* 2017;4:11608–16. <https://doi.org/10.1016/j.mtpr.2017.09.072>.
- [52] Bououdina M, Grant D, Walker G. Review on hydrogen absorbing materials - Structure, microstructure, and thermodynamic properties. *Int. J. Hydrogen Energy* 2006;31:177–82. <https://doi.org/10.1016/j.ijhydene.2005.04.049>.
- [53] Ouyang L, Liu F, Wang H, Liu J, Yang XS, Sun L, et al. Magnesium-based hydrogen storage compounds: A review. *J. Alloys Compd.* 2020;832:154865. <https://doi.org/10.1016/j.jallcom.2020.154865>.
- [54] Ichikawa T, Isobe S, Hanada N, Fujii H. Lithium nitride for reversible hydrogen storage. *J. Alloys Compd.* 2004;365:271–6. [https://doi.org/10.1016/S0925-8388\(03\)00637-6](https://doi.org/10.1016/S0925-8388(03)00637-6).
- [55] Rönnebro E, Majzoub EH. Calcium borohydride for hydrogen storage: Catalysis and reversibility. *J. Phys. Chem. B* 2007;111:12045–7. <https://doi.org/10.1021/jp0764541>.
- [56] Pinkerton FE, Meissner GP, Meyer MS, Balogh MP, Kundrat MD. Hydrogen desorption exceeding ten weight percent from the new quaternary hydride Li₃BN₂H₈. *J. Phys. Chem. B* 2005;109:6–8. <https://doi.org/10.1021/jp0455475>.
- [57] Wan C, An Y, Xu G, Kong W. Study of catalytic hydrogenation of N-ethylcarbazole over ruthenium catalyst. *Int. J. Hydrogen Energy* 2012;37:13092–6. <https://doi.org/10.1016/j.ijhydene.2012.04.123>.
- [58] Yang M, Cheng X, Xie D, Zhu T, Dong Y, Ke H, et al. Study of hydrogenation and dehydrogenation of 1-methylindole for reversible onboard hydrogen storage application. *Int. J. Hydrogen Energy* 2018;43:8868–76. <https://doi.org/10.1016/j.ijhydene.2018.03.134>.
- [59] Sarkar S, Kumar A. Large-scale biohydrogen production from bio-oil. *Bioresour Technol* 2010;101:7350–61. <https://doi.org/10.1016/j.biortech.2010.04.038>.
- [60] Zhang Y, Brown TR, Hu G, Brown RC. Comparative techno-economic analysis of biohydrogen production via bio-oil gasification and bio-oil reforming. *Biomass Bioenergy* 2013;51:99–108. <https://doi.org/10.1016/j.biombioe.2013.01.013>.
- [61] Galera S, Gutiérrez Ortiz FJ. Techno-economic assessment of hydrogen and power production from supercritical water reforming of glycerol. *Fuel* 2015;144:307–16. <https://doi.org/10.1016/j.fuel.2014.12.033>.
- [62] Yao J, Kraussler M, Benedikt F, Hofbauer H. Techno-economic assessment of hydrogen production based on dual fluidized bed biomass steam gasification, biogas steam reforming, and alkaline water electrolysis processes. *Energy Convers Manag* 2017;145:278–92. <https://doi.org/10.1016/j.enconman.2017.04.084>.
- [63] Li G, Wang S, Zhao J, Qi H, Ma Z, Cui P, et al. Life cycle assessment and techno-economic analysis of biomass-to-hydrogen production with methane tri-reforming. *Energy* 2020;199:117488. <https://doi.org/10.1016/j.energy.2020.117488>.
- [64] Okolie JA, Nanda S, Dalai AK, Kozinski JA. Techno-economic evaluation and sensitivity analysis of a conceptual design for supercritical water gasification of soybean straw to produce hydrogen. *Bioresour Technol* 2021;331:125005. <https://doi.org/10.1016/j.biortech.2021.125005>.
- [65] Nouwe Edou DJ, Onwudili JA. Comparative techno-economic modelling of large-scale thermochemical biohydrogen production technologies to fuel public buses: A case study of West Midlands region of England. *Renew Energy* 2022;189:704–16. <https://doi.org/10.1016/J.RENENE.2022.02.074>.
- [66] Ma Z, Liu X, Li G, Qiu X, Yao D, Zhu Z, et al. Energy consumption, environmental performance, and techno-economic feasibility analysis of the biomass-to-hydrogen process with and without carbon capture and storage. *J Environ Chem Eng* 2021;9:106752. <https://doi.org/10.1016/J.JECE.2021.106752>.
- [67] Gholkar P, Shastri Y, Tanksale A. Renewable hydrogen and methane production from microalgae: A techno-economic and life cycle assessment study. *J Clean Prod* 2021;279:123726. <https://doi.org/10.1016/j.jclepro.2020.123726>.
- [68] Khamhaeng P, Laosiripojana N, Assabumrungrat S, Kim-Lohsoontorn P. Techno-economic analysis of hydrogen production from dehydrogenation and steam reforming of ethanol for carbon dioxide conversion to methanol. *Int J Hydrogen Energy* 2021;46:30891–902. <https://doi.org/10.1016/J.IJHYDENE.2021.04.048>.
- [69] Vatsala TM, Raj SM, Manimaran A. A pilot-scale study of biohydrogen production from distillery effluent using defined bacterial co-culture. *Int J Hydrogen Energy* 2008;33:5404–15. <https://doi.org/10.1016/J.IJHYDENE.2008.07.015>.
- [70] Ljunggren M, Wallberg O, Zacchi G. Techno-economic comparison of a biological hydrogen process and a 2nd generation ethanol process using barley straw as feedstock. *Bioresour Technol* 2011;102:9524–31. <https://doi.org/10.1016/j.biotech.2011.06.096>.
- [71] Dasgupta CN, Suseela MR, Mandotra SK, Kumar P, Pandey MK, Toppo K, et al. Dual uses of microalgal biomass: An integrative approach for biohydrogen and biodiesel production. *Appl Energy* 2015;146:202–8. <https://doi.org/10.1016/j.apenergy.2015.01.070>.
- [72] Mahmood SS, Jahim JM, Abdul PM, Luthfi AAI, Takriff MS. Techno-economic analysis of two-stage anaerobic system for biohydrogen and biomethane production from palm oil mill effluent. *J Environ Chem Eng* 2021;9:105679. <https://doi.org/10.1016/J.JECE.2021.105679>.
- [73] Tawfik A, Ali M, Danial A, Zhao S, Meng F, Nasr M. 2-biofuels (H₂ and CH₄) production from anaerobic digestion of biscuits wastewater: Experimental study and techno-economic analysis. *J Water Process Eng* 2021;39:101736. <https://doi.org/10.1016/J.JWPE.2020.101736>.
- [74] Han W, Hu YY, Li SY, Li FF, Tang JH. Biohydrogen production from waste bread in a continuous stirred tank reactor: A techno-economic analysis. *Bioresour Technol* 2016;221:318–23. <https://doi.org/10.1016/j.biotech.2016.09.055>.
- [75] Han W, Fang J, Liu Z, Tang J. Bioresource Technology Techno-economic evaluation of a combined bioprocess for fermentative hydrogen production from food waste. *Bioresour Technol* 2016;202:107–12. <https://doi.org/10.1016/j.biotech.2015.11.072>.
- [76] Li Y, Liu Y, Chu C, Chang P, Hsu C. Techno-economic evaluation of biohydrogen production from wastewater and agricultural waste. *Int J Hydrogen Energy* 2012;37:15704–10. <https://doi.org/10.1016/j.ijhydene.2012.05.043>.
- [77] Ljunggren M, Zacchi G. Techno-economic evaluation of a two-step biological process for hydrogen production. *Biotechnol Prog* 2010;26:496–504. <https://doi.org/10.1002/btpr.336>.
- [78] Taylor P, Mohsen S, Ehteshami M, Chan SH. Techno-Economic Study of Hydrogen Production via Steam Reforming of Methanol, Ethanol, and Diesel Techno-Economic Study of Hydrogen Production via Steam Reforming of Methanol, Ethanol, and Diesel 2014;37–41. <https://doi.org/10.1080/23317000.2014.933087>.
- [79] Khojasteh Salkuyeh Y, Saville BA, MacLean HL. Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies. *Int J Hydrogen Energy* 2017;42:18894–909. <https://doi.org/10.1016/j.ijhydene.2017.05.219>.
- [80] Yan Y, Manovic V, Anthony EJ, Clough PT. Techno-economic analysis of low-carbon hydrogen production by sorption enhanced steam methane reforming (SE-SMR) processes. *Energy Convers Manag* 2020;226:113530. <https://doi.org/10.1016/j.enconman.2020.113530>.
- [81] Bahzad H, Shah N, Dowell N, Mac, Boot-Handford M, Soltani SM, Ho M, et al. Development and techno-economic analyses of a novel hydrogen production process via chemical looping. *Int J Hydrogen Energy* 2019;44:21251–63. <https://doi.org/10.1016/j.ijhydene.2019.05.202>.
- [82] Luk HT, Lei HM, Ng WY, Ju Y, Lam KF. Techno-economic analysis of distributed hydrogen production from natural gas. *Chinese J Chem Eng* 2012;20:489–96. [https://doi.org/10.1016/S1004-9541\(11\)60210-3](https://doi.org/10.1016/S1004-9541(11)60210-3).
- [83] Nicita, A., Squadrito, G., Pietro, A., Andaloro, F., Maggio, G., Avanzate, T., Nicola, E., n.d. The Green Hydrogen as a Feedstock : A Techno-Economic Analysis of a Photovoltaic-Powered Electrolysis Plant 1–20.
- [84] Amin M, Rad V, Ghasempour R, Rahdan P, Moosavi S, Arastounia M. Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, A case study in Iran. *Energy* 2019. <https://doi.org/10.1016/j.energy.2019.116421>.
- [85] Salkuyeh YK, Saville BA, MacLean HL. Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. *Int J Hydrogen Energy* 2018;43:9514–28. <https://doi.org/10.1016/j.ijhydene.2018.04.024>.
- [86] Prince-Richard S, Whale M, Djilali N. A techno-economic analysis of decentralized electrolytic hydrogen production for fuel cell vehicles. *Int J Hydrogen Energy* 2005;30:1159–79. <https://doi.org/10.1016/j.ijhydene.2005.04.055>.
- [87] Li G, Wang S, Zhao J, Qi H, Ma Z, Cui P, et al. Life cycle assessment and techno-economic analysis of biomass-to-hydrogen production with methane tri-reforming. *Energy* 2020;199:117488. <https://doi.org/10.1016/j.energy.2020.117488>.

- [88] Shaner MR, Atwater HA, Lewis S, Mcfarland EW. Environmental Science A comparative technoeconomic analysis of energy †. *Energy Environ Sci* 2016; 9(10):1039/C5EE02573G. <https://doi.org/10.1039/C5EE02573G>.
- [89] Wang Y, Li G, Liu Z, Cui P, Zhu Z, Yang S. Techno-economic analysis of biomass-to-hydrogen process in comparison with coal-to-hydrogen process. *Energy* 2019; 185:1063–75. <https://doi.org/10.1016/j.energy.2019.07.119>.
- [90] Ahmed SF, Rafa N, Mofijur M, Badruddin IA, Inayat A, Ali MS, et al. Biohydrogen Production From Biomass Sources: Metabolic Pathways and Economic Analysis. *Front Energy Res* 2021;9:1–13. <https://doi.org/10.3389/fenrg.2021.753878>.
- [91] Dagdougi H, Sacile R, Bersani C, Ouammi A. Hydrogen Production and Current Technologies. *Hydrog Infrastruct Energy Appl* 2018;7–21. <https://doi.org/10.1016/b978-0-12-812036-1.00002-0>.
- [92] Fúnez Guerra C, Jaén Caparrós M, Nieto Calderón B, Sendarrubias Carbonero V, Nieto Gallego E, Reyes-Bozo L, et al. Viability analysis of centralized hydrogen generation plant for use in mobility sector. *Int J Hydrogen Energy* 2018;43: 11793–802. <https://doi.org/10.1016/j.ijhydene.2018.04.178>.
- [93] Karaeva JV. Hydrogen production at centralized utilization of agricultural waste. *Int J Hydrogen Energy* 2021;46:34089–96. <https://doi.org/10.1016/J.IJHYDENE.2021.08.004>.
- [94] Lundblad T, Taljegard M, Johnsson F. Centralized and decentralized electrolysis-based hydrogen supply systems for road transportation – A modeling study of current and future costs. *Int J Hydrogen Energy* 2022. <https://doi.org/10.1016/j.ijhydene.2022.10.242>.
- [95] Kim J, Lee Y, Moon I. Optimization of a hydrogen supply chain under demand uncertainty. *Int J Hydrogen Energy* 2008;33:4715–29. <https://doi.org/10.1016/j.ijhydene.2008.06.007>.
- [96] Moreno J, Dufour J. Life cycle assessment of hydrogen production from biomass gasification. Evaluation of different Spanish feedstocks. *Int J Hydrogen Energy* 2013;38:7616–22. <https://doi.org/10.1016/j.ijhydene.2012.11.076>.
- [97] Siddiqui O, Dincer I. A well to pump life cycle environmental impact assessment of some hydrogen production routes. *Int J Hydrogen Energy* 2019;44:5773–86. <https://doi.org/10.1016/j.ijhydene.2019.01.118>.
- [98] Kumar D, Murthy G. Life cycle assessment of energy and GHG emissions during ethanol production from grass straws using various pretreatment processes. *Int J Life Cycle Assess* 2012;17(4):388–401.
- [99] Kalinci Y, Hepbasli A, Dincer I. Life cycle assessment of hydrogen production from biomass gasification systems. *Int J Hydrogen Energy* 2012;37:14026–39. <https://doi.org/10.1016/j.ijhydene.2012.06.015>.
- [100] Hajjaji N, Martinez S, Trably E, Steyer JP, Helias A. Life cycle assessment of hydrogen production from biogas reforming. *Int J Hydrogen Energy* 2016;41: 6064–75. <https://doi.org/10.1016/j.ijhydene.2016.03.006>.
- [101] Ochs D, Wukovits W, Ahner W. Life cycle inventory analysis of biological hydrogen production by thermophilic and photo fermentation of potato steam peels (PSP). *J Clean Prod* 2010;18:S88–94. <https://doi.org/10.1016/j.jclepro.2010.05.018>.
- [102] Ferreira AF, Ortigueira J, Alves L, Gouveia I, Moura P, Silva C. Biohydrogen production from microalgal biomass: Energy requirement, CO₂ emissions and scale-up scenarios. *Bioresour Technol* 2013;144:156–64. <https://doi.org/10.1016/j.biortech.2013.06.079>.
- [103] García CA, Morales M, Quintero J, Aroca G, Cardona CA. Environmental assessment of hydrogen production based on *Pinus patula* plantations in Colombia. *Energy* 2017;139:606–16. <https://doi.org/10.1016/j.energy.2017.08.012>.
- [104] Sambusiti C, Bellucci M, Zabaniotou A, Beneduce L, Monlau F. Algae as promising feedstocks for fermentative biohydrogen production according to a biorefinery approach: A comprehensive review. *Renew Sustain Energy Rev* 2015;44:20–36. <https://doi.org/10.1016/j.rser.2014.12.013>.
- [105] Srivastava N, Srivastava M, Mishra PK, Kausar MA, Saeed M, Gupta VK, et al. Advances in nanomaterials induced biohydrogen production using waste biomass. *Bioresour Technol* 2020;307:123094. <https://doi.org/10.1016/j.biortech.2020.123094>.
- [106] Lam MK, Loy ACM, Yusup S, Lee KT. Biohydrogen Production From Algae. *Biohydrogen* 2019;219–245. <https://doi.org/10.1016/B978-0-444-64203-5.00009-5>.
- [107] Bossel U, Eliasson B. *Energy and Hydrogen Economy*. Fuel Cell Forum, Lucerne: Eur; 2002. p. 36.
- [108] Rozzi E, Minuto FD, Lanzini A. Dynamic modeling and thermal management of a Power-to-Power system with hydrogen storage in microporous adsorbent materials. *J Energy Storage* 2021;41:102953. <https://doi.org/10.1016/J.EST.2021.102953>.
- [109] Liu YL, Zhao YZ, Zhao L, Li X, Chen H, gang, Zhang, L.F., Zhao, H., Sheng, R.H., Xie, T., Hu, D.H., Zheng, J.Y.. Experimental studies on temperature rise within a hydrogen cylinder during refueling. *Int J Hydrogen Energy* 2010;35:2627–32. <https://doi.org/10.1016/j.ijhydene.2009.04.042>.
- [110] Abdalla AM, Hossain S, Nisifdy OB, Azad AT, Dawood M, Azad AK. Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy Convers Manag* 2018;165:602–27. <https://doi.org/10.1016/j.enconman.2018.03.088>.
- [111] Chang HM, Kim BH, Choi B. Hydrogen liquefaction process with Brayton refrigeration cycle to utilize the cold energy of LNG. *Cryogenics (Guildf)* 2020; 108:103093. <https://doi.org/10.1016/J.CRYOGENICS.2020.103093>.
- [112] Kushwaha, A.K., 2019. TECHNO ECONOMIC EVALUATION OF BIO-HYDROGEN PRODUCTION FROM Submitted to Dr . JADI BALA KOMARAIAH Submitted by Amrendra Kumar Kushwaha.
- [113] Clifford chance, 2022. Focus on Hydrogen: Japan'S Energy Strategy for Hydrogen and Ammonia.
- [114] Ministry of Environment G of J. Japan Hydrogen Strategy (Summary) 2020. https://www.env.go.jp/seisaku/list/ondanka_saisei/lowcarbon-h2-sc/PDF/Summary_of_Japan%27s_Hydrogen_Strategy.pdf (accessed November 25, 2022).
- [115] Erbach G, Jensen L. EU Hydrogen Policy, Hydrogen as an energy carrier for a climate-neutral economy. *Eur Parliam Res Serv* 2021;8.
- [116] Recent Developments in EU Hydrogen Initiatives, 2022 (accessed 12.15.22).
- [117] Amazon invests in green hydrogen companies [WWW Document], 2022. URL <https://www.aboutamazon.com/news/sustainability/amazon-invests-in-green-hydrogen-companies> (accessed 12.15.22).
- [118] Federal Ministry for Economic Affairs and Energy, 2020. The National Hydrogen Strategy. Fed. Minist. Econ. Aff. Energy (BMWI), Berlin 1–32.
- [119] Germany launches first auction for green ammonia imports – EQ Mag – The Leading Solar Magazine In India [WWW Document]. n.d. URL <https://www.eqmagpro.com/germany-launches-first-auction-for-green-ammonia-imports-eq-mag/> (accessed 12.15.22).
- [120] Germany To Build First Green Ammonia Import Terminal in Hamburg [WWW Document], n.d. URL <https://www.saurenergy.com/solar-energy-news/germany-to-build-first-green-ammonia-import-terminal-in-hamburg> (accessed 12.15.22).
- [121] Raj K, Lakhina P, Stranger C. Harnessing GREEN HYDROGEN 2022:1–88. <https://www.niti.gov.in/documents/reports/> (accessed October 15, 2022).
- [122] Ministry of petroleum & natural gas [WWW Document], n.d. URL <https://pib.gov.in/PressReleasePage.aspx?PRID=1818482> (accessed 12.15.22).
- [123] Ministry of Petroleum & Natural Gas [WWW Document], 2022. URL <https://pib.gov.in/PressReleasePage.aspx?PRID=1824727> (accessed 12.15.22).
- [124] US Department of Energy. Draft National Clean Hydrogen Strategy and Roadmap. 2022. <https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf>.
- [125] Goseins J, Jotzo F. China 's hydrogen plans 2022:1–19. https://iceds.anu.edu.au/files/ANU%20Policy%20brief-China%27s_hydrogen_plans.pdf (accessed November 16, 2022). Goseins, J., Jotzo, F., 2022. China 's hydrogen plans 1–19.
- [126] China building world's biggest green hydrogen factory [WWW Document], 2022. URL <https://balkangreenenergynews.com/chinas-sinopec-building-worlds-biggest-green-hydrogen-factory/> (accessed 12.15.22).
- [127] Barhorst, N., 2016. Green hydrogen. 39th World Energy Eng. Conf. WEEC 2016 2, 886–897.
- [128] "World's Largest" Green Hydrogen Plant on Tap [WWW Document], 2021. URL <https://www.powermag.com/worlds-largest-green-hydrogen-plant-on-tap/> (accessed 12.15.22).
- [129] World's largest green hydrogen project – with 100MW electrolyser – set to be built in Egypt | Recharge [WWW Document], 2021. URL <https://www.rechargenews.com/energy-transition/worlds-largest-green-hydrogen-project-with-100mw-electrolyser-set-to-be-built-in-egypt/2-1-1104709> (accessed 12.15.22).