Biomass gasification for hydrogen production

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Summary

Low emission hydrogen produced with non-fossil fuels is expected to be key in the efforts de-fossilizing hard-to-abate sectors. Water electrolysis based on fossil-free electricity is regarded as the most promising technology to fulfil the anticipated exponentially growing demand for low emissions hydrogen, however securing the power supply for production of electrolytic hydrogen could in many world-regions be challenging, mainly coupled to the required large expansion of power production and distribution.

Production of hydrogen via biomass gasification currently receives less attention but could be an important complement to electrolysis in many regions with available biomass resources. Biomass gasification possesses several beneficial characteristics such non-intermittent and fossil-free hydrogen production in a wide capacity range. The technology leads to many process integration opportunities, for example with water electrolysers since electrolysers generate significant amounts of oxygen, which potentially can be used as gasification media. Also, low temperature excess heat from electrolysers can be utilized for feedstock drying etc. This paves the way for more cost-efficient hydrogen production systems. One of the most prominent technology features is that the CO_2 separation process is an integral part of the gasification system, which means that negative CO_2-emissions can be obtained if carbon storage (CCS) is applied. LCA-studies show that combined with CCS, the greenhouse gas emission for hydrogen produced via biomass gasification may be as low as in the range of -15 to -22 kg CO_{2eq} per kg produced hydrogen.

The main aim of this report is to describe different biomass gasification technologies suitable for hydrogen production and to provide information of on-going commercial initiatives. The report also aims at identifying potential techno-economic opportunities and challenges as well as knowledge gaps to better understand its potential future role and need of further development.

The hydrogen yield from biomass gasification varies depending on feedstock and process conditions, but an approximate value is about 100 kg of hydrogen per ton dry biomass. The energy efficiency also varies depending on process design but is normally in the range of 40-70% (based on the lower heating value).

The Technology Readiness Level (TRL) of biomass gasification for hydrogen production is estimated to be in the 5 to 7 range depending on assessment methodology. All the main sub-processes of the conversion have a high technological maturity, but there is a need to demonstrate integrated operation of the complete hydrogen production chain in relevant scale to reach a higher TRL-score. Additional research is required to increase the knowledge on potential impurities, trace elements and their possible effects on for example fuel cells. This could serve as valuable inputs to updated ISO standards where biomass gasification-based hydrogen should be included

It is estimated that the current production cost for a large-scale gasification plant (200 MW) would be approximately 4 € per kg hydrogen at a biomass price of 20 € per MWh. With potential process improvements and utilisation of CCS, the production cost could reduce to below 3 € per kg hydrogen at the same biomass price. With the current price levels of fossil methane in Europe, these cost levels are comparable to hydrogen produced via steam methane reforming. It is also shown that the cost levels are competitive to future foreseen production cost of renewable hydrogen produced via solar- and wind-based electrolysis in many world regions.

The report concludes that biomass gasification is an economical and environmentally beneficial technology well suited for producing climate-positive hydrogen. It is highly likely that negative carbon emissions will be essential to reach climate targets and hydrogen produced via biomass gasification is one of few hydrogen production pathways that can result in negative emissions.

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Introduction

The global hydrogen demand is steadily growing and amounted to 97 Mt in the year 2023. This is a historical high and an increase of 2.5% compared to 2022. The hydrogen use remains concentrated in traditional sectors such as petroleum refining and the chemical industry. Most of the hydrogen supply is still based on unabated fossil fuels, mainly in form of natural gas as shown in Figure 1. (International Energy Agency, 2024a).

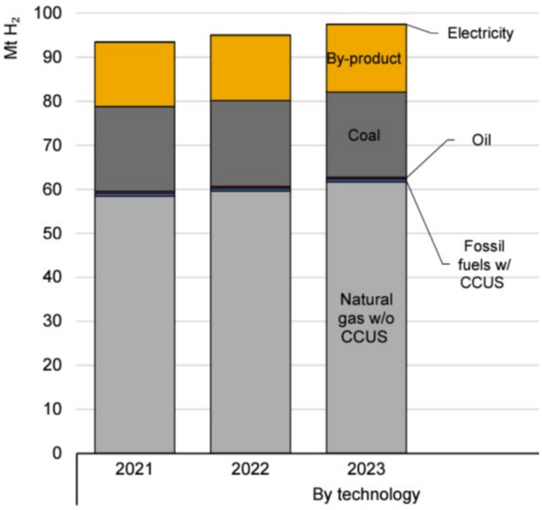
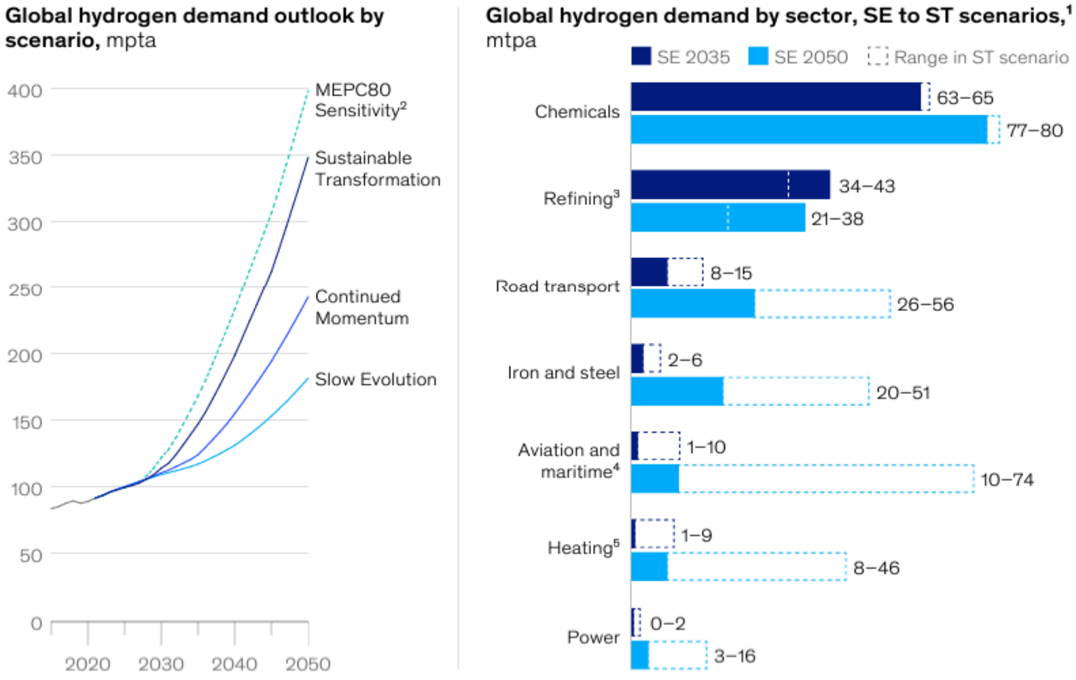


Figure 1. Hydrogen production mix 2021-2023. CCUS = Carbon Capture Utilization/Storage (Modified from International Energy Agency (IEA), 2024a).

To reach a net zero energy system, unabated hydrogen must be replaced by low-emission hydrogen. Low-emission hydrogen offers a variety of ways to reduce carbon emissions in a wide range of different sectors including long-distance transports, chemicals, and heavy process industry – i.e., so-called *hard-to-abate* sectors difficult to directly electrify. The demand of low-emission hydrogen increased by almost 10% in the year 2023 but still representing only around 1% of the total hydrogen demand (less than 1 Mt) (International Energy Agency, 2024a).

The low-emissions hydrogen demand is however expected to increase rapidly, in particular in the above mentioned *hard-to-abate* sectors as well as for energy storage. The number of projects announced for low-emission hydrogen production is growing fast and based on these announcements, low-emissions hydrogen demand could reach 49 Mtpa already by the year 2030 according to the International Energy Agency (2024a). McKinsey Energy Solutions (2024) makes somewhat more moderate assessments ending up with a “clean” hydrogen demand in the range of 37-38 Mtpa in 2030 of which the major use share is anticipated in already existing industrial applications. In 2050, the use of low emission hydrogen for mobility purposes may have surpassed the industrial demand as shown in Figure 2.

Demand for clean hydrogen is projected to grow two to four times by 2050[15]


Global hydrogen demand outlook by scenario, mpta

Global hydrogen demand by sector, SE to ST scenarios,[1] mtpa

[1]SE = Slow Evolution; ST = Sustainable Transformation. [2]MEPC80 Sensitivity includes the implications of the 2023 adoption of IMO Greenhouse Gas Strategy. [3]Refining is the only sector where demand in 2035 and 2050 in the ST scenario is lower than in the SE scenario. Includes conventional fuels refining and biofuels hydrogenation and refining. [4]Aviation and maritime include the direct use of hydrogen and hydrogen-derived synfuels including kerosene, diesel, methanol, gasoline, and ammonia. The category also includes some hydrogen-derived synfuels in road transport. Maritime in Sustainable Transformation includes MEPC72. [5]Includes hydrogen demand for heating in other industry and buildings.

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[15] Including green hydrogen (hydrogen produced by the electrolysis of water using RES) and blue hydrogen (hydrogen produced from natural gas with carbon capture and storage).

Figure 2 Different scenarios of the hydrogen demand development until 2050 (McKinsey Energy Solutions, 2024).

The International Energy Agency (2023) estimates that more than 70% of the low-emission hydrogen supply will be based on electrolysis using low-emission electricity and 26% based on fossil fuels with carbon capture, utilisation, and storage (CCUS). One important reason for electrolysis based on renewable electricity being the main alternative is the anticipated decrease in the costs for producing renewable power via solar PV and wind.

As water electrolysis is predicted as the main future technology for hydrogen production, very large amounts of low emission electricity will be required. The increased electricity demand in many countries is foreseen to be met within the next decade by intermittent electricity production, mainly in the form of wind and solar power, which in turn means challenges when balancing the electricity system. The power supply may be a limiting factor and electricity prices might become more volatile. The expansion of electricity production required for the electrification of society, including for hydrogen production, also requires local acceptance and municipal approval, not the least for wind power and new transmission connections. It must also be ensured that the power network owners can expand the network at the rate required to be able to meet the market's needs. Long lead times for permits processes and limited land availability are other issues that might slow down and limit the expansion (Wendt & Wallmark, 2022).

There are however several other alternative production pathways for low emission hydrogen that can help mitigate these challenges, but which presently receive less attention. One of these alternatives is to produce hydrogen via biomass gasification, which provides some important beneficial key features.

- The production is non-intermittent, fossil-free, and can be done in large-scale.
- As it is a complementary technology to electrolysis, the demand for low-emission electricity may be reduced and thereby free capacity in the electricity transmission grids.
- Biomass gasification brings many process integration opportunities, for example with water

electrolysers. Besides hydrogen, electrolysers generate significant amounts of oxygen, which potentially can be used as gasification media. Also, low temperature excess heat from electrolysers can be utilized for feedstock drying etc. This paves the way for more cost-efficient hydrogen production systems.

- Biomass gasification generates a clean, food-quality CO_2-stream, which opens for negative CO_2-emissions if storage (CCS) is applied.

- Biomass gasification systems can result in additional value-added products besides hydrogen, such as biochar, heat, electricity, and off-gases.

- Gasification of biomass also offers the potential for *in-situ* CO_2 utilization in case PtX is combined with BtX (CCU), i.e. production of bio-electrofuels. This is however not feasible when producing hydrogen as discussed later in this report.

Lou et.al (2023) conclude that biomass gasification-based hydrogen production does not receive adequate attention from policymakers and industry leaders, despite its carbon removal potential. The technology was for example neither acknowledged in important reports such as the IEA's Net-Zero 2050 Scenario (International Energy Agency, 2024b) or in the IRENA's World Energy Transition 2022-report (IRENA, 2022) (Lou et.al (2023)).

The main aim of this report is to provide descriptions of different gasification technologies suitable for biomass-based hydrogen production as well as information of on-going commercial initiatives in the field. The report also aims at identifying potential techno-economic opportunities and challenges as well as knowledge gaps to better understand its potential future role and need of further development.

This report is an update and complementary to a previously published report by IEA Bioenergy on gasification-based hydrogen (Binder et.al (2018)), which primarily focused on hydrogen production via fluidized bed steam gasification.

Gasification pathways for production of biogenic hydrogen

Gasification is a thermochemical process in which a carbon-containing feedstock, here biomass, is heated at elevated temperatures in the presence of an oxidant (oxygen, air and/or steam) under sub-stoichiometric conditions to avoid complete combustion.

There are mainly three types of gasifiers: fixed-bed, fluidized-bed, and entrained-flow. Fixed-bed gasifiers are less advanced, suitable for small-scale heat and electricity production (CHP). Fluidized-bed gasifiers are more efficient than fixed-bed gasifiers, and better at handling a variety of feedstocks. Entrained-flow gasifiers are suitable in larger capacity ranges capable of handling both solid and liquid feedstocks. Their operation at elevated temperatures, exceeding ash slagging points, guarantees thorough carbon conversion and the production of tar- and phenol-free syngas (Wagner et.al, 2008). In general, a gasifier needs pretreatment of feedstock, gas conditioning and final purification of products to reach the required gas product (here hydrogen). Emerging gasification concepts such as plasma gasifiers or heat-pipe reformers, are also described briefly in this report. Figure 3 shows different gasification technologies that can be used for biohydrogen production.

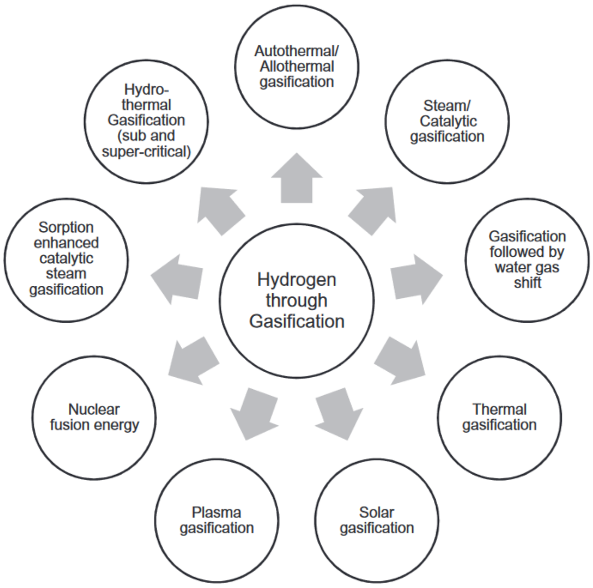

Figure 3. Classification of different approaches for H_2 production using biomass gasification (Bhaskar et.al, 2013)

Depending on operating conditions such as temperature, catalysts and oxidant, a producer gas is formed consisting of varying shares of H_2, CO, CO_2, CH_4, C_xH_y and tars. Table 1 shows typical compositions of producer gas obtained from different types of biomass gasifiers. Since the concentration of produced hydrogen in gasifier reactors is usually lower than 50%, different gas conditioning units as well as pre- and post-treatment steps are implemented to produce high concentrated hydrogen.

Table 1. Gas compositions obtained from different types of gasifiers (main components only) (Moioli & Schildhauer, 2022)

Technology	Main gas composition [vol. %]					H_2:CO ratio
	CO	H_2	CO_2	CH_4	C_xH_y	
Entrained Flow (EF)	60	35	5	-	-	0.58
Entrained Flow (EF)[1]	27-39	26-35	14-28	<0.1	-	0.75-1.0
Bubbling Fluidized Bed (BFB)	26	19	37	17	1	0.73
Circulating Fluidized Bed (CFB)	33	30	31	6	<1	0.91
Dual Fluidized Bed (DFB)	23	39	25	10	3	1.70
(Oxy)-SER	4	70	8	15	3	17.5

Gas cleaning and upgrading are needed to remove CO and CO_2 as well as trace components like H_2S, NH_3, HCl, and tar. The produced gas is upgraded and conditioned followed by a water gas shift (WGS) reactor in which steam reacts with CO in the presence of a catalyst to generate H_2 and CO_2. The gas leaving the WGS typically contains 65–70 vol% hydrogen, that can be further purified by pressure swing adsorption (PSA), resulting in a high purity hydrogen stream. The CO_2 is separated into a concentrated residual stream as an integral part of the process, thus providing a favourable source for CO_2 capture and storage and consequently negative CO_2-emissions.

In the following chapter, different types of gasifiers suitable for hydrogen production from biomass are described.

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[1] The Bioliq-plant at Karlsruhe Institute of Technology - High-pressure oxygen-blown entrained flow gasification

Established biomass gasification technologies relevant for hydrogen production

The following descriptions are, with permission, from the Swedish Gasification Centre (2024).

Steam and/or oxygen blown circulating fluidized bed gasification

Fluidized bed gasifiers are well suited for hydrogen production. In fluidized bed gasifiers the reaction space contains a sand-like bed material that is fluidized (the sand is lifted by the gas stream and gets a liquid appearance) or entrained by the oxidant gas (air or oxygen), steam or mixtures thereof being added in the bottom. Autothermal or direct gasifiers use an oxidant, and allothermal or indirect gasifiers, see below, use steam without an oxidant being fed to the gasifier section.

A large variety of feedstocks can be converted in fluidized bed gasifiers, but larger shares of small fuel particles are undesirable. In the case of a stationary (or bubbling) fluidized bed the bed material is kept suspended by the gas in a defined bed volume through which gas in the form of interstitial gas and bubbles pass. Above the bed there is a freeboard section used for disengagement of particles mainly ejected by bubbles erupting on the bed surface.

In a circulating fluidized bed, the gas velocity is higher than for a stationary (bubbling) bed and the bed material is carried up in the gasifier shaft by the gas. Some of this material moves radially to the wall and transported back to the bottom by gravity as part a wall layer sliding down. The remainder of the solid-gas suspension is carried out by the gas to an external primary particulate separator, typically a cyclone, from which it is returned to the bottom of the gasifier by means of a recycle line with a moving bed of solids. The effect is huge net circulation rate between the bottom and the top of the reactor.

The vigorous movement of the bed material in combination with the large circulation of bed materials gives a high internal heat transfer rate that assists in maintaining an even temperature in the entire bed. This avoids hot spots and thereby avoiding or restricting agglomeration. The temperature is in the range 750-950°C and is limited by ash melting properties.

Even if the feedstock is fed into a hot environment, the temperature is not enough to completely decompose tars. The raw producer gas typically contains tar in a magnitude of 5-20 g/Nm^3. properties and handling.

Direct fluidized beds can be built at large scale. The largest biomass gasifier in operation at atmospheric pressure, at Vaasa, Finland, has a capacity of 140 MW$_{th}$. They can also be pressurized up to 1-3 MPa to further increase the single vessel capacity.

Steam and/or oxygen blown indirect fluidized bed gasification

Indirect fluidized beds (i.e. that use a gasifier-combustor combination, e.g. Milena, FICFB and Batelle designs) can have different combinations of fluidization types in the two beds, such as two stationary fluidized bed reactors, one stationary fluidized bed gasifier and circulating bed combustor, one circulating fluidized bed gasifier and one stationary bed combustor or two circulating fluidized beds. Indirect double fluidized beds function in the same way as a fluidized bed. The main difference is that there is no oxidant, instead typically steam is added to the gasifier: The energy required is provided by hot sand bed material being transferred at high rate from the second, combustor bed.

After releasing heat in the gasifier, the sand is returned to the combustor from the bottom of the gasifier and where entrained carbonaceous char material from the gasifier and other fuels are combusted with air to generate the temperature required to re-heat the massive flow of sand. Since the combustor is subjected to the same limitations on operating temperature as other fluidized beds to avoid agglomeration, the gasifier is operated at slightly lower temperature, compared to when air or oxygen is used directly, to have a temperature difference that matches the sand flow. Therefore, the tar content is of the same magnitude or slightly higher than for a direct fluidized bed. The heated sand is the returned to the gasifier via a bed overflow in the case of a stationary fluidized bed combustor, or via the primary separator for circulating fluidized beds.

The need for a close-coupled circulation loop in practice restricts the capacity of such reactors from layout limitations to somewhere in the range of 50 and 150 MW thermal. Due to the small pressure differential between the two reactors, pressurizing such units become very challenging. The main advantage of these systems is that a medium calorific value (MCV) gas can be produced without the recourse to the use of oxygen.

Other forms of indirect fluidized bed gasifiers use indirect heat transfer into the bed via heat exchanger tube bundles immersed in the bed using flue gases from combustion of part of the product gas outside of the gasifier section, or so-called heat pipes immersed in the bed that work as an intermediate heat transfer unit.

Oxygen blown entrained flow gasification

Oxygen blown entrained flow gasifiers can also be used for hydrogen production. Most entrained flow gasifiers are vessels where the fuel is injected and partially oxidized in one or more burners and where the residence time is sufficient to complete the reactions, including both the gasification of the solids and the decomposition of tars and other hydrocarbons, within a few seconds. For this reason, the fuel must either be a pumpable liquid that can be dispersed to droplets in the burner nozzle or small particles (~ 1 mm or smaller) that can be consistently fed by means of dense phase pneumatic transport to the fuel register of the burner.

Entrained flow gasifier also typically operates in an ash melting mode, i.e. the ash is removed as slag in the bottom of the reactor. This requires operation at very high temperature, e.g. 1200 - 1500 °C, to reduce the slag viscosity and make it free flowing to avoid build-up of slag in the reactor. To reach such high temperatures with low energy content feedstocks and still retain a significant heating value the use of oxygen mixed with steam is required. Air is not possible to use.

Entrained flow gasifiers are also typically pressurized up to 1-3 MPa for solids or even higher for some high-energy liquids. The high gas velocity and short reaction time at pressure makes it possible to scale this type of technology to large capacities, up to 400 MW or more. However, the complexity of fuel preparation in the case of solids, and the requirement of using oxygen typically do not make small installations feasible. One advantage of this gasifier type is the ash melting which yields a dense slag by-product with less leaching rate. Since many lighter inorganic species and heavy metals are evaporated at the high temperatures in the gasifier, such dense slag may even be recycled as construction material. The downstream gas cleaning becomes simplified because impurities are broken down to molecules easier to remove.

There are also other forms of entrained flow gasifiers where fuel is injected into a gasifier or pyrolizer in which the resulting gas and char solids are heated indirectly by radiation and convection in several heated tubes. The tubes are then heated on the other side by firing product gas and/or char to heat the tubes. In addition, a type of “entrained flow” post-treatment is common downstream of fixed or fluidized bed gasifiers as a mean to reduce the tar content from the gasifier itself. Such devices can be air- or oxygen-blown and sometimes are assisted by a plasma generator.

Emerging gasification concepts for hydrogen production

Solar gasification

Solar gasification is a process that utilizes solar energy to convert biomass into hydrogen. This approach has been successfully demonstrated for various biomass feedstocks. Combining steam reforming with solar energy further enhances the process efficiency. For instance, Liu et al. (2008) showed that solar hydrogen production using methanol steam reforming can achieve over 90% conversion of methanol to hydrogen with a solar reactor at 150-300°C. This method boasts a maximum hydrogen yield of 2.65-2.9 mol/mol methanol, close to the theoretical limit, and a 30-50% solar thermochemical efficiency, competitive with other high-temperature methods. Research on thermochemical cycles for solar hydrogen production shows promising results, with energy conversion efficiencies reaching up to 28.4% (Kaur et.al, 2019).

Boujjat et al. (2021) studied the economic feasibility of large-scale solar biomass gasification for hydrogen production. It was concluded that pure solar-powered gasification is more expensive than conventional autothermal biomass gasification for hydrogen production. However, combining solar with conventional methods (hybrid process) improved the economic performance. Significantly reduced costs for solar technologies and components could make all three processes (solar-only, hybrid, conventional) more competitive.

Xu et al. (2024) proposed a novel solar-driven biomass chemical looping gasification (SBCLG) system for co-production of pure hydrogen and syngas from biomass wastes using magnetite as oxygen carrier. The SBCLG system uses solar radiation instead of biomass combustion for high-temperature process heat, resulting in a higher syngas yield and a pure hydrogen stream. The study demonstrated the viability of SBCLG for co-producing pure hydrogen and syngas.

Absorption-enhanced reforming (AER)

In situ CO_2 capture during gasification yields a H_2-rich producer gas with minimal carbon oxides and tars (see Table 2, oxy-SER). This is achieved by separating the CO_2 from the reactor using an adsorbent. The heat generated during CO_2 absorption further enhances gasification reactions. A nearly nitrogen-free product gas with a caloric value of 12-14 MJ Nm^{-3} is produced (Koppatz et.al, 2009). According to Chen et.al, (2011), sorption enhanced processes can be applied in different gasification/pyrolysis processes to boost the concentration of H_2 in the producer gas and obtain a purity exceeding 90%. Balasubramanian et.al (1999) reported that hydrogen with a higher purity than 95% was produced in a single step using adsorption enhanced process.

Hydrothermal gasification

When biomass is gasified in the presence of water at high pressures, the process is known as hydrothermal gasification. This process breaks down the polymeric structure of biomass quickly, resulting in a high yield of gas at low temperatures. Water acts as a catalyst and reduces the formation of tar and coke. Researchers have investigated the chemistry of hydrothermal gasification and found that it is a complex process involving a series of reactions. Model compounds like glucose have been used to understand the degradation of biomass under hydrothermal conditions. Based on the reaction conditions, hydrothermal gasification can be classified as subcritical or supercritical (Kaur et.al, 2019). Subcritical conversion of biomass is a hydrothermal gasification process below the critical point of water. This process is known for its high gas yield and low tar and char formation. Researchers have investigated the use of different catalysts, including alkali catalysts, to enhance the gasification process. Alkali catalysts have been shown to promote biomass decomposition, improve hydrogen yield, and reduce char and tar yield (Kaur et.al, 2019).

$NaOH > KOH > Ca(OH)_2 > K_2CO_3 > Na_2CO_3 >$ (T= 330°C and P= 13.5 MPa.)

Supercritical water gasification (SCWG) of biomass occurs at temperatures above 374°C and pressures above 22 MPa. This process produces a high yield of hydrogen and carbon dioxide, with minimal formation of char and tar.

Research on reactor materials revealed that stainless steel promotes hydrogen production, while Inconel 625 enhances CO methanation. Decomposition of cellulose initiates below the critical temperature of water, with hemicellulose and lignin undergoing decomposition above 190°C. The main reactions involved are dehydration, fragmentation, isomerization, and condensation. Studies on the effect of alkali catalysts have shown that potassium compounds boost hydrogen yield during SCW gasification. Ni-impregnation into wheat straw and pinewood for hydrothermal gasification resulted in higher yields of hydrogen from Ni-doped wheat straw than pinewood. Recent patents (Miguelez et.al, 2023; Jiafu et.al, 2020; Yán et.al, 2020) are based on SCWG reactors. SCWG has been successfully established in the VERENA plant at Karlsruhe Institute of Technology reaching a hydrogen concentration up to 77% after CO_2 separation (Ahlström, 2020)

Sorption-Enhanced Gasification Process

Sorption-enhanced catalytic steam gasification (SEG) using a combined downdraft flow fluidized-bed and fixed-bed reactor yielded high-purity hydrogen (>99.9 vol%) with H_2 yield of 90% from lignocellulosic biomass. Pd/Co-Ni catalyst derived from a hydrotalcite-like material and dolomite as a CO_2 acceptor were employed in the process (Bhaskar et.al, 2013; Kaur et.al, 2019) A study by Han et al. (2011) investigated the effect of operation variables (CaO/C, H_2O/C, T) on hydrogen production. Higher CaO/C, H_2O/C, and T favored H_2 production. CaO sorption-enhanced SG of rice husk was modeled by Beheshti et al. (2015), demonstrating the ability to predict hydrogen yield and optimize process parameters. The main challenge with sorption enhanced gasification is that hot CO_2 capture occurs, and the sintering induced agglomeration after repeated cycle decreases the efficiency of the sorbent. Tiwary et al. (2022) reviewed the CaO modification and modeling necessary for designing plants including hot CO_2 capture.

Blasiak and Yang (2009) patented a type of sorption enhanced gasification with calcined lime to produce H_2 with a purity exceeding 90%. In a recent Chinese patent, a type of Ca mineral is used for sorption enhanced H_2 production in gasifier (Yang et.al, 2023). Calcium looping process for high purity hydrogen production integrated with capture of carbon dioxide, sulfur and halides is reported in a patent in 2013. This process is mostly based on the reaction of shifted gas with CaO to obtain a hydrogen rich producer gas (Hossain & Al-Attas, 2023)

Chemical looping steam reforming (CLR)

The chemical looping steam reforming (CLR) process differs from conventional steam reforming by cycling between fuel-steam feed and air-oxidation steps, eliminating the need for external oxygen supply for partial oxidation (Bhaskar et.al, 2013). This approach utilizes an oxygen transfer material (OTM), which acts as a catalyst for steam reforming when reduced. CLR offers several advantages over traditional steam reforming, including lower operating temperatures and the ability to mitigate catalyst deactivation caused by carbon deposition from bio-oils. The heat generated during the air-oxidation step can be used for steam reforming in the subsequent fuel feed cycle, further enhancing the process's efficiency. Lea-Langton et al. (2012) investigated the feasibility of producing hydrogen from pine and pine empty fruit bunches (EFB) pyrolysis oil using CLR. They found that a Ni/Al_2O_3 catalyst could effectively convert both oils into hydrogen, achieving fuel conversions of up to 97% for pine oil and 89% for EFB oil. This resulted in hydrogen yields of around 60% for pine oil and 80% for EFB oil, despite equilibrium limitations and minimal methane production. These results demonstrate the potential of CLR for efficient hydrogen production from biomass-derived oils.

Plasma gasification

Plasma gasification, also known as plasma arc decomposition, converts organic matter into synthesis gas (syngas) at high temperatures (>1400°C). This process produces a high yield of hydrogen (up to 95%) and eliminates tar and aerosol formation. The produced slag can be repurposed into valuable construction materials or used as fertilizer.

A gasification process developed by the company SGH2 (https://www.sgh2energy.com/) utilizes a plasma-enhanced thermal catalytic conversion process optimized with oxygen-enriched gas. Inside the gasification island's catalyst-bed chamber, plasma torches generate extremely high temperatures (3500°-4000° C) causing the waste feedstock to disintegrate into its molecular components, without producing ash or toxic fly ash. These gases leave the chamber and recombine into a hydrogen-rich bio-syngas free of tar, soot, and heavy metals. The syngas is further processed through a water gas shift reactor before entering a Pressure Swing Absorber system, resulting in hydrogen with a purity exceeding 99.97%. The process extracts all carbon from the waste feedstock, eliminates particulates and acid gases, and produces zero toxins or pollution. The final product is high purity hydrogen alongside biogenic CO_2, which can be further captured to achieve carbon negative hydrogen. The plant of SGH2 Energy can process 120 metric tons per day of biomass (Seliver, 2021).

Miscellaneous approaches for H_2 production using gasification

A patent by Dengxiang et al. (2019) couples biomass gasification (liquid-solid phase reaction) and absorbent catalytic reforming (gas-solid phase reaction) in the molten salt all in one reactor, thereby greatly improving the energy utilization rate in the gasification system. Co-gasifying vacuum gas oil (VGO) with biomass (glucose) is tried in Saudi Arabia in a recently filed patent for efficient hydrogen production (Hossain & Al-Attas, 2023)

Another novel gasification technique called reaction integrated novel gasification has been proposed and implemented by Lin et al. (2005) that integrates the water-carbon oxidation-reduction reaction in combination with CO_2 absorption by CaO in a single reactor. This process has a high yield of hydrogen production at relatively low temperatures. Although this process is developed for hydrogen production from coal, it can be adopted for biomass.

Operational parameters influencing the hydrogen yield

There are several operational parameters influencing the composition of the producer gas and ultimately the hydrogen yield. In the following, the most important factors affecting the hydrogen yield are described.

Fuel characteristics

Fuel characteristics can be grouped in three categories. First the main composition with respect to C, H, O, N and S. These components will end up in the gas phase and determine the yield of hydrogen. For instance, if the oxygen content is high, a part of the hydrogen will be bound to form water. If it is lower, more hydrogen can be formed. For this reason, biomass containing plastics can yield more hydrogen per ton of dry feedstock. Secondly, the amount and composition of the ash is an important factor for the operability of the gasifier. Fluidized bed gasifiers must keep temperatures below agglomeration temperatures and for an entrained flow gasifier the composition of ash determines a proper slag within the gasifier. Depending on these temperatures the conversion will have certain limitations, leading to different hydrogen yields. The third factor is the moisture content of the feedstock. In principle, steam is needed to shift the CO towards H_2 with the water gas shift reaction. However, if the moisture content is high, the gasifier will consume more feedstock to generate energy resulting in CO_2 (and hence no H_2). Therefore, it is beneficial to provide H_2O as steam to allow more H_2 to be generated in the gasifier.

When the biomass moisture content exceeds 35%, hydrothermal gasification is a viable approach (see previous chapter on Hydrothermal gasification).

Steam gasification of bio-oil/char slurry is another promising approach for hydrogen production. This method involves mixing char, a by-product of fast pyrolysis, with bio-oil to form a denser slurry. The slurry is then gasified using steam and further processed through methanation and shift equilibria to enhance hydrogen yields. Reverse Boudouard reaction may also occur under certain conditions (gasification of char in carbon dioxide is popularly known as the Boudouard reaction and reverse of this reaction result in carbon deposition and fouling) (Sircar & Golden, 2009) The maximum theoretical yield of hydrogen from bio-oil is 171 g per kilogram, as calculated from stoichiometry. Henrich et al. (2004) demonstrated gasification of bio-oil/char slurry with oxygen in a 3-6 MW entrained flow gasifier at 26 bar and temperatures between 1200 and 1600°C. The slurry contained 23-26% char and 3% straw ash, and the oxygen gas-feeding rate corresponded to 0.4-0.6 times the stoichiometric amount for complete combustion. High gasification temperatures (>1000°C) achieved complete carbon conversion (>99%) and yielded tar-free synthesis gas at 1200°C. Steam gasification of biomass-derived oil at 800°C yielded a gas product primarily consisting of H_2, CO, CO_2, CH_4, C_2, C_3, and C_{4+} components, with syngas (H_2 + CO) comprising 75-80% of the mixture, including 48-52% H_2 and 12-18% CH_4. These results demonstrate the potential of steam gasification for producing syngas, hydrogen, and medium-heating-value gas from biomass-derived oil.

Gasification temperature

The temperature for fluidized bed gasification is in the range of 650 °C and 950 °C. Higher temperatures will increase the carbon conversion efficiency and reduce the amount of tar produced. However, in the case of a fluidized bed reactor the maximum operating temperature is limited by the melting point of ashes or of the bed material. Additionally, reactor construction materials can become an issue. In practice the reaction temperature is directly linked to the equivalence ratio, as for a higher temperature more product gas needs to be oxidized, which in its turn reduces the cold gas efficiency (Siedlecki, 2011). In a fluidized bed gasifier, the oxygen is always co-fed with a dilutant to avoid hotspots. Typically, air (N_2 as a dilutant) is used but this will also dilute the product. Next to that steam or CO_2 can be used to mitigate the heat development in the fluidized bed and steer the product gas composition somewhat.

For entrained flow gasification, higher temperatures are usually required, and oxygen is the preferred oxidant. This results in a higher gas yield and hence a high potential to produce H_2. See also the previous chapter on Oxygen blown entrained flow gasification.

Bed material and catalysis

In fluidized bed gasifiers, the bed material plays a critical role in maintaining a stable and efficient process. It acts as a heat exchanger, absorbing heat from exothermic reactions like oxidation and water-gas shift, and then transferring it to endothermic processes like drying, pyrolysis, and most of the gasification reactions. This continuous heat exchange keeps the entire reactor at a uniform temperature, typically around 800°C, avoiding undesirable temperature fluctuations especially in the oxidation zone. While quartz sand is commonly used due to its inertness and affordability, it has limitations. For instance, its high silica content can react with alkali metals and chlorine in certain fuels, causing problematic clumps (agglomeration) at those same high temperatures (Siedlecki, 2011).

To address these limitations, alternative bed materials and in-bed additives are being explored. Natural rock minerals offer promise due to their affordability and high-temperature stability. They can be less mechanically strong than sand, but synthetic materials like alumina provide superior strength at a higher cost. In-bed additives, like kaolin, can also be mixed with the bed material to prevent agglomeration by forming higher-melting-point compounds when interacting with fuel ash.

Choosing the optimal bed material requires careful consideration of several factors: mechanical strength to withstand the harsh environment, resistance to agglomeration based on the fuel type, potential catalytic activity for improved process efficiency, and of course, cost-effectiveness for large-scale operations. While quartz sand remains a common choice due to its simplicity, materials like magnesite and olivine offer advantages. Magnesite, with its lower silica content have higher agglomeration resistance and might even possess catalytic properties. Olivine sits between sand and magnesite in terms of properties, making it a viable option for specific gasifiers, especially when considering its potential for tar cracking under certain treatments (Siedlecki, 2011).

In addition to common catalysts including dolomite, alkaline metal oxides, and Ni-based catalysts in gasification units, other catalysts have recently been developed for thermochemical production of hydrogen from biomass. Song et al. (2023) filed a patent where a catalyst for promoting the pyrolysis or gasification of mixed biomass to produce hydrogen is reported. The catalyst comprises nickel (Ni -30wt%), iron (Fe 20wt%) and calcium oxide (CaO-50wt%). Method to prepare carbon-based single metal (Zinc) as an efficient gasification catalyst is filed in 2023 (Zeng et.al, 2023). Co-Ni/ hydrotalcite-like catalyst is reported by He et al. (2010) for sorption enhanced gasification with capability to obtain hydrogen with purity of 99%.

Low-Temperature Catalytic Gasification of Biomass

Low-temperature catalytic gasification of biomass utilizes low temperatures (350-600°C) and catalysts to enhance gasification efficiency. Researchers have studied the effects of catalysts, reaction mechanisms, and compound interactions to optimize the process. Minowa et al. (1998) found that alkali catalysts lower cellulose degradation temperatures and increase gas and oil yields. Metal catalysts promote gasification of water-soluble products, leading to early CO_2 and H_2 production followed by methane formation through methanation. Limited char and oil are formed. Numerous studies involving different biomass feedstocks and catalysts have concluded that catalysts can boost hydrogen production via the WGS reaction and methane reformation (Kaur et.al, 2019).

High-Temperature Catalytic Gasification of Biomass

High-temperature catalytic gasification of biomass employs higher temperatures (500-750°C) and catalysts to enhance gasification efficiency. Model compounds like glucose and cellulose have been used to elucidate reaction pathways. Studies have shown that higher concentrations of biomass (>5-10 wt%) negatively impact hydrogen yield and gasification efficiency. Increasing the temperature to 650°C with biomass concentrations below 3% can lead to 100% hydrogen and carbon dioxide yields.

Gas upgrading and hydrogen purification

As previously mentioned, the producer gas requires different cleaning and upgrading before it can be fed to the hydrogen purification unit. Table 2 summarizes overall producer gas characteristics desirable for production of hydrogen via biomass gasification. Generally, the characteristics are more critical for fuels and chemical synthesis applications than for hydrogen and fuel gas applications.

Table 2. Desirable producer gas characteristics for hydrogen production (based on Ciferno et.al, 2002)

Product	Characteristics for hydrogen production
H_2/CO-ratio	A high ratio is preferable.
CO_2	Not important. The water gas shift is used to convert CO to H_2; The CO_2 in the synthesis gas can be removed together with the CO_2 generated by the water gas shift reaction.
Hydrocarbons	Low concentrations required. Methane and heavier hydrocarbons need to be removed or recycled for conversion to syngas.
N_2	Low concentrations to reduce the size and cost of downstream equipment.
H_2O	High. Water is needed for the water gas shift reaction.
Contaminants	<1 ppm Sulfur. low number of particles. No HCN
Heating value	Not important.

The requirement of the hydrogen purity is different depending on application as shown in Table 3.

Table 3. Required purity of hydrogen for different applications, modified based on Sato et.al (2005)

Hydrogen purity (%)	Application
99,999999	Rocket engine fuel, semiconductor manufacture
99,99	Polymer electrolyte fuel cell On-site hydrogen generating equipment
90	Hydrodesulfurization
70~80	Adjustment of a molecular weight distribution
54~60	Fuel gas

The existing ISO standard for required hydrogen purity (ISO, 2019) is however mainly based on hydrogen produced via water electrolysis and steam methane reforming. Hydrogen produced via biomass gasification (and other emerging hydrogen production technologies) may include impurities which are not, or at least not sufficiently, covered in these ISO standards. More research is needed to increase the knowledge on potential impurities and assessing their effects on for example fuel cells.

However, the purity of hydrogen produced via biomass gasification can in principle reach any purity level shown in Table 3, since the back-end solutions are off the shelve technologies (cryogenics, or Pressure Swing Absorption PSA). These processes are briefly described below.

Pressure Swing Adsorption (PSA) utilizes molecular sieves to isolate gas species based on their molecular size. PSA boasts exceptional impurity removal capabilities, reaching purities of 99-99.99% which is necessary for fuel cell application. Membrane separation systems harness the selective permeation of H_2 through polymer, metallic, or ceramic membranes. Metallic membranes employ H_2 dissociation and recombination (e.g. Pd-Ag alloys), while dense ceramic membranes utilize H^+ and electron transfer (Polfus et.al, 2015). Sodalite and other microporous materials can also be utilized for H_2 purification for instance Yang et al. (2019) separate hydrogen from nitrogen using Nanosized sodalite.

Membrane technology holds the potential to reduce costs, enhance efficiency, and simplify H_2 separation. However, current membrane separation systems face challenges like durability, defect-free fabrication, and sealing issues. Graphdiyne, a newly synthesized carbon allotrope, emerges as a promising separation membrane due to its atomic porosity and mechanical stability. Makaruk et al. reports 98% H_2 content and 75% recovery using a two-stage graphdiyne membrane system (Bhaskar et.al, 2013).

Cryogenic separation is the earliest approach for H_2 purification though due to need for low temperature is energy intensive and less favored (Abdul Muin et.al, 2021). In combination with membrane technology, cryogenic separation can be used to produce high purity hydrogen. As mentioned in earlier section, adsorption-based process can also be used to purify H_2 mainly by removing CO_2 not only as a post treatment procedure but also directly inside gasification and reforming reactor (Abdul Muin et.al, 2021).

A process and relating apparatus to make pure hydrogen from a syngas originated from wastes gasification is described in a filed patent by Gaetano et al. (2019). Their system, address different units for syngas purification after gasification and in final step a PSA unit is utilized to obtain pure hydrogen. Their gas condition has acid and base scrubbing units as well as wet electrostatic precipitation unit. These units, remove HCl, HCN and particulate in syngas, and purified syngas send to WGS unit, finally H_2S is removed from the gas and PSA unit utilized to obtain high purity hydrogen.

CO_2 scrubber (mostly amine based) is also used with many other purification and reforming steps to obtain ultra-pure hydrogen. For instance, a type of high-performance CO_2 scrubber is used in US patent by Tawfik (2019) in outlet of a compact gasifier which in combination with other units offer a promising approach for high purity hydrogen production.

The purity of the hydrogen produced via biomass gasification has in laboratory scale, shown to be very high. For example, Indian Institute of Science has together Indian Oil Ltd demonstrated hydrogen production of fuel-cell quality via fixed-bed biomass gasification and hydrogen purification via vPSA (70-72 % recovery). A small fuel-cell system was tested using the produced hydrogen during more than 250 hours of operation (Mohana & Badhe, 2024). The Advanced Biofuel System Ltd (ABSL) plant in Swindon has upgraded slipstreams of their synthesis gas taken after the WGS in a PSA (Xebec), which met the specification for proton electron membrane fuel cells.

Opportunities to obtain negative carbon emissions

Carbon Capture and Usage (CCU) or Storage (CCS) means that CO_2 is separated and captured for example from substantial point sources like flue gases from power production or industrial facilities that use either fossil fuels or biomass as fuel (BECCU/S). If the captured CO_2 is stored, so called negative carbon emissions are obtained. Around 45 commercial CCS-plants are already in operation applying CCUS to industrial processes, fuel conversion and power production (International Energy Agency, 2023)

In addition, the captured CO_2 can be compressed and transported by pipeline, ship, rail, or truck for usage in several different applications. The CO_2 can also be injected into deep geological formations, for example depleted oil and gas reservoirs or saline aquifers. The CO_2 can be used either directly or indirectly (i.e. transformed) into a wide range of different products. Around 230 Mt of CO_2 are currently used each year, mainly in direct use pathways in the fertiliser industry for urea manufacturing (~130 Mt) and for enhanced oil recovery (~80 Mt). (International Energy Agency, 2024c)

BECCS brings a cost, which varies extensively depending on technologies, plant size, type of feedstocks, and outputs etc. Beiron et al (2022) estimated the cost for integrating CO_2-separation at 110 biomass or waste fired combined heat and power (CHP) plants in Sweden to in the range of 45-125 € per ton of CO_2. This cost includes the cost for the CO_2 separation and the transportation via truck to intermediate storage hubs. The costs for ship transport and end-storage of the CO_2 are estimated at the range of 35-55 € per ton CO_2, leading to a total cost for BECCS in bio-CHP plants in the range of 80-180 € per ton CO_2. In biomass gasification systems, the CO_2 separation process is already an integral part of the system, which consequently means a lower cost range when BECCS is applied in biomass gasification applications.

However, by selling or storing the CO_2 (i.e. the latter with negative emissions as a result) may bring additional revenues to the plant owner. One example of this is the Swedish biomass-based combined heat and power company, Stockholm Exergi, who has sold 3.3 million tons of permanent negative carbon emissions to Microsoft (Stockholm Exergi, 2024). The price is not official, but based on carbon credits statistics published by CDR, it may be worth approximately 0.45 billion Euros. Recently the same company announced selling negative emissions to Frontier, an advance market commitment founded by Stripe, Alphabet, Shopify, Meta, McKinsey and tens of thousands of businesses, to a value of approximately 45 million Euros. (Frontier, 2024).

For every ton of dry biomass gasified, about 0.1 ton of H_2 can be produced together with 1.5-2.0 ton of CO_2, i.e., 15-20 CO_2 per kg H_2. As mentioned, as an integral part of a gasification system, the CO_2 is separated into a high-quality concentrated stream, thus providing a great opportunity for selling the CO_2 or storing it and thereby reach negative CO_2-emissions. Both options can bring important benefits for the plant profitability depending on the cost for CO_2 transport and permanent storage.

It should however be noted that it makes no sense to use the formed CO_2 (i.e, CCU) by adding externally produced hydrogen to make PtX-products (i.e. electrofuels like methanol, SAF etc). This because it is likely less expensive and more efficient to convert the biomass-based synthesis gas directly to the desired product.

It should also be noted that some biomass gasification concepts generate a co-product in form of biochar. The biochar normally contains a large share of carbon (approx. 85-90 $\%_{wt}$), while the remaining part being ashes originating from the original biomass. The biochar also includes nitrogen, phosphorous and potassium, which are all important elements for soil improvement. By returning the produced biochar to the soil, carbon depletion in (agricultural) soils as well as the demand for synthetic fertilizers are reduced whilst obtaining a carbon negative value chain.

Techno-economic and environmental performance

In the following, the technical, economic and environmental performances of hydrogen produced via biomass gasification is discussed.

YIELDS AND EFFICIENCIES

According to IEA (2024a), the hydrogen yield is generally high for thermochemical processes like gasification, pyrolysis, and reforming, and can produce in the range of 40-190 kg hydrogen per ton of feedstock. The energy efficiency of most of these processes is in the span of 40-67% (based on the lower heating value). Previous studies on biomass gasification-based hydrogen show a large spread in technical performance, for example in energy efficiency that ranges in between 35 and 75%. The variations relate to a wide range of different assumptions, prerequisites, definitions of products and efficiency, etc. that differentiate the studies.

The hydrogen yield of biomass gasification also depends on several factors as earlier discussed in the report. Turn et al (1998) showed that it is theoretically possible to reach a hydrogen yield up to 165 kg hydrogen per ton of biomass when applying WGS and SMR to steam gasification of biomass. In practice, they managed to reach a maximum of 128 kg hydrogen per ton biomass in their experiments, which corresponds to a hydrogen production rate of a factor approximately 2.1 times higher than the hydrogen available in biomass (assuming a hydrogen content of 6% on mass basis daf) (Minowa et.al, 1998)

Gubin et.al (2024) reports that fixed-bed gasification (1 MW) and dual fluidized bed (50 MW) generates 68 and 87 kg of hydrogen per ton of dry biomass, respectively, with overall energy efficiencies of 59.5% and 64.2%. These numbers are based on process modelling. There are also lower efficiencies reported in the literature. For example, Rey et.al (2024) claims that hydrogen produced via biomass gasification can be done with an efficiency in the range of 35-50% (based on LHV). Exactly how they define the efficiency is however unclear.

Tock & Maréchal (2012) analysed a system in which the torrefaction- and gasification plants are integrated in a CHP plant. A multi-objective optimization approach was applied to optimize the cost-efficiency and GHG emission reduction, resulting in hydrogen yield of 107 kg hydrogen per kg biomass and a biomass to hydrogen efficiency of nearly 70 % (on LHV_{daf} basis) The overall energy efficiency was calculated to 60 %.

The approximate yield used in this report is 100 kg of hydrogen for every ton of dry biomass gasified. On energy basis, this corresponds to a biomass to hydrogen efficiency of approximately 67 % (HHVdaf basis).

Assessment of the Technology Readiness Level (TRL)

The TRL-level was assessed according to a framework described in Jafri et.al (2020). Here, each sub-process was assessed and assigned a TRL score with the aid of definitions from the European Union Horizon 2020 program and the United States Department of Energy Clean Coal Program, see box below. The overall score for the technology was determined from the component scores using two complementary approaches: (a) the weighted average approach, (b) the weakest link approach.

European Union Horizon 2020 TRL scale (European Commission, 2014)

TRL 1 - basic principles observed
TRL 2 - technology concept formulated
TRL 3 - experimental proof of concept
TRL 4 - technology validated in lab
TRL 5 - technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6 - technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7 - system prototype demonstration in operational environment
TRL 8 - system complete and qualified
TRL 9 - actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

In the weighted average approach, each of the components were assessed for importance and given a weight, which was used to calculate a weighted average TRL score. In the weakest link approach, the entire technology was assigned the TRL of the lowest scoring component to account for the possibility that some key components and sub-components may be significantly lagging in development compared to others. The integrated operation, i.e. the demonstration of all parts of the process configuration in an integrated assembly is treated as an independent, separate step. The results of the assessment are provided in tabular form following the structure presented in Table 4.

Table 4. Tabular format used for the presentation of technology readiness assessment results.

Step	TRL	Weight	Comments
Feedstock handling system	1-9	10-50 %	TRL scores between 1 and 9. Weights between 10% and 50%.
Conversion process	1-9	10-50%	TRL scores between 1 and 9. Weights between 10% and 50%.
Required upgrading to H_2	1-9	10-50%	TRL scores between 1 and 9. Weights between 10% and 50%.
Integrated process operation	1-9	10-50%	TRL scores between 1 and 9. Weights between 10% and 50%.
Overall “Weighted Average”	1-9		Weighted average of all individual component scores
Overall “Weakest Link”	1-9		Component with the lowest TRL

The weighting was based on the assessment of the sub-process novelty, complexity, and its centrality to the overall process configuration. Table 5 shows the result of the TRL assessment carried out in this work.

Table 5. TRL assessment of hydrogen produced via biomass gasification

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	9	10	Covers the conveyance of the feedstock to the gasifier. Most feedstock handling systems applied for gasification are off-the shelf technology.
Gasification reactor with heat supply	7-8	30	Biomass gasification aimed for more advanced products than CHP, can be considered proven in demonstration scale (GoBiGas etc).
Product gas separation cleaning	8	20	This concerns off-the shelf technology and is commercial for coal gasification. Not fully tested in large-scale commercial biomass gasifiers.
Integrated operation	5	40	Tests in pilot scale are reported.
Overall “Weighted Average”	6.6-6.9		
Overall “Weakest Link”	5		Integrated operation to be proven

Here, the average weighted average TRL is assessed to be close to 7, while the weakest link is 5. There are a few other TRL-assessments made for hydrogen produced via biomass gasification found in the literature. For example, Rey et.al (2024) claim that the TRL-level is in the range of 7-8, while IEA Hydrogen assesses the TRL-level to 6 (International Energy Agency, 2023a, right in between the weighted average and the weakest link TRL in this report.

Economic performance

Several estimates on production costs for hydrogen produced via biomass gasification are found in the literature. Table 6 shows a summary of selected studies on hydrogen production cost estimates with different gasification technologies and at different scales.

Table 6. Estimates of hydrogen production costs from biomass gasification

Technology	H_2 output (MW)	Biomass cost (€ MWh^{-1})	Production cost		Ref.
			€ MWh^{-1}	€ kg^{-1}	
Dual Fluidised Bed (DFB)	3	19.4	222	7.4	Yao et al (2017)
Dual Fluidised Bed (DFB)	145	17.6	120	4.0	Awgustow et al. (2023)
Dual Fluidised Bed (DFB)	50	18	66	2.2	Binder et.al (2018)
O_2-blown Entrained Flow (EF)	630	18	141	4.7	Salkuyeh et al. (2018)
O_2-blown Circular Fluidised Bed (CFB)	59	10	137	4.6	Hannula et al. (2021)

In Ahlström (2020), published cost estimates for biohydrogen produced via thermochemical technologies are also summarized showing a range of 78 to 210 € per MWh (equal to 2.6-7 € per kg hydrogen). This span agrees well with the costs presented in Table 8.

The cost of feedstock is an important factor influencing the hydrogen production cost. In this report, the production cost was calculated as a function of the biomass feedstock price. The capital- and operational cost (excluding feedstock cost) are based on data presented in an IEA Bioenergy-report by Brown et.al (2020) for production capacities of 200 MW nominal product output and 8,000 hrs of annual operation. Hydrogen produced via biomass gasification is however not included in that report, but it can reasonable be assumed that the capital and operational costs are very close to that of gasification-based bio-methanol and bio-methane. These numbers have therefore been used.

In Brown et.al (2020), the cost data are fully transparent and standardized regarding capital return requirements and the different cost elements (capital, raw material etc.) meaning that relevant adjustments to the costs can easily be made. In addition, the report presents both high and low-cost levels considering process improvements, technological learning effects etc. The upper level (denoted as HI in Figure 5) represents the current state-of-the art cost. The lower level (denoted LO in Figure 5) foresees reductions in capital and operating costs of the range of 10-20%, resulting from a combination of scale-up effects on investments as well as efficiency improvements. In this report, 10 % was added to the costs to somewhat compensate for increases in capital cost and inflation in the recent years.

Figure 4 shows the resulting production cost of hydrogen via biomass gasification as a function of the biomass price.

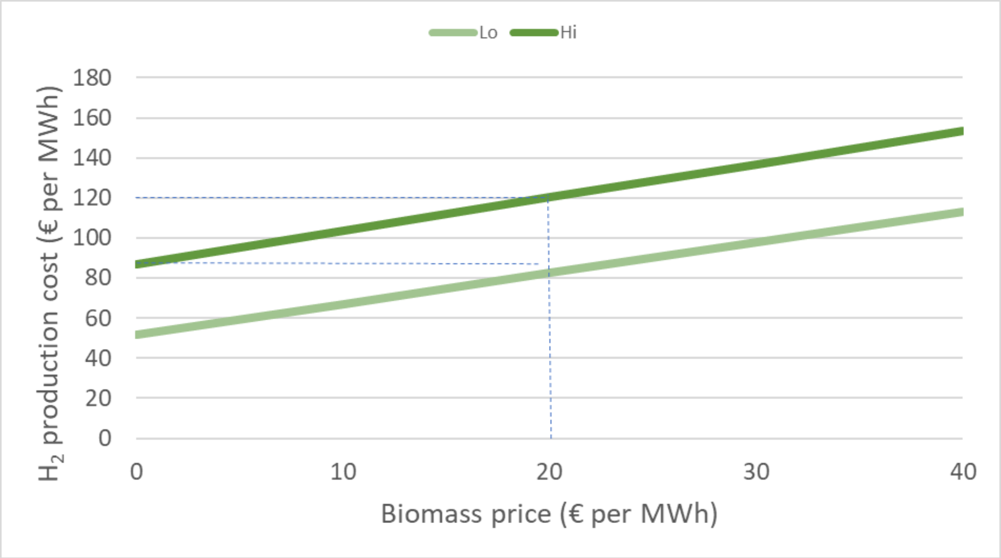

Figure 4. Estimated production cost of hydrogen via biomass gasification as a function of the biomass price. The higher level (Hi) can be considered as the current state-of-the art.

With made assumptions, the production cost amounts to in between 82-120 € per MWh or 2.7 to 4 € per kg hydrogen at a biomass price of 20 € per MWh, which agrees fairly well with the previous cost estimates presented in Table 6.

The production cost for hydrogen based on steam methane reforming (SMR) in Europe has historically been close to 2 € per kg hydrogen (or 60 € per MWh) as an average. However, the production cost in year 2022 became extraordinarily high reaching 5.7 € per kg hydrogen, due to high natural gas prices caused by significant downturn of the ammonia production in the EU. Since then, natural gas prices have decreased, and in 2023 the SMR-based hydrogen production cost in Europe was on average 3.8 € per kg hydrogen. (Hydrogen Europe, 2023). Even if the current hydrogen production cost level for biomass gasification (HI) is higher, it is still not far from the current cost of hydrogen produced via SMR.

It should however be noted that the estimated production costs for gasification based biohydrogen in Figure 4, does not consider that the separated pure CO_2-stream may have an economic value as previously argued. If it is assumed that

- For every ton of dry biomass gasified, about 100 kg of hydrogen can be produced together with 15-20 kg CO_2 per kg hydrogen
- 85% of the CO_2 is captured and sold to a negative emissions price of 100 € per ton CO_2
- The cost for CO_2 management at site and transportation via truck to an intermediate storage hub assumed to 50 € per ton CO_2 (the costs for ship transport and end-storage of the CO_2 are estimated at the range of 35-55 € per ton CO_2 according to Beiron et.al (2022)).

This means that a net credit of approximately 50 € per ton CO_2 can "subsidise" the hydrogen production cost. Figure 5 illustrates how the hydrogen production cost decreases when the CO_2 credits is considered for the level of 20 kg CO_2 per kg hydrogen.

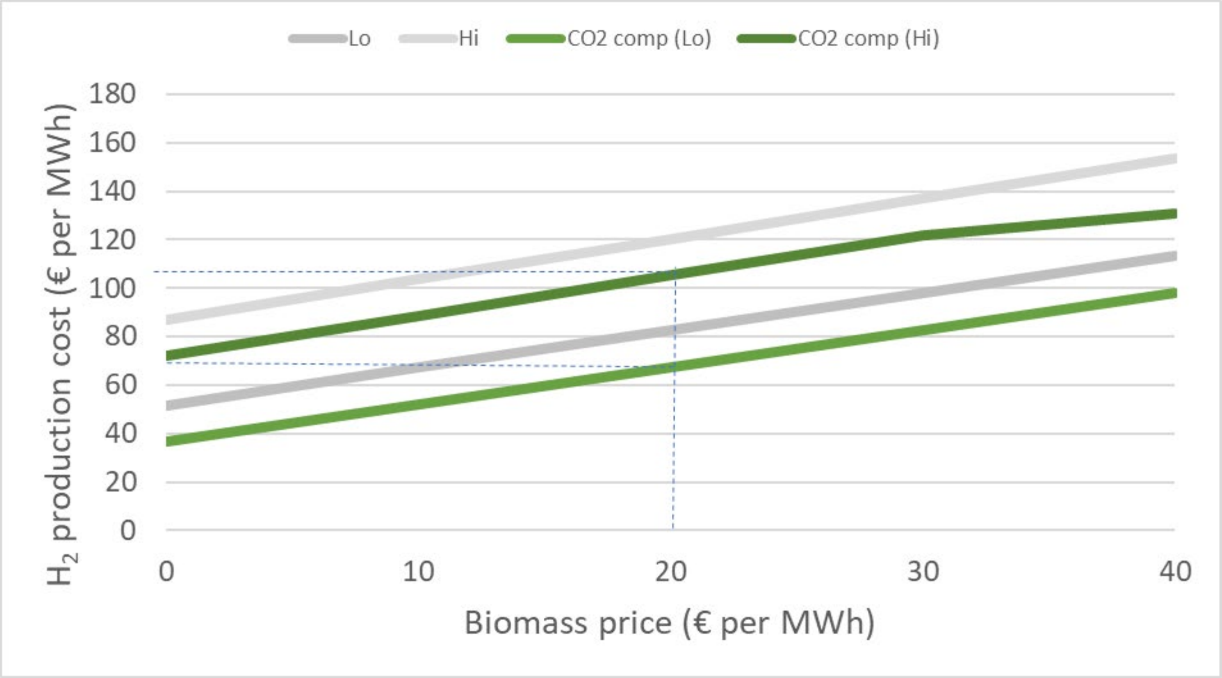

Figure 5. Estimated production cost of hydrogen via biomass gasification as a function of the biomass price, taking into account CO_2-credits.

With these assumptions, the production cost is estimated to reduce to in between 67 to 105 € per MWh (or 2.2 to 3.5 € per kg hydrogen) a biomass price of 20 € per MWh. This cost range is competitive to the current cost for producing hydrogen with SMR.

International Energy Agency (2024a) estimated geographically explicit costs of hydrogen from electrolysis based on solar cells and onshore wind power beyond 2040–2050, shown in Figure 6. It is observed that the hydrogen production cost range for biomass gasification-based hydrogen calculated in this report is strongly competitive to the cost ranges of renewable electrolytic hydrogen in many regions in the world.

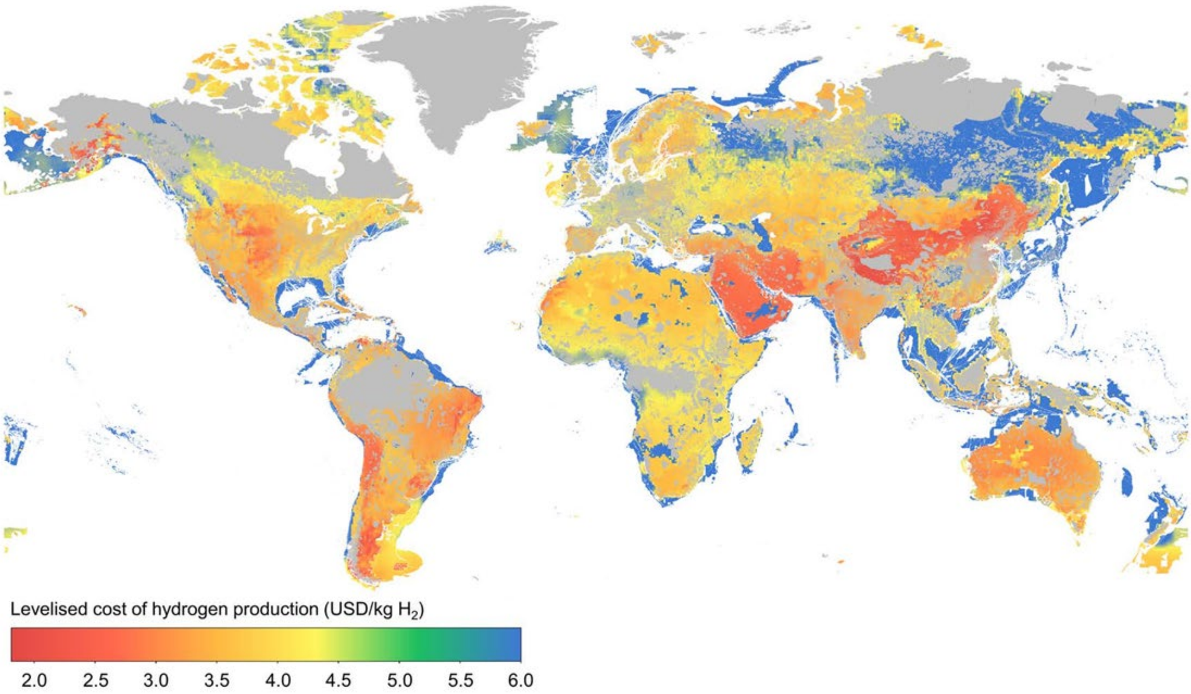

Figure 6. Estimated cost of hydrogen based on solar cells and onshore wind power beyond 2040–2050 (International Energy Agency, 2024c)

The CO_2 performance of gasification-based bio-hydrogen

Several Life Cycle Analyses (LCA) studies investigating the carbon footprint of different types of hydrogen production pathways have been published in the literature. Puig-Samper et.al (2024) recently reviewed 100 LCA studies of different types of hydrogen production technologies, of which 12 were biomass gasification concepts as shown in Figure 7.

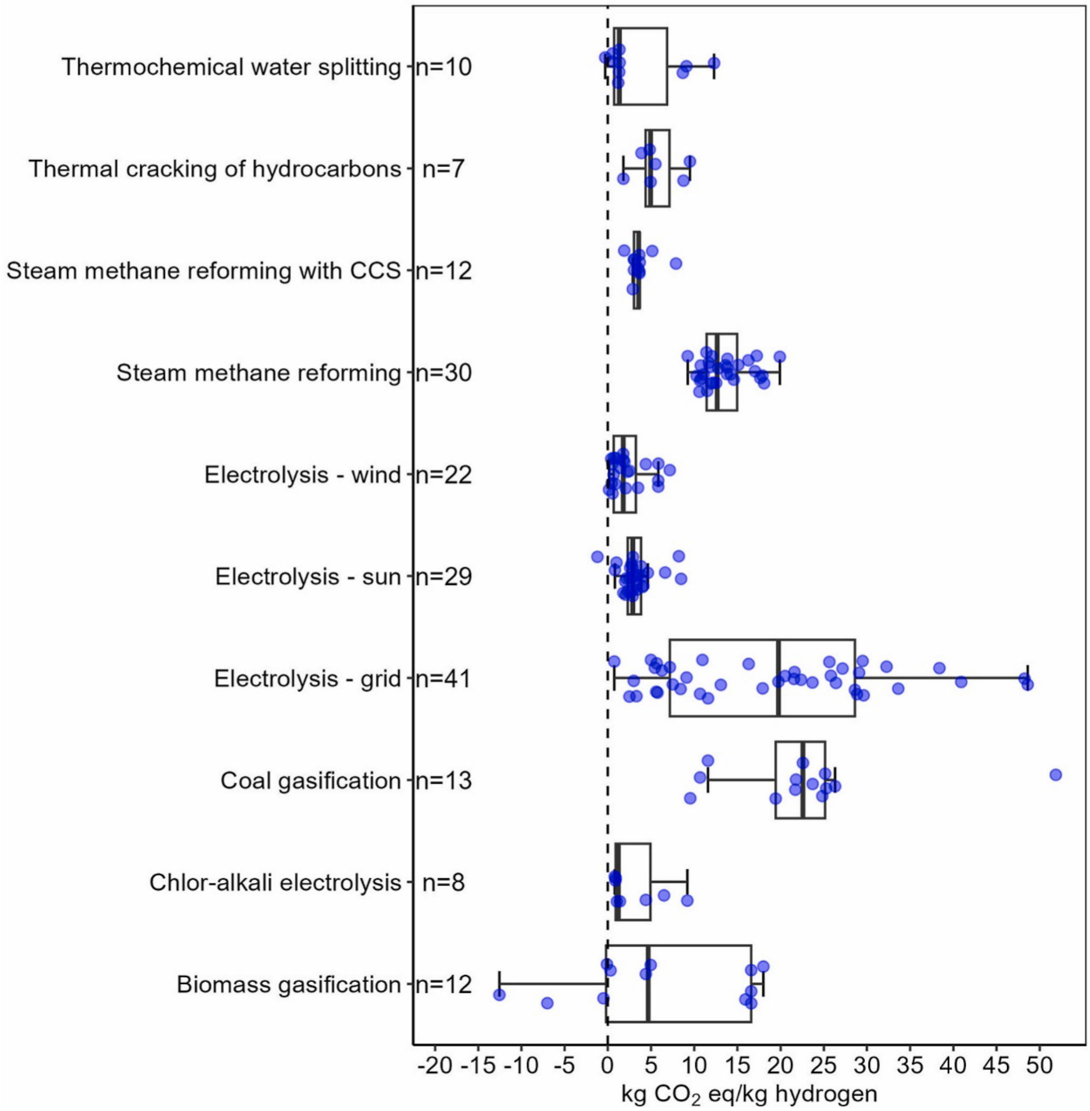

Figure 7. Carbon footprints based on LCA studies of different types of hydrogen production technologies (figure from Puig-Samper et.al (2024))

Hydrogen produced via biomass gasification showed a median value of 4.7 kg CO_{2eq} per kg hydrogen, ranging from −12.6 to 18 kg CO_{2eq} per kg hydrogen. When applying CCS, the greenhouse gas emissions reduce to an average of −15.8 kg CO_{2eq} per kg hydrogen, ranging between −21.8 and −14.6 kg CO_{2eq} per kg hydrogen.

Also, Lou et.al (2023) reviewed published data on the carbon footprint, specifically on hydrogen produced via woody-biomass gasification. They found that the CO_2-emissions were ranging from 0.75 to 2.1 kg CO_{2eq} per kg hydrogen, which is among the lowest carbon intensity production pathways from a LCA perspective. Arfan et.al (2023) made a gate-to-gate Life Cycle Assessment (LCA) of entrained flow gasification of pyrolysis liquids in a Swedish case study, showing a greenhouse gas performance of approximately 1.5 kg CO_{2eq} per kg hydrogen.

A strong influencing parameter on the carbon footprint is the type of biomass feedstock that is considered. If residual biomass feedstocks such as agricultural and forest residues is used instead of woody-biomass like pellets and pure woodchips, the carbon footprint becomes lower due to its lesser Land Use Change (LUC)-contribution (Lou et.al, 2023).

It can be concluded that biomass gasification is one of very few low emission hydrogen production pathways that can result in negative emissions due to the opportunity to utilize CCS. However, even though CCS is not applied, the carbon footprint of hydrogen produced via biomass gasification is still low.

CO_2 ABATEMENT COST FOR HYDROGEN PRODUCED VIA BIOMASS GASIFICATION

The CO_2 abatement cost of a specific value chain depends on the production cost difference and the GHG reduction compared to a fossil reference Hansson et.al (2023). It is therefore a measure of the cost-efficiency for a replacement action aiming at reducing CO_2-emissions and calculated as:

$$\frac{Cost_{bio-H2} - Cost_{fossil\ H2\ ref}}{Emission_{fossil\ H2\ ref} - Emission_{bio-H2}}$$

In this report, the production cost of the biomass-based hydrogen ($Cost_{bio\text{-}H2}$) is according to Figure 5 and Figure 6. The fossil reference cost is assumed to 2 € per ton, the historical average cost of hydrogen produced via SMR in Europe (Hydrogen Europe, 2023). The CO_2 emission from the fossil reference (here hydrogen produced via SMR without CCS) is set to 66 g CO_2 per MJ (Swedish Energy Agency, 2024).

As discussed earlier, depending on how the CO_2 is managed, different abatement costs are achieved. The separated CO_2-stream can either be:

a) vented to the atmosphere using the CO_2 emission factors for biomass-based H_2 (0.75 to 2.1 kg CO_{2eq} per kg hydrogen according to Lou et.al (2023))

or

b) sold to an external customer with the net-credits from the sale (50 € per tom CO_2) and the CO_2 emission factor for biomass-based H_2 (0.75 to 2.1 kg CO_{2eq} per kg hydrogen (Lou et.al, 2023))

or

c) transported and end-stored with negative emissions - the abatement cost is calculated using the production cost shown in Figure 5, but with an added cost for transports and end-storage of 90 € per ton CO_2 (Beiron et.al (2022) estimates the total cost for BECCS in bio-CHP plants to in the range of 80-180 € per ton CO_2) along with negative CO_2 emission factors of ranging between −21.8 and −14.6 kg CO_{2eq} per kg hydrogen according to Puig-Samper et.al (2024).

Figure 8 shows the resulting CO_2 abatement for the three scenarios (a-c) as well as the corresponding CO_2-abatement cost for hydrogen produced via electricity based on renewable power with a CO_2-emission factor of 12.3 g CO_2 per MJ) (Grahn et.al, 2022).

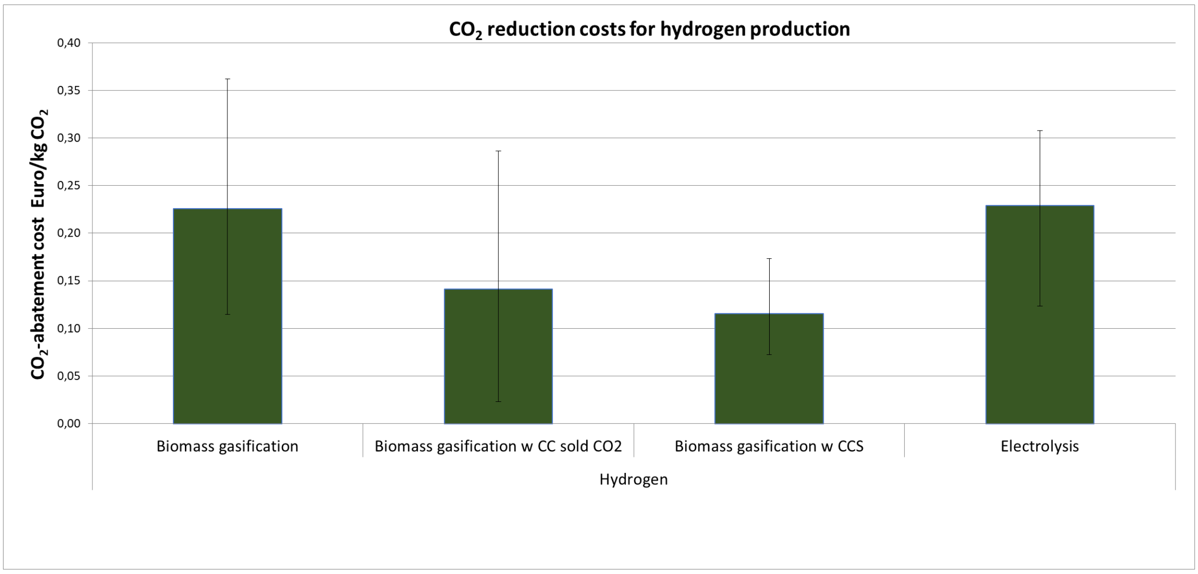

Figure 8. CO_2 abatement costs for hydrogen produced via biomass gasification with different CO_2 management as well as renewable electrolysis.

Due to the large influence of the great value of negative carbon emissions, the lowest CO_2 reduction cost is obtained when CCS is utilized, despite the added cost for that. However, even without CCS, the hydrogen produced via biomass gasification results in lower abatement cost compared to hydrogen generated via electrolysis operated on renewable power.

Potential role of hydrogen produced via biomass gasification

As shown in Figure 2, the demand for hydrogen is expected to grow significantly (two- to fourfold) by 2050 compared to present level. Most of the foreseen demand is predicted to be for low emission hydrogen, accounting for 50 to 70 percent of total demand (McKinsey, 2024).

Low emission hydrogen produced via biomass gasification should be regarded as a complementary to electrolysis and other low emission hydrogen production technologies. It can for example play an important role in many regions around the world with availabilities of sustainable biomass or in regions with limited access to, or expensive, fossil-free electricity, whilst having a demand for low emission hydrogen.

In Table 7, a short assessment is being made in which sectors that hydrogen produced from biomass gasification can play a potential role. The table also include the predicted demand in the different sectors and their general hydrogen purity specifications.

Table 7. Assessment in which sectors biomass gasification-based hydrogen can play a role. Dark green = viable, light green = in some cases viable, orange = not viable

Sector	**Req. H_2 purity (Kew, 2019)**	**Estimated demand (Mtpa)**		**Comments on potential contribution from biomass gasification**
		2035	**2050**	
Chemicals	95-98 %	63-65	77-80	Biomass gasification-based synthesis gas can be used to produce many different chemicals, and it may be more efficient to produce the chemicals directly from the synthesis gas (for example methanol), rather than first producing hydrogen to react with an external Carbon-source. However, hydrogen from biomass could replace fossil-based hydrogen in for example ammonia production. The latter may result in process integration opportunities if an Air Separation Unit (ASU) is used for the nitrogen supply. The residual oxygen could be used as gasification agent. Lou et.al (2023) has shown that ammonia can be produced with negative emissions.
Refining	95-98 %	34-43	21-38	Hydrogen is required in refining for oil hydrotreatment and hydrocracking. The increasing interest to de-fossilize the sector has driven oil refineries to retrofit their oil refiners to “stand-alone biorefineries” producing lower emission, drop-in biofuels (Su et.al, 2022) As the case for chemicals, it may be more efficient to produce biofuels directly from the synthesis gas, rather than first producing hydrogen. Hydrogen produced by biomass gasification can potentially replace fossil fuel-based hydrogen in refining. However, current hydrogen production and use are well integrated with the refining operations, resulting in a large economic challenge replacing existing capacity

Road transport	99.5% or higher[2]	8-15	26-56	Hydrogen can be used in fuel cell vehicles (FCV's) as well as in internal combustion engines (ICE). Very high hydrogen purity is required in FCV's. But contrarily to FC powertrain systems, Hydrogen fuelled ICEs can be fuelled with non-purified hydrogen, resulting in significantly lower production cost of hydrogen fuel. (Onorati et.al, 2022). Consequently, hydrogen produced via biomass gasification can potentially be used both in FC and ICE-vehicles.
Iron & Steel	95-98 %	2-6	20-51	Sponge iron can be produced via direct reduction of iron ore using hydrogen (DRI). Lower purity hydrogen can be used, as long as the content of nitrogen, CO_2 and H_2O is kept minimal in the gas. Nitrogen should be avoided because it increases the gas volume, H_2O and CO_2 should be absent because it otherwise limits the gas utilization. Large concentrations of CO_2 and H_2O also lead to that more gas must be recirculated leading to gas- and energy losses. Hydrogen produced from biomass gasification is well suitable for the application. Lou at.al (2023) shows that carbon-negative hydrogen from biomass can potentially produce carbon-negative steel (−0.61 tCO_2/t steel to 0.39 tCO_2/t steel)
Aviation & Maritime	99.5% or higher[2]	1-10	10-74	The maritime and aviation sectors have limited options for fossil fuel replacement. In the former, methanol, ammonia and hydrogen are the ones with largest potential. Along with synthetic jet-fuels, hydrogen-based liquid fuels provide an attractive option for aviation. Both fuel cells and combustion engines are potential propulsion technologies for hydrogen powered aircraft. (International Energy Agency, 2019). The latter is in particular of interest for long-haul flights. Hydrogen produced via biomass gasification can be used in all mentioned applications. (Svensson et.al, 2024).

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[2] Lower efficiency for combustion engines

Heating	80-95%	1-9	8-46	Hydrogen can be used in many heat production applications, for example domestic hydrogen heating and cooking without emissions of CO, CO_2, and NO_x. Blending hydrogen into natural gas can be done (Habib et.al, 2024). Hydrogen produced via biomass gasification can be used in all mentioned applications.
Power	80-95%	0-2	3-16	It hardly makes any sense to first produce hydrogen via biomass gasification and then use the hydrogen to produce electricity. It is more efficient to directly use the producer gas from gasification in a gas engine or a gas turbine for power production.

The conclusion is that biomass gasification-based hydrogen could play a significant role in many different sectors and applications. In the efforts in de-fossilizing the hard-to-abate sectors, biomass gasification is of particular interest as CCS can be applied resulting in carbon-negative products, such as steel and ammonia.

Commercial developments on hydrogen production via biomass gasification

There is currently no commercial plant biomass gasification plant for hydrogen production in operation in the world. However, several commercial technology providers exist, and there is an increasing number of biomass gasification for hydrogen production projects are announced world-wide, see examples in Figure 9. In the following, a selection of ongoing activities is briefly described.

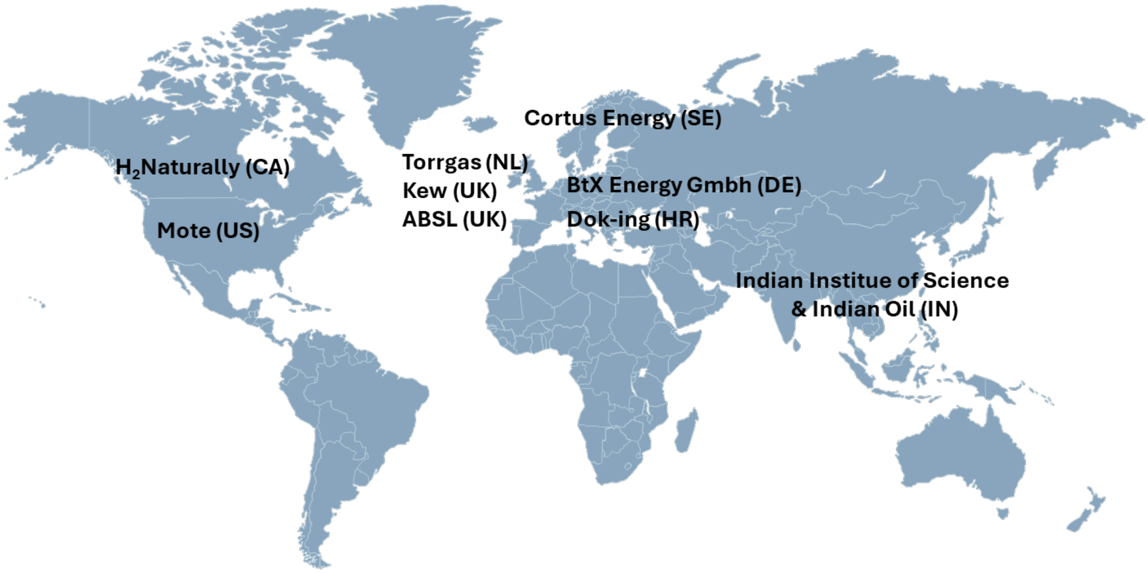

Figure 9. Examples of technology providers and projects on gasification based biohydrogen production.

Torrgas Technology BV (The Netherlands)

The Dutch company Torrgas Technology BV provides a concept for converting torrefied biomass residues in a patented two-stage gasification technology for production of biochar and a tar-free and nitrogen-free syngas for production of hydrogen (as well as other green commodities like methanol and SNG), see Figure 10. A 10 MW First-of-a-kind demonstration plant is being planned on the Brightlands Chemelot Campus in the Netherlands to produce biomethanol by gasifying torrefied biomass, based on the technology developed by Torrgas (project BrigH2).

HyCarb is a development company owned by Torrgas that presently is planning a biohydrogen plant in the north of The Netherlands with a plant capacity of 100 MWth gasification input and its own on-site torrefaction plant. The feedstock comes from residual flows such as demolition wood and prunings. The plant production capacity is approximately 15,000 tons of green hydrogen annually.

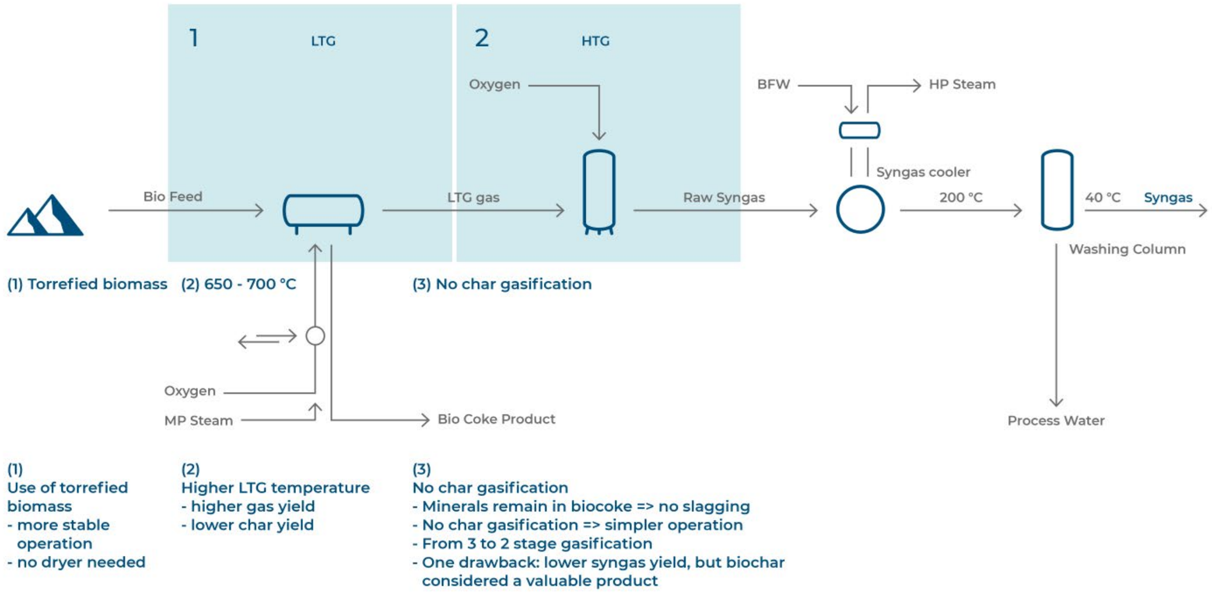

Figure 10. Overview of the Torrgas two-stage gasification system (Figure provided by Torrgas)

Mote (USA)

The US company Mote was awarded funding to deploy a first-of- a-kind (FOAK) biomass gasification facility for hydrogen production with integrated carbon capture and geological sequestration as illustrated in Figure 11. Annually, the project will process at least 300 000 tons of wood waste producing more than 20 000 tons of hydrogen and geologically sequester more than 450 000 tons of CO_2. The gasification technology is an oxygen-blown, fluidized bed. This facility is planned to produce approximately 21 000 tons per year of carbon-negative hydrogen for use in transportation and energy storage. (Mote, 2024).

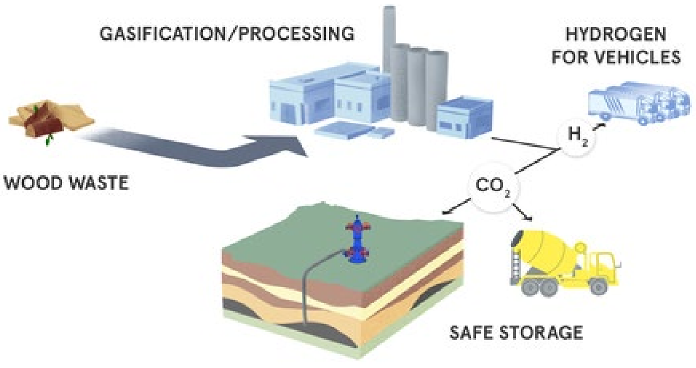

Figure 11. Mote hydrogen production concept based on biomass gasification and CCS (Mote, 2024)

Haffner Energy (France)

The French technology provider Haffner Energy has announced plans to establish three smaller scale biohydrogen producing plants in Europe, one in Gloveller in Switzerland, one in Alkmaar in the Netherlands and one in Montbélliard in France. The first two will have a production capacity of 720 kg per day of hydrogen with planned start of operation in the year 2026, while the third plant in France may become a bit larger, aiming at above 1000 kg of hydrogen per day and with a planned start-up in the beginning of 2027. (Nait Saidi, 2024). Figure 12 shows their so-called Hypergas® Module used for gas upgrading.

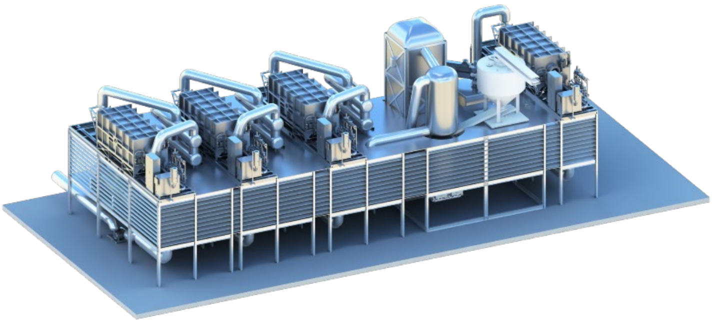

Figure 12 The Hypergas® Module provided by Haffner Energy (Illustration from Haffner Energy, 2024)

Cortus Energy (Sweden)

The Swedish company Cortus Energy AB is the owner of the patented WoodRoll® gasification technology that converts low-grade biomass to ultra clean syngas with a high concentration of hydrogen (about 55 – 60 %). The technology is demonstrated in the 6 MW WoodRoll® plant, where the produced syngas is used to replace fossil natural gas at the Höganäs steel plant.

To maximize the hydrogen yield, a dual hydrogen separation process is foreseen to be used. In the first PSA stage, the hydrogen is separated from the original syngas stream, while in the second PSA extracts hydrogen after the tail-gas from the first PSA has been subject to further hydrogen generation via water-gas shift of the remaining CO in the gas.

Indian Institute of Science (IISc) & Indian Oil Ltd (India)

IISc has in collaboration with Indian Oil Ltd demonstrated the production of fuel-cell quality biohydrogen produced in a small-scale woody-biomass gasifier and Vacuum Pressure Swing Absorption (vPSA). The production capacity is 5 kg of hydrogen per hour and an average yield of 100-105 g hydrogen per dry kg biomass was reported. The hydrogen recovery in the vPSA was in the range of 70-72 %. The fuel-cell system was operated in more than 250 hours using the produced biohydrogen. A scaled-up plant to 2 tons of hydrogen per day is planned at one of the Indian Oil refineries (Mohana & Badhe, 2024)

H_2Naturally (Canada)

The Canadian company H_2Naturally (H_2N) plans to build three gasification-based bio-hydrogen plants with CCS in British Columbia, Canada. They have chosen CFB gasifiers from SunGas Renewables as gasification technology, which is as previously mentioned based on GTI's U-Gas® technology. For the syngas upgrading, H_2N are using conventional water gas shift catalyst and amine absorption. (Couillard, 2024).

KEW (United Kingdom)

KEW develops a pressurised fluidised bed gasification unit, which can utilise a wide variety of non-recyclable waste and low-grade biomass feedstocks. By KEW's proprietary process, the Equilibrium Approach Reformer (EAR), the system produces a clean, hydrogen-rich synthesis gas. The reformed synthesis gas is then further upgraded through water-gas shift (WGS) conversion to hydrogen for industrial use (as a replacement for fossil derived hydrogen or natural gas) with the CO_2 selectively removed from the syngas stream via pre-combustion capture. The removed CO_2 will be liquefied and purified before being transported to the nearest pipeline or utilised in the production of concrete or building materials.

The hydrogen can be further purified (e.g. using Pressure Swing Adsorption: PSA) to meet the specification required for fuel-cell / transport applications. KEW has constructed, commissioned and is now operating a commercial scale, advanced gasification plant in the West Midlands, UK to demonstrate CO_2 capture and sequestration via the production of hydrogen from biomass and waste feedstocks (Kew, 2024).

Advanced Biofuel Solutions Ltd (United Kingdom)

The ABSL gasification plant in Swindon, UK, converts household waste into bio-substitute natural gas (BioSNG) that is injected into the local gas grid. In this plant, a slipstream of syngas was taken after the WGS and further purified in a PSA (Xebec) to meet the specification for proton electron membrane (PEM) fuel cells (Blanco-Sanchez, 2023).

Indeloop (Croatia)

The Croatian company Indeloop Ltd.has developed their own gasification concept, Looper. Looper is a thermal gasification plant converting organic material, such as non-recyclable plastics, sludge and textiles, into hydrogen and carbon black. Indeloop Ltd. has two testing systems located at the company's headquarters in Zagreb. These systems can process 1-2 tons of organic material per day, respectively.

The concept is a three-stage process: thermal conversion, cleaning and cooling, and hydrogen upgrading. In the first stage, the feedstock is gasified in a reactor to produce synthesis gas and carbon black. The syngas is further processed to maximize the hydrogen content, while the carbon black is removed from the system. The hot syngas is then cooled and cleaned before entering the final stage where a portion is used to fuel the system and the remainder is separated into pure hydrogen using a Pressure Swing Adsorption (PSA) unit. While the exact hydrogen output depends on the input material and system settings, tests have shown an average yield of 40 kilograms of hydrogen per ton of organic material processed. Figure 13 shows an illustration of the Looper gasification process.

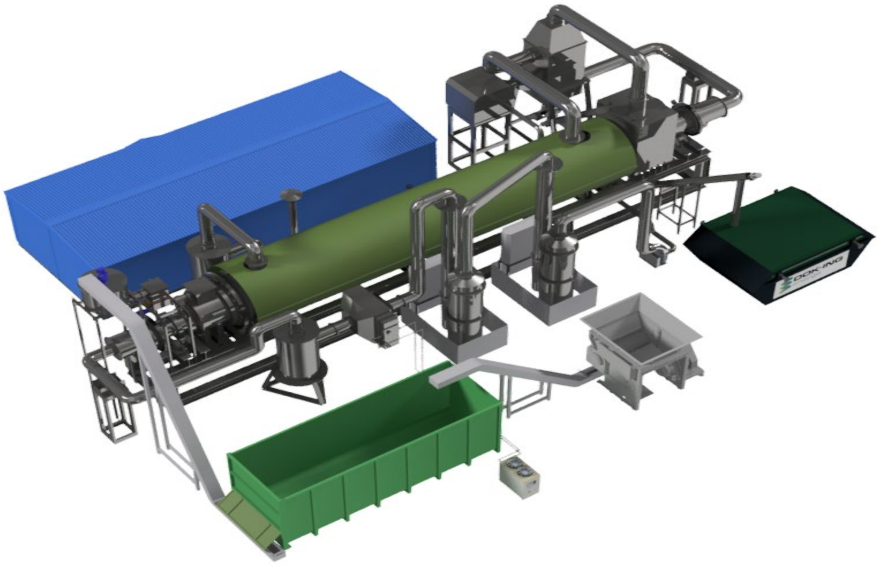

Figure 13. Illustration of the Looper gasification process developed by the Croatian company Indeloop Ltd.

BtX energy GmbH (Germany)

In a joint project in between A.H.T. Syngas Technology N.V. and BtX energy GmbH, a container system for decentralized production of hydrogen from pelletized biogenic residues will be developed, see Figure 14.

Figure 14. Picture of the BtX Energy test facility (https://btx-energy.de/projekte/bidrogen/)

The project is based on the gasification technology provided by BtX energy and the technology of Ferro-Hy-Tunnel (FHT) for the separation of pure hydrogen from mixed gases. The latter has been tested in laboratory scale (see Figure 15) but has not yet been applied in larger scale.

The project aims to maximise the hydrogen yield with a high purity from pelletised waste wood. Depending on the gas quality, one kilogram of pure hydrogen can then be obtained from 12 – 15 kg of wood. The project has a total budget of €630,800 (BtX energy, 2024).

Concluding discussion

Low-emission hydrogen will play an increasingly important role in the transition to a fossil-free society and the demand is predicted to develop exponentially by the year 2050. It is generally anticipated that most of the low emission hydrogen will be produced by water electrolysis using fossil-free power. However, there are several other sustainable production pathways that can serve as complementary to electrolysis. Biomass gasification is one of these technologies and in this report, the current technology status including techno-economic opportunities and challenges, future potential role, and the need of further development are discussed.

Technical performance: The hydrogen yield is generally considered high for thermochemical processes like gasification, pyrolysis, and reforming, producing in the range of 40-190 kg hydrogen per ton of biogenic feedstock. The energy efficiency varies depending on process design amongst other things but is normally in the span of 40-70% (based on the lower heating value). An approximate estimation used in this report is that for every ton of dry biomass gasified, about 100 kg of hydrogen can be produced per ton dry biomass.

Biomass gasification technologies in general have a high level of technology maturity. The technology is for example commercially applied in combined heat and power production and for industrial fossil gas replacement in wide capacity ranges. In this report, each of the individual sub-processes for producing hydrogen via biomass gasification were assessed resulting in ” weighted” average” TRL of 6-7. A number of hydrogen production tests are reported in pilot-scale or using slip-streams, but integrated production of hydrogen in demonstration scale still remains leading to a ”weakest” link TRL of 5. It can be concluded that there is a high level of process understanding of all included sub-processes, but that integrated operation in industrially relevant scale is needed and should be the next step in the development.

Production of high purity hydrogen of fuel cell quality via biomass gasification in lab or pilot scale has been showed possible by several commercial and research actors. However, there will be an increasing demand also for lower purities hydrogen as well, both industrial grade purity hydrogen (95-98%) for chemicals, iron- and steel making etc. and for lower grade hydrogen (80-95%) for example for cooking and heating. These applications provide a significant opportunity for hydrogen based on biomass gasification.

It is however noted that the existing ISO standards for hydrogen purity are mainly based on hydrogen produced via water electrolysis and steam methane reforming. Hydrogen produced via biomass gasification (and other emerging biogenic hydrogen production technologies) may include impurities which are not, or not sufficiently, covered in these ISO standards. More research is therefore needed to increase the knowledge on potential impurities and assessing their effects on for example fuel cells.

Economic performance: In this report, it is assessed that the current production cost of hydrogen produced via large-scale biomass gasification (200 MW_{th}) would be approximately 4 € per kg hydrogen at a biomass feedstock price of 20 € per MWh.

The developments in technologies for CCU and CCS are likely to lead to that the capital costs of CO_2-separation are pushed down and that the technologies can be applied on smaller scales. This is favourable for gasification processes, which previously have been one of the primary drivers of the CO_2-separation technology development. Any progress made in CCU and CCS thus means more competitive gasification systems. In addition, with anticipated future reductions in capital and operating costs in the range of 10-20% (Brown et.al, 2020), resulting from a combination of technological learning effects, as well as efficiency improvements, the production cost can reduce to below 3 € per kg hydrogen for the same biomass price.

If it is furthermore assumed that the separated CO_2-stream can result in a net credit of 50 € per ton CO_2, the hydrogen production cost reduces to in between 2.2 to 3.5 € per kg hydrogen at a biomass price of 20 € per MWh.

It can therefore be concluded that biomass gasification-based hydrogen is, with the current price levels of fossil methane, competitive against SMR-based hydrogen. Comparing to the future foreseen production cost of renewable hydrogen produced via solar- and wind-based electrolysis, it is noted that biomass gasification-based hydrogen is also competitive in many world regions.

Greenhouse gas emissions: It is highly likely that negative carbon emissions will be essential to reach climate targets. Hydrogen produced via biomass gasification is one of very few low emission hydrogen production pathways that can result in negative emissions. As the CO_2 separation process is an integral part of the gasification system, CCS can be applied. LCA-studies show that combined with CCS, the greenhouse gas emission for hydrogen produced via biomass gasification may be as low as in the range of -15 to -22 kg CO_{2eq} per kg hydrogen.

It should however be noted that it makes no sense to use the separated CO_2 (i.e., CCU) by adding H_2 to make PtX-products (electrofuels like methanol, SAF etc). This is due to that it is likely less expensive and more efficient to convert the biomass-based synthesis gas directly to the desired product.

Research & Development needs: This report concludes that biomass gasification is economical and environmentally beneficial technology well suited for producing climate-positive hydrogen (i.e. negative carbon emissions). However,

- Even if the main sub-processes of the conversion have a high technological maturity, there is a need to demonstrate integrated operation of the complete production chain in relevant scale.
- More research is required to increase the knowledge on potential impurities, trace elements and their possible effects on for example fuel cells. This could serve as valuable inputs to updated ISO standards where biomass gasification-based hydrogen should be included.
- An increased understanding on the hydrogen production cost as a function of the desired hydrogen purity would be valuable as a large demand for non-fuel cell quality of hydrogen is foreseen.

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