European Biogas Association

# Decarbonising Europe's hydrogen production with biohydrogen

## The role of sustainable biohydrogen in the total energy mix

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# Executive summary

The European Biogas Association (EBA), in collaboration with biogas experts, has compiled this paper to outline the important role of biohydrogen, as a complement to biogas and biomethane, in ensuring the sustainability, affordability and accessibility of green gases in Europe. Insights are provided as to the place of biohydrogen within total hydrogen production (*Chapter 1*), the technologies available to produce biohydrogen (*Chapter 2*), the ways in which biohydrogen contributes to the decarbonising of Europe's hydrogen production (*Chapter 3*), the economics of biohydrogen production (*Chapter 4*) and the readiness of the markets to facilitate its commercialisation (*Chapter 5*). Taking into consideration the current policy context as well as the technical background, the paper concludes by making recommendations for an EU regulatory framework to support the production and use of biohydrogen (*Chapter 6*).

Hydrogen as an element can be produced from biological and non-biological sources. There are a number of production pathways for hydrogen; these are categorised by colour according to the feedstocks, power source and technique used in the production process (*Chapter 1*). Biohydrogen refers to the hydrogen obtained from biogenic sources (for instance biogases and biomass). It can be produced via a range of production technologies. Dark fermentation, photofermentation and bio-photolysis are examples of the biological processes which can be used; thermochemical processes include gasification, (bio)methane/biogas steam reforming (BMSR) and pyrolysis. Microbial electrolysis (ME) is one example of a bioelectrochemical process. In terms of practicability and energy efficiency, each method has its own set of pros and cons[1] (*Chapter 2*).

One of the main challenges facing the hydrogen sector is to decarbonise its production. Over 95% of European hydrogen production capacity in 2020 was derived from fossil fuels[2]. Compared to grey hydrogen (see table 1 for a breakdown of the colour categories), the share of green and blue hydrogen produced is still small: in 2020 it comprised less than 1% of production in the EU[2]. The carbon footprints of the different types of hydrogen vary, ranging from –26.5 to 20.0 kg $CO_2$/ kg $H_2$.

*Unlike its counterparts, biohydrogen can be carbon negative if, for example, it is combined with carbon dioxide capture and storage (CCS) or obtained from feedstocks such as wastes and manure.*

As a result, the carbon footprint of biohydrogen ranges from -26.5 to 10.8 kg $CO_2$/ kg $H_2$ whereas the carbon footprint of grey hydrogen ranges from 10 to 20 kg $CO_2$/ kg $H_2$ (*Chapter 3*).

According to the International Energy Agency (IEA)[3], producing hydrogen from fossil fuels is currently the lowest-cost option (EUR 0.46-1.8/kg $H_2$). Hydrogen production from electrolysis, using green electricity (wind, solar) is much costlier in most places, at EUR 2.51-11.94/kg $H_2$. The renewable electricity costs can make up 50-90% of total production expenses. Biohydrogen can be obtained at a cost ranging from EUR 1.15 to EUR 9.65/kg $H_2$), making it considerably cheaper than hydrogen from electrolysis *(Chapter 4)*.

[1] Balachandar, G., Khanna, N., & Das, D., (2013). Biohydrogen Production from Organic Wastes by Dark Fermentation. In A. Pandey, J.-S. Chang, P. C. Hallenbecka, & C. Larroche (Eds), *Biohydrogen* (1st ed, pp.103-144). Elsevier B.V. https://doi.org/10.1016/B978-0-444-59555-3.00006-4
[2] Gas for Climate. (December 2020). *Market state and trends in renewable and low-carbon gases in Europe. A Gas for Climate report.* Guidehouse Netherlands B. V. https://gasforclimate2050. eu/wp-content/uploads/2020/12/Gas-for-Climate-Market-State-and-Trends-report-2020.pdf.
[3] International Energy Agency. (2021). *Global Hydrogen Review 2021.* https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

Because of the unique ability of biohydrogen to remove carbon from the atmosphere, it is well placed to help sectors with limited decarbonisation options achieve carbon neutrality by compensating for hard-to-eliminate residual emissions. Examples of sectors that can benefit hugely from biohydrogen production are the iron and steel industry, the chemical industry and ethylene synthesis. At the same time, biogas producers are keen to diversify their outputs and further increase the flexibility of anaerobic digestion plants (*Chapter 5*).

As the European Union moves toward the establishment of a single market for energy, it is at a critical point in the development of laws governing the future of biohydrogen. Biohydrogen is an innovative product and the regulatory framework has not yet fully adapted to allow it to reach commercial maturity. An enabling EU regulatory framework can be achieved by enforcing legal and market recognition, driving market access via consumption targets, using taxation to send a price signal in support of renewable sources of hydrogen, and facilitating network access (*Chapter 6*).

# Policy context

The European Union has been developing a policy framework for hydrogen since 2018. Meanwhile, more and more Member States have established their own official hydrogen strategy. The sector was further strengthened in 2022 when the REPowerEU Plan anticipated an acceleration of investment in hydrogen production capacity.

In the European Commission's long-term climate vision, published in November 2018, the share of hydrogen in the EU's energy mix is projected to grow from less than 2%[4] to reach 13-14% by 2050[5]. As part of the European Green Deal, the European Commission released the Energy System Integration Strategy[6], along with a dedicated Hydrogen Strategy[7], in July 2020. It confirmed the role of hydrogen as an energy carrier in the effort to reach climate neutrality by 2050. Hydrogen is seen as a vector for the storage of electricity from intermittent renewable sources, as well as 'for connecting production locations to more distant demand centres'[8]. An additional aim is to use hydrogen to replace fossil fuel in some carbon intensive industrial processes and, to some extent, in heavy-duty transport modes[9].

The Hydrogen Strategy set **a target of 10 million tonnes of renewable hydrogen production per year by 2030** (equivalent to 333 TWh/year), while considering the possibility of importing the same quantity. The strategy outlined 5 areas of action: investment support; production and demand support; creating a hydrogen market and infrastructure; research and cooperation; and international cooperation. The European Commission has since worked towards delivering on these areas via legislative proposals, such as the reform of the gas market rules[10], as well as executive[11] and political actions[12].

**Alongside the actions of the European Commission, more and more European governments have adopted their own hydrogen strategy since 2020.** Germany, France and Spain are among them. Renewable hydrogen targets in these countries as well as in Portugal and the Netherlands already make up more than 50% of the EU's overall target of 40 GW of installed electrolyser capacity by 2030[13].

The energy response of the European Commission to the outbreak of war in Ukraine – **the REPowerEU Plan** – gave greater importance to hydrogen in the future energy mix of the European Union. Outlined in a Communication of March 2022[14], then fully published in May 2022, the REPowerEU Plan and its package of proposals aim to disentangle the European Union from its dependence on Russian fossil fuels by 2027[15]. The plan is structured around three key areas of action: diversification of energy sources, acceleration of the clean energy transition and increase of energy savings. It underlines the need for urgent regulatory reforms and accelerated investment into renewable electricity sources, hydrogen and biomethane.

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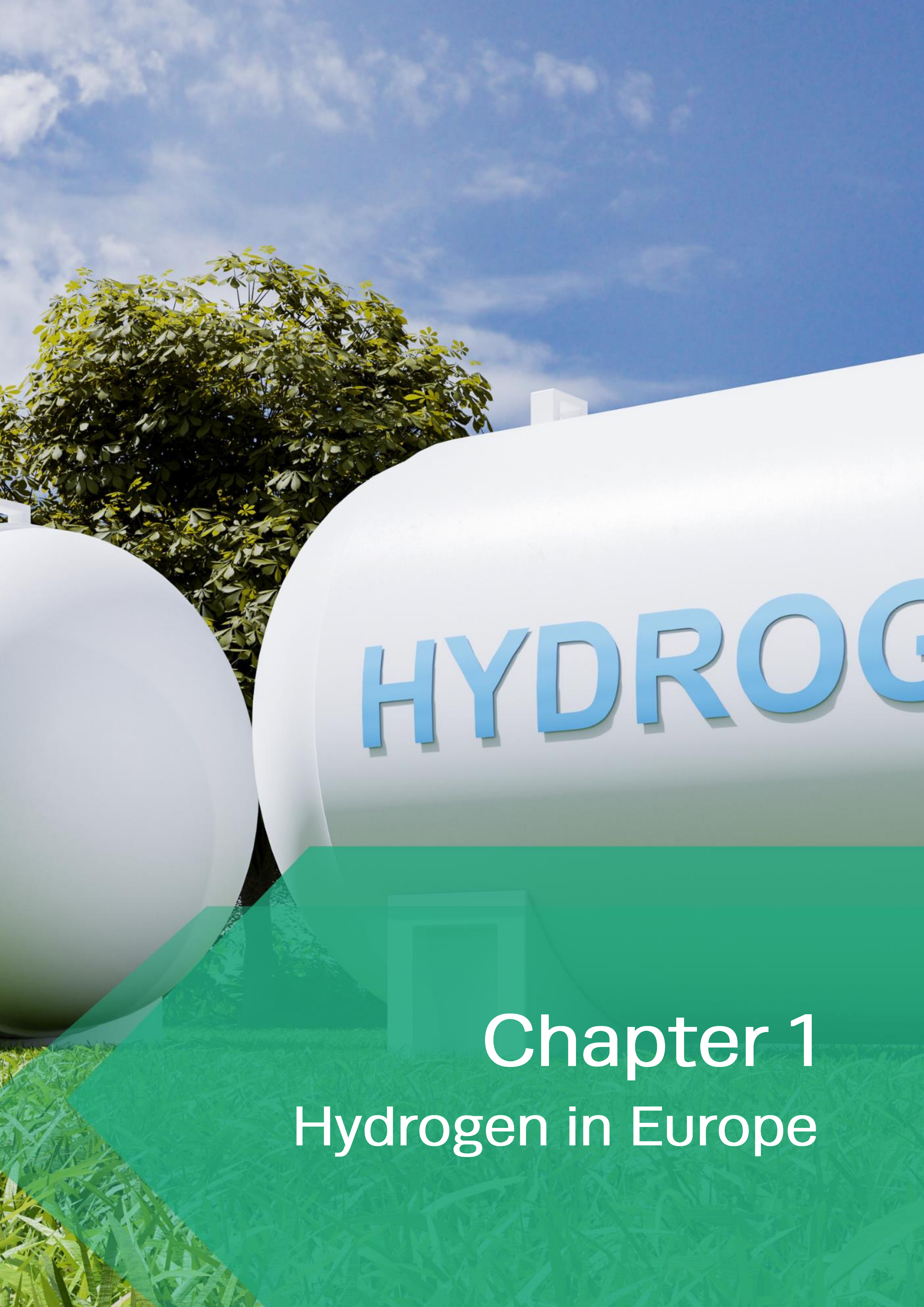
[4] Fuel Cells and Hydrogen 2 Joint Undertaking. (2019). *Hydrogen Roadmap Europe – A sustainable pathway for the European Energy Transition*. Publications Office of the European Union. https://data.europa.eu/doi/10.2843/341510 This includes the use of hydrogen as feedstock.
[5] European Commission. (28 November 2018). *A Clean Planet for All. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. COM(2018) 773 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0773. 96% of this hydrogen was produced with natural gas.
[6] European Commission. (8 July 2020). Powering a climate-neutral economy: An EU strategy for Energy System Integration. COM(2020) 299 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0299
[7] European Commission. (8 July 2020b). *A hydrogen strategy for a climate-neutral Europe*. COM(2020) 301 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
[8] European Commission. (8 July 2020b), p. 1.
[9] See also article 39 in European Parliament resolution of 19 May 2021 on a European Strategy for Hydrogen. (2020/2242(INI)). CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021IP0241, and articles 2..4, 2.5 and 2.7 in European Council. (11 December 2020). Council Conclusions "Towards a hydrogen market for Europe". https://www.consilium.europa.eu/media/47373/st13976-en20.pdf
[10] See the Commission's proposals on a revision of the Gas Directive: EUR-Lex - 52021PC0803 - EN - EUR-Lex (europa.eu); on the revision of the Gas Regulation: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0804&qid=1644485351703
[11] For example, the Horizon 2020 Framework Programme call to 'develop and demonstrate a 100W electrolyser upscaling the link between renewables and commercial/industrial applications', which was launched in September 2020. https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/lc-gd-2-2-2020
[12] For instance, the establishment of the European Clean Hydrogen Alliance and the issuing of a Joint Communication with hydrogen production as a new strategic priority: European Commission. (2021). *Renewed partnership with the Southern Neighbourhood: A new Agenda for the Mediterranean*. JOIN(2021) 2 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=JOIN:2021:2:FIN
[13] Patel, Sonal. (1 February 2021). Countries Roll Out Green Hydrogen Strategies, Electrolyzer Targets. Power: News & Technology for the Global Energy Industry. https://www.powermag.com/countries-roll-out-green-hydrogen-strategies-electrolyzer-targets/
[14] European Commission. (8 March 2022). *REPowerEU: Joint European Action for more affordable, secure and sustainable energy*. COM(2022) 108 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0108
[15] European Commission. (18 May 2022a). *REPowerEU Plan*. COM(2022) 230 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022DC0230

The REPowerEU Plan identifies a shortfall of **14 million tonnes of renewable hydrogen** that would be needed in order to achieve its objective, in addition to the 10 million tonnes foreseen in the 2020 Hydrogen Strategy. Of these 14 million tonnes, 4 million would come from additional domestic production.[16] Renewable hydrogen, ammonia and other derivatives would 'greatly reduce the EU's dependence on natural gas (by approximately 27 bcm), oil (by approximately 3.9 Mtoe) and coking coal imports (by approximately 156 Kt) from Russia'[17]. Substitution would initially take place in refineries, steelmaking and heavy-duty road transport. Although the European Commission makes plans based on the use of 'renewable hydrogen', it generally restricts the concept to hydrogen from renewable electricity sources and its derivatives, i.e. 'renewable fuels of non-biological origin' (RFNBO). In order to implement the REPowerEU Plan, the Commission thus identifies the need for 'further additional investments in renewable energy production requiring around 500 TWh of additional power generation in 2030'.[18]

The European Union as a whole now faces the challenge of mobilising the necessary finance to set up the desired electrolyser capacity and import corridors, while preparing and implementing European regulations to unlock the emergence of the hydrogen market.

*As the European Union moves toward the establishment of a single market for energy, it is at a critical point in the development of laws governing the future of biohydrogen.*

[16] European Commission. (18 May 2022a), Annex I.
[17] European Commission. (18 May 2022b). *Implementing the REPowerEU Action Plan: Investment needs, hydrogen accelerator and achieving the bio-methane targets*. SWD(2022) 230 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52022SC0230
[18] European Commission. (18 May 2022b).




# Chapter 1

## Hydrogen in Europe

## 1.1. Introduction

The European Union aims to fully decarbonise its economy, requiring a complete overhaul of the energy system and its infrastructure by 2050[19]. Since the announcement of the European Green Deal in December 2019, a wide range of plans have been put forward to augment climate mitigation policies. A decarbonised Europe will be jointly based on the production of renewable electricity and deployment of green molecules to transport, store and supply all sectors with renewable energy at the lowest possible cost.

The plans to fully decarbonise the EU energy system, in conjunction with and the current energy crisis, will change the demand for gas in the near future. Natural gas demand, reported at 412 bcm in 2021[20], is expected to decrease to an estimated 271 bcm by 2050[21]. By then, two major renewable gases will be capable of meeting this remaining gas demand: biomethane and green hydrogen. These sustainable gases can be used for almost all energy end-uses and can ensure security of supply.

Green hydrogen produced via electrolysis using green electricity is still expensive and scarce today. Although it will become more readily available in the future, not all locations will have access to it at an acceptable price. Locally produced biohydrogen, a type of green hydrogen derived or produced from biogenic sources, will therefore have a clear role to play.

## 1.2. Different types of hydrogen

Hydrogen as an element can be produced from biological and non-biological sources. There are several production pathways for hydrogen; these are categorised with colours according to the nature of the generation process. Table 1 sets out the different categories of hydrogen together with their feedstock, the energy source used during their production process, and the products obtained.

*Biohydrogen refers to hydrogen obtained from biogenic sources (for example, biogases and biomass) using a variety of technologies.*

[19] Gas for Climate. (April 2020). *Gas Decarbonisation Pathways 2020-2050*. Guidehouse. https://gasforclimate2050.eu/wp-content/uploads/2020/04/Gas-for-Climate-Gas-Decarbonisation-Pathways-2020-2050.pdf
[20] European Commission. (2022) *Quarterly report on European gas markets – with focus on 2021, an extraordinary year on the European and global gas markets* (Vol.14, Issue 4). https://energy.ec.europa.eu/system/files/2022-04/Quarterly%20report%20on%20European%20gas%20markets_Q4%202021.pdf
[21] Gas for Climate (April 2020). The report anticipates that gas demand will reach 2,880 TWh (equal to 271 bcm) by 2050.

<table>
<tr><th colspan="7">Table 1. Concept map of hydrogen categories and production pathways</th></tr>
<tr><th colspan="2">Type of hydrogen</th><th>Feedstock</th><th>Energy source</th><th>Process</th><th>Products</th><th>Comment</th></tr>
<tr><td colspan="2">Brown/Black</td><td>Coal or lignite</td><td>Coal</td><td>SMR in combination with gasification</td><td>$H_2$ + CO + $CO_2$ (released)</td><td>Established process used in industries that convert organic or fossil-based carbon materials into CO, $H_2$, and $CO_2$.</td></tr>
<tr><td colspan="2">White</td><td colspan="3">Naturally occurring</td><td>$H_2$</td><td>Naturally occurring geological hydrogen, found in underground deposits and created through fracking.</td></tr>
<tr><td colspan="2">Grey</td><td>Natural Gas</td><td>Natural Gas</td><td>SMR</td><td>$H_2$ + $CO_2$ (released)</td><td>Sources are derived from fossil fuels. Grey hydrogen is currently the most common form of $H_2$ production, in which the hydrogen is created from natural gas (methane), using SMR, with no GHG capture process.</td></tr>
<tr><td colspan="2">Blue</td><td>Natural Gas</td><td>Natural Gas</td><td>SMR</td><td>$H_2$ + $CO_2$ (% captured and stored)</td><td>Produced mainly from natural gas, using SMR technology. $CO_2$ obtained as co-product, is captured using CCS technology.</td></tr>
<tr><td colspan="2">Turquoise</td><td>Natural Gas</td><td>Natural Gas</td><td>Pyrolysis</td><td>$H_2$ + C (solid)</td><td>Uses methane pyrolysis to produce $H_2$ and carbon materials.</td></tr>
<tr><td colspan="2">Red</td><td>Water</td><td>Nuclear Power</td><td>Catalytic splitting</td><td>$H_2$ + $O_2$</td><td>Generated through catalytic splitting powered by nuclear energy.</td></tr>
<tr><td colspan="2">Purple/Pink</td><td>Water</td><td>Nuclear Power</td><td>Electrolysis</td><td>$H_2$ + $O_2$</td><td>Generated through electrolysis powered by nuclear energy.</td></tr>
<tr><td rowspan="2">Green</td><td>RFNBO (non-biological origin)</td><td>Water</td><td>Renewable electricity</td><td>Water splitting processes (thermolysis, photolysis, electrolysis)</td><td>$H_2$ + $O_2$</td><td>The best known green $H_2$ is obtained via electrolysis of water using clean electricity from surplus renewable energy sources, such as solar or wind power.</td></tr>
<tr><td>Bio-hydrogen (biological origin)</td><td>Biogenic sources (biomass, Biogas, Biomethane</td><td>Biomass derived energy[22]</td><td>Biological, thermochemical and bioelectrochemical (See Chapter 2)</td><td>$H_2$ + biogenic $CO_2$ + co-product (digestate, C, biochar, others)</td><td>Can be C negative when combined with CCS or when obtained from feedstocks such as wastes and manure. Low electricity needs.</td></tr>
</table>

*SMR: steam methane reforming; CSS: carbon capture and storage; RFNBO: renewable fuels of non-biological origin. Adapted from Sustainable NI (2022).*

[22] Energy contained in biohydrogen is derived from biomass, but renewable electricity can be used to drive the process.

Almost all hydrogen in Europe currently derives from grey hydrogen production routes. Green and blue hydrogen production routes are in the early stages of commercialisation. In the EU, around 379 TWhLHV (11.4 Mt $H_2$, 37 bcm natural gas equivalent) of hydrogen was produced in 2020[23]. In the same year, over 95% of European hydrogen production capacity was from fossil fuels[24]. The share of green and blue hydrogen produced is still small in comparison, accounting for less than 1% of production in the EU[25].

As shown in table 1, green hydrogen is derived from two main production routes: renewable fuels of non-biological origin (RFNBO), and biohydrogen produced from biogenic feedstocks such as biomass, biogas and biomethane. This paper focuses on the production of green hydrogen of biological origin, such as biohydrogen from biogas and biomethane, as well as the co-products originating from its production such as digestate, carbon materials and biochar. It highlights the unique technical and environmental benefits of biohydrogen. Most significantly, unlike other types of hydrogen, biohydrogen can be carbon negative, if, for example, its production is combined with CCS or it is obtained from feedstocks such as wastes and manure.

## 1.3. Biohydrogen definition

**Biohydrogen refers to hydrogen obtained from biogenic sources (for example, biogases and biomass) using a variety of technologies, including biological, thermochemical and bioelectrochemical processes.**

A general overview of the different production processes for biohydrogen can be found in section 2.3, with a further detailed description in the Annex to this paper.

## 1.4. Energy system integration with biohydrogen

Flexibility – in the form of flexible operations and power generation, stronger grids, more energy storage, and demand response – is paramount in enabling the transition to a power system dominated by renewables, which will include increasing quotas of variable sources providing fluctuating levels of electricity.

Enabling and encouraging different energy sectors to work together optimises the function of the energy system as a whole: it is more effective than decarbonising and making separate efficiency gains in each sector individually.

The fastest and most cost-efficient way in which to decarbonise the EU economy is the simultaneous deployment of complementary energy solutions. Although the electrification of end uses offers a partial route towards decarbonisation, heat accounts for half of EU energy consumption and transport emissions are on the rise. In most cases, the combination of electricity with gas decarbonisation technologies yields the most cost-effective results.

In rural areas where there could be a future need for hydrogen, biohydrogen can be produced from raw biogas or biomethane to provide a local source of green energy. This approach lowers costs for remote locations, as the expense associated with hydrogen transport is avoided. At the same time, recent innovation aims to increase the methane yield at anaerobic digestion plants by combining hydrogen with raw biogas. The carbon dioxide present in the biogas will then combine with hydrogen to form additional biomethane.

[23] Allsop, A., & Bortolotti, M. (Eds). (2022). *Clean Hydrogen Monitor 2022*. Hydrogen Europe. https://hydrogeneurope.eu/clean-hydrogen-monitor-2022/
[24] Allsop & Bortolotti (2022)
[25] Gas for Climate (December 2020)

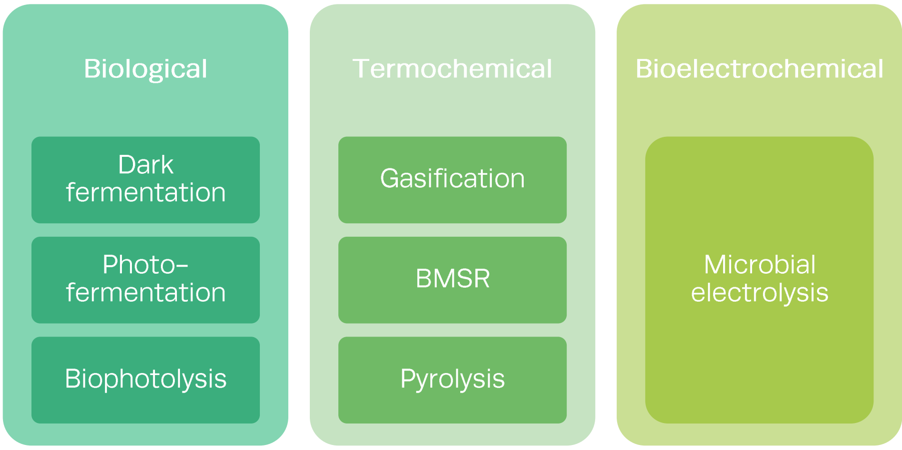
# Chapter 2
## Biohydrogen production technologies

## 2.1. Overview of biohydrogen production technologies

Biohydrogen generation from biomass, biogas and biomethane has attracted increased interest because of its high yields and long-term sustainability, as well as its low energy consumption. There are a number of technologies available to produce biohydrogen (Figure 1). Dark fermentation, photofermentation and biophotolysis are examples of biological processes. Thermochemical processes include gasification, biomethane/biogas steam reforming (BMSR) and pyrolysis. Microbial electrolysis (ME) is an example of a bioelectrochemical process.

Each method has its own set of pros and cons in terms of practicality and energy efficiency[26]. The different technologies for biohydrogen production are set out in Figure 1 below.

**Figure 1.** Overview of biohydrogen production technologies




### 2.1.1. Biological processes

#### Dark Fermentation

During dark fermentation, microorganisms generate hydrogen, biogenic carbon dioxide, organic acids, and alcohols from biomass, under anaerobic conditions. The metabolic stages of dark fermentation include hydrolysis, acidogenesis and acetogenesis. These three steps are identical to the biogas production process but, in dark fermentation, the methanogenesis stage (the fourth step in the biogas production process), is prevented. Hydrogen and carbon dioxide are therefore mainly produced during acido- and acetogenesis. Suitable operational conditions (temperature, pH, hydraulic retention time, etc.) should be maintained to maximise hydrogen production according to the specific substrate[27]. Different organic materials can be digested during dark fermentation, including agricultural waste, residues and sewage sludge.

Dark fermentation is an alternative biohydrogen technology that is still under development (with a technology readiness level (TRL) of 3-4): it requires a greater level of maturity for market prices to be established. Current projects that aim to demonstrate the use of dark fermentation in an industrially relevant environment are described in section 2.3.

#### Biophotolysis and Photofermentation

Biophotolysis includes all hydrogen production by photosynthesis under aerobic conditions. In principle, all photosynthetically active algae and cyanobacteria can produce hydrogen[28]. Two variants of biophotolysis exist today: direct and indirect biophotolysis. During direct biophotolysis,

[26] Balachandar et al (2013).
[27] Pan, J., Zhang, R., El-Mashad, H. M., Sun, H., & Ying, Y. (December 2008). Effect of food to microorganism ratio on biohydrogen production from food waste via anaerobic fermentation. *International Journal of Hydrogen Energy*, *33*(23), 6968-6975. https://doi.org/10.1016/j.ijhydene.2008.07.130
[28] McKinlay, J. B., & Harwood, C. S. (June 2010). Carbon dioxide fixation as a central redox cofactor recycling mechanism in bacteria. *Proceedings of the National Academy of Sciences*, *107*(26), 11669-11675. https://doi.org/10.1073/pnas.1006175107

the transfer of excess electrons to protons occurs directly during light irradiation. During indirect biophotolysis, the electrons are first used for the biosynthesis of hydrocarbons (starch, glycogen) and only converted to hydrogen in a subsequent step.

Photofermenation in purple non-sulfur bacteria that perform a specific variation of photosynthesis under anaerobic conditions is also considered a biohydrogen production technology. These bacteria need organic substrates and light to grow and produce hydrogen.

Both biophotolysis and photofermentation are able to provide valuable co-products such as omega-3 fatty acids, carotenoids and terpenoids, which are suitable for the food and pharmaceutical industries. Despite intensive study and development in recent decades, biophotolysis and photofermenation are still at the stage of application-oriented basic research.

### 2.1.2. Thermochemical processes

The three most prominent thermochemical conversion routes are gasification, pyrolysis and biomethane/biogas steam reforming. All of these processes, when using bioenergy or sustainable biomass feedstocks and twinned with carbon capture and storage (CCS) technologies, are capable of delivering substantial net removals of carbon dioxide from the atmosphere.

#### Gasification

Gasification is a versatile technology that converts biomass and other solid wastes into a gas (named syngas) at high temperatures (800 – 1,200 °C). The presence of oxygen or steam as oxidising agents is limited, preventing complete combustion to carbon dioxide and water. Although syngas is the main product, other solid and liquid by-products are also generated (namely biochar and tars after gas condensation). Gasification processes may be conducted in different reactor configurations and generate distinct compositions of syngas, which is made up of varying proportions of carbon monoxide, hydrogen, carbon dioxide, methane and traces of lighter hydrocarbons.
Residual lignocellulosic biomass and the biogenic fraction of waste are both useful feedstocks for the production of biohydrogen via gasification. Residual biomass is derived from forestry, agriculture (e.g. cereal straw, corn stover, pruning), agro-industry (e.g. dried fruit shells, olive pomace, citrus pulp), and wood processing, as well as waste streams from other processes.

Syngas cleaning and upgrading processes (including water-gas shift and pressure swing adsorption) are currently well-developed: they use proven technologies, which are available on the open market. The integration of gasification technology with established gas conditioning operations needs to be further advanced, however, in order to consolidate gasification as a sustainable technology for biohydrogen production.

#### Pyrolysis

Biomass pyrolysis, like gasification, is a thermal process for converting biomass into other energy-carrying products. Whereas in gasification, the main energy product is syngas, pyrolysis generates combustible liquids as well as gas. Both the liquid and the gas have a high potential to produce biohydrogen. A solid fraction (biochar) is produced as a co-product. The technology is currently in the demonstration phase, although it is approaching readiness for commercialisation[29].

Pyrolysis is a seemingly simple process, involving the thermal decomposition of the biomass in the absence of oxygen, usually performed in an inert atmosphere at high temperatures (400 to 650 °C) and a pressure between 0.1 and 0.5 MPa. Operational conditions such as heating rate and solids residence time greatly affect product types and quantities. Fast pyrolysis targets liquid fuels as the desired output, whereas slow pyrolysis often targets solid biochar. Different temperatures and catalysts can drive the pyrolysis reaction in favor of hydrogen production, but the hydrogen yield is lower than that of gasification due to the absence of steam and oxygen[30]. Pyrolysis enjoys some

[29] Lou, Y., Fan, Z., Friedmann, Dr J., Corbeau, A-S., Agrawal, M., & Khatri, A. (January 2023). *The Potential Role of Biohydrogen in Creating a Net-Zero World: The Production and Applications of Carbon-Negative Hydrogen*. Columbia University Center on Global Energy Policy. https://www.energypolicy.columbia.edu/publications/the-potential-role-of-biohydrogen-in-creating-a-net-zero-world/
[30] Wang, G., Dai, Y., Yang, H., Xiong, Q., Wang, K., Zhou, J., Li, Y., & Wang, S. (16 November 2020). A Review of Recent Advances in Biomass Pyrolysis. *Energy & Fuels*, *34*(12): 15557–15578. https://doi.org/10.1021/acs.energyfuels.0c03107

advantages over gasification, including a smaller land requirement, fewer pollutant emissions, and greater flexibility of end-product type. Like gasification, however, pyrolysis faces challenges such as tar formation (10–35 percent), as well as corrosiveness and low heat stability. Moreover, the hydrogen concentration in its gaseous products is insufficient to make it a financially viable hydrogen production process.

Recent innovations, such as cold pulse pyrolysis, also comprise a range of different process conditions, including lower temperature requirements (around 200 °C). Such innovations open up the possibility of converting biomethane directly to biohydrogen. Current projects that aim to demonstrate the use of cold pulse biomethane pyrolysis are described in section 2.3.

#### Raw Biogas and Biomethane Steam Reforming (BMSR)

Steam methane reforming (SMR) is the most common industrial hydrogen production process in use[31]. The process requires high temperatures and a catalyst to facilitate the reaction of methane with steam (water) to produce hydrogen and carbon dioxide. The process is typically carried out in high-temperature reactors using top-fired reformers along with a subsequent water-gas shift process. In the reformer, methane reacts to form mostly hydrogen and carbon monoxide. The water-gas shift process follows to convert carbon monoxide to carbon dioxide while increasing the hydrogen yield from the steam.

Steam reforming can also be applied to raw biogas (or biomethane), in which case it is referred to as BMSR. Raw biogas steam reforming can be conducted in compact reformers on-site at biogas plants. Biomethane on the other hand can be injected into the gas grid and used at a central large-scale steam reformer. Compact steam reformers that can operate on-site at biogas plants to produce biohydrogen from raw biogas are now being used in pilot projects (capacity between 4.5 and 9 kg/h of biohydrogen). Steam reforming units for on-site production are currently available with a capacity of around 300 tonnes of hydrogen per year.

### 2.1.3. Bioelectrochemical processes

#### Microbial Electrolysis

Microbial electrolysis is based on the same principle as electrochemical water electrolysis. The main difference is the oxidation of organic substances instead of water at the anode of the electrolysis cell. In microbial ellectrolysis, biological catalysts, i.e. electroactive bacteria, oxidise organic substances such as volatile fatty acids and transfer electrons directly to the anode.
The hydrogen evolution reaction at the cathode is identical to water electrolysis (abiotic) but can also be completed using a biological catalyst[32,33]. The cell voltage generated by the oxidation of the carbon source is usually complemented by an additional voltage. However, this additional voltage is much lower (around 0.123 V) than the theoretical cell voltage of 1.23 V required for water electrolysis[34].

In terms of practical application, it is possible to use aqueous organic waste streams such as wastewater or liquid digestate as a substrate for microbial electrolysis.

Additional information regarding the different technologies can be found in the Annex to this document.

## 2.2. Technology readiness level of biohydrogen production technologies

The technology readiness level (TRL) of biohydrogen production technologies varies. **Some technologies are well developed, such as the thermochemical production processes. Other technologies, including biological and bioelectrochemical processes, are still in the early stages of development.**
Thermochemical technologies have been implemented in the industry for several years, using fossil natural gas as the energy source.

[31] International Energy Agency. (June 2019). *The Future of Hydrogen: Seizing today's opportunities.* https://www.iea.org/reports/the-future-of-hydrogen
[32] Liu, H., Grot, S., & Logan, B. E. (22 April 2005). Electrochemically assisted microbial production of hydrogen from acetate. *Environmental Science & Technology*, *39*(11), 4317–4320. https://doi.org/10.1021/es050244p
[33] Rozendal, R. A., Hamelers, H. V. M., Euverink, G. J. W., Metz, S. J., & Buisman, C. J. N. (September 2006). Principle and perspectives of hydrogen production through biocatalyzed electrolysis. *International Journal of Hydrogen Energy*, *31*(12), 1632–1640. https://doi.org/10.1016/j.ijhydene.2005.12.006
[34] Rousseau, R., Etcheverry, L., Roubaud, E., Basséguy, R., Délia, M.-L., & Bergel, A. (1 January 2020). Microbial electrolysis cell (MEC): Strengths, weaknesses and research needs from electrochemical engineering standpoint. *Applied Energy*, *257*, 113938. https://doi.org/10.1016/j.apenergy.2019.113938

These mature technologies were easily adapted to use sustainable and carbon-neutral energy sources like biomethane and therefore, already rate highly in terms of their TRL. In contrast, processes such as biophotolysis, photofermentation and dark fermentation are emerging technologies still under development. The TRL of each biohydrogen technology discussed in this white paper is set out in table 2.

Table 2. Technology readiness level (TRL) of each biohydrogen production technology[35]

| TRL Explanation | Biohydrogen technologies | TRL | Source |
|---|---|---|---|
| 0-3: Idea | Photo-fermentation | 3 | Roy et al., 2022 |
| 4-5: Prototype | Bioelectrochemical | 3 | Skillen et al., 2022 |
| | Dark fermentation | 3-4 | Buffi, M. et al., 2022. |
| 6-7: Validation | Biophotolysis | 4 | Skillen et al., 2022 |
| | Pyrolysis | 3-8 | Shahbaz et al., 2022; Schneider et al., 2020 |
| 8-9: Production | Gasification | 7-8 | International Energy Agency, 2020 |
| | BMSR | 9 | Khan et al., 2022 ; Buffi et al., 2022. |

## 2.3. Research projects and pilot plants

Biohydrogen production technologies are constantly evolving thanks to a number of research projects and pilot plants throughout Europe. All of them help to improve the technological basis for biohydrogen production. Some examples are given below.

### BioHydroGen Project (Leipzig, Germany)

*Technology: BMSR*

This project aims to develop a compact, innovative reformer system for the conversion of biogas (raw biogas, without prior upgrading to biomethane) using the steam reforming process to produce 9 kg/h of biohydrogen, with a purity of up to 99.97%. The aim is to develop a standardisable, modular system for small and medium-sized capacities that is suitable for typical biogas plants. The biohydrogen generated is intended for use as transport fuel. The project started in December 2021 and will finish in May 2024.
*(Contact: Kathrin Bienert, VNG AG)*

### Grünland H2 (Weimar/Mühlhausen, Germany)

Technology: BMSR

This now completed project evaluated technologies for hydrogen production at biogas plants and the feasibility of decentralised concepts, principally for mobility, but also aimed at local industry. Dark fermentation, biomethane plasmalysis, and steam reforming of biogas and biomethane were initially considered. Focus was then placed on steam reforming due to its overall efficiency and technology readiness level. Options for the steam reforming of biogas (or biomethane) at two existing biogas plants in Thuringia were examined and costs were calculated for the local use in public transport of the hydrogen generated. In addition, the basic potential of this approach and the scope for future integration of biogas plants into regional hydrogen supply networks around the city of Mühlhausen were evaluated. The project ran from April 2022 until March 2023.

[35] Khan, S. N., Yang, Z., Weiguo, D., & Zhao, M. (9 August 2022). Cost and technology readiness level assessment of emerging technologies, new perspectives and future research directions in H2 production. Sustainable Energy & Fuels, 6, 4357-4374. https://doi.org/10.1039/D2SE00988A
Buffi, M., Prussi, M., & Scarlat, N. (October 2022). Energy and environmental assessment of hydrogen from biomass sources: Challenges and perspectives. Biomass and Bioenergy, 165, 106556. https://doi.org/10.1016/j.biombioe.2022.106556
Jafri, Y., Waldheim, L., & Lundgren, J. (December 2020). Emerging gasification technologies for waste & biomass. (Task 33). IEA Bioenergy.. https://www.ieabioenergy.com/wp-content/uploads/2021/02/Emerging-Gasification-Technologies_final.pdf
Shahbaz, M., Al-Ansari, T., Inayat, A., & Inayat, M. (2022). Technical readiness level of biohydrogen production process and its value chain. In S. Yusup & N. A. Rashidi (Eds), Value-Chain of Biofuels (pp. 335-355). Elsevier. https://doi.org/10.1016/B978-0-12-824388-6.00017-8
Schneider, S., Bajohr, S., Graf, F., & Kolb, T. (August 2020). State of the art of hydrogen production via pyrolysis of natural gas. ChemBioEng Reviews, 7(5), 150-158. https://doi.org/10.1002/cben.202000014
Roy, M., Aryal, N., Zhang, Y., Patil, S. A., & Pant, D. (June 2022). Technological progress and readiness level of microbial electrosynthesis and electrofermentation for carbon dioxide and organic wastes valorization. Current Opinion in Green and Sustainable Chemistry, 35, 100605. https://doi.org/10.1016/j.cogsc.2022.100605
Skillen, N., Daly, H., Lan, L., Aljohani, M., Murnaghan, C. W., Fan, X., Hardacre, C., Sheldrake, G. N., & & Robertson, P. K. J. (18 June 2022). Photocatalytic reforming of biomass: what role will the technology play in future energy systems. Topics in Current Chemistry (Z), 380, 33. https://doi.org/10.1007/s41061-022-00391-9

*(Contact: Angela Clinkscales – Institute for Biogas, Waste Management and Energy, Weimar, Germany)*

## FH Münster (Germany)

### *Technology: dark fermentation*

In the research project HyTech, dark fermentation (DF) as well as innovative reactor designs are being tested to increase the overall efficiency of biological hydrogen production through microorganism retention. In addition, biogenic residual and wastewater streams are used. DF primarily produces hydrogen, carbon dioxide and organic acids from biomass via anaerobic fermentation. The process is being developed as a two-stage concept, suitable for treatment of industrial wastewater streams: it reduces the organic load of wastewater by up to 90% and simultaneously produces biohydrogen and biogas. The HyTech research project is funded by the Federal Ministry of Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz, or BMWK) and overseen by the project management agency Projektträger Jülich (PtJ); it is being carried out in collaboration with EMCEL GmbH and BlueMethano GmbH (Funding Code: 03EI5419A).
*(Contact: Elmar Brügging, FH Münster University of Applied Sciences).*

## Cortus Energy (Sweden)

### *Technology: pyrolysis in combination with gasification*

Cortus Energy has developed a new biomass gasification technology, named WoodRoll®, for biohydrogen production via pyrolysis gasification. A first commercial-scale installation, with a capacity of 6 MW, is being operated at Höganäs AB in southern Sweden. The WoodRoll®-process is based on the drying, pyrolysis and gasification of biomass. The first industrial plant runs twenty-four hours a day, seven days a week, producing pure syngas from biomass. Green diesel, methanol and biomethane are also the subject of ongoing projects at this demo-plant, alongside hydrogen. WoodRoll® is a three-stage gasification technology, which starts with the drying of wet biomass to less than 5% humidity, using indirect heating by flue gases. This stage is followed by the pyrolysis of dry biomass to solid char and pyrolysis gas (at 400°C), and finally the gasification of char powder in steam at a high temperature (1100°C). The syngas produced is mainly hydrogen (60%), along with carbon monoxide (30%), methane (1%) and carbon dioxide (9%).
*(Contact: Marko Amovic, Cortus SE)*

## BtX Energy GmbH (Hof, Germany)

### *Technology: gasification*

The BiDRoGen project produces biohydrogen from pelletised biogenic residues. The basis of the project is BtX gasifier technology, which delivers a very clean gas, along with the use of ferro-hy tunnels (FHT) hydrogen separation, to separate pure hydrogen from mixed gases. The aim is to maximise the biohydrogen content in the syngas via Water-Gas Shift. One kilogram of pure biohydrogen can be obtained from 12 – 15 kg of wood, depending on the syngas quality. If the technology can be successfully implemented, a mobile container solution will be available, allowing the decentralised production and local provision of biohydrogen from fine residues. The BMWK is supporting the project with a total funding amount of EUR 630,800. *(Contact: Dr. Andy Gradel, BtX Energy GmbH)*

## TITAN Horizon Europe Project

### *Technology: microwave catalytic conversion*

The European project, TITAN, is developing an innovative catalyst- and microwave-heated reactor that will offer a high biohydrogen yield and facilitate electrical self-sufficiency. The TITAN technology aims to convert biogas directly into biohydrogen, without greenhouse gas emissions. The technology is expected to rise from TRL 3 to TRL 5 by the end of the project. Thanks to its efficient process and significant reductions in expenditure, TITAN will yield biohydrogen at a competitive cost. The co-produced carbon material may be used for soil amendment at nearby delocalised biogas plants, allowing long term carbon sequestration and a sustainable circular economy. The project started in September 2022 and has a duration of 48 months.
*(Contact: Dr. David Farrusseng, CNRS)*

### ColdSpark Horizon Europe Project

*Technology: cold plasma pyrolysis*

The Horizon Europe project, ColdSpark®, which started in June 2022, involves a consortium of 7 partners from Norway, Spain, Bulgaria, Germany and the UK. The project will use non-thermal plasma technology, which is able to run on power from intermittent renewable energy sources, to produce biohydrogen from methane and biomethane on an industrial scale, with zero carbon dioxide emissions. This will be achieved by designing an industrially relevant reactor that includes all the best features of the non-thermal plasma technologies. The process has a low energy cost (<15kWh/kg$H_2$ produced) and does not use a catalyst, which reduces operational costs. There is also no requirement for high temperatures or pressures in order to operate. The technology is expected to develop from TRL 3 to TRL 5 by the end of the project. The reactor design is scalable and flexible, lowering both capital and operational expenditure. The duration of the project is 42 months.
*(Contact: Terje Hauan, SEID)*

*Biohydrogen generation from biomass, biogas and biomethane has attracted increased interest because of its high yields and long-term sustainability, as well as its low energy consumption.*

# Chapter 3

# Decarbonising Europe's hydrogen production

## 3.1. Sustainability of the different types of hydrogen

One of the main challenges of the hydrogen sector is to decarbonise its own production. The carbon footprints across the different types of hydrogen vary[36], ranging from –26.5 to 20 kg $CO_2$/kg $H_2$.

Comparing greenhouse gas emissions from different hydrogen production technologies is complex, especially in the case of biohydrogen.

While the data for wind and solar power generation can be calculated based on technical specifications, the carbon footprint of biohydrogen varies from –26.5 to 10.8 kg CO2/kg H2 depending on the feedstock type and plant setup. A substantial portion of the greenhouse gas (GHG) emissions for any form of hydrogen is caused by its distribution. Compression for storage and transport uses approximately 5 kWh/kgH2. If power from the electricity grid is used, distribution raises the emissions by 1.8 kg CO2-eq / kg H2.

Table 3. Carbon footprint comparison of the different types of hydrogen in 2021

| Hydrogen type | Carbon footprint (kg $CO_2$/kg $H_2$) |
|---|---|
| Grey hydrogen | 10 to 20 |
| Blue hydrogen | 1.5 to 5 |
| Green hydrogen (RFNBO) | 0.5 to 1.5 |
| Biohydrogen (with or without CCS) | -26.5 to 10.8 |

*Source: Adapted from Lou et al. (2023)*

## 3.2. Sustainability of biohydrogen

Table 4 details the carbon footprint of the various biohydrogen production technologies available today. **In contrast to the other forms of hydrogen, biohydrogen can be carbon negative if it is obtained from feedstocks such as wastes and manure**.

Table 4. General comparison of the various biohydrogen production technologies

| Biohydrogen production technologies | Carbon footprint (kg $CO_2$/kg $H_2$) |
|---|---|
| Gasification without CCS | 0.31 to 8.63 |
| Gasification with CCS | -22.15 to -11.66 |
| Pyrolysis | -13.8 to -3.8 |
| BMSR (with or without CCS) | -26.5 to 8.6 |
| Biophotolysis | Data not available |

*Source: Adapted from Lou et al. (2023)*

The carbon footprint of biohydrogen production depends on two aspects in particular: the feedstock used and the combination of biohydrogen production with carbon sequestration technologies. Under the terms of the Renewable Energy Directive 2018/2001 (RED II), some substrates are considered to be more sustainable than others depending on the resources used during their production, such as water consumption or synthetic fertiliser requirement. Low-carbon feedstocks such as sequential crops can deliver low-carbon or net-zero biohydrogen but biohydrogen from waste streams or manure present an even greater scope for carbon reduction. Biohydrogen production from feedstocks such as manure, wastewater and other organic wastes not only replaces fossil fuels but also avoids emissions that would otherwise have been released into the atmosphere. When biohydrogen production is paired with carbon capture and storage technologies, which effectively remove carbon dioxide from the atmosphere, still more emission savings are achieved. Alongside biomethane, biohydrogen

[36] Lou et al. (2023).

originating from sustainable biomass will be key to fully meeting the energy needs of the transport and industry sectors as Europe mover towards decarbonisation.

## 3.3. Life cycle of biohydrogen

The life cycle of biohydrogen (Figure 2) begins with the production of biogenic substrates such as manures, crops, woody waste, wastewater sludges, and agro-industrial waste, all of which originate from agricultural and industrial activities. The substrates are then transported to biohydrogen facilities for their conversion into hydrogen

**Figure 2.** Life cycle approach of biohydrogen


Depending on the technology, the process either produces hydrogen directly or produces intermediate products first. In the case of BMSR, for example, biogas is produced first, and hydrogen is then synthesised from the methane molecule. Other technologies use organic substrates to produce biohydrogen directly, although in this case it occurs mixed with biogenic carbon dioxide. Some production technologies generate bio-fertilisers as a co-product; these can then return to the soil the organic matter that has been extracted from the substrates.

Once biohydrogen has been produced, it is distributed to clients in the transport and industrial sector for their use. The output of hydrogen combustion processes is water vapor, and once released into the air, it will condense to form clouds bringing rain to the fields. In this way, water is returning to the soil, closing the biohydrogen cycle.

## 3.4. Production potential of biohydrogen

The biogas and biomethane sectors are well established in Europe and, together with hydrogen, these renewable gases are the focus of considerable attention due to the current energy crisis and the REPowerEU plan. The scope for renewable gas production is far from exhausted. Increased incentives for municipalities and industries would make it possible to exploit the potential of industrial organic waste and wastewater as well as additional municipal waste. Developing synergies between the renewable gases biomethane and biohydrogen will be key to ensuring they can complement each other in Europe´s future energy mix.

Because both renewable gases use the same resources for most production routes, feedstock availability for biogases also relates to most types of biohydrogen production. A recent study by the Gas for Climate (GfC) group[37] shows that enough sustainable feedstocks will be available in the EU-27 to meet the REPowerEU 2030 biomethane target (35 bcm). According to GfC estimate[38], biomethane production could reach 41 bcm per year by 2030 (figure 3) and 151 bcm per year by 2050. This calculation of potential biomethane production for 2030 and 2050 shows that there is significant scope to produce biohydrogen as well.

To give an example: 435 TWh (41 bcm) of biomethane could produce 226-313 TWh of biohydrogen via BMSR[39]. This equates to 6.8 to 9.5 million tonnes of biohydrogen[40]. Naturally, a balance needs to be found between the use of biomethane in its own right and its conversion to biohydrogen; this should reflect the circumstances and requirements of the different sectors involved.

*In contrast to other forms of hydrogen, biohydrogen can be carbon negative if it is obtained from feedstocks such as wastes and manure.*

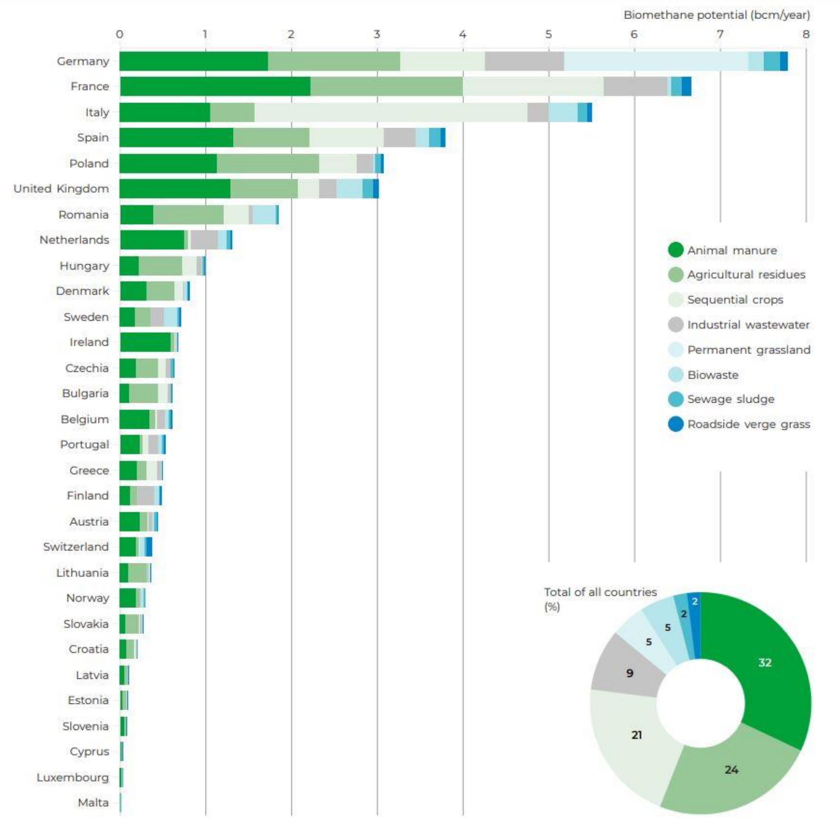



**Figure 3.** 2030 biomethane production potential according to feedstock availability estimates per country
*Source: Gas for Climate (2022)*

[37] European Biogas Association. (7 July 2022). *Gas for Climate publishes updated biomethane production potentials for EU Member States, assessing the feasibility of the 35 bcm REPowerEU target for 2030 and providing outlook to 2050.* https://www.europeanbiogas.eu/gas-for-climate-publishes-updated-biomethane-production-potentials-for-eu-member-states-assessing-the-feasibility-of-the-35-bcm-repowereu-target-for-2030-and-providing-outlook-to-2050/

[38] Gas for Climate. (July 2022). *Biomethane production potentials in the EU: Feasibility of REPowerEU 2030 targets, production potentials in the Member States and outlook to 2050.*Guidehouse Netherlands B. V.. https://gasforclimate2050.eu/wp-content/uploads/2022/10/Guidehouse_GfC_report_design_final_v3.pdf

[39] Energy conversion efficiency range of 52-72%. See Lou et al. (2023).

[40] A kilogram of hydrogen - the unit most often used – has an energy value of about 33.3 kWh. A tonne of hydrogen therefore delivers about 33 MWh and a million tonnes about 33 terawatt hours (TWh). To provide a sense of scale, the UK uses about 300 TWh of electricity per year. See Goodall, C. (11 June 2021). Some rules of thumb of the hydrogen economy. *Carbon Commentary.* https://www.carboncommentary.com/blog/2021/6/11/some-rules-of-thumb-of-the-hydrogen-economy

# Chapter 4

## Economics of hydrogen and biohydrogen

## 4.1. Cost of hydrogen and biohydrogen production

The supply and demand of renewable electricity, hydrogen, and biomethane will accelerate as innovations and investment opportunities are fully exploited. Gas infrastructure will increasingly diversify to facilitate flows of hydrogen and biomethane.

According to the International Energy Agency (IEA)[41], producing hydrogen from fossil fuels is currently the lowest-cost option in most parts of the world. Depending on regional gas prices, the levelised cost of hydrogen produced from natural gas is in the range of EUR 0.46–1.8/kg $H_2$ (Table 5). Green hydrogen production from electrolysis, currently the most developed green hydrogen technology, uses green electricity such as wind and solar. This way of obtaining hydrogen is still much costlier in most places, at EUR 2.51–11.94/kg $H_2$. In fact, the cost of renewable electricity can make up 50–90% of the total production expenses, depending on both electricity price and the full-load hours of the renewable electricity supply. **Biohydrogen, in contrast, can be adapted to suit to different occasions and areas, brings with it additional environmental benefits, and can be obtained at a lower production cost (EUR 1.15–9.65/kg $H_2$) than green hydrogen**.

The price gap between fossil and green hydrogen production methods is expected to shrink as technologies develop, processes are scaled up and efficiency is gained. Incorporating the cost of carbon dioxide emissions in calculations (e.g. via carbon pricing) can further narrow the gap in costs, to the benefit of biological processes such as biohydrogen production from biogas or dark fermentation.

Table 5. Production cost of biohydrogen compared to other types of hydrogen in 2021

| Hydrogen type | Cost range (€/kg $H_2$) | Cost range (€/kWh $H_2$) |
|---|---|---|
| Grey hydrogen | 0.46 – 1.8 | 0.01 – 0.05 |
| Blue hydrogen | 1.3 – 2.2 | 0.04 – 0.07 |
| Green hydrogen (RFNBO) | 2.51 – 11.94 | 0.08 – 0.36 |
| Biohydrogen (with or without CCS) | 1.15 – 9.65 | 0.03 – 0.29 |

*Source: Adapted from Lou et al. (2023)*

Table 6 shows the costs associated with the different biohydrogen production technologies vary considerably[42]: costs depend on the TRL of each technology process, infrastructure support, and the availability of feedstocks. Gasification, pyrolysis, BMSR and biophotolysis start from a production cost (approximately EUR 1.15–1.3/kg $H_2$) that are comparable to the mean cost of grey hydrogen today (EUR 0.46–1.8/kg $H_2$; see Table 5 and 6). These low costs depend on cheap and abundant biomass supplies located no more than a short distance from the manufacturing site. The top end of the cost range for gasification, pyrolysis, BMSR and dark fermentation today (EUR 7.86–9.65/kg $H_2$) is on a par with the highest ranges of green hydrogen costs[43].

Table 6. Biohydrogen production cost according to production technology

| | Cost range (€/kg $H_2$) | Cost range (€/kWh $H_2$) |
|---|---|---|
| Gasification (with or without CCS) | 1.3 – 9.47 | 0.03 – 0.28 |
| Pyrolysis | 1.19 – 9.65 | 0.04 – 0.29 |
| BMSR (with or without CCS) | 1.15 – 7.34 | 0.03 – 0.22 |
| Dark fermentation | 5.19 – 7.86 | 0.17 – 0.26 |
| Biophotolysis | 1.3 – 6.65 | 0.04 – 0.20 |

*Source: Adapted from Lou et al. (2023)*

[41] International Energy Agency (2021).
[42] Lou et al. (2023).
[43] Lou et al. (2023).

An important aspect influencing the cost of hydrogen is its transport and distribution, especially in the case of imported hydrogen. Hydrogen can be transported either in gaseous form via pipelines and in tube trailers or in liquefied form in cryogenic tanks. For longer distances, alternatives such as transporting liquefied hydrogen by ship, or using hydrogen carriers such as biomethane or ammonia may be more attractive. For instance, making use of the already existing gas infrastructure, biohydrogen can be converted to biomethane, which can be injected into the gas grid, facilitating energy storage.

There are projects currently underway that aim to establish hydrogen-specific pipelines across Europe. In April 2021, a group of European gas infrastructure companies from 21 countries presented their plan for the development of a dedicated pipeline network, the European Hydrogen Backbone (EHB; see Figure 4). This network, based on converted 20-, 36- and 48-inch gas pipelines, could transport 2 GW, 5 GW and 15 GW hydrogen (higher heating value or HHV) respectively per pipeline[44]. Their estimate is that the transportation cost of hydrogen via a European hydrogen backbone constructed in this way, consisting of 70% converted gas pipelines and 30% new hydrogen pipelines, with 5,000 full load operating hours per year, would be about €0.11-0.21/kg $H_2$/1000 km. Building large, dedicated pipelines and transporting base-load hydrogen at 80 bar could reduce transport costs still further, however, to below €0.1/kg $H_2$/1000 km[45].

## 4.2. Additional benefits of biohydrogen production

As a drop-in replacement for grey hydrogen or natural gas, the value of biohydrogen exceeds its cost. Generating biohydrogen from domestically produced biogases reduces the need to import gas and directly improves Europe's energy independence and security. This helps to cushion against exposure to volatile natural gas prices. Furthermore, biohydrogen contributes to fuel diversity and energy system flexibility[46].

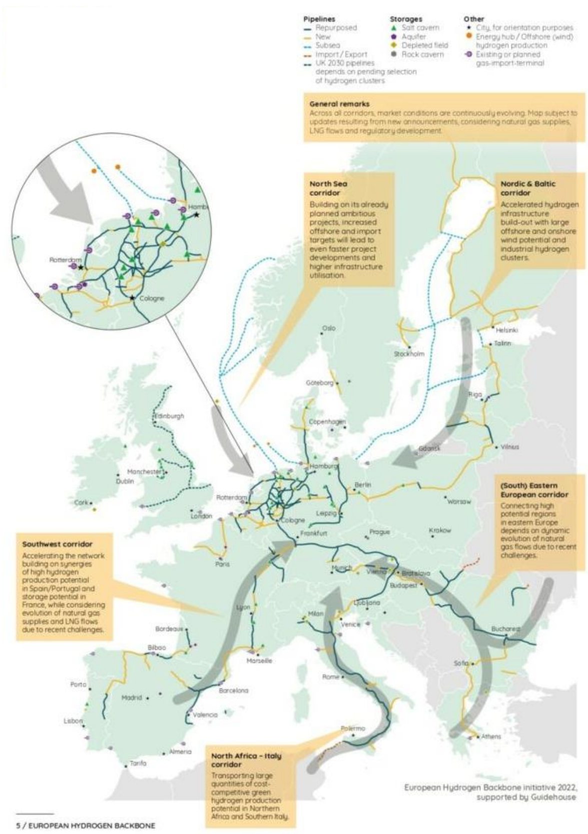



**Figure 1.** European Hydrogen Backbone 2040: about 40,000 km hydrogen pipelines, consisting of 70% retrofitted gas pipelines and 30% new constructed hydrogen pipelines
*Source: European Hydrogen Backbone 2022*

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[44] European Hydrogen Backbone. (April 2022). *European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Covering 28 Countries.* Guidehouse. https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf
[45] European Hydrogen Backbone (2022).
[46] Connell, N., Lin, J., Nelson, Dr L., Backer, L., Gorman, J., Zeranski, T., Childs, E., Bartell, J., Davidson, M., Ahern, J., & Animas, E. (April 2022). *Green hydrogen guidebook* (2nd Ed.). Green Hydrogen Coalition. https://www.ghcoalition.org/education

Depending on the chosen production technology, pure biogenic carbon dioxide can be obtained as a co-product of the biohydrogen production process. Biogenic carbon dioxide can be used as a feedstock in multiple industrial applications, largely displacing fossil carbon dioxide sources. Alternatively, it can be permanently stored within geological features, thus delivering greenhouse gas removal (GGR).

Biohydrogen production from organic waste feedstocks also provides a waste processing service, which plays a valuable role in the circular economy by recycling organic waste and turning it into useful products.
A further advantage of green hydrogen obtained by biological or biotechnological production pathways is that the remaining digestate can be used as biofertiliser, encouraging the flow of soil nutrients, and once more contributing to the circular economy. Moreover, biochar and other carbon materials produced by the gasification and pyrolysis processes can store carbon permanently or be put to further use. The application of digestate and biochar to the soil, for example, improves the soil's physical characteristics and promotes water retention and humus formation.

*Biohydrogen can be adapted to suit to different occasions and areas, brings with it additional environmental benefits, and can be obtained at a lower production cost (EUR 1.15–9.65/kg H2) than green hydrogen.*

# Chapter 5

## The market for (bio)hydrogen

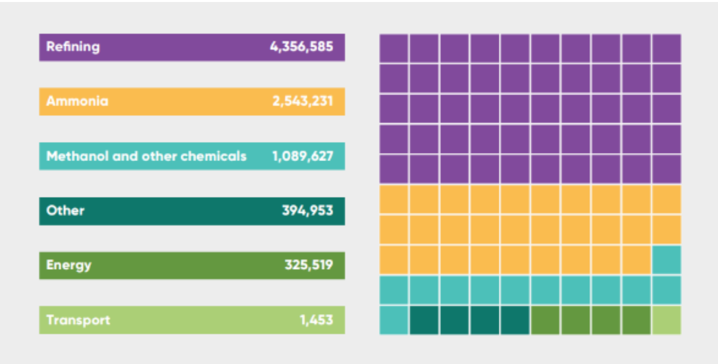
## 5.1. (Bio)hydrogen: demand and use

According to Hydrogen Europe, the total demand for hydrogen in Europe in 2020 reached an estimated 8.7 Mt[47]. The biggest share of hydrogen demand comes from refineries, which accounted for 49% of total hydrogen use in 2020, followed by the ammonia industry at 31%. Together these two sectors were responsible for 80% of the total hydrogen consumption in the EU, EFTA, and UK.

About 13% was consumed by the chemical industry, with methanol production accounting for 5% of that[48]. Emerging hydrogen applications, for example in the transport sector, make up a very small portion of the market (0.02% in 2019[49]).

More than half of Europe's total hydrogen consumption takes place in just four countries: Germany (20%), the Netherlands (15%), Poland (9%), and Spain (7%)[50].

**Figure 5.** Total demand for hydrogen in 2020 by application




*Source: Allsop & Bortolotti (2022)*

Hydrogen Europe has summarised the different uses of hydrogen within the European industry[51]: given the ambitious emissions targets that are being put in place, many hydrogen-consuming sectors are transitioning from fossil-based hydrogen to green and biohydrogen, as the emissions involved in the production of fossil-based hydrogen are considered together with their own direct carbon emissions. This is especially the case for refineries, which already typically use hydrogen to reduce sulfur content in diesel fuel. The transition to green and biohydrogen offers a way of lowering the emissions in this sector.

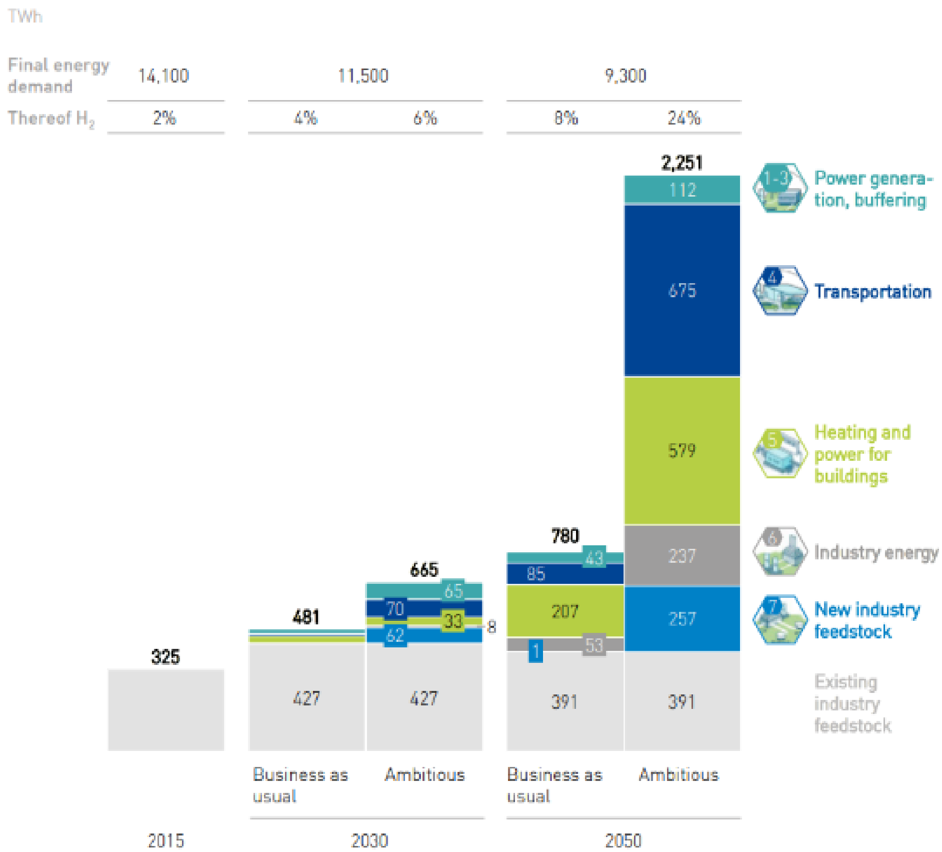
Similarly, the ammonia production process is a big consumer of hydrogen and would benefit considerably from the switch to green and biohydrogen. Although it is typically used as a feedstock for fertiliser production, ammonia is also seen as a potential energy carrier and fuel and is already considered a suitable e-fuel for maritime applications. The same reasoning can be applied to the production of methanol, used both in chemical processes and, as of recently, as an e-fuel. E-fuels are synthetic hydrogen-based fuels that can be burned in combustion engines and help decarbonise hard-to-electrify sectors (e.g., aviation and maritime). Sustainable e-fuels can be produced both from biohydrogen and from green hydrogen of non-biological origin.

Provided that carbon is captured from the atmosphere, renewable electricity is used during synthesis and the hydrogen source is low-carbon, e-fuels such as e-methanol, e-ammonia, e-diesel, e-methane and e-kerosene are a good way to reduce emissions in mobility. Carbon dioxide is still emitted during the combustion of e-fuels but is fully compensated for by photosynthesis.

[47] Allsop & Bortolotti (2022).
[48] Allsop & Bortolotti (2022).
[49] Fuel Cells and Hydrogen Observatory. (September 2021). Chapter 2: Hydrogen Supply and Demand. *2021 Report.* https://www.fchobservatory.eu/index.php/reports
[50] Allsop & Bortolotti (2022).
[51] Hydrogen Europe. (2021). *Hydrogen – Enabling a Zero Emission Society. Hydrogen Report 2021.* https://hydrogen.revolve.media/2021/

Biohydrogen can also be used to help decarbonise the steel industry, which depends on a highly energy-intensive production process. Although this process can take different routes, each of them consuming different amounts of fossil fuels[52], the steel industry as a whole is responsible for 4% of the total GHG emissions in Europe. The steel industry is also, however, the sector with the highest projected consumption of clean hydrogen by 2030, according to the *Clean Hydrogen Monitor*[53].

**Figure 6.** Projected hydrogen demand across different sectors until 2050
*Source: Fuel Cells and Hydrogen 2 Joint Undertaking (2019)*




The more ambitious projection envisages a sevenfold increase in demand for hydrogen in the period from 2015 to 2050, which would entail a rise from about 325 TWh to 2,250 TWh (6). In the business-as-usual scenario, demand would reach only about 780 TWh by 2050. In each case, however, the increased hydrogen demand would stem from new uses in the power, transport, industry (as heat and as feedstock), and building sectors. The total planned consumption of low-carbon hydrogen in the industrial projects tracked by Hydrogen Europe amounts to 5.2 Mt $H_2$/year by 2030[54]. If the current industry trends continue, emerging technologies such as new ways to produce steel and the e-fuels industry will be the biggest consumers of clean hydrogen.

[52] In Europe, 60% of steel production involves a blast furnace and a basic oxygen furnace (BF/BOF), where coal is used as a reductant to transform iron ore into steel. The second route makes use of an electric arc furnace (EAF), powered by electricity, to produce steel from steel scrap and direct reduced iron (DRI) in different proportions. Although the EAF route is less carbon-intensive than the BF/BOF method, emissions still occur when natural gas is used as a reductant to produce the DRI pellets. Replacing the natural gas with low-carbon hydrogen, and using renewable electricity to power the EAF, will help decarbonise the entire steel production process.
[53] Allsop & Bortolotti (2022).
[54] Hydrogen Europe (2021)

## 5.2. Biohydrogen application opportunities

Biomass-based hydrogen not only serves as an energy source or energy-carrying product; it also has the unique ability to remove carbon from circulation and thus be carbon-negative. This quality should be considered independently from the general advantages of low-carbon hydrogen. When produced from waste and coupled with CCS, biohydrogen can provide its users with additional climate benefits and help sectors with limited decarbonisation options achieve carbon neutrality by compensating for difficult-to-eliminate residual emissions[55].

The iron and steel industry is a prime example of a hard to abate sector. Most emissions from this sector's existing facilities are attributable to blast furnaces, not electricity, which accounts for only 13% of the industry's total emissions[56] Consequently, renewable electricity alone is not sufficient to decarbonise this sector. Among all steelmaking routes, the most mature low-emission technology is currently green hydrogen-based direct reduced iron (DRI) combined with an electric arc furnace (EAF) fueled by carbon-free electricity. The use of biohydrogen can effectively double the carbon credit of hydrogen-based steelmaking routes. In some cases, this can result in carbon-negative steel (-0.6 t $CO_2$/t steel), providing a unique opportunity to achieve net zero or net negative emissions in a sector that is difficult to treat.

The chemical industry also presents a serious barrier to plans for widespread decarbonisation. In SMR-based ammonia production, the generation of the hydrogen required for the process is responsible for a significant portion of the carbon footprint. Consequently, the use of biohydrogen as a feedstock can dramatically reduce the carbon dioxide emissions associated with ammonia production. When CSS technology and/or waste as a substrate are used, the resulting carbon-negative biohydrogen enables the production of carbon-negative ammonia.

In the same way, the ethylene synthesis process is well suited to the use of hydrogen-based heat generation because it already uses fossil gases, including hydrogen, to heat the steam cracker and other process units. By using carbon-negative biohydrogen, the final ethylene product can achieve a negative carbon footprint (-2.93t $CO_2$/t ethylene; see Table 7). Similarly, the use of biohydrogen as a feedstock can have a significant impact on emissions from methanol ($CH_3OH$) production[57].

At the same time, biogas producers are keen to diversify their outputs and further increase the flexibility of anaerobic digestion plants. Biohydrogen derived from biogases or other sustainable processes will play an important role in developing new prospects in the energy market. Biohydrogen addresses the key challenges of the European hydrogen economy by enabling local, safe, efficient, and cost-effective hydrogen production.

*Biomass-based hydrogen not only serves as an energy source or energy-carrying product; it also has the unique ability to remove carbon from circulation and thus be carbon-negative.*

[55] Lou et al. (2023).
[56] Lou et al. (2023).
[57] Lou et al. (2023).

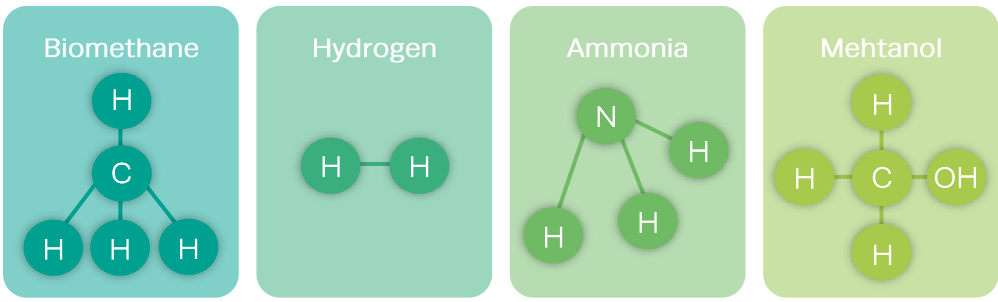
| Product and technology process | Baseline carbon intensity | Carbon intensity using green hydrogen | Carbon intensity using carbon-negative biohydrogen |
|---|---|---|---|
| BF-BOF steel production (t $CO_2$/t HM) ($H_2$ replacing pulverised coal hot air blast) | 2.20 | 1.78 | 1.13 to 1.65 |
| DRI-EAF gas steel production (t$CO_2$/t HM) ($H_2$ replacing all DRI gas consumption) | 1.35 | 0.29 (renewable electricity)<br>0.80 (grid electricity) | -0.61 to 0.39 |
| NG SMR-based ammonia production (t $CO_2$/t ammonia) (1:1 replacement of original $H_2$ consumption) | 1.97 | 0.27 | -4.04 to -0.6 |
| NG SMR-methanol production (t $CO_2$/t methanol) (1:1 replacement of original $H_2$ consumption) | 2.57 (including feedstock emission)<br>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 ethylene) (1:1 replacement of original $H_2$ consumption) | 1.42 (including feedstock emission) | 0.58 | -2.93 to -0.43 |

Table 7. Carbon intensity of various products made with green hydrogen and biohydrogen

*Source: Lou et al. (2023)*
*Note: This table illustrates the potential for carbon-negative biohydrogen 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 CO2/kg H2; the carbon intensity of electricity 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; biohydrogen is assumed to be produced using waste biomass combined with CCS. The range of the carbon intensity of biohydrogen is -3.4 kg CO2/kg H2 to -22 kg CO2/kg H2. HM stands for hot metal, which is a standard measurement for iron and steel output. The calculation of carbon intensity for BF-BOF steel production using green hydrogen assumes that all the pulverised 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 the energy consumed during the manufacturing process comes from electricity. Therefore, the steel manufactured via 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 carbon dioxide as an input and release that carbon (as carbon dioxide) once they are combusted or at the end of their life-cycle. 'No feedstock emission' in NG SMR-based methanol production assumes that carbon dioxide used in the production is recycled. NG stands for natural gas.*

## 5.3. Hydrogen carriers

**Figure 7.** Diagram of hydrogen carrier molecules




Hydrogen, as a molecule, contains the highest energy content per kilogram of any molecule in the universe, but it is also the smallest molecule in existence. Consequently, the volumetric energy density of hydrogen at normal atmospheric conditions is extremely low (0.09 kg/m³ compared to 0.66 kg/m³ for (bio)methane). Solutions must therefore be found to transport hydrogen cost effectively.

The liquefaction of hydrogen comes with challenges, as the condensation point of hydrogen (-253°C) is close to absolute zero. Liquifying hydrogen therefore requires a great deal of energy. Another option is to store hydrogen in so-called hydrogen carriers (hydrogen-rich chemical substances) such as bio-ammonia and bio-methanol. These make it possible to ship (bio-)

hydrogen across long distances, especially where pipelines do not exist or are not feasible.

## Biomethane

Biomethane and hydrogen will increasingly complement each other in Europe's future energy mix, with several synergies already in place today. Hydrogen converted to biomethane helps match energy production to usage, providing an important form of seasonal energy storage. Biomethane can be injected into the existing gas infrastructure, which functions as an energy storage unit and has the capacity to cover up to 2-3 months of current gas consumption in the EU. Biomethane offers dispatchable power generation and the decarbonisation of existing fossil-based district heating systems, as well as greening the gas grid and supporting applications in industry and transport.
The bio-methanation process is another good example of the mutually beneficial nature of these two renewable gases when used in conjunction with each other. Green hydrogen, produced from excess green electricity, can be combined with raw biogas to convert biogenic carbon dioxide into biomethane, which can be used or stored as explained above. Conversely, where hydrogen is the required energy carrier, biohydrogen can be produced from biomethane or raw biogas directly.

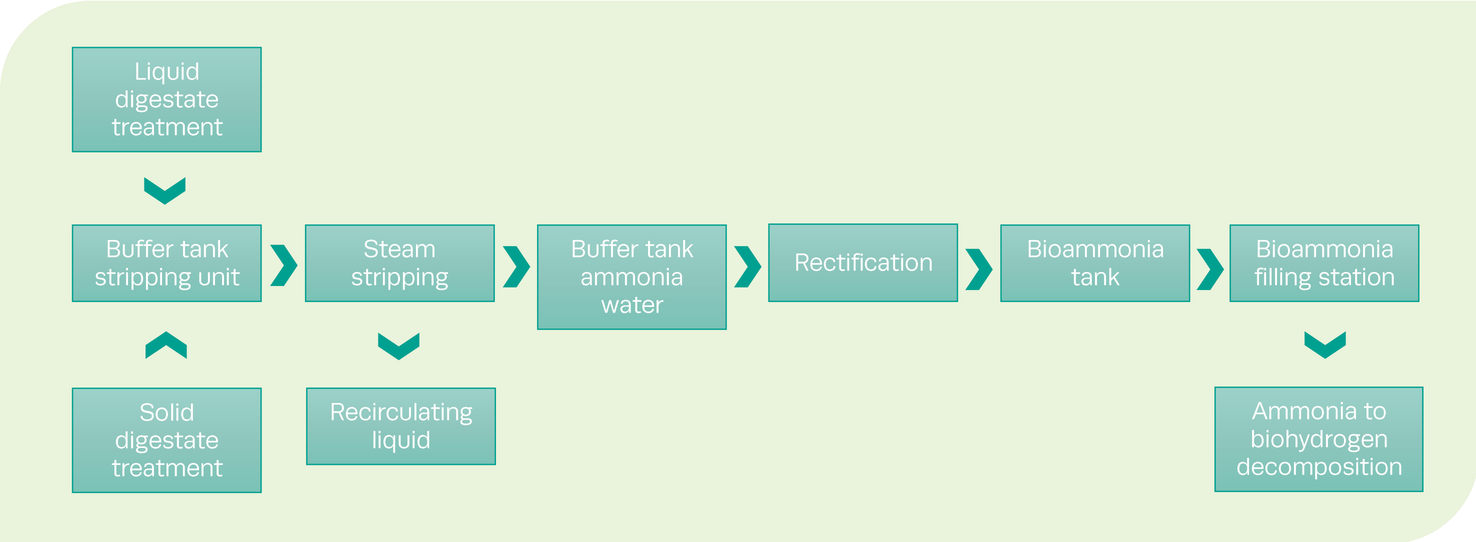
## Bio-ammonia

Green hydrogen and ammonia are often associated with each other, both because ammonia serves as a hydrogen carrier[58] and because renewable ammonia for the production of fertilisers or fuels can be generated using green hydrogen.[59]. Bio-ammonia can also be directly, biologically produced at the biogas plant, however. In the digestate, a co-product from biogas plants that use nitrogen-rich substrates, there are high amounts of ammonium, which can be extracted as ammonia[60]. This bio-ammonia is directly available on the market after extraction and purification, supplementing biomethane and biohydrogen production from the biogas reactor. Conversion losses that occur when converting hydrogen to ammonia are avoided during this process. If hydrogen is needed in a specific area, bio-ammonia can be transported and stored before being transformed to obtain biohydrogen and nitrogen gas[61].

In digestate treatment there are several thermal process units that make it possible to extract ammonia-rich steam. Figure 8 shows a block scheme of one possible upgrading pathway to produce bio-ammonia from digestate. In this example, the ammonium steam contained in the digestate is condensed and collected in buffer tanks. Steam stripping brings the ammonia to a concentration of 15-20%. In the rectification unit, the ammonia stream is purified up to 99.98 %, which meets technical standards[62].

[58] Riemer M., Wachsmuth J., Isik V., & Köppel W. (28 February 2022). *Kurzeinschätzung von Ammoniak als Energieträger und Transportmedium für Wasserstoff. Stärken, Schwächen, Chancen und Risiken.* Umweltbundesamt. https://www.umweltbundesamt.de/sites/default/files/medien/479/dokumente/uba_kurzeinschaetzung_von_ammoniak_als_energietraeger_und_transportmedium_fuer_wasserstoff.pdf
[59] Heberl, M. (31 October 2017). *Power-to-Ammoniak: Möglichkeiten zur erneuerbaren Elektrifizierung und Dekarbonisierung der Ammoniakindustrie* [Master's thesis, Ostbayerische Technische Hochschule, Regensburg]. https://opus4.kobv.de/opus4-oth-regensburg/frontdoor/deliver/index/docId/2216/file/17_10_26_MA_Power_to_Ammoniak_Michael_Heberl.pdf
[60] Schädel, H. (2020). *Ammoniak ist ein Problem.* energiePLUSagrar GmbH. https://energieplusagrar.de/ammoniak-ist-ein-problem/
[61] Ristig, S., Poschmann, M., Folke, J., Gómez-Cápiro, O., Chen, Z., Sanchez-Bastardo, N., Schlögl, R., Heumann, S., & Ruland, H. (22 July 2022). Ammonia Decomposition in the Process Chain for a Renewable Hydrogen Supply. *Chemie Ingenieur Technik, 94*(10), 1413–25. https://doi.org/10.1002/cite.202200003
[62] skw Piesteritz. (28 September 2015). *Ammoniak, flüssig, technisch rein. Sicherheitsblatt gemäß Verordnung (EG) Nr. 1907/2006 (REACH).* https://www.skwp.de/fileadmin/content/05_mediacenter/broschueren/reach/skwp_erweitere_sicherheit_ammoniak_rein.pdf

Figure 8. Diagram of a bio-ammonia upgrading unit




### Biomethanol

Like bio-ammonia, biomethanol can also serve as a hydrogen carrier[63]. Biomethanol has the same chemical composition as fossil methanol – $CH_3OH$. The methanol value chain is mature, with a well-established production and distribution network. Biomethanol represents an environmentally friendly alternative fuel that can be used in hard-to-decarbonise transport modes. Cargo vessels currently used to transport crude oil could be used to transport methanol with only minor modifications. Methanol can be used in the transport and chemical sectors and receives particular attention among researchers as a viable future marine fuel[64]. Using biomethanol as a hydrogen carrier avoids the need to carry large hydrogen tanks on board, considerably improving safety. In the future, it may also prove to be an attractive solution for cruise liners. Furthermore, methanol is already traded today as a base chemical and gives rise to a wide range of possible follow-up products, from ethers and higher alcohols, to drop-in gasoline and even kerosene[65,66].

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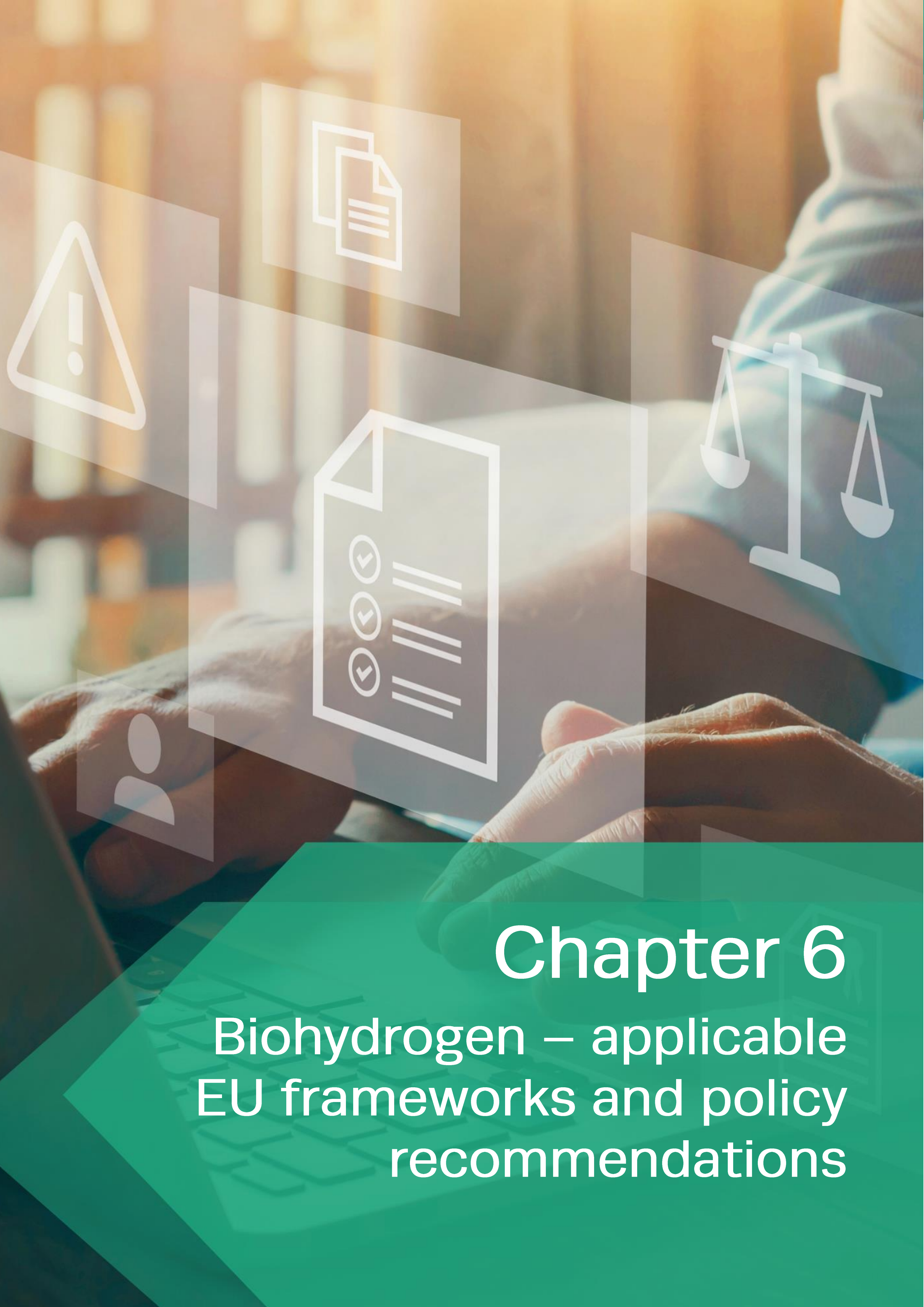
[63] Schorn, F., Breuer, J. L., Samsun, R. C., Schnorbus, T., Heuser, B., Peters, R., & Stolten, D. (25 August 2021). Methanol as a renewable energy carrier: An assessment of production and transportation costs for selected global locations. *Advances in Applied Energy, 3*, 100050. https://doi.org/10.1016/j.adapen.2021.100050

[64] Andersson, K., Brynolf, S., Hansson, J., & Grahn, M. (30 April 2020). Criteria and decision support for a sustainable choice of alternative marine fuels. *Sustainability, 12*(9), 3623. https://doi.org/10.3390/su12093623

[65] Schemme, S., Breuer, J. L., Köller, M., Meschede, S., Walman, F., Samsun, R. C., Peters, R., & Stolten, D. (14 February 2020). H2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production. *International journal of hydrogen energy, 45*(8), 5395-5414. https://doi.org/10.1016/j.ijhydene.2019.05.028

[66] Schmidt, P., Batteiger, V., Roth, A., Weindorf, W., & Raksha, T. (5 January 2018). Power-to-Liquids as renewable fuel option for aviation: a review. *Chemie Ingenieur Technik, 90*(1-2), 127-140. https://doi.org/10.1002/cite.201700129



# Chapter 6

## Biohydrogen – applicable EU frameworks and policy recommendations

Biohydrogen as it aims to support the development of a single market for energy[67]. As an innovative product, biohydrogen is not yet commercialised on a broad scale and the existing regulatory framework may not have anticipated its commercial maturity. Following an overview of the EU frameworks applicable to biohydrogen (section 1), this chapter will identify regulatory barriers (section 2) and put forward recommendations to remove them (section 3).

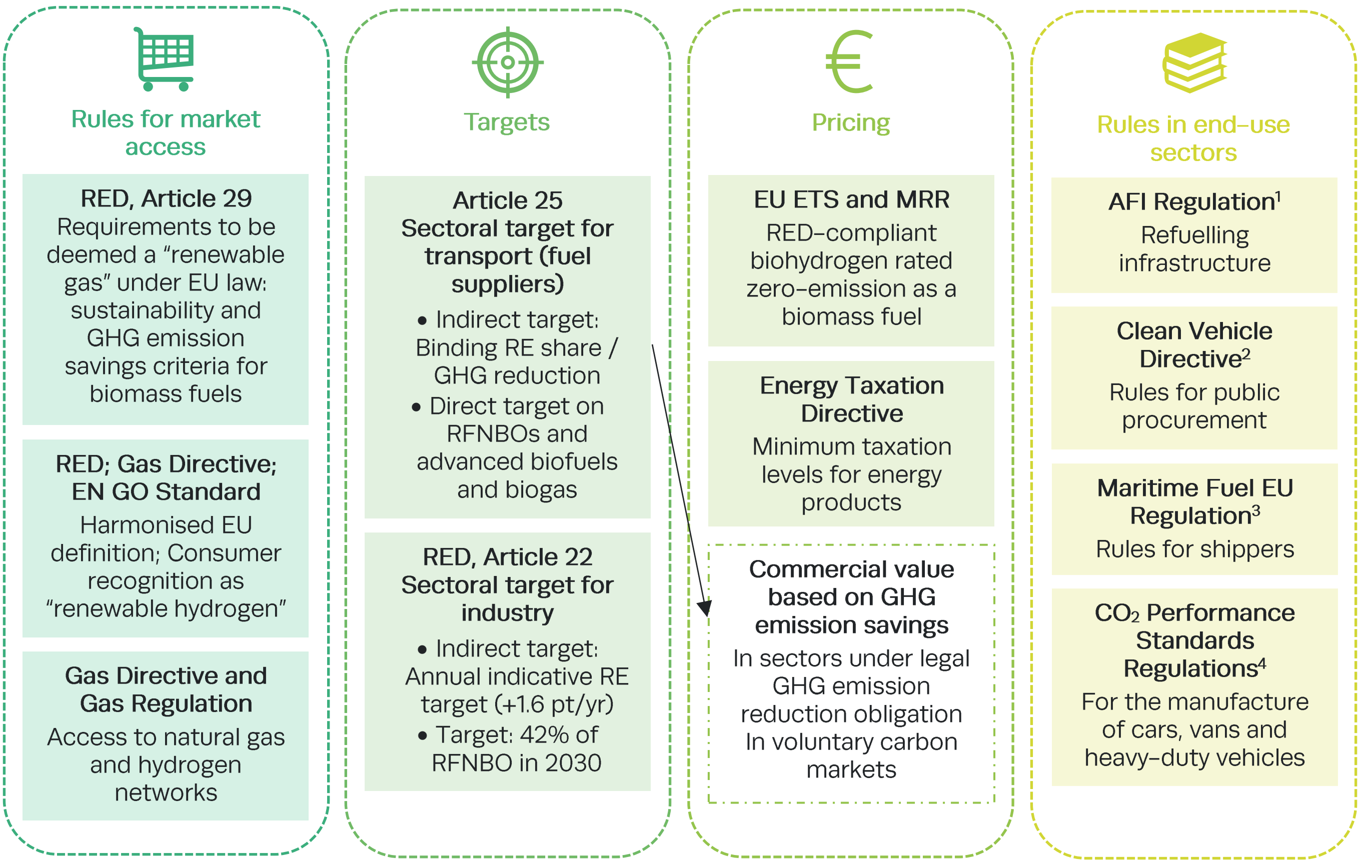
## 6.1. Overview of the EU frameworks applicable to biohydrogen

The EU regulatory frameworks applicable to biohydrogen cover production, distribution and consumption. They can be divided into the following 4 main areas or types of policy instrument, so as to facilitate the identification of drivers and barriers to the further deployment of biohydrogen:

1) Authorisations for market access, i.e. access to networks and recognition as a 'renewable' hydrogen on the European market
2) Targets for reductions in consumption or GHG emissions; such targets can be drivers of growth
3) Pricing mechanisms
4) Rules governing production (applicable to all biomass fuels) and use in transport

Figure 9 shows the main EU laws applicable to the biohydrogen market, broken down into these four areas.

**Figure 9.** Overview of EU frameworks applicable to biohydrogen




[67] The European Union has a shared competence with Member States in the field of energy, according to article 194, paragraph 2 of the Consolidated Version of the Treaty of the Functioning of the European Union (2012). ELI: https://eur-lex.europa.eu/eli/treaty/tfeu_2012/oj

Emission accounting rules within the EU European Trading Scheme (ETS) create a pricing mechanism based on the cost of emission allowances, commonly referred to as the 'carbon price'. All biogases consumed by companies under the EU ETS will be reported as zero emission, if they are compliant with the sustainability and GHG emission savings requirements of the RED[68], thus avoiding the purchase of emission allowances.

Similarly, in other sectors with a GHG emission reduction obligation or that are directly included in a national ETS (as is the case for transport fuel suppliers in Germany), the commercial value of biogases, including biohydrogen, is tied to the GHG emission savings they can provide relative to fossil fuels, as well as to penalty risks.

Five main EU laws regulate the use of energy carriers in the transport sector at different levels (refuelling infrastructure, public procurement, ship fleets and road vehicle manufacture, as per the orange boxes in Figure 9). They all support the use of hydrogen as a fuel with zero direct emission of greenhouse gases, whether it is of biological or non-biological origin[69]. The $CO_2$ Performance Standard Regulation for cars and vans was recently revised and now includes a ban on new vehicles using internal combustion engines from 2035 onwards[70]. This is expected to drive increased production of hydrogen fuel cell vehicles, along with electric vehicles.

## 6.2. Regulatory barriers for the uptake of biohydrogen

The existing EU regulatory framework hinders the deployment of biohydrogen at the level of market access and consumption drivers.

A) Lack of market access. This refers to the current failure to recognise biohydrogen as a hydrogen of renewable origin as well as to the lack of access to gas networks.

- The Renewable Energy Directive 2018/2001 (RED II), Article 19, mandates the set-up of registries of **Guarantees of Origin for renewable gases** for the purpose of proving and disclosing to consumers the renewable origin of the gases purchased. The **implementation to date** (May 2023) **has been slow**, however, preventing the recognition of the 'renewable' value of biomethane as well as biohydrogen.
- Article 19 of RED II also mandates the compliance of Guarantees of Origin (GOs) with EN Standard 16325: this is currently being revised to suit renewable gases but **the long revision process is delaying the adoption of interoperable GOs for renewable gases** across GO registries in the EU. If there is to be a distinct GO for biogas and biomethane and a GO for hydrogen, it should be ensured that biohydrogen is classed as a hydrogen and not as a biogas.
- **Access to dedicated hydrogen networks** is not regulated at EU level (as of May 2023) but should be soon thanks to the revision of the Gas Directive and the Gas Regulation[71]. Natural gas network operators are not yet allowed to operate 100% hydrogen networks. In December 2021, the European Commission published a Gas Package, one of the principle aims of which was to create a European hydrogen market based on dedicated infrastructure[72].
- **Blending of hydrogen in existing natural gas networks** is allowed in some Member States at the transmission level only, but rules differ between countries. In general, the

[68] See Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions. ELI: https://eur-lex.europa.eu/eli/reg_impl/2018/2066/2021-01-01 The consumer also has to support their accounting with Proofs of Sustainability and purchase records, according to European Commission. (17 October 2022). *Biomass issues in the EU ETS: MRR guidance document No. 3, Updated Version.* https://climate.ec.europa.eu/system/files/2022-10/gd3_biomass_issues_en.pdf

[69] The proposed regulation on the deployment of alternative fuels infrastructure (AFIR), Article 2, defines 'hydrogen' as one of the 'alternative fuels for zero-emission vehicles, vessels or aircraft'. European Commission. (14 July 2021). COM(2021) 559 final. CELEX: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021PC0559

[70] Regulation (EU) 2019/361 … of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles. Consolidated text. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02019R0631-20230515

[71] Directive 2009/73/EC … of 13 July 2009 concerning common rules for the internal market in natural gas. ELI: https://eur-lex.europa.eu/eli/dir/2009/73/oj
Regulation (EC) No 715/2009 … of 13 July 2009 on conditions for access to natural gas transition networks. ELI: https://eur-lex.europa.eu/eli/reg/2009/715/oj

[72] European Commission. (15 December 2021). Proposal for a directive of … on common rules for the internal markets in renewable and natural gases and in hydrogen. COM(2021) 803 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0803
European Commission. (15 December 2021). Proposal for a regulation … on the internal markets for renewable and natural gases and for hydrogen. (COM(2021) 804 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0804

responsibility of gas distribution operators to ensure the integrity of the gas systems and the quality delivered to end-users **does not empower them to engage in blending**.

B) Lack of price signals through taxation. The Energy Taxation Directive of 2003 does not recognise hydrogen as an energy product and does not therefore provide a common minimum level of taxation for it[73]. The revision proposal published in July 2021, as part of the Fit-for-55 Package, grants RFNBOs the lowest minimum taxation level[74]. According to the definitions set out in the RED II, however, as a gaseous fuel produced from biomass, biohydrogen would be classed as a biogas. Biogases are discriminated against in the proposed revisions to the 2003 Energy Taxation Directive because of the type of 'sustainable' feedstock used in their production. This means that, as they stand, the proposed revisions would prohibit biohydrogen from enjoying a level playing field with non-biological hydrogen, leaving it instead subject to the three-tiered taxation minima that applies to 'sustainable biogas'.

C) Insufficient and discriminatory consumption targets. The Renewable Energy Directive (RED) set sectoral consumption targets to support the growth of renewable energy production. Yet targets set under the RED II and the RED III discriminate against biohydrogen[75].

- In the transport sector, fuel suppliers are under an obligation to reach a specific share of renewable energy in their supply mix by 2030 (article 25). Under the RED III, this obligation can be translated into a GHG emission reduction. Such targets can indirectly support the uptake of biohydrogen in local transport modes if market access is made easy and Proofs of Sustainability can be easily used for the purpose of target accounting. The RED II, however, sets out two sub-targets, one for RFNBO and one for 'advanced biofuels and biogas'. As biohydrogen would be classed in the latter category, it cannot be considered on equal terms with RNFBO, i.e. hydrogen of non-biological origin, placing it at a disadvantage.
- RED III creates a specific target for the consumption of RFNBO in industry (article 22). At least 42% of hydrogen consumed as a feedstock or energy carrier must be of non-biological origin by 2030. This constitutes unjustifiable discrimination against biohydrogen.

## 6.3. Recommendations for an enabling EU framework

The following recommendations address biohydrogen only.

### A) Enforcing legal and market recognition

*1. Recognise biohydrogen as hydrogen of renewable origin in EU legislation and ensure harmonised application of this status across Member States.*

- The Renewable Energy Directive 2018/2001 should include a definition of renewable hydrogen that encompasses hydrogen of biological origin: **Renewable hydrogen refers to hydrogen produced through the electrolysis of water (powered by electricity stemming from renewable sources) as well as to hydrogen obtained from biogenic sources (such as biogases and biomass) via different production processes, including biological, thermochemical, and bioelectrochemical processes, provided that the biogases or biomass used are in compliance with sustainability criteria set out in Article 29 of Directive (EU) 2018/2001 of the European Parliament and of the Council.**
- Include an EU-wide definition of 'hydrogen' in the Gas Directive 2009/73/EC and the Gas Regulation 715/2009/EC that incorporates the

[73] Council Directive 2003/96/EC … of 27 October 2003 restructuring the Community framework for the taxation of energy products and electricity. ELI: https://eur-lex.europa.eu/eli/dir/2003/96/oj
[74] European Commission. (14 July 2021). Proposal for a Council directive restructuring the Union framework for the taxation of energy products and electricity. COM(2021) 563 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0563
[75] RED: Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources. ELI: https://eur-lex.europa.eu/eli/dir/2009/28/oj
REDII: Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. ELI: https://eur-lex.europa.eu/eli/dir/2018/2001/oj
REDIII: European Commission. (14 July 2021). *Proposal for a directive of the European Parliament and of the Council amending Directive (EU) 2018/2001 … as regards the promotion of energy from renewable sources.* COM(2021) 557 final. CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0557

- above definition of 'renewable hydrogen', so as to fully integrate biohydrogen into the gas and hydrogen markets.
- These definitions should also be referenced as appropriate in all relevant legislation, including the state aid rules, namely the GBER (General Block Exemption Regulation) and the CEEAG (State Aids Guidelines for Climate, Energy and Environment).

### B) Driving market access through consumption targets

*2. Expand targets for RFNBO in RED III to include all types of renewable hydrogen.*

Sectoral consumption targets focused on hydrogen in RED III should be technology neutral. The targets for RFNBO consumption in industry (Article 22a) and transport (Article 25(1)) should therefore be extended to all 'renewable hydrogen' based on the aforementioned definition.

*3. Ensure in the relevant EU legislation that corporate hydrogen consumers under reporting obligations[76] can fulfil those obligations by reporting their biohydrogen consumption and related GHG emission savings using market instruments such as Guarantees of Origin and Proofs of Sustainability.*

### C) Sending a price signal for renewable sources of hydrogen via taxation

*4. In the revision of the minimum taxation levels in the Energy Taxation Directive, a level playing field should be established for all sources of renewable hydrogen. If hydrogen of non-biological origin is awarded the lowest minimum, this should also be the case for hydrogen of biological origin.*

The revision of the Energy Taxation Directive should reference the above proposed definition of renewable hydrogen. If biohydrogen is 'sustainable' as per the sustainability and GHG savings criteria of the RED, then it should be granted the lowest minimum taxation level just like RFNBOs.

### D) Enabling network access

*5. The Gas Directive and the Gas Regulation should allow flexibility in the distribution methods for biohydrogen so as to facilitate its integration into gas markets.*

The growth of biohydrogen in energy markets will depend on its capacity to meet local needs (for transport and industry) quickly and cost-effectively[77]. Biohydrogen is expected to be produced in a decentralised way for local consumption, in addition to distribution via the central hydrogen backbone. As a consequence, distribution methods will have to adapt to local features.

Three main network-based distribution models should be allowed:

- Blending into existing gas distribution and transmission networks, based on a clear definition of roles and liabilities in the management of gas and hydrogen quality
- Dedicated hydrogen distribution networks built and operated by existing gas distribution system operators
- Private direct pipelines operated by a producer of hydrogen for a commercial consumer.

Allowing these three pathways will facilitate the development of an economically viable renewable hydrogen market.

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[76] That is, companies engaged in the EU ETS or under the reporting obligations of the Corporate Sustainability Reporting Directive.

[77] 'Even for short distances, it costs four times less to distribute hydrogen by pipeline than by truck'. Ready4H2. (March 2022). *Europe's Local Hydrogen Networks. Part 1: Local gas networks are getting ready to convert.* https://www.ready4h2.com/projects-3

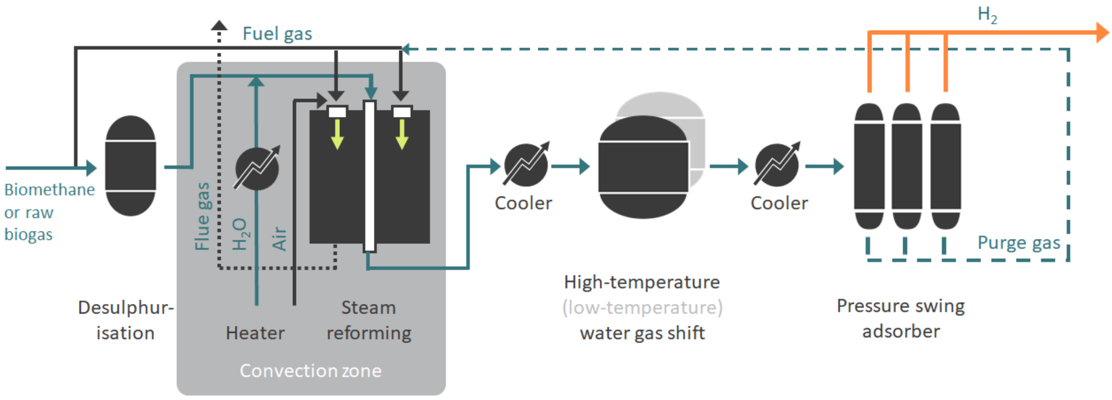
# Annex

## Biohydrogen technologies

### Raw Biogas and Biomethane Steam Reforming (BMSR)

After the water-gas shift, the hydrogen needs to be separated from the residual gases. In many cases, this is carried out with a pressure swing adsorber due to the level of purity this can achieve. The reformer is typically fueled by the purge gas from the pressure swing adsorber and part of the input gas stream. Biomethane (upgraded biogas) can be used in the process in exactly the same way as natural gas. Raw biogas from biogas plants can also be used in the process, although this can result in a slight reduction of efficiency due to extra carbon dioxide in the input stream. Steam reforming of raw biogas (or biomethane) can be conducted in compact reformers on-site at biogas plants. Alternatively, biomethane can be injected into the gas grid and used in a reforming process at a central, large-scale steam reformer. Heat management can play a significant role in the efficiency of the process and modern compact reformers strive to make the most of potential savings in this area. Both the reformate gas and the flue gas can be used to heat input streams. Compact steam reformers that can be used on-site at biogas plants to produce hydrogen from raw biogas are already being used in pilot projects. Steam reforming units for on-site production are currently available with a capacity of around 300 tonnes of hydrogen per year.

**Figure 10.** Schematic overview of the steam reforming process.




*Source: adapted from Gellert (2013) and Häussinger et al. (2000)*

### Dark Fermentation

During dark fermentation, microorganisms form hydrogen, biogenic carbon dioxide, organic acids and alcohols from biomass under anaerobic conditions. The process is identical to the first three of a total of four stages of biogas production. By preventing methanogenesis, the process is rendered less susceptible to high nitrogen concentrations, among other issues[78]. The metabolic stages of dark fermentation include hydrolysis, acidogenesis and acetogenesis. Hydrogen and carbon dioxide are produced during acido- and acetogenesis or via acetate oxidation (reverse homoacetogenesis), e.g. by bacteria from the family Clostridiaceae[79]. It is important to establish operational conditions suitable for hydrogen-producing bacteria, i.e., by regulating temperature and pH as well as hydraulic retention time according to the specific substrate, in order to maximise hydrogen production[80].

Biomass such as agricultural waste and residues or sewage sludge can be used for dark fermentation, which prefers low total solids and high

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concentrations of carbohydrates[81]. Substrate pre-treatment and adaptation of the inoculum are two possible strategies to increase the efficiency of dark fermentation[82].

As with all biohydrogen production routes, the further development of dark fermentation depends on the environmental and economic benefits. Dark fermentation will only become economically viable if use can be made of the volatile fatty organic acids that it generates as a co-product of hydrogen[83]. The simplest approach is to use these to produce biogas in a second fermenter.

### Microbial Electrolysis

Microbial electrolysis is based on the same principle as electrochemical water electrolysis. The main difference is that organic substances instead of water are oxidised at the anode of the electrolysis cell. In microbial electrolysis, biological catalysts, i.e. electroactive bacteria, oxidise organic substances such as volatile fatty acids and transfer electrons directly to the anode. In most cases, bacteria of the genus *Geobacter* are used for microbial electrolysis. These bacteria form self-sufficient biofilms on the surface of the anode (i.e. bioanode). The electrons released during the microbial oxidation of organic substances are transferred from the anode to the cathode (that is separated from the anode by an ion exchange membrane) and thus contribute to the generation of a cell voltage.

The hydrogen evolution reaction at the cathode is identical to water electrolysis (abiotic), but can also be realised using a biological catalyst [84][85]. The cell voltage generated by the oxidation of the carbon source is not sufficient to generate the necessary cathode potential for hydrogen evolution from water, however; for this reason, an additional voltage must be applied to the cell. At around 0.123 V, this voltage is much lower than the theoretical cell voltage of 1.23 V required for water electrolysis.

### Biophotolysis and Photofermentation

Biophotolysis includes all processes that produce hydrogen during photosynthesis under aerobic conditions (with oxygen). In principle, all photosynthetically active algae and cyanobacteria can produce hydrogen. Hydrogen serves as a kind of valve, expelling excess redox equivalents that are generated during intense photosynthesis activity. Two variants of biophotolysis exist today: direct and indirect biophotolysis. During direct biophotolysis, the transfer of excess electrons to protons occurs directly during light irradiation.

During indirect biophotolysis, the electrons are first used for the biosynthesis of hydrocarbons (starch, glycogen) and only converted to hydrogen in a subsequent step.

Alongside biophotolysis, there is also photofermenation in purple non-sulfur bacteria that perform a specific variation of photosynthesis under anaerobic conditions (without oxygen). These bacteria need organic substrates and light to grow and produce hydrogen.

Despite intensive study and innovation in recent decades, biophotolysis and photofermenation are still at the stage of application-oriented basic research. The advantage of biophotolysis is the easy availability of the reactants, namely, water and light.  An extra source of dissolved organic matter (e.g. organic acids such as acetate) is necessary for photofermentation. Both processes are able to provide valuable co-products such as omega-3 fatty acids, carotenoids and terpenoids, suitable for the food- or pharmaceutical industry.

The disadvantages of both pathways are still low hydrogen yields, low efficiency (of light conversion) and, especially in the case of biophotolysis, the oxygen sensitivity of the key enzymes involved (hydrogenases and nitrogenases). Furthermore, the reactor technology and operation are relatively expensive.

### Pyrolysis

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[85] Rozendal et al. (September 2006).

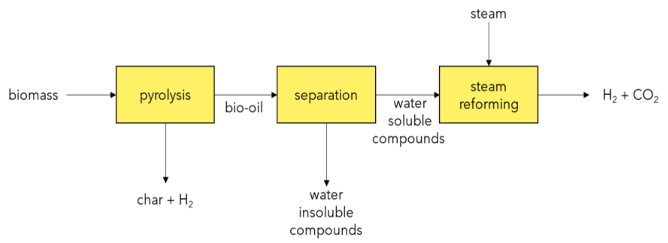
Biomass pyrolysis is one of the most interesting routes to valorise lignocellulosic biomass, affording the direct generation of condensable products (bio-oil) and incondensable gaseous products, both of which have significant potential to produce higher purity biohydrogen. A solid fraction (char) is also produced but this is used in other applications. Pyrolysis is a seemingly simple process, involving the thermal decomposition of biomass in the absence of oxygen, usually performed in an inert atmosphere at high temperatures (400 – 650 °C) and at a pressure between 0.1 and 0.5 MPa. The pyrolysis process can be divided into two categories: conventional (slow) and fast/flash pyrolysis. Slow pyrolysis is associated with high char production, while in the fast pyrolysis of biomass, high-temperature gas and low-temperature tars are generated. Fast pyrolysis is therefore favored for the direct production of hydrogen from solid biomass based on the following reaction[86]:

$$CnHmOk + heat \rightarrow CO + H_2 + CH_4 + others$$

The hydrogen production yield can be improved through the catalytic reforming of gaseous intermediates, i.e., steam reforming of methane or water-gas shift between gaseous carbon monoxide and water.
More recently, reforming bio-oil has also been proposed as a pathway to produce hydrogen. A two-step process is used, involving the conversion of biomass to bio-oil via fast pyrolysis followed by the catalytic steam reforming of the bio-oil via the following reactions[87]:

$$CnHmOk + (n-k)\ H_2O \rightarrow n\ CO + (n + (m/2) - k)\ H_2$$
$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

**Figure 11.** Diagram of biohydrogen production via pyrolysis and steam reforming




*Source: Aziz et al. (2021)*

Fast pyrolysis and bio-oil steam reforming can be carried out at different locations, which can be more convenient depending on biomass availability, hydrogen demand and distribution infrastructure. The economy of the process is an essential issue to consider in the catalytic steam reforming of bio-oils. Constraints to production on an industrial scale using this method are catalyst deactivation caused by carbon deposition, and technical difficulties arising from the complex chemistry of bio-oil composition. This has so far hindered the scaled-up application of steam reforming. The development of catalysts with increased coke resistance, and with a good regeneration ability to restore catalytic activity, is crucial. In general, deactivated catalysts can be regenerated and processes such as combustion or gasification with air, oxygen, or steam can be used for the removal of coke from the catalyst surface[88].

### Gasification

Gasification is a versatile technology converting biomass and other solid wastes into a producer gas at relatively high temperatures. Other solid and liquid co-products are also generated (namely chars and tars after gas condensation); these and can be minimised by adjusting operating conditions.
Gasification processes may be conducted in different reactor configurations with different gasification agents and generate distinct compositions of producer gas, which can include carbon monoxide, hydrogen, carbon dioxide, methane and traces of lighter hydrocarbons and

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[88] Setiabudi et al. (2020)

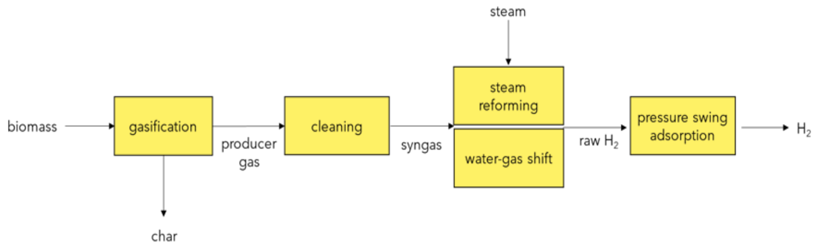
contaminants (ammonia, hydrogen sulphide and hydrogen chloride). Alongside air gasification, which is the most-used technology due to its simple design and low cost, oxygen is often employed as the gasifying agent in order to optimise hydrogen production. In oxygen gasification technology, adding steam is common practice, not only due to the stoichiometric effect, but also for enhanced char gasification and temperature moderation within the reactor[89]. Residual lignocellulosic biomass and the biogenic fraction of wastes are both useful feedstocks for the production of green hydrogen via gasification. Residual biomass is derived from forestry, agriculture (e.g. cereal straw, corn stover, pruning), agro-industry (e.g. dried fruit shells, olive pomace, citrus pulp) and wood processing; waste streams from other processes can also be valorised for energy purposes rather than being disposed of. The table below presents the typical producer gas composition in terms of hydrogen, according to the oxidising agent used in gasification. Other gasification-based technologies, such as sorption-enhanced gasification and chemical loop gasification, can yield gas streams with higher hydrogen contents.

Table 8. Hydrogen concentration and other relevant characteristics of gasification producer gas as a function of the oxidising agent[90]

| Oxidising agent | $H_2$ concentration | $H_2$ to CO ratio | Typical HHV ($MJ/Nm^3$) |
|---|---|---|---|
| Air | 15% | 0.75 | 5-7 |
| Oxygen | 40% | 1.0 | 10-15 |
| Steam | 40% | 1.6 | 8-16 |

As for pyrolysis processes, the catalytic upgrading of gaseous intermediates via steam reforming and water-gas shift is the most widely practised route for biohydrogen production. Appropriate cleaning steps are essential before upgrading the hydrogen-rich producer gas into a high purity hydrogen stream. As the final step, pressure swing adsorption is the most used hydrogen separation technique, capable of achieving a purity higher than 99.99%[91].

**Figure 12.** Diagram of biohydrogen production via gasification




*Source: Aziz et al. (2021)*

Gas cleaning and upgrading unit operations (including water-gas shift and pressure swing adsorption) are currently well-developed, technology-proven and available on the market. The integration of gasification technology with established gas conditioning operations needs to be further developed, however, in order to consolidate gasification as a sustainable pathway for bio-hydrogen production

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[90] Aziz et al. (2021).
[91] Voldsund, M., Jordal, K. & Anantharaman R. (9 March 2016). Hydrogen production with CO2 capture. *International Journal of Hydrogen Energy, 41*(9), 4969-4992. https://doi.org/10.1016/j.ijhydene.2016.01.009

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## About the EBA

The EBA is the voice of renewable gas in Europe. Founded in February 2009, the association is committed to the active promotion of sustainable biogas and biomethane production and their use across the continent. The EBA today counts on a well-established network of over 250 national organisations, scientific institutes and companies from Europe and beyond.

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## Imprint

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