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Advancing Clean Energy: The Role of Biohydrogen Technology

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Abstract

The process of gasification turns carbonaceous materials derived from biomass or fossil fuels into gases, with nitrogen (N_2), carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2) being the main fractions. By reacting carbonaceous materials (coal, petroleum, and biomass) with a regulated amount of oxygen and/or steam at high temperatures, a thermochemical process known as gasification produces carbon monoxide and hydrogen. Methanol and chemicals, like urea and ammonia, which are the building blocks of many fertilizers, can be produced via the gasification process. Additionally, gasification can assist in the production of transportation fuels from biomass, coal, oil, and sands. Drying, pyrolysis, combustion, cracking, and reduction are the five distinct thermal processes that make up gasification. Gasifiers can be broadly divided into three categories: (i) fluidized-bed gasifiers; (ii) entrained-flow gasifiers; and (iii) fixed-bed gasifiers, also known as moving-bed gasifiers. Gasification is a versatile and efficient process that offers several advantages over direct combustion, including higher energy efficiency and lower emissions of pollutants, such as sulfur oxides (SO_x) and nitrogen oxides (NO_x). The synthesis gas (syngas) produced can be further processed to generate electricity, synthetic natural gas (SNG), or even liquid fuels through Fischer-Tropsch synthesis. Additionally, gasification technology plays a crucial role in waste-to-energy applications, allowing for the conversion of municipal solid waste (MSW) and industrial waste into valuable energy products. Advances in gasification technology continue to improve its economic feasibility and environmental sustainability, making it a key player in the transition to cleaner energy sources.

Keywords: Biohydrogen (Bio-H2), carbon capture and storage (CCS), negative carbon emissions, industrial decarbonization, biomass gasification

INTRODUCTION

The global energy sector stands at a crossroads, facing the dual challenge of meeting escalating energy demands while mitigating environmental impacts. Traditional reliance on fossil fuels has proven unsustainable, driving the urgent need for renewable and eco-friendly energy solutions. Among the array of emerging technologies, biohydrogen production, biorefineries, and gasification processes have garnered significant attention for their potential to revolutionize energy generation. These innovations not only promise cleaner energy alternatives but also align with global efforts to combat climate change and foster a circular economy. This paper delves into the advancements, applications, and future prospects of these transformative technologies, highlighting their critical role in shaping a sustainable energy future. As the global energy landscape evolves, the transition towards sustainable and renewable energy sources becomes imperative. Among the most promising technologies are biohydrogen production, biorefineries, and gasification processes, each offering innovative pathways for energy generation [1] while addressing environmental concerns. This article explores these cutting-edge advancements and their potential to revolutionize the energy sector.

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Low-carbon hydrogen, produced with minimal or no greenhouse gas (GHG) emissions, has become a promising option in the shift toward a net-zero carbon economy. By enabling the reduction, recycling, reuse, or removal of emissions while maintaining the functionality of existing infrastructure, it plays a vital role in global decarbonization efforts (Table 1). This report builds on the Carbon Management Initiative's 2021 analysis of green hydrogen, turning attention to biohydrogen (Bio-H_2) – hydrogen generated through either the metabolic or thermochemical conversion of biomass feedstocks. Notably, Bio-H_2 produced from waste biomass feedstocks, coupled with carbon capture and storage (CCS), offers the potential to serve as a carbon-negative hydrogen source, contributing to a circular carbon economy.

Table 1. Different pathways for biomass-based energy utilization with CCS.

Acronym	Pathways	Definition	Sources
BECCS	Bioenergy with carbon capture and storage	BECCs is a technique for extracting bioenergy from biomass. The carbon dioxide released in the conversion process is captured and stored rather than released into the atmosphere.	Larson et al., 2021
BICRS	Biomass carbon removal and storage	BICRS describes a range of processes that use plants and algae to remove carbon dioxide from the atmosphere and store it underground or in long-lived products.	Sandalow et al., 2020
HyBECCs (or Bio-H, BECCs/ BHCCS)	Hydrogen bioenergy with carbon capture and storage	HyBECCs refers to the production of hydrogen from residual or waste biomass with efficient CCS, resulting in negative-emission or climate-positive hydrogen.	Full et al., 2021; BP 2022; Larson et al., 2021; Rosa and Mazzotti, 2022

As this report highlights, Bio-H_2 differs from other forms of low-carbon hydrogen, such as green hydrogen (produced via water electrolysis powered by low-carbon electricity) and blue hydrogen (derived from natural gas with CCS), due to its distinct technical, economic, operational, and governance features. Most notably, Bio-H_2, when integrated with CCS, can achieve carbon negativity. By providing energy while simultaneously removing significant amounts of carbon from the atmosphere and oceans, Bio-H_2 emerges as a valuable resource for policymakers and business leaders aiming to meet net-zero objectives. However, realizing its carbon-negative potential depends on two key factors: 1) utilizing biomass feedstocks with exceptionally low-carbon footprints, such as agricultural waste, municipal waste, manure, or sewage, and 2) employing production technologies that enable high rates of carbon capture through CCS [2–3].

BIOHYDROGEN PRODUCTION

Hydrogen, a clean, renewable, and adaptable energy source, holds the potential to displace fossil fuels. However, conventional hydrogen production methods often rely on energy-intensive processes fuelled by fossil energy, undermining their sustainability. In contrast, photobiological hydrogen production using microorganisms represents an innovative alternative, harnessing sunlight and water to generate energy. Recent advances in producing hydrogen from microalgae have marked significant milestones, although the technology remains in a nascent stage.

Biohydrogen Production Pathways

Biohydrogen (Bio-H_2) can be generated through either biological or thermochemical methods. Biological pathways, such as fermentation, anaerobic digestion, and biophotolysis, rely on microorganisms to produce hydrogen. On the other hand, thermochemical pathways include biomass gasification, pyrolysis, and steam (bio)methane reforming. Compared to biological methods, thermochemical processes are significantly more advanced in terms of technology and have gained more attention due to their cost-effectiveness and high efficiency (Kumar et al., 2020) (Figure 1). These processes offer a promising near-term solution for large-scale Bio-H_2 production using biomass feedstocks like wood, straw, grass clippings, and other bioenergy sources, such as biomethane or biogas [4].

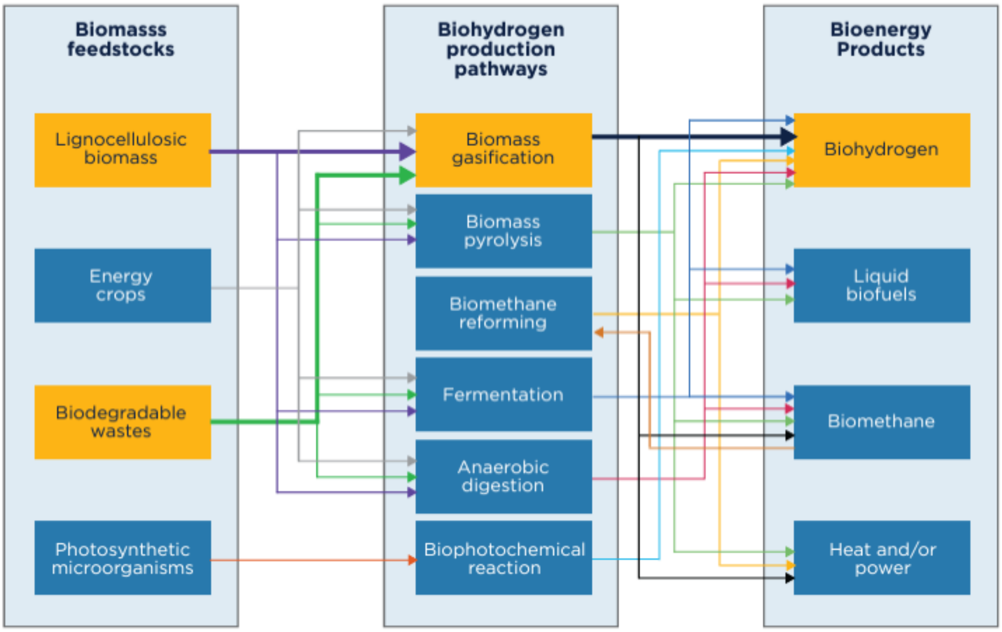

Figure 1. Biohydrogen production: biomass feedstocks, pathways, and bioenergy products.

Biohydrogen Production – Thermochemical Conversion Pathways

The three primary thermochemical conversion pathways for biohydrogen (Bio-H_2) production are gasification, pyrolysis, and steam (bio)methane reforming. The efficiency and output of each method largely depend on the type and quality of the biomass feedstock utilized.

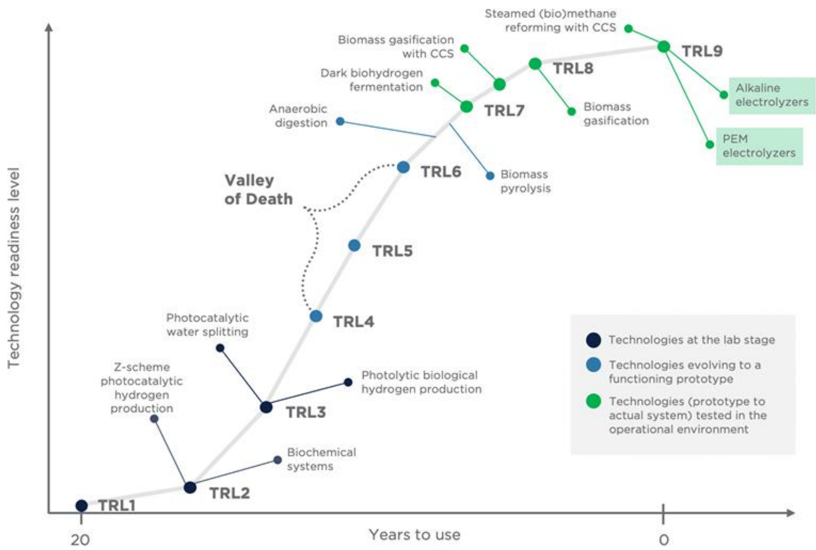

Figure 2. Thermochemical conversion pathways.

Biomass Gasification

Gasification is the oldest and most well-established thermochemical process for biomass conversion, widely recognized for its efficiency in converting biomass into fuel (Kumar et al., 2020; Glushkov et al., 2021). This process uses controlled heat (600 to over 1000°C), steam, and oxygen to convert various biomass sources into hydrogen and other gaseous products without combustion (DOE, n.d.; Molino et al., 2016). Through partial oxidation, gasification generates syngas, a mixture primarily composed of hydrogen and carbon monoxide (CO), with minor amounts of carbon dioxide (CO_2). The hydrogen can then be separated into a purified stream, while the CO_2 can be captured and stored using carbon capture and storage (CCS) technology. A dedicated Bio-H_2 production facility can optimize this process by minimizing unwanted byproducts and enhancing hydrogen yield (Cao et al., 2020). Additionally, integrating a CCS unit into such facilities can result in carbon-negative hydrogen production. Key advantages of gasification include its industrial feasibility, ability to process high-moisture biomass waste, and its effectiveness in treating animal manure by Figure 2 eliminating odors and pathogens (Kumar et al., 2020). Despite these advantages, challenges, such as feedstock quality control (removing inorganic impurities), catalyst degradation, tar formation, and efficient hydrogen separation remain barriers to widespread adoption (Kumar et al., 2020).

Biomass Pyrolysis

Pyrolysis involves heating biomass to temperatures ranging from 200 to 600°C in the absence of oxygen (Wang et al., 2020). While currently in the demonstration phase and approaching commercialization, pyrolysis yields solid biochar, liquid bio-oil, and non-condensable gases, including Bio-H2 (Kan et al., 2016). The heating rate and solid residence time significantly influence product distribution. Fast pyrolysis primarily aims to produce liquid bio-oil, whereas slow pyrolysis focuses on generating solid biochar [5–6]. The use of specific temperatures and catalysts can enhance hydrogen production, although the yield is typically lower than gasification due to the absence of steam and oxygen (Wang et al., 2020). Compared to gasification, pyrolysis offers benefits, such as lower land requirements, reduced pollutant emissions, and greater flexibility in end-product applications. However, challenges persist, including tar formation (10–35%), high corrosiveness, and low thermal stability (Kumar et al., 2020; Glushkov et al., 2021; Ruan et al., 2020). Additionally, the relatively low hydrogen concentration in pyrolysis gas products currently limits its economic viability (Chen et al., 2021).

Biomethane Reforming

Steam methane reforming (SMR) remains the dominant hydrogen production method, accounting for approximately 97% of global production (IEA, 2021). Biomethane reforming follows the same fundamental process as natural gas reforming, with the primary distinction being the source of methane—biomethane versus fossil-based methane (Blumberg, 2018). The switch to biomethane influences the overall energy costs and carbon footprint without requiring significant modifications to existing infrastructure. Biomethane, which is derived from purified biogas, serves several key purposes, including direct replacement of natural gas. For instance, Europe currently operates over 20,000 biogas and biomethane plants, primarily for electricity and heat generation (EBA, 2022). Consequently, biogas is an essential resource with significant immediate applications, and its utilization for these purposes should take precedence over its conversion to Bio-H2 [7–10].

Biorefineries: Integrating Sustainability

Biorefineries present a holistic approach to utilizing microalgae biomass, producing biofuels and high-value products while addressing environmental challenges. Microalgae cultivation aids in wastewater treatment and CO_2 mitigation, offering a sustainable feedstock for biofuel production.

Economic and Environmental Benefits

The integration of biorefineries can lower biofuel production costs by simultaneously generating value-added products, such as bioactive compounds, pharmaceuticals, and animal feed. For instance, spent microalgal biomass (SMAB) can be repurposed for nutrient recycling, enhancing the circular economy in biofuel production.

Gasification plays a pivotal role in biorefineries, producing syngas – a mixture of H_2, CO, and methane (CH_4). Syngas serves as a versatile energy carrier, powering turbines and engines or acting as a feedstock for chemical synthesis. Optimizing moisture content and leveraging catalytic processes can further improve syngas quality and production efficiency.

Synthesis Gas (Syngas) and Fischer–Tropsch Synthesis

Syngas production technologies, particularly gasification and reforming, are integral to Fischer-Tropsch (FT) synthesis, converting carbon-rich feedstocks into synthetic fuels. Coal and natural gas are commonly used feedstocks, but gasification's adaptability allows the use of diverse materials, including biomass and waste.

Applications and Advancements

The syngas produced through gasification is cleaned and processed into various products, including:

- Chemicals like methanol.
- Synthetic fuels.
- Electric power.

Historically, gasification has been a cornerstone technology, with commercial applications dating back to the early 20th century. Modern advancements focus on enhancing efficiency and reducing costs, making gasification a mature and reliable technology for energy production.

Power Generation and Carbon Capture

Coal continues to play a significant role in power generation despite growing concerns about global warming. Integrated Gasification Combined Cycle (IGCC) technology represents a promising solution, combining gasification with carbon capture and storage (CCS) to reduce greenhouse gas emissions.

IGCC and Efficiency

IGCC plants utilize a combination of processes, including:

- Gasification to produce syngas.
- Water-gas shift reactions to enhance hydrogen production.
- Combined cycle power generation for higher efficiency.

With CCS, IGCC plants achieve efficiencies of up to 38%, significantly reducing carbon emissions. Although capital costs remain high, ongoing research aims to improve the economic viability of IGCC systems.

Biohydrogen Production – Biological Conversion Pathways

Biological conversion pathways for biohydrogen (Bio-H_2) production include fermentation, anaerobic digestion, and biophotolysis. Among these, fermentation is considered the most promising due to its relatively high net energy ratio. However, all biological methods face challenges related to low volumetric and substrate-specific yields. Except for dark fermentation, most biological pathways remain at lower technology readiness levels (TRLs [11]).

Fermentation and Anaerobic Digestion

Fermentation is currently the most developed biological method (TRL 7) for converting biomass feedstocks into Bio-H_2, along with byproducts, such as methane and carbon dioxide (Ghimire et al., 2015). Dark fermentation, in particular, stands out for its high net energy ratio of 1.9, compared to steam methane reforming (SMR) at 0.64 (Łukajtis et al., 2018). This process relies on anaerobic bacteria to break down biomass through glycolysis in the absence of light. However, like biomass pyrolysis, the presence of multiple byproducts limits the overall hydrogen yield and energy efficiency. Additional costs and energy inputs are required for product separation and upgrading (Vane, 2005).

Another form, photo-fermentation, involves photosynthetic bacteria that produce hydrogen in the presence of light. However, this method is hampered by low conversion efficiency and poor overall performance (Hitam and Jalil, 2020). Anaerobic digestion, commonly used to convert lignocellulosic biomass into biogas (a mixture of biomethane and CO_2), is still under development for Bio-H_2 production (TRL 6) (Sawatdeenarunat et al., 2015). A two-phase anaerobic digestion system can simultaneously generate hydrogen and methane, but most of the energy is retained in the biomethane rather than the Bio-H_2, making it less efficient than dedicated hydrogen production pathways (Demirel et al., 2010). However, biomethane produced via anaerobic digestion can later be reformed to generate Bio-H2 through the biomethane reforming process.

Bio-Photochemical Reaction

Biophotolysis, or bio-photochemical hydrogen production, utilizes water and sunlight to produce hydrogen. This process involves splitting water molecules into hydrogen and oxygen using microorganisms or catalysts in the presence of light (Anisha and John, 2014). Unlike other biological pathways, biophotolysis does not require biomass feedstock, which can be an advantage. However, its production rates are currently low, and it remains limited to laboratory-scale research (TRL 3), the lowest readiness level among all Bio-H_2 production methods. Furthermore, the cost and carbon footprint of this process are still largely uncertain.

Challenges and Prospects of Biological Pathways

While biological methods for Bio-H_2 production are promising, they are still primarily in the research and development phase, with low efficiency and yield limitations. Anaerobic digestion and biophotolysis require further advancements, as they are not yet optimized for dedicated hydrogen production and remain at lower TRLs. Fermentation and biomass pyrolysis, which are closer to commercialization, offer potential but face similar technical challenges.

At present, the most mature and viable pathways for large-scale Bio-H_2 production are biomass gasification and biomethane reforming, though biomethane is a limited resource with competing applications. As a result, gasification continues to be the most promising pathway for industrial-scale Bio-H_2 production.

Comparative Analysis of Biohydrogen Production Pathways

Table 2 summarizes key parameters of the six Bio-H_2 production methods, highlighting cost variations based on technological readiness, infrastructure, and feedstock availability. Gasification, pyrolysis, biomethane SMR, and biophotolysis have low-end costs (\$1.25–\$1.4/kg), comparable to the current cost of gray hydrogen (\$0.5–\$2/kg). However, these low costs depend on access to affordable and readily available biomass located close to production sites. The highest cost estimates for gasification, pyrolysis, biomethane SMR/autothermal reforming (ATR), and fermentation align with the upper range of green hydrogen prices (\$8–\$10/kg) (Tables 2 and 3).

Carbon footprints across the pathways vary widely, from −26.5 to 10.8 kg-CO_2/kg-H_2, with negative values achievable through carbon capture and storage (CCS) or biochar carbon sequestration. In contrast, the highest emissions are comparable to those of gray hydrogen production (>10 kg-CO_2/kg-H_2), reinforcing the importance of using sustainable biomass feedstocks with low life-cycle emissions (LCA) and land-use change (LUC) impacts to avoid surpassing the carbon intensity of fossil-based hydrogen production.

BIOHYDROGEN APPLICATION OPPORTUNITIES AND CHALLENGES

Application Opportunities

Biohydrogen (Bio-H_2) is chemically and physically identical to other hydrogen types (gray, blue, green), allowing it to be used across various applications. However, the primary advantage of Bio-H_2 lies in its potential for carbon removal when combined with carbon capture and storage (CCS). When derived from waste and coupled with CCS, Bio-H_2 can achieve negative carbon emissions, offering climate benefits and assisting sectors with limited decarbonization options to achieve carbon neutrality by offsetting residual emissions.

Table 2: General comparison of different Bio-H_2 production pathways

	Cost ($/kg-$H_2$)	C-footprint (kg-CO_2/kg-H_2)	Hydrogen mass conversion ratio (kg-H_2/kg-feedstock)	Energy conversion efficiency (percent)	Sources
Gasification (with or without CCS)	1.4 to 10.31	0.31 to 8.63 (without CCS) −22.15 to −11.66 (with CCS)	0.068 to 0.080	35 to 60	Khan et al. 2018; Kumar et al. 2020; NREL 2011, Rosa and Mazzotti 2022
Pyrolysis	1.3 to 10.51	−13.8 to −3.8	0.063 to 0.117	56 to 64	Khan et al. 2018; Kumar et al. 2020; L. Liu et al. 2022; Q. Lu et al. 2020; Nasir Uddin et al. 2013; Sarkar and Kumar 2010
Biomethane SMR (with or without CCS)	1.25 to 8	−26.5 to 8.6	0.0888	52 to 72	Milbrandt et al. 2016; Rosa and Mazzotti 2022
Biomethane ATR (with or without CCS)	6.92 to 7.8	−26.5 to 8.6	0.06	28 to 40	Marcoberardino et al. 2018; Minutillo et al. 2020; Zhou et al. 2021
Fermentation	5.65 to 8.56	0.96 to 8.6	0.01 to 0.07	About 10	Djomo et al. 2008; Ferreira et al. 2012; Oncel 2015; Osman et al. 2020
Anaerobic digestion	About 5	9 to 10.8	0.01 to 0.04	72 to 85	Hajizadeh et al. 2022; Khan et al. 2018; Park et al. 2010; Saidi et al. 2018
Biophotolysis	1.42 to 7.24	Data not available	About 0.01	Data not available	Osman et al. 2020

Note: Waste sources may be different for different pathways, but in the paper the phrase generally refers to the use of waste biomass such as forest residue, agricultural waste, or municipal solid waste. C-footprint is based on low heating value of H_2 energy conversion and carbon neutral biomass feedstocks. Energy conversion efficiency is defined as hydrogen output energy over total input energy. Pyrolysis can be further divided into fast and slow pyrolysis; the results shown in the pyrolysis row pertain to biohydrogen is produced via bio-oils obtained from fast pyrolysis as it is more favorable for liquid product generation. The lowest C-footprint value for pyrolysis assumes that carbon black, the by-product of pyrolysis, is permanently stored.

Table 3: Levelized cost and carbon footprint comparison between types of hydrogen in 2021

Hydrogen type	Cost range ($/kg-$H_2$)	Carbon footprint (kg-CO_2/kg-H_2)
Gray hydrogen	0.5 to 2	10 to 20
Blue hydrogen	1.4 to 2.4	1.5 to 5
Green hydrogen	2.73 to 13	0.5 to 1.5
Biohydrogen (with or without CCS)	1.25 to 10.51	−26.5 to 10.8

Key application opportunities include:

1. *Industrial Heating:* Bio-H_2 can replace natural gas in industries requiring high-temperature thermal energy, such as blast furnaces in the iron and steel sector.
2. *Transportation:* Bio-H_2 offers a low-carbon solution for long-haul trucking, marine shipping, and aviation, helping to reduce emissions and air pollution.
3. *Energy Storage:* Hydrogen serves as an energy carrier, addressing the seasonal and variable availability of renewable energy.
4. *Fuel Cells:* Bio-H_2 can be used in fuel cells for backup power and to power vehicles, such as private cars, trucks, buses, and marine vessels.

Unique Application Opportunities in Hard-to-Abate Sectors

Bio-H_2 presents unique opportunities in hard-to-abate sectors like iron and steel manufacturing.

Currently, the blast furnace-basic oxygen furnace (BF-BOF) method accounts for approximately 71% of steel production, with limited potential for hydrogen substitution. Direct reduced iron (DRI) combined with an electric arc furnace (EAF) powered by zero-carbon electricity represents the most mature low-emission pathway. The application of Bio-H_2, particularly from waste gasification with CCS, can lead to net-negative steel production (–0.6 ton-CO_2/ton-steel), offering significant decarbonization potential.

Challenges in Bio-H_2 Production

Despite its potential, several challenges hinder the widespread adoption of Bio-H_2.

Improving Gasification Technology

- Optimization is needed to minimize energy loss during biomass pretreatment.
- Efficiency improvements in reactors and reduction of tar formation.
- Enhanced gas cleaning processes for effective H_2 separation.
- Addressing catalyst contamination and fouling.

Environmental Impacts

- Gasification plants produce by-products, such as soot, char, and ash, which require proper disposal and mitigation strategies.
- Effective supervision and preventive measures are crucial for large-scale deployment.

Competing Biomass Uses

- Biomass has competing applications, such as power generation, biochar production, and biofuel synthesis.
- Policy frameworks should balance biomass allocation among these uses.

Biomass Resource Limitations

- The availability of biomass is geographically uneven, with South America and Southeast Asia having abundant resources, while Europe and Japan face constraints.
- Increasing biomass residue utilization is key to maximizing Bio-H_2 potential.

CO_2 Storage Constraints

- The availability of geological storage for captured CO_2 is unevenly distributed.
- Some regions require additional CCS infrastructure to support Bio-H_2 deployment.

Policy and Market Support

- Bio-H_2 lacks sufficient recognition and policy support compared to other hydrogen forms.
- Standardized carbon accounting methods are necessary to ensure sustainable biomass procurement.

Key Findings

1. Bio-H_2 is underrepresented in major energy transition reports despite its carbon removal potential.
2. Biomass feedstocks vary in carbon emissions, necessitating rigorous governance and carbon accounting.
3. Bio-H_2 with CCS can achieve significant negative carbon footprints (–21 to –15 kg-CO_2/kg-H_2).
4. Biomass gasification is the most promising production method due to its CCS compatibility and cost-effectiveness.
5. Bio-H_2 production costs range from \$3–4/kg, with potential to reach \$2/kg through technology improvements.
6. Bio-H_2 is an effective solution for hard-to-abate sectors, such as steel and chemical production.
7. Flexibility in Bio-H_2 production enables localized solutions and circular carbon economies.

8. By addressing these challenges and leveraging its carbon-negative potential, Bio-H_2 can play a crucial role in achieving net-zero goals and supporting a sustainable energy transition.

CONCLUSIONS

Biohydrogen (Bio-H_2) presents a promising pathway for decarbonization, offering significant climate benefits through its ability to achieve carbon-negative emissions when coupled with carbon capture and storage (CCS). Its versatility across various industrial, transportation, and energy storage applications makes it a valuable alternative to conventional hydrogen sources. However, several challenges, including technological limitations, environmental concerns, feedstock availability, and policy gaps, must be addressed to unlock its full potential.

Despite these hurdles, the unique ability of Bio-H_2 to contribute to hard-to-abate sectors, such as steel and chemical production, and to support circular carbon economies highlights its critical role in the global energy transition. With targeted technological advancements, stronger policy support, and optimized biomass resource management, Bio-H_2 can become a key driver in achieving carbon neutrality and a sustainable future.

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