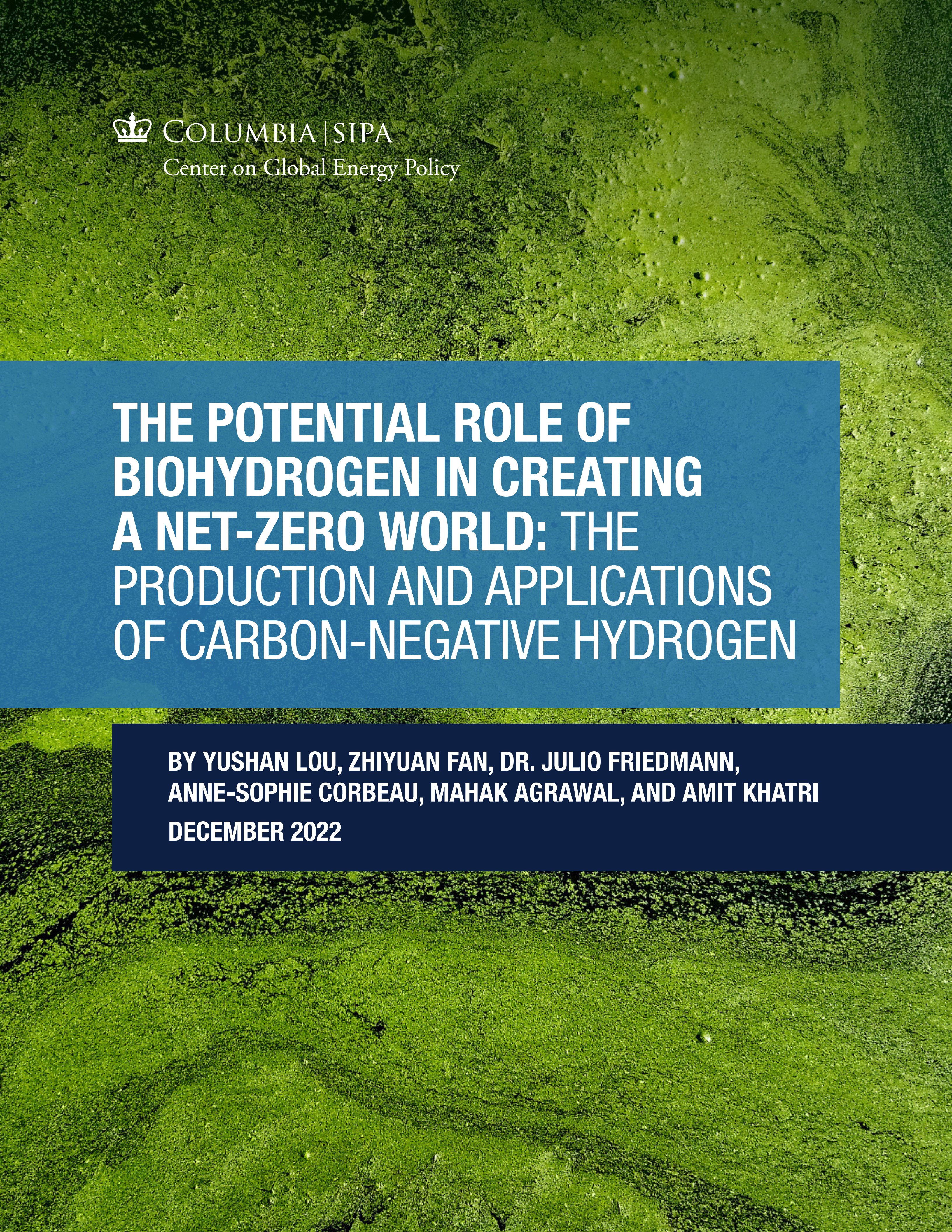

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THE POTENTIAL ROLE OF BIOHYDROGEN IN CREATING A NET-ZERO WORLD: THE PRODUCTION AND APPLICATIONS OF CARBON-NEGATIVE HYDROGEN

BY YUSHAN LOU, ZHIYUAN FAN, DR. JULIO FRIEDMANN,
ANNE-SOPHIE CORBEAU, MAHAK AGRAWAL, AND AMIT KHATRI

DECEMBER 2022

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EXECUTIVE SUMMARY

As the window of opportunity to avert the worst effects of climate change closes, rapid decarbonization efforts have been turning to novel low-carbon hydrogen applications in the fields of heat, energy storage, and fuel cell technology as a potential solution for traditionally hard-to-abate sectors. Green hydrogen, in particular, defined as hydrogen produced from water electrolysis using renewable or low-carbon electricity, has received the lion's share of attention. By comparison, little attention has been paid to biohydrogen (Bio-H_2), a type of hydrogen produced from organic waste streams (e.g., agricultural waste) that can potentially yield a carbon-removing (or climate-positive) fuel when coupled with efficient CO_2 absorption and subsequent storage. Indicatively, few hydrogen supply-and-demand forecasts or high-level hydrogen strategies mention it. However, Bio-H_2 presents opportunities not only to establish a cyclical hydrogen system with waste converted into energy but also to address emissions that remain after all technically and economically feasible efforts have been made to eliminate them.

This report, part of the Carbon Management Initiative at the Center on Global Energy Policy, explores the current state of play for Bio-H_2 and its potential contribution to decarbonization efforts. The report begins with an analysis of the varying definitions and categorization of Bio-H_2 in the literature, which may relate to its classification as both a hydrogen and a bioenergy with a diverse selection of sources and manufacturing pathways. Next, it assesses the crucial question of Bio-H_2's carbon intensity, which has additional specifications to those of blue hydrogen (defined as hydrogen manufactured from natural gas with carbon capture and storage [CCS]) and green hydrogen production, including land use, land use change, use of dedicated fuel crops (and associated land use issues), status and footprint of wastes (agricultural, forestry, and municipal), and avoided or reduced methane emissions. The report shows that if the biomass feedstock is not carefully selected and the energy consumed during its processing is not closely monitored and controlled, Bio-H_2's carbon footprint can potentially exceed that of fossil-based hydrogen today. Therefore, to avoid any potential negative climate impacts from utilizing Bio-H_2, the assessment and governance of biomass feedstock for Bio-H_2 manufacturing is critical.

This report also shows that the potential carbon-removing value of Bio-H_2, particularly the carbon-negative hydrogen derived from biomass wastes and CCS, far outweighs its energy value and that Bio-H_2 can be manufactured using technologies that are relatively mature and near commercial stage. Nonetheless, because the carbon-negative value of Bio-H_2 is contingent on the use of biomass wastes, which is a constrained resource, Bio-H_2 should only be employed when the capacity of other decarbonization methods is limited. Key opportunities for its application present in hard-to-abate sectors with potential for manufacturing zero carbon or even carbon-negative steel or chemicals. In regions where waste biomass is abundant and underutilized (e.g., East or Southeast Asia), Bio-H_2 can also enable a circular carbon economy and offer flexible carbon management solutions. For example, local food scraps and agricultural waste (e.g., rice husk) can be converted into fertilizers (created from hydrogen-derived ammonia), which can cut carbon emissions from food production.

At present, however, the wide deployment of carbon-negative Bio-H_2 still faces considerable obstacles. If policy-makers and business leaders wish to overcome these obstacles, the following recommendations may be pertinent:

- **Incorporate Bio-H_2 manufactured from biomass wastes and CCS technologies into national hydrogen strategy and planning.** With a potential carbon footprint of between around −21 kg-CO_2/kg-H_2 and −15 kg-CO_2/kg-H_2 (using a median estimation of life-cycle assessment and land use change), Bio-H_2 manufactured in this way can offer a significant climate benefit.
- **Apply Bio-H_2 manufactured from biomass wastes coupled with CCS technologies as a deep decarbonization tool for hard-to-abate sectors.** Carbon-negative Bio-H_2 can potentially enable the production of zero carbon or even carbon-negative steel (−0.61 tCO_2/t to 0.39 tCO_2/t) and/or chemicals such as ammonia (−4.04 tCO_2/t to −0.6 tCO_2/t) and methanol (−3.89 tCO_2/t to −0.17 tCO_2/t) (see Table 5 for details).
- **Establish standardized, verifiable, and transparent carbon-accounting methods as well as a governance infrastructure for biomass procurement and Bio-H_2 production.** These can help ensure that the use of Bio-H_2 produces climate benefits and can help anchor agreements between suppliers, purchasers, and countries to prevent malpractices in the harvesting of biomass and miscalculation in the carbon accounting of Bio-H_2's footprint.
- **Introduce government incentives for the production and consumption of carbon-negative Bio-H_2.** Such incentives can encourage the production and use of carbon-negative Bio-H_2 toward the development of a Bio-H_2 market.
- **Encourage government investment in and policy support for:**
  - **Enhancing waste management infrastructure and the collection and usage rate of biomass wastes.** This can help to eliminate the widespread burning and landfill disposal of biomass waste, including crop residue and municipal solid waste, which leads to air and water pollution and additional greenhouse gas emissions.
  - **Improving Bio-H_2 production technologies, particularly for gasification.** This can help to address remaining barriers to scaling up certain thermochemical Bio-H_2 production technologies, including catalyst fouling, inconsistent feedstock quality, and gas cleaning, as well as metabolic technology pathways, which are still subjected to low volumetric and subject-specific yields.
  - **Further reducing Bio-H_2 production costs, which will require a lower feedstock cost across regions and a reduced CAPEX cost from improved and scaled biomass gasification technology.** This can help make Bio-H_2 consistently cost-competitive at \$2/kg-H_2. Currently, production costs for Bio-H_2 range widely (\$1.25–\$10.51/kg-H_2). The lower-range costs are comparable to the mean costs of gray hydrogen (\$0.5–\$2/kg-H_2), but they are limited to regions with cheap and abundant biomass supplies situated within a short distance of the manufacturing site.

INTRODUCTION

Low-carbon hydrogen, or hydrogen produced with little to no greenhouse gas (GHG) emissions, has emerged as an attractive solution in the transition to a net-zero carbon economy. By potentially reducing, recycling, reusing, or removing emissions while retaining the key functions and features of existing infrastructure, it can critically enhance efforts at decarbonization around the world. This report, which builds on a prior report by the Carbon Management Initiative focused on green hydrogen (2021), puts the spotlight on biohydrogen (Bio-H_2), or hydrogen synthesized through either metabolic or the thermochemical conversion of biomass feedstocks, as a potentially carbon-negative hydrogen source. The focus, therefore, is on Bio-H_2 produced from waste biomass feedstocks with carbon capture and storage (CCS) in particular, which can potentially contribute to a circular carbon economy.[1]

As this report seeks to show, Bio-H_2 is different from other forms of low-carbon hydrogen (e.g., green hydrogen produced from water electrolysis with low-carbon electricity and blue hydrogen produced from natural gas with CCS) due to its unique technical, economic, operational, and governance characteristics. Most significantly, unlike its counterparts, Bio-H_2 can potentially be carbon negative when combined with CCS. By furnishing energy while quickly removing substantial amounts of carbon from the air and oceans, **Bio-H_2 can be a critical tool for policy-makers and business leaders invested in achieving net-zero targets. Importantly, though, Bio-H_2's carbon-negative potential is dependent on: 1) securing biomass feedstocks with extremely low-carbon footprints, such as agricultural or municipal waste, manure, or sewages, and 2) using production technology that is compatible with CCS at a high rate of capture.**

The report begins by introducing the complexity of using biomass as a feedstock. It then discusses the current status of Bio-H_2 in the literature and future energy scenarios. Finally, the report reviews the existing literature on the technologies, costs, and carbon footprints of Bio-H_2 and examines core challenges to its expansion at a scale that would allow it to contribute to net-zero emissions scenarios.

Biomass Feedstock: Sources and Carbon Footprint

In the broadest sense, biomass refers to all organic material found on Earth, including plants, animals, and microorganisms. It is regarded as a renewable resource because it can regrow by absorbing CO_2 from the atmosphere or being harvested from waste (NREL n.d.). For centuries, biomass has served as the principal source of heat generation (e.g., for cooking or home heating). Since 2009, when the European Union committed itself to 20 percent renewable energy by 2020 and included biomass on its list of renewable energy sources, biomass has been classified as a form of "renewable" energy (European Commission 2009). In 2021, it constituted almost 60 percent of the renewable energy mix in the European Union (European Commission 2021).

Biomass-based energy has been a controversial subject in the climate debate due to uncertainties surrounding its carbon footprint and associated environmental impacts. The carbon footprint of biomass-based energy depends heavily on the provenance of the biomass feedstocks and how they are processed. In the production process of a biomass-based product, a significant amount of energy can be required for harvesting, gathering, transporting, storing, and converting feedstocks. These "process-based emissions" are represented by the term "life-cycle assessment" (LCA)[2] (Murphy et al. 2016; Patel et al. 2016). Even before raw biomass feedstocks are available, emissions can be released through land use change (LUC) in cases where the production of biomass for energy replaces the original biomass grown on the land (Tamburini et al. 2020). **If the origin of the biomass feedstock and the process of energy production are not carefully selected, monitored, and controlled, biomass-based energy could potentially have a substantial carbon footprint—even exceeding that of fossil-based energy today (Osman et al. 2020; Singh and Rathore 2017).**

Given that the value of Bio-H_2 (and bioenergy in general) is directly related to its LCA and LUC, this study focuses on waste and residual biomass used for Bio-H_2 generation, which are generally estimated to have low and potentially negative carbon footprints (Thakur et al. 2014). However, even when waste biomass is being considered, questions about potential carbon "leakage" associated with project expansion and attendant deforestation or land degradation remain (Bird et al. 2011). Therefore, avoiding any negative climatic impacts of Bio-H_2 requires rigorous governance and standardized LCA-accounting methodologies for harvesting and determining the emissions of biomass resources, including waste biomass. Unfortunately, biomass production currently has a poor track record of environmental stewardship (Correa et al. 2019), with many documented cases of damage to local ecosystems (Efroymson and Langholtz 2017) and local communities (van der Horst and Vermeylen 2011) as well as eco-colonialism[3] (Havnevik et al. 2011; Howes et al. 2016). Depending on the system boundary selected, the carbon-accounting method can also have a substantial impact on the estimated emissions of a bioenergy system, especially for slow-growing biomass such as forestry (Tanzer and Ramirez 2019). Furthermore, carbon accounting of biomass feedstocks, including both fuel crops and wastes, frequently overlooks carbon leakage or degradation (e.g., through peatland oxidation). **A rigorous, consistent, transparent, and verifiable accounting method[4] for biomass procurement and biohydrogen (and, more generally, bioenergy) production is necessary to help avoid negative climate consequences.**

Combining CCS technologies with biomass-based energy can play a critical role in the decarbonization of energy systems. This section shows several different pathways of doing so that have been deployed or discussed in the field (see Table 1):

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$_2$ 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

BECCS emphasizes the use of biomass as an energy source (C. Consoli 2019); **BiCRS** leverages the ability of plants and algae to extract CO_2 and store it underground or in long-lived products, allowing biomass to be used entirely for carbon removal rather than energy production (Sandalow et al. 2020); and, most recently, **HyBECCs**, or Bio-H_2 combined with CCS, enables the manufacture of carbon-negative hydrogen (Full et al. 2021). Although this report does not endorse any specific terminology for carbon-negative Bio-H_2, one of the naming conventions observed in the literature for the Bio-H_2 discussed in this report is HyBECCs. HyBECCs has also been labeled “BECCS hydrogen” (BP 2022), “BECCS- H_2” (Larson et al. 2021), and “BHCCS” (Rosa and Mazzotti 2022), the latter of which stands for biohydrogen with carbon capture and storage.

Definition and Classification of Biohydrogen

In line with recent literature (Kumar and Sarkar 2011; Mohan and Pandey 2013; S. C. Bhatia 2014), this report defines Bio-H_2 as the synthesis of H_2 gas through both biological production and the thermochemical conversion of biomass feedstocks. This definition of Bio-H_2 is wider in scope than that of an earlier literature, which assumed that the term “Bio-H_2” is limited to hydrogen produced biologically (Levin et al. 2004).

There has been considerable confusion over the nomenclature around hydrogen. Bio-H_2 is often regarded as a type of “green hydrogen,” a term that tends to be used interchangeably with “renewable hydrogen.” In reality, however, Bio-H_2 and green hydrogen are both “renewable” forms of hydrogen but are distinguishable from each other. The European Commission rightly defines “renewable hydrogen” as H_2 produced through electrolysis of water using renewable electricity (i.e., what is typically considered “green hydrogen”) or through biogas reforming or biochemical conversion of biomass (i.e., Bio-H_2).

Because Bio-H_2 is a form of both hydrogen and bioenergy, there has likewise been confusion around how to classify it. For instance, the accelerated and net-zero scenarios of BP’s *Energy Outlook 2022* feature a brief discussion of Bio-H_2 labeled “BECCS” that lists it as both a type of demand for bioenergy and part of a projection for future low-carbon hydrogen supply (BP 2022). Princeton’s *Net-Zero America* report gives Bio-H_2, labeled “BECCS-H_2,” an important role in its 2050 H_2 projection and recognizes it as one of the key technologies for biomass use in 2050 scenarios. The significance of Bio-H_2 in achieving climate neutrality is not explicitly acknowledged in similar reports, however. The *IEA’s Net-Zero 2050* scenario analysis and the IRENA’s *World Energy Transition 2022* report, for instance, do not mention Bio-H_2 expressly in their future scenario analyses. These discrepancies and omissions are indicative of the lack of recognition of Bio-H_2’s potential as a climate mitigation method among industry leaders and government bodies.

BIOHYDROGEN PRODUCTION: TECHNICAL OVERVIEW

Background

Compared to fossil-based hydrogen, Bio-H_2 has the potential to have an extremely low-carbon footprint: Bio-H_2 produced with low-carbon biomass feedstocks and renewable energy can be nearly carbon neutral; when its production in this manner is paired with CCS, it can be net carbon negative, effectively removing CO_2 from the atmosphere (Baker et al. 2020; Sandalow et al. 2020). **The carbon-negative property of Bio-H_2 is, however, dependent on which biomass inputs and conversion techniques are used.**

A variety of biomass feedstocks and technical methods can be used to produce Bio-H_2, leading to a wide range of carbon intensities. In attempt to provide a complete picture of Bio-H_2's carbon emissions profile, the following section performs a technical evaluation of Bio-H_2 production techniques and associated biomass feedstocks.

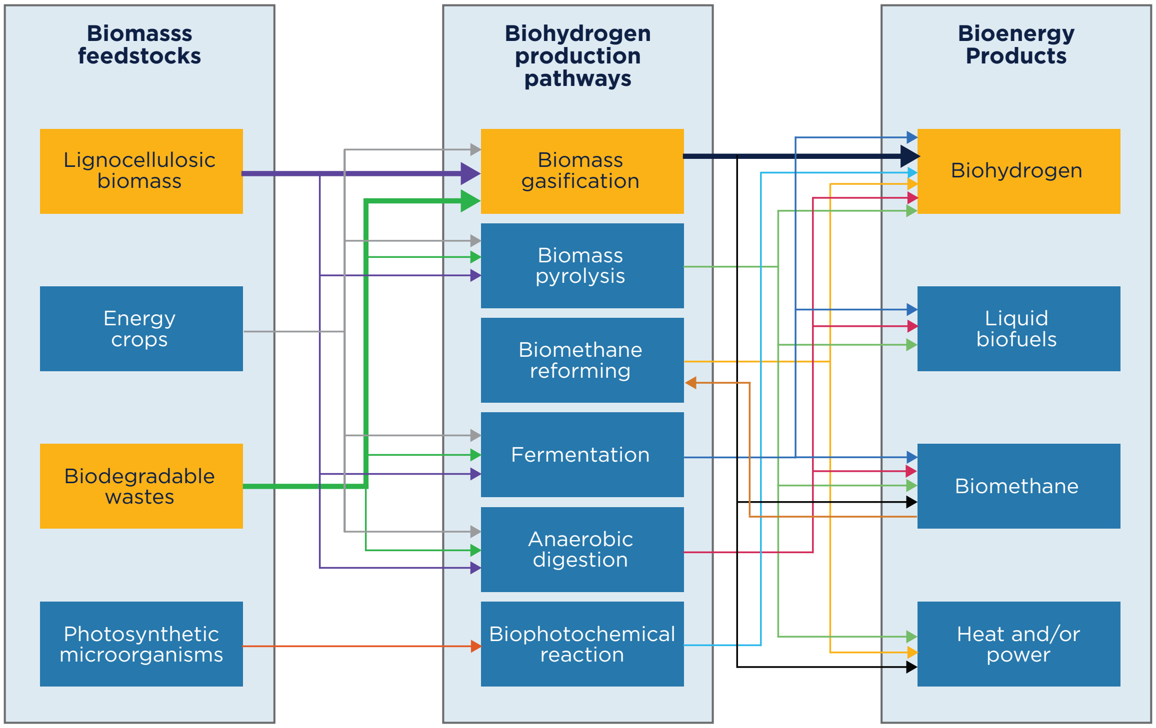
Feedstock and Bioenergy Product Types

A broad definition of biomass includes all organic material found on Earth, including plants, animals, and microorganisms. Biomass feedstock can thus be diverse in form and sources, resulting in a complex LCA and LUC profile. Previous studies have categorized biomass feedstock differently based on specific biomass features such as level of effect on global food and agricultural systems (e.g., first through fourth generation) (Dutta et al. 2014) or origin and function (e.g., forest biomass versus aquatic biomass) (Sikarwar et al. 2017). This study instead classifies biomass by its harvesting method, using the following categories:

1. **Lignocellulosic (woody) biomass:** the most common type of biomass for energy production (e.g., wood pellets).
2. **Energy crops:** oil, sugar, and starch crops cultivated for dedicated energy uses using crop lands.
3. **Biodegradable wastes:** agricultural and wood wastes/residue, animal manure, municipal solid wastes, and sewage sludge that typically have very little economic value or have minimal environmental impact in current economic models.
4. **Photosynthetic microorganisms:** a distinct way of producing Bio-H_2 through bio-photochemical routes using light energy as a primary input.

In addition to having diverse origins, biomass feedstocks can be converted into a range of bioenergy products beyond Bio-H_2 and employed in a variety of applications such as heat and power, biodiesel, bioethanol, methanol and dimethyl ether (DME), other liquid fuels, and biomethane (see Figure 1). The latter, which is chemically identical to methane, is an upgraded form of biogas that is typically produced from biomass-based wastes such as manure or sewage sludge through anaerobic digestion. As a biomass-based energy product and a potential feedstock for Bio-H_2 production, its sources, carbon footprint, and conversion pathway to Bio-H_2 will be discussed here separately.

Figure 1: Biomass feedstock conversion chains



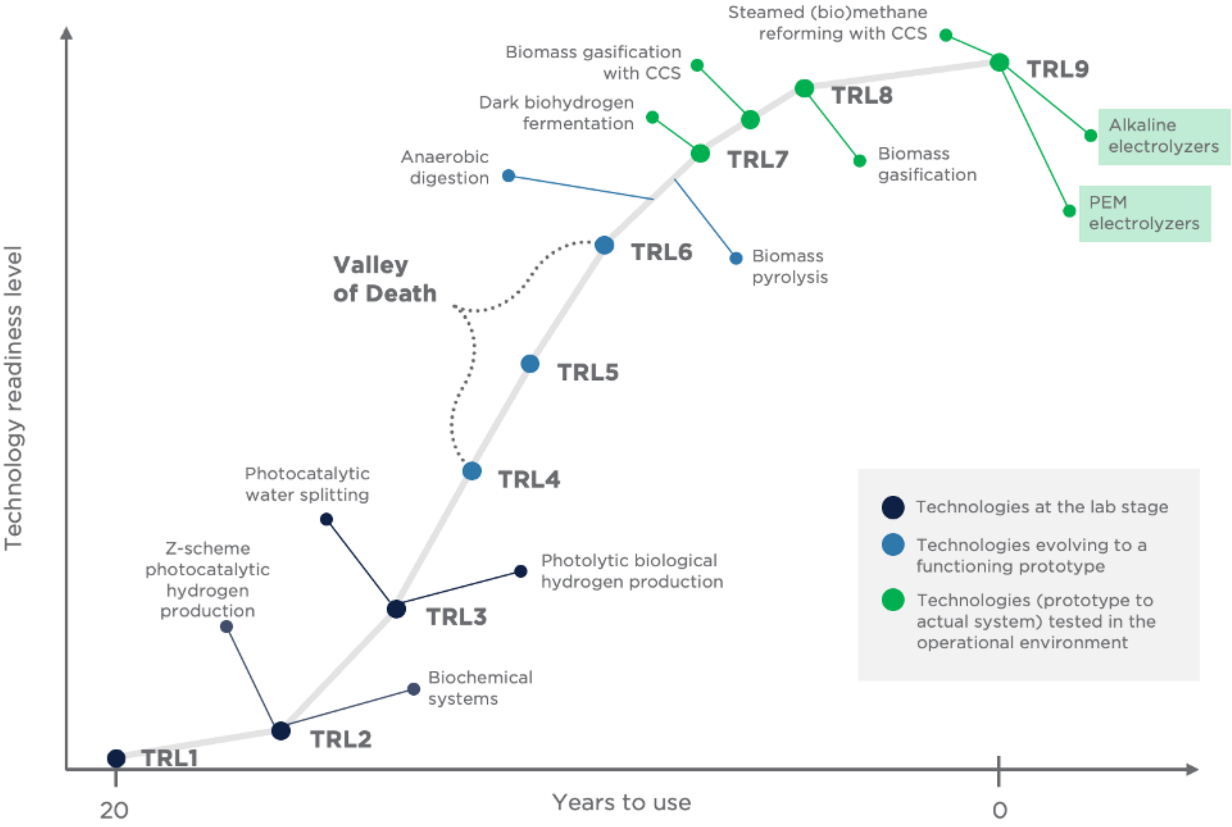
Note: Biomethane is an input as well as an output in the conversion chain; as a final energy product, it can be transformed into Bio-H_2 via biomethane reforming.

Source: Anisha and John 2014; Cao et al. 2020; Chen et al. 2021; Demirel, Scherer, Yenigun, and Onay 2010; DOE, n.d.; Ghimire et al. 2015; Guiot and Frigon 2012; Hitam and Jalil 2020; Iribarren, Susmozas, Petrakopoulou, and Dufour 2014; Kaparaju et al. 2009; Łukajtis et al. 2018; Ruan et al. 2020; Sawatdeenarunat et al. 2015.

Biohydrogen Production Pathways

Bio-H_2 can be produced either biologically or thermochemically. Biological Bio-H_2 production routes include fermentation, anaerobic digestion, and biophotolysis, all of which involve microorganisms; thermochemical Bio-H_2 production routes include biomass gasification, pyrolysis, and steam (bio)methane reforming. In general, thermochemical processes are far more technologically advanced than biological processes (see Figure 2). Due to their low cost and high efficiency, they have also garnered greater attention (Kumar et al. 2020). Thermochemical processes represent a near-term prospect for industrial-scale Bio-H_2 production from biomass (wood, straw, grass clippings, etc.) or other bioenergy sources (e.g., biomethane/biogas).

Figure 2: Technology readiness levels of various biohydrogen production pathways



Note: Technology readiness level (TRL) is a measurement system used to assess the maturity level of a particular technology. Numerical ascendance signifies increasing maturity of the technologies. Academia tends to focus on TRLs 1–4, whereas industry tends to work with TRLs 7–9. Hence, TRLs 4–6 is dubbed the "Valley of Death," where many new technologies die due lack of investment from either academia or industry (Rossini n.d.). Biomass pyrolysis is a different technology from methane pyrolysis. Technologies highlighted in green are green hydrogen production routes, included in this figure to illustrate that green hydrogen is more technically mature than many Bio-H_2 pathways.

Source: Anisha and John 2014; Blumberg 2018; Cao et al. 2020; Chen et al. 2021; Demirel et al. 2010; DOE n.d.; EBA 2022; Ghimire et al. 2015; Glushkov et al. 2021; Hitam and Jalil 2020; IEA 2021a; Kan, Strezov, and Evans 2016; Kumar et al. 2020; Łukajtis et al. 2018; Molino, Chianese, and Musmarra 2016; Ruan et al. 2020; Sawatdeenarunat et al. 2015; Vane 2005; Wang et al. 2020.

Biohydrogen Production—Thermochemical Conversion Routes

The three most prominent thermochemical conversion routes are gasification, pyrolysis, and steam (bio)methane reforming. The efficiency and yield of the products produced via each of these pathways largely depends on the feedstock used.

Biomass Gasification

Among the thermochemical processes for biomass conversion, gasification is the oldest, the most well established, and, by many estimates, among the most efficient biomass-to-fuel conversion methods (Kumar et al. 2020; Glushkov et al. 2021). Through a controlled process using heat (600 to >1000°C), steam, and oxygen, it can convert a variety of biomass sources into hydrogen and other gaseous products without combustion (DOE, n.d.; Molino et al. 2016). This form of conversion via partial oxidation has been used to produce syngas (a mixture of hydrogen, carbon monoxide [CO], and traces of carbon dioxide [CO_2]), which is then separated into a purified stream of H_2 gas and a concentrated stream of CO_2 suitable for CCS. A dedicated Bio-H_2 production gasification facility can minimize the production of unwanted gases and solids while increasing the Bio-H_2 yield (Cao et al. 2020). Such a facility can also be retrofitted with a CCS unit, making the Bio-H_2 greatly carbon negative (see the "CCS Opportunity" section below).

The main advantages of the gasification production route are its feasibility for industrial applications, potential to process high moisture content biomass waste, and ability to eliminate odors and pathogens when treating animal manure (Kumar et al. 2020). When solid biomass is used as an input for gasification technology, which can accept a variety of biomass feedstock forms, it can potentially create high Bio-H_2 yield. However, the gasification production route still faces major barriers in regard to feedstock quality control (i.e., removing inorganic constituents from the feedstock), catalyst corrosion or fouling, tar formation, and the separation of H_2 gas from many other compounds in the off-gases (Kumar et al. 2020).

Biomass Pyrolysis

The pyrolysis process involves heating biomass (200–600°C) in the absence of oxygen (Wang et al. 2020). Currently in the demonstration phase though approaching the commercial phase (see Figure 2), this pathway produces solid biochar, liquid bio-oil, and non-condensable gas products, including Bio-H_2 (Kan et al. 2016). Operational conditions such as heating rate and solid residence time greatly affect product types and quantity. Fast pyrolysis targets liquid fuels as the output, whereas slow pyrolysis often targets solid biochar. Different temperatures and catalysts can drive the pyrolysis reaction in favor of H_2 production, but the H_2 yield is lower than that of gasification due to the absence of steam and oxygen (Wang et al. 2020). Compared to gasification, pyrolysis has advantages such as less land requirement, less pollutant emission, and more flexible end-product type but faces similar challenges such as tar formation (10–35 percent) (Kumar et al. 2020) as well as other issues such as high corrosiveness and low heat stability (Glushkov et al. 2021; Ruan et al. 2020). Moreover, the hydrogen concentration in its gaseous products is insufficient to make it a financially viable hydrogen production process (Chen et al. 2021).

Biomethane Reforming

Steam methane reforming (SMR) is currently the most widely used pathway by far for H_2 production (approximately 97 percent) (IEA 2021a). Given that the methane molecules it uses are the same as those for biomethane and natural gas fossil methane, there is little technical difference between these reforming pathways (Blumberg 2018). Feeding biomethane instead only affects the cost of energy and the carbon footprint of methane itself. However, biomethane, which is purified from biogas, also has other major uses such as the direct substitution of natural gas (e.g., Europe has over 20,000 biogas/biomethane plants in operation, mainly for power or heat generation [EBA 2022]). As a result, biogas is a valuable resource in and of itself and should be prioritized for its immediate applications over and above the production of Bio-H_2.

Challenges

In gasification and pyrolysis systems, H_2 gas is often combined with CO, CH_4, and H_2S. Before it can be utilized in any practical manner, the H_2 gas must be isolated from the other gases, concentrated, and stored. Separating H_2 from other gases at low concentrations and partial pressures and storing the purified H_2 remain formidable obstacles. In addition to low-quality gas output, equipment obstructions, decreased system efficiency, and tar formation are intrinsic problems in the biomass gasification process. Moreover, the performance of catalysts utilized in thermochemical processes must be enhanced.

Another challenge is pollution. Unless adequate and effective preventive measures (e.g., installing pollutant sensors and filters or scrubbers) are implemented and continuously enforced, biomass gasification plants can produce environmental problems such as water and air pollution (Barahmand and Eikeland 2022).

Biohydrogen Production—Biological Conversion Routes

Biological conversion routes include fermentation, anaerobic digestion, and biochemical reactions. Fermentation is the most promising metabolic pathway for hydrogen production due to its high net energy ratio. But all biological pathways are subjected to very low volumetric and substrate-specific yield. Other than (dark) fermentation, these pathways remain low on the TRL scale.

Fermentation and Anaerobic Digestion[5]

Fermentation is the most mature biological pathway (TRL 7) for consuming biomass feedstocks to produce Bio-H_2 as well as other products such as methane and CO_2 (Ghimire et al. 2015). Among the various forms of fermentation, dark fermentation is considered especially promising due to its high net energy ratio of 1.9 (SMR 0.64) (Łukajtis et al. 2018). This process involves converting biomass feedstocks using anaerobic bacteria grown in the dark via glycolysis. Similar to biomass pyrolysis, several end-products of this pathway limit the overall Bio-H_2 yield and energy efficiency. Extra costs and energy must also be added to account for product separation and upgrading (Vane 2005). Another form, photo-fermentation, proceeds through a series of biochemical reactions involving a diverse group of photosynthetic bacteria in the presence of light. This process, however, has low conversion efficiency and poor performance (Hitam and Jalil 2020).

Anaerobic digestion is typically used for converting lignocellulosic biomass into biogas (a mixture of biomethane and CO_2) (Sawatdeenarunat et al. 2015). The technology of anaerobic digestion for Bio-H_2 is still under development (TRL 6). A two-phase system of anaerobic digestion has the advantage of producing hydrogen and methane simultaneously (H_2-methane coproduction), but most bioenergy is carried by the biomethane production rather than the Bio-H_2 production, a critical disadvantage compared to dedicated Bio-H_2 production pathways (Demirel, Scherer, Yenigun, and Onay 2010). It is worth noting that the biomethane could be used produce Bio-H_2 via reforming (referring to biomethane reforming pathway).

Bio-photochemical Reaction

Bio-photochemical reaction, or biophotolysis, is the production of hydrogen using only water and sunlight. This process involves water dissociating into molecular hydrogen and oxygen in the presence of light with the aid of microorganisms or other mediums such as catalysts (Anisha and John 2014). Although typically considered a potential pathway of Bio-H_2 production, bio-photochemical reaction does not require the input of biomass as a feedstock, which is a potential advantage. For now, however, its production rates remain low and the technology is limited to lab-scale research (TRL 3, which is the lowest level among all the Bio-H_2 production pathways; see Figure 3). The cost and carbon footprint of bio-photochemical reaction also remain largely unknown.

Overall, although biological production methods of Bio-H_2 show promise, they are still largely in lab-scale research stage with low volumetric and substrate-specific yields. Anaerobic digestion and biophotolysis, in particular, require more development and face the challenge of not being dedicated to Bio-H_2 production technology and a low TRL, respectively. Biomass pyrolysis and fermentation are both near commercial stage, but currently the most mature and technologically available routes are biomass gasification and biomethane reforming, which is a limited resource with competitive uses. Therefore, gasification remains the most promising pathway for Bio-H_2 production.

Comparative Analysis of Biohydrogen Production Pathways

Table 2 below summarizes and compares the key parameters of the six Bio-H_2 production pathways.

The costs associated with each pathway may vary greatly depending on level of technology readiness, infrastructure support, and availability of biomass feedstock. Gasification, pyrolysis, biomethane SMR, and biophotolysis have low-range costs (approximately \$1.25–\$1.4/kg) that are comparable to the mean cost of gray hydrogen (\$0.5–\$2/kg) today (see Table 2 and 3). However, these low costs are contingent on cheap and abundant biomass supplies situated within a short distance of the manufacturing site. Meanwhile, the highest cost ranges of gasification, pyrolysis, biomethane SMR/autothermal reforming (ATR), and fermentation are consistent with high ranges of green hydrogen costs (\$8–\$10/kg).

The carbon footprints across pathways have a wide range (−26.5 to 10.8 kgCO_2/kgH_2; see Table 2), including negative values obtained either through CCS or carbon sequestration through biochar. The highest ranges are consistent with current gray hydrogen values (>10kg-CO_2/kg-H_2), which correspond to the earlier discussion about how using biomass feedstocks with high LCA and LUC values for Bio-H_2, production can exceed the carbon intensity of today's fossil-based hydrogen.

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

Source: Adapted from Fan et al. 2021; Global CCS Institute 2021a; IEA 2021a; Woodall et al. 2022.

CCS OPPORTUNITY: BIOMASS GASIFICATION COSTS AND CARBON FOOTPRINT

This section focuses explicitly on biomass gasification. In general, it is thermodynamically advantageous to the carbon capture process if the gas mixture to be separated already contains a high concentration of CO_2 (Ghiat and Al-Ansari 2021). As observed in the previous review, the solid biomass gasification pathway shows the greatest promise for Bio-H_2 production, with a high Bio-H_2 yield, a concentrated CO_2 stream for CCS compatibility, reasonable costs (i.e., low-range values; see Table 2), and a spectrum of possible biomass feedstock selections. Like SMR, biomethane reforming is a production method that offers CCS compatibility. However, aside from dedicated Bio-H_2 production, biomethane is a limited resource with numerous existing competitive applications. Biomass gasification, on the other hand, has widely available feedstock sources and high CCS compatibility. Given these advantages, this section examines the cost and carbon footprint of Bio-H_2 production associated with biomass gasification.

Biomass gasification typically involves several steps: feedstock preparation, feedstock gasification, gas cleanup, and separation (IEA Bioenergy 2018). The latter step refers to the separation of Bio-H_2 from other gases, which naturally yields a high-concentration stream of CO_2 that in turn poses a relatively low-cost opportunity for integrating a CCS unit. Different configurations of technology and carbon management methods yield different costs and carbon footprints (Salkuyeh, Saville, and MacLean 2018). Depending on its design, the gasification process may require additional heat from extra biomass or fossil energy, resulting in a different biomass consumption rate, carbon footprint, and cost of production (Salkuyeh, Saville, and MacLean 2018). However, in general, the unit abatement cost for Bio-H_2 with CCS (\$/ton-CO_2) is among the lowest of all CCS applications (Rubin et al. 2015). Therefore, Bio-H_2 with carbon-removing potential may prove a near-term opportunity that can play a vital role in achieving net-zero emission goals (Larson et al. 2021).

Most existing biomass gasification plants consist of downdraft fixed-bed gasifiers designed for syngas production (i.e., the production of H_2 and CO mixtures and associated gas-turbine electricity generation) (Pandey et al. 2015). Compared with gasification of other feedstocks such as coal or heavy oils, the quality control of biomass resources is complex and uncertain, requiring a more complicated plant design and therefore driving up the overall cost. More compact advanced technologies such as fluidized bed (FB) and entrained flow (EF) are better suited for biomass gasification and associated H_2 purification and CO_2 removal (X. Lu et al. 2019). Salkuyeh, Saville, and MacLean (2018) evaluated the CCS option for biomass gasification using FB and EF gasification technologies for their experimentally verified performance in commercial applications. Fixed/moving-bed downdraft and updraft gasification configurations have simpler design principles than FB and EF but require longer residence time and have a lower conversion rate. They have been found to be more suitable for smaller scale power generation instead of dedicated Bio-H_2 production (Siedlecki et al. 2011; Warnecke 2000).

Table 4: Technology descriptions for FB and EF gasification technology

Fluidized bed gasification	FB gasification operates at atmospheric pressure with air blown for oxygen input. Solid biomass feedstock and gas (air blown and steam) are fed separately. To sustain the fluidization of the process and avoid solid clinker formation, the operation temperature of FB (approximately 1,000°C) is typically less than the ash fusion temperature, which is why it forms tar as a by-product. Due to its ability to handle unconvertable materials by tar formation, FB is flexible in terms of solid feedstocks, including low-grade feedstocks.
Entrained flow gasification	EF gasification operates through pressurized condition and pure oxygen blown as input. Solid biomass feedstock and gases (air blown and steam) are fed concurrently, operating at much higher temperature (approximately 1300°C). The high operation temperature permits high gas conversion rates, which means negligible tar, oil, and other liquid as by-products as well as the conversion of almost all carbon content of biomass into CO_2, resulting in a much higher overall CO_2 capture rate than FB. The pure oxygen blown design makes the flue gas for CCS nitrogen free, raising the CO_2 concentration and thereby facilitating CO_2 separation and liquefaction. EF is therefore more CCS suitable than FB.

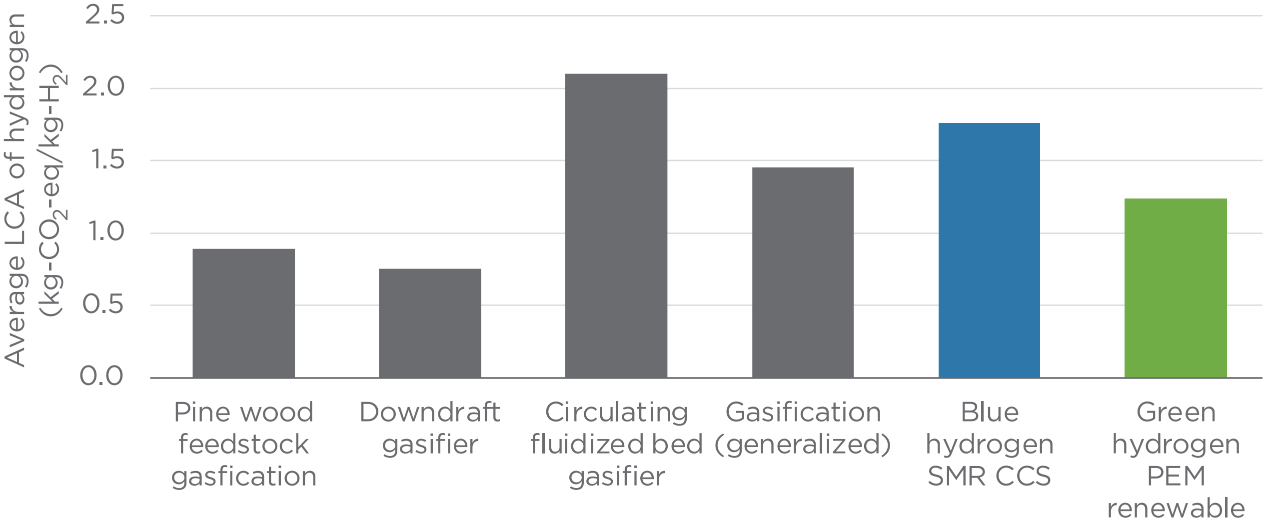
Source: Adapted from Salkuyeh, Saville, and MacLean 2018.

Salkuyeh, Saville, and MacLean (2018) estimate that using minimal fossil energy for Bio-H_2 production through either FB or EF gasification technologies results in a slightly negative carbon footprint for Bio-H_2 even absent CCS units (assuming the biomass feedstock and bioenergy used are strictly carbon neutral as biomass wastes). Equipped with CCS units, Bio-H_2 production can be greatly carbon negative (−21.8 to −15.8 kg-CO_2/kg-H_2, with the same assumptions in place). The life-cycle footprint of biomass is sensitive to many factors, however (Cherubini et al. 2009; Fritsche and Wiegmann 2009; Shen et al. 2015), and the value of Bio-H_2 (and biomass in general) is directly tied to its life-cycle emissions and the fuel it displaces (Sandalow et al. 2020).

LUC and LCA's Impact on Biohydrogen's Carbon Footprint

The following section summarizes the results of multiple studies to compare and contrast the impact of land use change (LUC) and life-cycle assessment (LCA) on Bio-H_2's total carbon footprint. Studies on the carbon footprint of Bio-H_2 from biomass gasification report similarly low LCA results (see Figure 3), ranging from 0.75 kg-CO_2-eq/kg-H_2 to 2.1 kg-CO_2-eq/kg-H_2, which is competitive with blue and green hydrogen regardless of the gasification process and feedstock used. This analysis shows that the impact of necessary fossil energy input on the gasification of Bio-H_2 is small, posing minimal climate risk. Bio-H_2 production from biomass gasification is among the lowest carbon intensity production pathways from a strictly LCA perspective.

Figure 3: Biomass gasification LCA summary and comparison

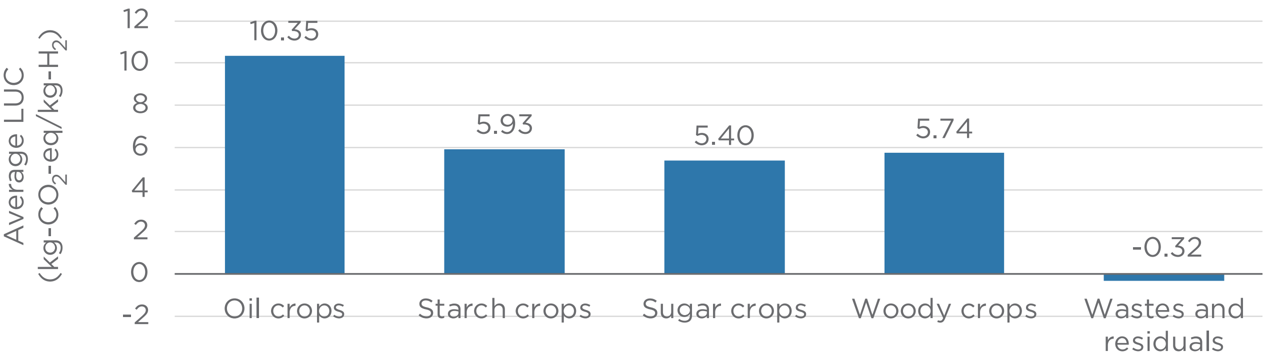


Note: Green hydrogen's carbon intensity here is not zero due to the inherent residual emissions associated with processes such as electricity transmission and distribution (Fan et al. 2021). PEM refers to polymer electrolyte membrane.

Source: Iribarren, Susmozas, Petrakopoulou, and Dufour 2014; Kalcini, Hepbalsi, and Dincer 2012; Moreno and Dufor 2013.

From an LUC perspective, the picture looks very different (see Figure 4); Drews, Larsen, and Balderrama (2020) show that LUC-induced carbon emissions (median value) from all types of biomass feedstock greatly increase the total carbon emissions of Bio-H_2 production from biomass gasification, except those from confirmed "wastes and residuals." To account for the high uncertainty of LUC, the authors selected the results in the 25–75 percentile range (LUC values of the middle 50 percent), eliminating the effect of outliers. For most widely used woody crops, Bio-H_2 LUC-induced carbon emission can contribute to roughly half of the emissions from SMR baseline, greatly damaging the carbon credit expected from biomass (Drews, Larsen, and Balderrama 2020). For Bio-H_2 production from biomass gasification, LUC poses more uncertainty and damage to the environment than LCA.

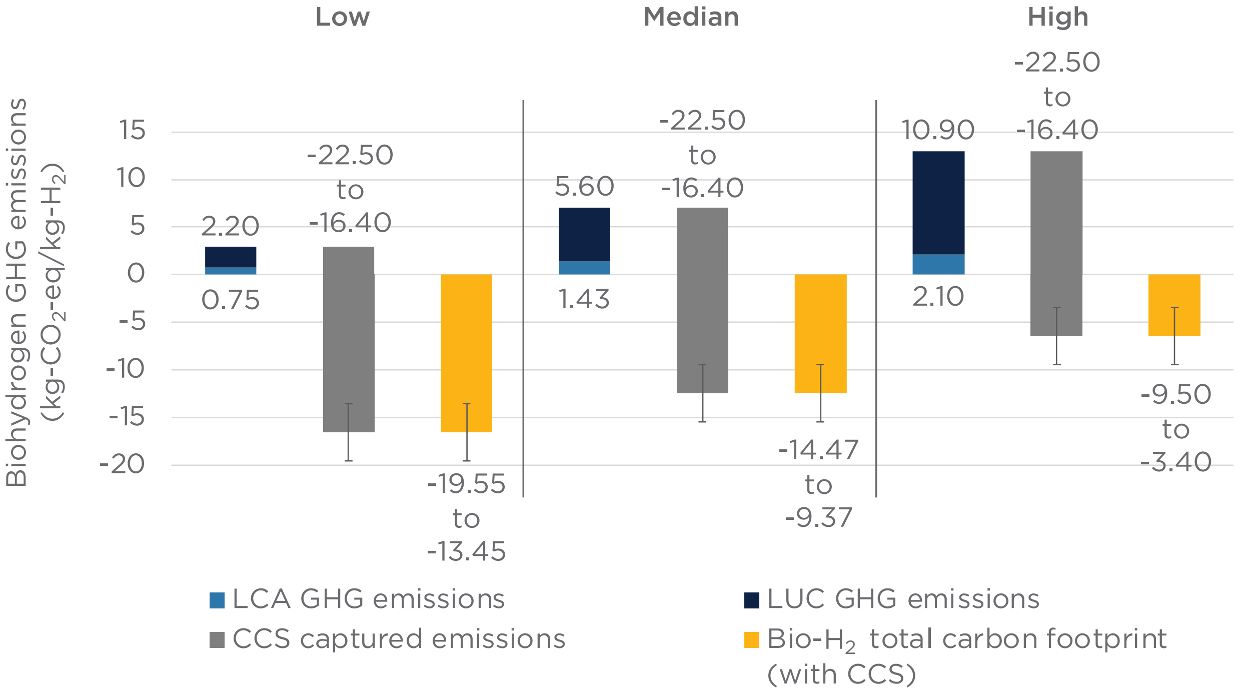
Figure 4: Biomass LUC summary by type of biomass feedstock



Source: Drews, Larsen, and Balderrama 2020; Salkuyeh, Saville, and MacLean 2018.

Figure 5 below summarizes the carbon emissions from both LCA and LUC using woody biomass feedstocks. Compared with LCA's emissions, LUC's are higher and have much greater uncertainty. Although both LCA and LUC add to the GHG emissions of Bio-H_2 production, the incorporation of carbon capture can enable net-negative emissions for Bio-H_2, even in the worst LCA and LUC scenarios.

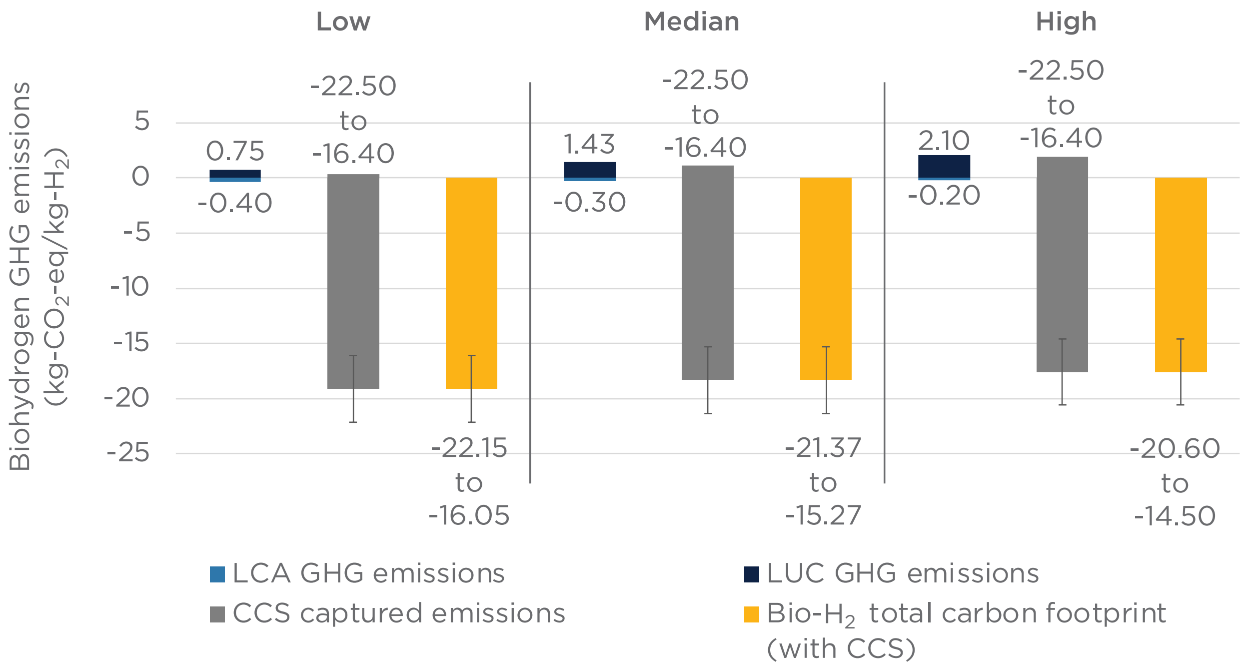
Figure 5: Carbon intensity of biohydrogen production from woody biomass gasification



Source: Authors' analysis based on data from Drews, Larsen, and Balderrama 2020; Iribarren, Susmozas, Petrakopoulou, and Dufour 2014; Kalincini, Hepbasli, and Dincer 2012; Moreno and Dufour 2013; Salkuyeh, Saville, and MacLean 2018.

Figure 6 summarizes the carbon intensity of Bio-H_2 production using waste biomass such as agricultural residuals or forest wastes instead of woody biomass. Due to waste biomass's low LUC, this type of Bio-H_2 production can have a near-zero carbon footprint; if combined with CCS, it can have a greatly negative carbon footprint, resulting in approximately 150 to 200 percent emissions reduction compared with gray H_2 (i.e., abating twice as much GHG as gray H_2).

Figure 6: Carbon intensity of biohydrogen production from waste biomass gasification

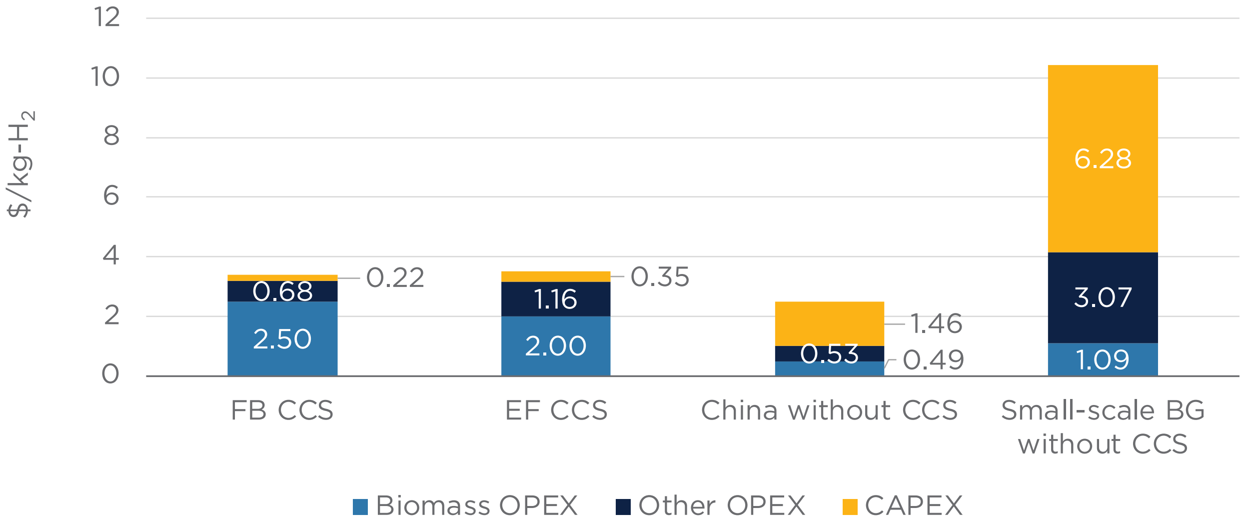


Source: Authors' analysis based on data from Drews, Larsen, and Balderrama 2020; Iribarren, Susmozas, Petrakopoulou, and Dufour 2014; Kalincini, Hepbasli, and Dincer 2012; Moreno and Dufour 2013; Salkuyeh, Saville, and MacLean 2018.

Cost Breakdown for Biohydrogen via Biomass Gasification

For Bio-H_2 production from biomass gasification, feedstock and capital expenditure (CAPEX) make up the overwhelming majority of the total cost (Salkuyeh, Saville, and MacLean 2018; Sara et al. 2016; Wang et al. 2019). Figure 7 (detailed in Table A-6) shows the results of different techno-economic analyses of Bio-H_2 production via biomass gasification, which vary dramatically.

Figure 7: Levelized cost of biohydrogen from biomass gasification



Note: FB CCS stands for fluidized bed with CCS technology; EF CCS stands for entrained flow with CCS technology; BG stands for biomass gasification technology.

Source: Wang et al. 2019; Salkuyeh, Saville, and MacLean 2018; Sara et al. 2016.

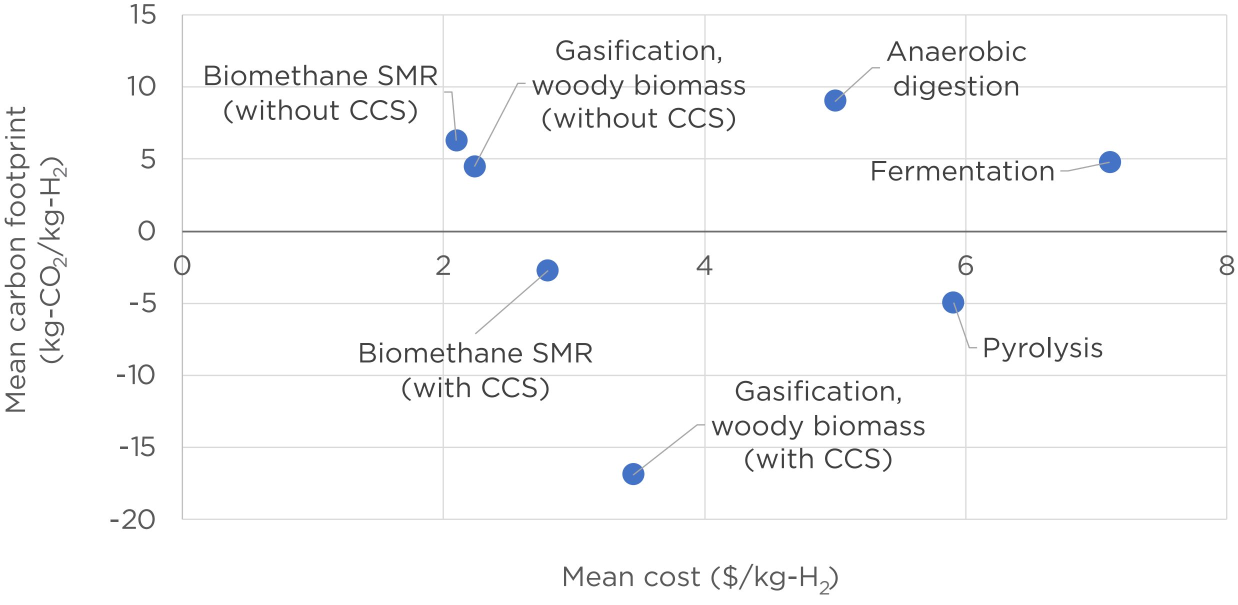
A deeper look at the results reveals that operational expenditure (OPEX) remains relatively stable across studies: the cost of biomass feedstock is in the range of \$0.50 to \$2.50/kg-H_2; and other OPEX components such as additional energy costs (for co-gasification) and O&M costs contribute 20 to 30 percent of the total cost (Salkuyeh, Saville, and MacLean 2018; Sara et al. 2016; Wang et al. 2019).

The biggest uncertainty around the cost of Bio-H_2 production through biomass gasification is CAPEX. By way of example, (Sara et al. 2016) shows that a small-scale (0.1 MW thermal power scale) biomass gasification plant can greatly increase the per-unit hydrogen production CAPEX compared with larger plants. This finding directly indicates how to further reduce the cost of Bio-H_2 production through biomass gasification: the systematic improvement of gasification plant design to reduce CAPEX. Other ways of driving down CAPEX are improved infrastructure such as CCS support and larger production scale.

Challenges remain for biomass gasification methods. (Cao et al. 2020) found that finding cost-effective catalysts for reaction temperature decrease and tar cracking is the greatest challenge to future biomass gasification, pointing to plant design and CAPEX components.

BIOHYDROGEN: PATHWAYS COMPARISON FROM A COST PERSPECTIVE

Figure 8: Average carbon footprint versus cost of different biohydrogen production pathways



Source: Djomo, Humbert, and Blumberga 2008; Ferreira et al. 2012; Gilani and Sanchez 2020; Hajizadeh et al. 2022; Khan et al. 2018; Kumar et al. 2020; Liu et al. 2022; Lu et al. 2020; Marcoberardino et al. 2018; Milbrandt, Bush, and Melaina 2016; Minutillo, Perna, and Sorce 2020; Nasir Uddin, Daud, and Abbas 2013; Oncel 2015; Osman et al. 2020; Park et al. 2010; Rosa and Mazzotti 2022; Saidi et al. 2018; Sarkar and Kumar 2010; Zhou et al. 2021.

Consolidating information from Table 1 and the aforementioned analysis on biomass gasification, Figure 8 displays the carbon footprint versus cost of Bio-H_2 produced via different pathways. Biomass gasification (woody biomass feedstocks) shows the lowest possible overall carbon footprint while maintaining a reasonably low cost of $3–4/kg-$H_2$.

Steam reforming of biomethane is also a promising technology that is compatible with CCS. Studies have shown that SMR of biomethane with CCS can potentially generate Bio-H_2 with a negative carbon footprint and at a lower cost than gasification of woody biomass with CCS (see Figure 8). However, biomethane has competitive uses, such as directly substituting natural gas. As a result, biomethane is a valuable resource in and of itself, and should be prioritized for its most immediate applications above and beyond the production of Bio-H_2. Other production pathways without CCS are all still carbon positive and can be optimally near carbon neutral if the biomass feedstock itself is carbon neutral and the production process is strictly low carbon.

BIOHYDROGEN APPLICATION OPPORTUNITIES

Bio-H_2 is identical to other hydrogen atoms (gray, blue, green) from a chemical and physical standpoint, meaning it can be used for any potential hydrogen application. **The greatest advantage of biomass-based hydrogen, however, is not as an energy or energy-carrying product per se, but its ability to remove carbon when coupled with CCS.** As such, its utility should be considered independently from that of other forms of low-carbon hydrogen (i.e., green hydrogen or blue hydrogen). When produced from waste and coupled with CCS, Bio-H_2[6] can potentially be profoundly carbon negative, provide additional climate benefits to its users, and assist sectors with limited decarbonization options achieve carbon neutrality by compensating for difficult-to-eliminate residual emissions.

In general, hydrogen can immediately replace natural gas as a heating source for industrial operations that demand huge volumes of thermal energy at high temperatures (e.g., blast furnaces) (Friedmann et al. 2019; Sandalow et al. 2020). It can also reduce carbon emissions and air pollution in the long-haul transportation and marine shipping industries or be used as a medium for long-term storage of renewable energy to help address the latter's seasonality and variable availability (Schiavo and Nietvelt 2020). Finally, hydrogen can be used in a fuel cell for backup power or to power vehicles such as private cars, trucks, buses, and marine vessels.

Unique Bio-H_2 application opportunities exist in harder-to-abate sectors. One example is the iron and steel industry. Most of the emissions from this sector's existing facilities are attributable to blast furnace rather than electricity, which accounts for only about 13 percent of the industry's total emissions (Fan and Friedmann 2021). As a result, renewable electricity plays a minor role in decarbonizing this sector. At present, BF-BOF[7] remains the primary method of steel production (accounting for approximately 71 percent of all steel), and there is limited opportunity to use hydrogen in BF-BOF instead of coking coal.

Among all steel manufacturing pathways, the most mature low-emission technique is currently green hydrogen-based DRI (direct reduced iron) combined with an EAF (electric arc furnace) powered by zero-carbon electricity (Fan and Friedmann 2021; Hoffmann et al. 2020).[8] Applying Bio-H_2 (assumed to be produced from gasification using waste feedstocks with CCS) can effectively double the carbon credit of hydrogen injection for both BF-BOF and DRI. In the case of DRI-EAF, it can achieve net carbon-negative steel (−0.6 ton-CO_2/ton-steel). This poses a unique opportunity to use Bio-H_2 to achieve net-zero or net-negative emissions for a harder-to-abate sector (see Table 5).

Table 5: The carbon intensity of various products made with green H_2 and Bio-H_2

Product and technology pathways	Baseline carbon intensity	Carbon intensity using green H_2	Carbon intensity using carbon-negative Bio-H_2
BF-BOF steel production (t-CO_2/t-HM) (H_2 replacing pulverized coal for hot air blast)	2.20	1.78	1.13 to 1.65
DRI-EAF gas steel production (t-CO_2/t-HM) (H_2 replacing all DRI gas consumption)	1.35	0.29 (renewable electricity) 0.80 (grid electricity)	−0.61 to 0.39
NG SMR-based ammonia production (t-CO_2/t-NH_3) (1:1 replacement of original H_2 consumption)	1.97	0.27	−4.04 to −0.6
NG SMR-based methanol production (t-CO_2/t-MeOH) (1:1 replacement of original H_2 consumption)	2.57 (including feedstock emission) 0.86 (energy emission)	0.77 (no feedstock emission when using external captured CO_2 as feedstock)	−3.89 to −0.17 (no feedstock emission when using external captured CO_2 as feedstock)
NG-based ethylene production (t-CO_2/t-Eth) (1:1 replacement of original H_2 consumption)	1.42 (including feedstock emission)	0.58	−2.93 to −0.43

Note: This table illustrates the potential for carbon-negative Bio-H_2 to reduce residual emissions from hard-to-abate sectors and generate carbon-negative goods. Green hydrogen is assumed here to have a carbon intensity of 1.3 kg-CO_2/kg-H_2 (Fan et al. 2021); electricity's carbon intensity is assumed to be 425 kg/MWh, considering the high carbon intensity of grid electricity in Asia and other regions with low renewable energy in the mix; Bio-H_2 is assumed to be produced using waste biomass combined with CCS. The range of the Bio-H_2 carbon intensity is −3.4 kg-CO_2/kg-H_2 to −22 kg-CO_2/kg-H_2. HM stands for hot metal, which is a standard measurement for iron and steel output. The calculation of BF-BOF steel production's carbon intensity using green H_2 assumes that all the pulverized coal (for hot air blast) is replaced with 100 percent green hydrogen and not used as a reducing agent; coking coal is still used in the process as a reducing agent. Due to the involvement of EAF in DRI-EAF gas steel production, a large portion of energy consumed during the manufacturing process comes from electricity. Therefore, the steel manufactured through the DRI-EAF pathway is sensitive to the carbon intensity of electricity itself; the grid electricity figure shows the final carbon intensity for steel using renewable electricity and average grid electricity. Methanol and ethylene are both carbon-containing molecules that use CO_2 as an input and release that carbon (as CO_2) once they are combusted or at the end of their life-cycle. "No feedstock emission" in NG SMR-based methanol production assumes that CO_2 used in the production is recycled.

Source: Fan and Friedmann 2021; Woodall et al. 2022; authors' analysis.

Another example is the chemical industry, which continues to represent a serious hurdle for deep decarbonization plans. In SMR-based ammonia production,[9] H_2 production is responsible for a significant portion of the final ammonia carbon footprint. Consequently, using external, low-carbon hydrogen as a feedstock can drastically reduce ammonia's CO_2 emissions (Woodall et al. 2022). When CCS-generated Bio-H_2 is used, the carbon-negative H_2 enables the production of carbon-negative ammonia (see Table 5). Similarly, the ethylene-synthesis process lends itself well to hydrogen-based heat generation because it already uses fossil-based gases, including H_2, to heat the steam cracker and other process units; by using carbon-negative Bio-H_2 instead, the final ethylene product can potentially achieve a negative carbon footprint (−2.93 t-CO_2/t-Eth) (see Table 5). Other chemicals that can similarly use a hydrogen feedstock to potentially have a large impact on emissions include ammonia (NH_3) and methanol (CH_3OH).

Although Bio-H_2 is currently not as cost competitive as gray hydrogen, its cost varies widely depending on location and manufacturing process. In places with access to low-cost and abundant biomass waste feedstocks, the cost of Bio-H_2 can be comparable to that of blue and green hydrogen, and on rare occasions, to that of gray hydrogen (see Tables 2 and 3). The wide range in the cost of Bio-H_2 also underlines regional opportunities—in areas with an abundance of waste biomass resources and access to geological disposal of CO_2, there is potential to utilize biomass waste for local energy consumption while also contributing directly to climate change mitigation at a low cost (see Appendix, Table A-1). This enables a system of circularity that transforms waste products into fresh resources.

In the context of urban and city planning, Bio-H_2 can be produced from municipal solid waste or sewage sludge to provide fuel for the city's long-haul vehicles or to provide heating. This would reduce the amount of transportation needed for the import and delivery of fuel in the city as well as the overall carbon footprint. Bio-H_2 can also play a role in reducing the overall energy consumption linked to food production. Currently, hydrogen is most commonly used to manufacture ammonia and its derivative—nitrogen fertilizer—which are vital to global food production, accounting for roughly half of total hydrogen consumption worldwide. Various streams of organic waste from different points in the food supply chain, including crop residues (upstream), animal manures (upstream), and food waste (downstream), can be used as feedstocks to produce Bio-H_2. This hydrogen can in turn be used as both heat and a feedstock for fertilizer production, reducing the overall carbon footprint of the food system.

CHALLENGES

Further Improvement of Gasification Technology

The thermochemical synthesis of Bio-H_2 from diverse organic biomass is widely regarded as a promising and economically viable technology. The benefits of this method include higher product yield and flexibility with the currently available infrastructure. For Bio-H_2 synthesis on a large scale, however, challenges remain. The process still needs to be optimized to reduce the energy loss caused by pretreating the biomass prior to the conversion process, optimizing the conversion efficiency in the reactor, reducing tar formation, and improving gas cleaning for H_2 gas separation and further processing. Other challenges include fluctuation in equipment costs, availability of feedstocks, and inconsistent feedstock quality. Catalyst contamination/fouling likewise must be solved, making catalyst optimization critical (Kumar et al. 2020).

Biomass Gasification's Environmental Impacts

The environmental impacts of gasification plants still need to be evaluated. The thermochemical conversion of biomass typically generates unwanted contaminates such as soot, char particles, ash, and condensable hydrocarbons, which pollute the air and water (Barahmand and Eikeland 2022). If this technology is to be used at a wide scale, the emissions and by-product disposal of biomass gasification plants will require careful supervision and the implementation of adequate and effective preventive measures.

Competing Uses of Biomass Resources

Biomass resources, especially biomass with minimal environmental impact such as wastes and residuals, have production limits that prevent them from being used as a primary source of energy. Harvesting additional biomass greater than the sustainable limits may lead to deforestation or competing use of land for food production or other agricultural activities. Biomass itself can also be used for purposes other than being converted into hydrogen. These include power generation (e.g., biogas/biomethane for electricity generation), industrial applications (e.g., producing biochar or biocoke to replace coal), or as biofuel in transport (road, aviation, and shipping). Many outlooks envisage such uses of biomass (IEA 2019), which may be preferred by industrial players and policy-makers because most of them can be implemented right away to address the immediate policy need of diversification. The REPowerEU strategy envisages that biomethane production can increase to 35 bcm by 2030, thereby replacing natural gas use in the medium term without having to adapt the transport infrastructure or change how end users consume the fuel.

Though the aim of this report is not to compare different uses of biomass resources, particularly those that yield the lowest carbon footprint, previous analyses showed that Bio-H_2 has unique merits in its adaptability to different biomass resources as well as carbon removal potential. As such, it can be considered a key option for the energy transition and climate mitigation.

Biomass Resources Limitations

Despite the numerous advantages of Bio-H_2, the biomass feedstock on which it relies is not distributed equally around the globe. Certain regions (i.e., South America and Southeast Asia) have abundant resources whereas others (i.e., Europe, Japan, and South Korea) are constrained (see Appendix, Table A-1). Globally, there is potential for 130–300 Mt/y of hydrogen production using biomass wastes and residual biomass with minimal environmental impact (Sandalow et al. 2020), providing CO_2 removal potential of 2.14–7.56 Gt CO_2/y (assuming all biomass is used for Bio-H_2 production). As a greatly carbon-negative source of hydrogen, Bio-H_2 can potentially play an important role in decarbonization and the creation of a circular carbon economy.

This unequal geographical distribution of biomass is a result not only of differences in the availability of biomass potentials but also the current collection and utilization rate of biomass residues. In Asia, for instance, China produces the most agricultural waste and crop residues (followed by India), with more than 600 million tons annually from the production of rice, corn, and wheat alone (Jiang et al. 2022). Yet, the majority of these residues are incinerated or landfilled, leading to unnecessary waste and additional GHG emissions. Increasing the utilization rate of biomass residues is therefore also the key to enabling the full potential of Bio-H_2 (Shapiro-Bengtsen 2020).

Limitations on the Availability of Geology for CO_2 Disposal

Bio-H_2 has the greatest value when combined with CCS technologies for carbon-negative hydrogen production, naturally making CCS resources another limitation. The total capacity of the earth's crust to store CO_2 is effectively limitless—estimated at 10–20 trillion tons (C. P. Consoli and Wildgust 2017; Kearns et al. 2017). In addition, the technologies and tools of carbon management for geological CO_2 storage are well known and understood (Global CCS Institute 2021b; IEA 2021c). However, the geographical distribution of CO_2 storage sites is uneven. Several regions combine high Bio-H_2 production potential with high CO_2 storage potential (Minervini et al. 2021; Sandalow et al. 2020). These include the southeastern and central US (Baik et al. 2018), Southeast Asia (Hasbollah and Junin 2017; World Bank 2015), the North Sea region (Minervini et al. 2021), California (Tubbesing et al. 2020), and Alberta (Bachu 2003; NETL 2015). The rest of the world will need extra CCS infrastructure such as CO_2 transportation pipelines to support the deployment of Bio-H_2 with CCS.

Policy Support Limitations

The value of Bio-H_2 (and biomass in general) ties directly to its life-cycle emissions (Sandalow et al. 2020). The life-cycle footprint of biomass is sensitive to many factors (Cherubini et al. 2009; Fritsche and Wiegmann 2009; Shen et al. 2015). When waste serves as a biomass feedstock, the life-cycle footprint is generally estimated to be very low and potentially CO_2 removing (Thakur et al. 2014). However, researchers disagree on the status of biomass as waste (Langholtz et al. 2016; B. Liu and Rajagopal 2019). Even when biomass is acknowledged as such, questions remain about possible carbon "leakage" due to project expansion and associated deforestation or land degradation (Bird et al. 2011).

While LCA estimates of biomass from waste are relatively straightforward, those of biomass produced from agricultural crops for fuel are more complicated (Rodionova et al. 2017). In the latter case, land is altered to grow crops, sometimes through plowing or deforestation, which releases carbon into the atmosphere. Watering, harvesting, transporting, and converting biomass also emits CO_2 that must be accounted for in the life cycle. If the biofuel crop displaces food crops, leakage effects can be profound and lead to an increase in overall emissions due to substantial land use changes (Searchinger et al. 2008).

It is possible to mitigate these impacts and maximize life-cycle carbon reduction and removal through careful application of governance and technology (Bastos Lima 2009; 2021). Unfortunately, biomass production has a poor record of stewardship (Correa et al. 2019). Many documented examples exist of damage to local ecosystems (Efroymson and Langholtz 2017), harm to local communities (van der Horst and Vermeylen 2011), and eco-colonialism (Havnevik et al. 2011; Howes et al. 2016). Similarly, it is clear that carbon accounting of biomass feedstocks, both fuel crops and wastes, often fails to include carbon leakage or persistent carbon degradation (e.g., through peatland oxidation). Bio-H_2 production and procurement standards would help to avoid these poor outcomes (Sandalow et al. 2020).

Lack of Developed Emission-Accounting Method for Bioenergy and Biomass Systems

Although emission-accounting methods for bioenergy and biomass systems have been discussed widely in both academia and the business world and are an active area of research, they are still in development. Given the continued absence of such methods, it is important to point out that the misinterpretation or miscounting of negative emissions can have unintended, and possibly dangerous, consequences such as the introduction of policy incentives that reward increasing atmospheric greenhouse gas concentrations under the guise of negative emissions (Tanzer and Ramirez 2019).

FINDINGS

Finding 1: Bio-H_2 is not receiving sufficient attention from policy-makers and industry leaders, despite its carbon removal potential. For example, it was not recognized in major reports such as the IEA's *Net-Zero 2050 Scenario* and IRENA's *World Energy Transition 2022*. Other reports such as BP's (2022) *Energy Outlook 2022* acknowledge Bio-H_2 as a hydrogen source but discuss it only briefly within the hydrogen projection of their accelerated and net-zero scenarios. Princeton's (2022) *Net-Zero America* report, by contrast, lends Bio-H_2 a prominent role in future energy forecast as a form of bioenergy. That the Princeton report remains an exception demonstrates Bio-H_2's lack of recognition as a climate mitigation solution.

Finding 2: Bio-H_2 can be generated from diverse biomass feedstocks, but these feedstocks are linked to different carbon emissions levels. If they are to play an important role in decarbonizing hard-to-abate sectors, rigorous governance and standardized, verifiable, and transparent carbon-accounting methods for biomass procurement and Bio-H_2 production will be necessary. Absent these measures, the carbon footprint of Bio-H_2 could potentially exceed that of fossil-based hydrogen today.

Finding 3: Bio-H_2 manufactured from biomass wastes and CCS can potentially provide significant climate benefits. Carbon-negative hydrogen can potentially be produced by using waste biomass combined with CCS technology. The medium estimation of the carbon footprint of Bio-H_2 produced in this way is −21kg-CO_2/kg-H_2 to −15 kg-CO_2/kg- H_2, meaning it can be used as an energy source while removing carbon from the atmosphere.

Finding 4: Bio-H_2 can be generated from a wide range of technologies, of which biomass gasification is among the most promising. This is due to its 1) compatibility with CCS; 2) flexibility to accommodate a wide range of biomass feedstocks (liquid and solid); 3) relative technical maturity; and 4) relatively low cost. When this technique is combined with the use of biomass wastes and CCS, the resulting Bio-H_2 can potentially have a deeply negative carbon footprint.

Finding 5: Among the pathways for Bio-H_2 production, biomass gasification shows the lowest possible overall carbon footprint, while maintaining a reasonably low cost of $3–4/kg-$H_2$ (see Figure 8). Although steam reforming of biogas is also a promising technology that is compatible with CCS technologies, biogas is widely used to produce biomethane, which has competitive uses such as directly substituting natural gas. As such, biogas is a valuable resource in and of itself and should be prioritized for its immediate applications over and above the production of Bio-H_2.

Finding 6: The technology to create Bio-H_2 is relatively mature today, but major barriers still exist. Biomass gasification for Bio-H_2 production has yet to overcome the problems of catalyst contamination/fouling, inconsistent feedstock quality, and the difficulty of separating H_2 gas from other gases produced in the process.

Finding 7: Bio-H_2 with CCS can also be a solution for hard-to-abate sectors. Two examples are the iron and steel and the chemical production sectors. Due to their use of fossil fuel as a feedstock input, even the incorporation of green hydrogen has a limited influence on the carbon intensity of their processes. Using carbon-negative Bio-H_2 can propel these sectors toward full net-zero or even a negative carbon footprint, with carbon-negative steel (−0.61 tCO_2/t to 0.39 tCO_2/t) and chemicals such as ammonia (−4.04 tCO_2/t to −0.6 tCO_2/t) and methanol (−3.89 tCO_2/t to −0.17 tCO_2/t).

Finding 8: Bio-H_2 with CCS provides flexibility in carbon management in different markets and geographies and enables circular carbon economies: This applies in regions where waste biomass resources are abundant and underutilized. The hydrogen produced from these resources can be used locally or converted into fuels and chemicals for shipping, and the CO_2 captured as part of the process can be stored locally, shipped from a local production site, or shipped from a final production site. This flexibility creates opportunities to maximize local benefits while minimizing costs and carbon footprint depending on jurisdiction, natural resource mixes, and market configurations. In small communities where large amounts of local biomass wastes exist, Bio-H_2 can be used to replace local fossil fuel consumption.

Finding 9: In most markets, the cost of Bio-H_2 today is generally higher than that of conventional hydrogen, and between that of blue and green hydrogen. To achieve \$2/kg-H_2, Bio-H_2 production requires: 1) lower biomass feedstock costs (< \$50/dry-ton); 2) lower CAPEX (\$0.2–0.4/kg-H_2); 3) other OPEX components to remain below 20–30 percent of the total cost; and 4) significant improvements in gasification technology, notably in feed systems and ash handling. These gains could be accomplished with a dedicated innovation program led by key countries and industries.

APPENDIX

Table A-1: Bio-H_2 production potential summary

Country/ region	**Projected time, biomass type**	**Results** (original)	**Source**	**Results** (Mt H_2)	**Carbon Removal Potential** (Gt)
US	2050 All types	5–7 EJ H_2	Larson et al. 2021	35–50 Mt	0.58–1.11 Gt
EU	2050	120 TWh H_2 (for chemical feedstock)	FCH 2019	3.6 Mt	0.06–0.08 Gt
EU28	2010–2050 All types	2300 TWh biomass*	Ruiz et al. 2019	28–36 Mt	0.47–0.81 Gt
China	2010–present All types	350–700 Mt biomass*	Zhang et al. 2013	24–60 Mt	0.39–1.35 Gt
Brazil	2030 All types	2000 Mt biomass (green)*	Welfle 2017	67–86 Mt	1.10–1.93 Gt
India	Current	2.8–20.2 EJ biomass*	Usmani 2020	8–75 Mt	0.13–1.68 Gt
Africa	2050 All types	28 EJ biomass*	Stecher et al. 2013	81–103 Mt	1.33–2.32 Gt
Southeast Asia	2050 Wastes, etc.	4.65–7.83 EJ biomass waste 155.3 Mt biomass (wood)	IRENA 2017	24.0–40.5 Mt	0.39–0.91 Gt
Global	2050 Wastes, etc. (minimum environmental impact)	45–91 EJ biomass*	Sandalow et al. 2020	131–336 Mt	2.14–7.56 Gt

Note: The Southeast Asia study included only five countries: Indonesia, Malaysia, Philippines, Thailand, and Vietnam. The US, EU, and China are projected to be the largest hydrogen consumption countries/regions and have limited Bio-H_2 production potential; estimated biomass resources in these countries/regions does not cover the potential growth of hundreds of millions of tons of hydrogen demand (IEA 2021c). Brazil, Africa, and Southeast Asia have rich biomass resources and can serve as potential exporters for biomass, Bio-H_2 and other biomass-based fuels (e.g., ammonia, methanol, and biodiesel). Mt is million tons.

**Biomass to Bio-H_2 energy conversion efficiency (=Bio-H_2 energy output/biomass energy input) assumed 41–52 percent (Salkuyeh, Saville, and MacLean 2018). Biomass caloric value is 19.6 MJ/kg.*

Table A-2: Biomass gasification LCA summary

Biomass gasification LCA ($kg\text{-}CO_2\text{-}eq/kg\text{-}H_2$)	**Source**	**Remarks**
0.75	Kalinci et al. 2012	Downdraft gasifier
2.10	Kalinci et al. 2012	Circulating FB gasifier
0.89	Moreno and Dufour 2013	Pine wood feedstock gasification
1.45	Iribarren, Susmozas, Petrakopoulou, and Dufour 2014	General gasification

Table A-3: Biomass LUC summary by types of biomass feedstocks

Biomass feedstocks	**LUC median (25–75 pctl)** ($g\text{-}CO_2\text{-}eq/MJ$)	**H_2 LUC median (25–75 pctl)** ($kg\text{-}CO_2\text{-}eq/kg\text{-}H_2$)
Oil crops	37 (17 to 66)	10.3 (4.7 to 18.4)
Starch crops	21 (6.8 to 44.3)	5.9 (1.9 to 12.4)
Sugar crops	19 (10.5 to 38.5)	5.3 (2.9 to 10.7)
Woody crops	20 (8 to 39)	5.6 (2.2 to 10.9)
Other biomass potential (residuals and waste)	−1.1 (−1.4 to −1.0)	−0.3 (−0.4 to −0.2)

Note: Biomass thermal conversion efficiency is assumed to be 43 percent.
Source: Drews, Larsen, and Balderrama 2020; Salkuyeh, Saville, and MacLean 2018.

Table A-4: Bio-H_2 production carbon intensity from woody biomass gasification

Bio-H_2 from biomass gasification	**Bio-H_2 carbon intensity** (low)	**Bio-H_2 carbon intensity** (median)	**Bio-H_2 carbon intensity** (high)
LCA GHG emission ($kg\text{-}CO_2\text{-}eq/kg\text{-}H_2$)	0.75	1.43	2.10
LUC GHG emission: woody feedstock ($kg\text{-}CO_2\text{-}eq/kg\text{-}H_2$)	2.2	5.6	10.9
Total GHG emission	2.95	7.03	13.00
CCS captured emission ($kg\text{-}CO_2\text{-}eq/kg\text{-}H_2$)	16.4 to 22.5	16.4 to 22.5	16.4 to 22.5
Bio-H_2 carbon footprint ($kg\text{-}CO_2\text{-}eq/kg\text{-}H_2$)	−19.55 to −13.34	−15.47 to −9.37	−9.5 to −3.4

Source: Drews, Larsen, and Balderrama 2020; Iribarren, Susmozas, Petrakopoulou, and Dufour 2014; Kalinci et al. 2012; Moreno and Dufour 2013; Salkuyeh, Saville, and MacLean 2018.

Table A-5: Bio-H_2 production carbon intensity from waste biomass gasification

Bio-H_2 from biomass gasification	Bio-H_2 carbon intensity (low)	Bio-H_2 carbon intensity (median)	Bio-H_2 carbon intensity (high)
LCA GHG emission (kg-CO_2-eq/kg-H_2)	0.75	1.43	2.10
LUC GHG emission: woody feedstock (kg-CO_2-eq/kg-H_2)	−0.40	−0.30	−0.20
Total GHG emission	0.35	1.13	1.90
CCS captured emission (kg-CO_2-eq/kg-H_2)	16.4 to 22.5	16.4 to 22.5	16.4 to 22.5
Bio-H_2 carbon footprint (kg-CO_2-eq/kg-H_2)	−22.15 to −16.05	−21.37 to −15.27	−20.6 to −14.5

Source: Drews, Larsen, and Balderrama 2020; Iribarren, Susmozas, Petrakopoulou, and Dufour 2014; Kalinci et al. 2012; Moreno and Dufour 2013; Salkuyeh, Saville, and MacLean 2018.

Table A-6: Techno-economic analysis of Bio-H_2 from biomass gasification

Cost analysis	Case 1: Small-scale (0.1 MW-thermal) system without CCS	Case 2: FB CCS gasification	Case 3: EF CCS gasification	Case 4: Case study in China without CCS
LCOH (\$/kg-H_2)	10.45	3.40	3.50	2.49
Biomass OPEX (\$/kg-H_2)	1.09 (10.4%)	2.50 (73.5%)	2.00 (57.1%)	0.49 (19.6%)
Biomass cost assumption (\$/ton)	44	100	100	44
Other OPEX (O&M, energy, etc.) (\$/kg-H_2)	3.07 (29.4%)	0.68 (20.0%)	1.16 (33.1%)	0.53 (21.5%)
Total OPEX (\$/kg-H_2)	4.16 (39.8%)	3.18 (93.5%)	2.70 (77.1%)	1.02 (41.1%)
Total CAPEX (\$/kg-H_2)	6.28 (60.1%)	0.22 (6.5%)	0.35 (10.0%)	1.46 (58.9%)
Project lifetime (years)	20	30	30	25
Remark	€ to \$ ratio 1.1	N/A	N/A	\$ to CNY ratio 6.75
Source	Sara et al. 2016	Salkuyeh, Saville, and MacLean 2018	Salkuyeh, Saville, and MacLean 2018	Wang et al. 2019

Note: In Case 1, the steam-to-biomass ratio is 1.5.

NOTES

1. As mentioned by Alsarhan et al. (2021), a circular carbon economy is one where waste is turned into valuable resources while reducing or avoiding increases to carbon levels in the atmosphere.
2. LCA is a methodology for evaluating the environmental impact of a product or process from its origin to its final disposal (Maria et al. 2020).
3. Traditionally, eco-colonialism refers to ecological or environmental colonialism, which is the practice by colonists of exploiting natural resources and extracting wealth from indigenous people and thereby altering the original ecosystem (Atiles-Osoria 2014). In the context of climate change mitigation, eco-colonialism (also called climate-colonialism or neocolonialism by others) refers to rich countries' land-grabbing activities in less-developed countries (e.g., the Philippines or South Africa) that convert rainforests and agricultural lands for the production of biofuels, which are then exported to rich countries to help them achieve net-zero goals (Madoffe et al. 2009; Yanaizu 2019). These actions exacerbate food security issues and primary forest destruction in the less-developed countries.
4. Researchers are actively developing emissions-accounting methodologies for bioenergy and biomass systems (Tanzer and Ramirez 2019). While the selection of system boundaries for quantified emissions (as well as removals) should be as comprehensive as possible, including indirect emissions when applicable, this report neither evaluates these methodologies nor endorses a specific one, which is beyond the report's scope.
5. Fermentation is an anaerobic digestive process in which organic matter degrades in the absence of oxygen. Whereas fermentation refers to the conversion of sugar into alcohol or acid, digestion is a broader term that refers to the conversion of any organic substrate into tiny molecules (Bharathiraja et al. 2016).
6. In the remainder of this paper, Bio-H2 is implied to be carbon-negative hydrogen created from biomass waste via biomass gasification with CCS.
7. BF-BOF stands for blast furnace-basic oxygen furnace, which is the most commonly used method for steel production and remains a stubborn obstacle to any decarbonization strategy. ThyssenKrupp recently announced that it will convert its blast furnace (BF) to hydrogen DRI, while preserving BOF for steelmaking for another decade. This presents an intermediate step to a lower carbon footprint in steelmaking without making all the existing infrastructure obsolete.
8. In the production of steel, fossil fuels are used not only as a source of heat but also as an agent to reduce iron ore to pure iron. In a DRI plant, iron ore is reduced with hydrogen before it is heated and liquified together with steel scrap to produce raw steel using renewable electricity. This production pathway is considered nearly emission free. Currently, two companies use it: 1) MIDREX Technology, at its plant in North Carolina; and 2) Energiron, through its HYL DRI process developed with Tenova HYL and Danieli & C.

9. Hydrogen is used as a feedstock in SMR-based ammonia production. This process first produces hydrogen using methane and then combines hydrogen with nitrogen to form ammonia.

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