Renewable Hydrogen

Opportunities, limitations and threats of hydrogen for the energy transition in Europe

Position Paper
of ETIP RHC and ETIP Bioenergy

MARCH 2023

Authors: Dominik Rutz, Rainer Janssen, WIP Renewable Energies
Panagiotis Boutikos, Kostis Atsonios, Panagiotis Grammelis, CERTH
Christoph Brunner, AEE INTEC
Marco Calderoni, R2M Solution
Michael Friedmann, ICT-Impact
Franziska Müller-Langer, DBFZ
Teresa Mata, INEGI LAETA
António Martins, LEPABE ALICE
Walter Haslinger, BEST Research

Contact: Dominik Rutz, dominik.rutz@wip-munich.de, +49 (0)89 720 12 739

Websites: www.rhc-platform.org, www.etipbioenergy.eu

Funded by the
European Union

This position paper is the result of collaborative work in form of a Task force between ETIP RHC and ETIP Bioenergy. The opinions expressed in this document are the sole responsibility of the ETIP RHC and ETIP Bioenergy and do not necessarily represent the official position of the European Commission. Reproduction and translation for non-commercial purposes are authorised, provided the source is acknowledge and the Editor is given prior notice and sent a copy.
Both RHC ETIP and ETIP Bioenergy are officially endorsed by the European Commission and its activities are supported by the Horizon Europe research and innovation programme (GA N° 101075746 & GA N° 101075503).

TABLE OF CONTENTS

1 SUMMARY - OUR POSITION

Renewable hydrogen is an energy carrier which can be one contributor, among many, to support the energy transition in Europe. However, its production and use is subject to many limitations, particularly of an economic nature. Renewable hydrogen will only play an important role in value chains where the specific properties of hydrogen are of high value. For both, the bioeconomy, as well as for the renewable heating and cooling sector, multiple production routes and uses of hydrogen could be potentially applicable.

On the other hand, there is the risk that excessive focus on certain capital-intensive technologies, such as hydrogen, to the detriment of others with much faster impacts, can be a serious obstacle to a rapid and efficient decarbonization of the thermal sector. It is therefore important to carefully check the role of hydrogen in a hypothetical future under the assumption of large investments, but also to evaluate its potential application niches in comparison to commercially available renewable thermal technologies that can meet the same needs in a shorter term and with higher profitability.

In summary, the production and use of renewable hydrogen can be an important building block for the energy transition, but certainly not the only or even the most important solution. The positions of ETIP RHC and ETIP Bioenergy were presented in the paper. The key messages are summarised on the next page.

Our key messages:

- We need **massive financial support on innovations, research, further development, and market uptake for all types of renewable energy sources and systems.** Financial support on hydrogen should not cut or compromise the support for renewable energies.

- **Hydrogen per se is not necessarily sustainable** as it is no source of energy, but only an energy carrier. Its sustainability is closely related to the source of energy which is used to produce hydrogen. We consider that only renewable hydrogen, meaning hydrogen produced by renewable energy sources, can be in principle sustainable.

- In the light of the climate challenge and the enormous transition we are facing, we strongly recommend to focus any support of hydrogen on all forms of **renewable hydrogen** and to **stop supporting fossil or low-carbon hydrogen.**

- Hydrogen is a universal energy carrier and can be used for many purposes. Yet it will be **impossible to satisfy all demand for hydrogen**, and thus it should be used for applications with only few other alternatives, also called hard-to-abate sectors. These can be for example high temperature industrial processes or selected transport applications.

- **We do not see that the direct use of hydrogen in the domestic heating and cooling sector plays an important role** in the future. Instead, a massive deployment of different renewable energy technologies, including liquid, gaseous and solid biofuels, must happen and be supported.

- With this document, we are providing **feedback to the European Hydrogen Strategy** on the role we see for hydrogen for a climate-neutral Europe. We acknowledge the definitions of the European Hydrogen Strategy on renewable hydrogen, but we feel that other pathways such as biohydrogen and solar hydrogen are neglected and should be addressed as well.

- In terms of energy efficiency, **heat that is released** during hydrogen production should be used.

- **Various pathways** can be taken to produce hydrogen from renewable sources. The pathways are at different levels of technology and market maturity and come with specific R&D needs, costs and GHG emissions.

2 INTRODUCTION

To mitigate impacts of climate change and to reduce the dependency on energy imports, there is an urgent need to decarbonize the European energy supply as fast as possible. A rapid shift to 100% renewables in all sectors is required but needs the political will and support, and large investments from both the public and private sectors. To enable a complete energy transition, technologies, components and energy carriers are needed which facilitate energy storage and which manage intermittent and imbalanced energy supply and demand, hence enabling the decarbonization of **hard-to-decarbonize** (hard-to-abate) sectors.

Recently, hydrogen enjoyed renewed and rapidly growing attention. It is seen as key commodity for a successful energy transition. It can be used both as an energy carrier but also as a feedstock for the chemical industry. Thereby, it needs to be highlighted that **hydrogen is not a renewable energy source, but a means to store energy or facilitate its transformation and transport in given processes or of from pre-existing energy sources. It is more appropriately, thus, to term it as "energy carrier"**, that can be produced through different renewable energy technologies, as well as by means of fossil energy.

The European Commission has published "**A hydrogen strategy for a climate-neutral Europe**"[1] (EC Hydrogen Strategy) providing an overview on the current status of hydrogen in Europe as well as a clear vision on hydrogen development. In this document, "the Commission invites the Parliament, the Council, other EU institutions, social partners and all stakeholders to discuss how to leverage the potential of hydrogen to decarbonise our economy while making it more competitive, building on the actions set out in this Communication."

Furthermore, hydrogen has been identified as an important pillar in the **REPowerEU Plan**[2] of the European Commission, which objective is to make Europe independent from Russian fossil fuels well before 2030, in light of Russia's invasion of Ukraine. It is also considered in this context that hydrogen may play an important role in hard-to-decarbonise sectors, such as aviation and maritime and certain industrial sectors.

---

[1] https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
[2] https://ec.europa.eu/commission/presscorner/api/files/attachment/872548/FS_CleanEnergy.pdf

In the REPowerEU plan and its accompanying documents[3], the Commission outlines actions to scale up demand and supply even faster and higher than in the 2020 Hydrogen Strategy. The REPowerEU ambition is to produce 10 million tonnes (mt) of renewable hydrogen in the EU by 2030 – increased from the 5.6 mt already foreseen within the proposals of the EU framework to decarbonise gas markets published in December 2021 – and to import 10 mt of renewable hydrogen from third countries. The role of hydrogen is also highlighted in the "**Hydrogen Europe Position Paper** - Delivering REPowerEU through a strong European hydrogen industry"[4] from Hydrogen Europe.

The European Technology and Innovation Platform on Renewable Heating and Cooling (**RHC-ETIP**)[5] and the European Technology and Innovation Platform on Bioenergy (**ETIP Bioenergy**)[6] represent multiple stakeholders in their sectors and thus respond to the request, as stated by the EC above.

The **objective of this joint position paper** is to discuss and to take position on the role of hydrogen for a climate-neutral Europe from the perspective of both ETIPs.

---

[3] https://ec.europa.eu/info/news/commission-launches-consultation-regulatory-framework-renewable-hydrogen-2022-may-20_en#:~:text=The%20REPowerEU%20ambition%20is%20to%20produce%2010%20million,10%20mt%20of%20renewable%20hydrogen%20from%20third%20countries.
[4] https://hydrogeneurope.eu/wp-content/uploads/2022/05/2022.05.16_HE_PositionPaper_REPowerEU.pdf
[5] https://www.rhc-platform.org/
[6] https://www.etipbioenergy.eu/

3 PRODUCTION OF HYDROGEN

The Renewable Energy Directive II[7] (REDII) defines '**renewable energy**' as "energy from renewable non-fossil sources, namely wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas." The generation and utilization of these renewable energies should be **as efficient as possible**. The minimization of conversion steps between generation and use is required to reduce energetic losses.

However, intermediate conversion steps are needed to either **store energy** (also chemically), or to provide **condensed forms of energy**, which is important for transport applications, or to supply **hard-to-decarbonize sectors**, in particular energy intensive industries requiring large amounts of energy (e.g. chemical industry) and industries requiring high temperatures (e.g. glass industry).

The EC Hydrogen Strategy defined **different types of hydrogen**, including Electricity-based hydrogen, Renewable hydrogen, Clean hydrogen, Fossil-based hydrogen, Fossil-based hydrogen with carbon capture, Low-carbon hydrogen, and Hydrogen-derived synthetic fuels.

It is stated that the *"priority for the EU is to develop renewable hydrogen, produced using mainly wind and solar energy" and "in the short and medium term, however, other forms of low-carbon hydrogen are needed, primarily to rapidly reduce emissions from existing hydrogen production and support the parallel and future uptake of renewable hydrogen."*

Thereby the definitions for renewable hydrogen and low carbon hydrogen, **according to the Hydrogen Strategy**, are:

- '**Renewable hydrogen**' is hydrogen produced through the electrolysis of water (in an electrolyser, powered by electricity), and with the electricity stemming from renewable sources. The full life-cycle greenhouse gas emissions of the production of renewable hydrogen are close to zero. Renewable hydrogen may also be produced through the reforming of biogas (instead of natural gas) or biochemical conversion of biomass, if in compliance with sustainability requirements.

---

[7] 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 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

- ‘**Low-carbon hydrogen**’ encompasses fossil-based hydrogen with carbon capture and electricity-based hydrogen, with significantly reduced full life-cycle greenhouse gas emissions compared to existing hydrogen production.

A bottleneck of these definitions is that renewable hydrogen mainly focuses on the production route of electrolysis of water. Thermochemical pathways of hydrogen production from biomass, as well as technologies directly using solar irradiation (e.g. photocatalysis) are not addressed. Both need to be included in official definitions for renewable hydrogen, and their relative merits should be highlighted, taking into account the hydrogen production full life cycle.

Our position:

- We highly acknowledge the need to produce **renewable hydrogen using renewable surplus electricity in the power grid**, which is caused by intermittent renewable energy sources and imbalances between demand and supply.

- We suggest including in the definition of ‘renewable hydrogen’ also hydrogen that is produced by **biomass conversion routes**.

- We suggest including in the definition of ‘renewable hydrogen’ also hydrogen that is produced through **solar thermal energy and solar photons**. The generation of renewable hydrogen from photocatalytic or thermo-catalytic processes is a promising future conversion technology.

- There is a risk of supporting other forms of low-carbon hydrogen, as it still supports the use of fossil fuels. This continues the dependencies on fossil fuel imports to the EU. **We discourage the support of low-carbon hydrogen**, even in the short-to-medium term, and instead suggest to put full emphasis on renewable hydrogen.

3.1 Hydrogen from biomass

Bioenergy is heat, power or biofuels (solid, liquid or gaseous) using **biomass** as feedstock. Biomass means the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin (Renewable Energy Directive 2018)[8]. It is possible to use various processes to transform biomass into energy and other industrially relevant high-interest products, such as liquid biofuels (e.g. bioethanol) and hydrogen.

There are many options for producing hydrogen from biomass (biohydrogen). Two main pathways can be defined, namely **thermochemical and bio-chemical/biological** hydrogen production pathways (Figure 1)[9],[10]. Thermochemical conversion technologies include a series of chemical reactions for releasing hydrogen. The primary thermochemical routes for hydrogen production are gasification, pyrolysis, steam reforming and supercritical water gasification (SCWG). Biological pathways include anaerobic digestion, fermentative hydrogen production (dark- and photo-fermentation) and photolysis[11]. A promising technology is the chemical looping hydrogen process (CLH) to produce high-purity hydrogen[12],[13]. The process principle is based on the reduction of a suitable metal oxide by syngas or biogas in a first step and the subsequent reoxidation of the metal oxide with steam, producing hydrogen as a product.

---

[8] 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 (recast); https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

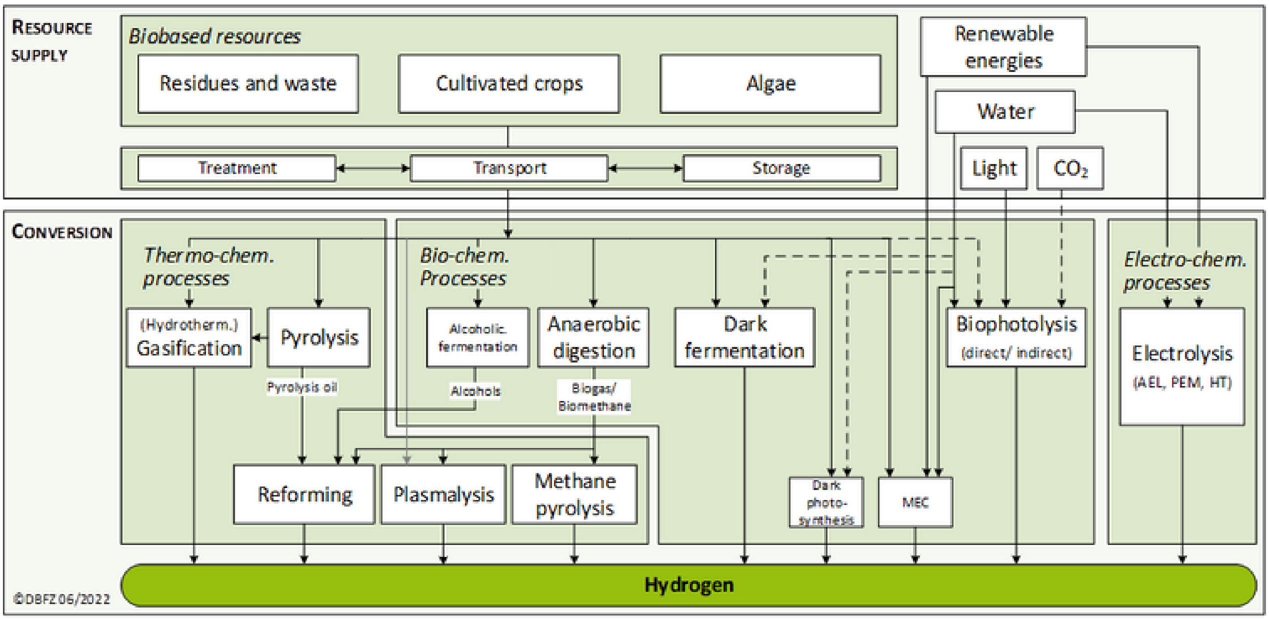
[9] Dögnitz, N.; Hauschild, S.; Cyffka, K.F.; Meisel, K.; Dietrich, S.; Müller-Langer, F.; Majer, S.; Kretzschmar, J.; Schmidt, C.; Reinholz, T.; Gramann, J. (2022): Wasserstoff aus Biomasse (DBFZ-Report, 46). Leipzig: DBFZ. 102 S. ISBN: 978-3-946629-88-7. DOI: 10.48480/b4wn-c154

[10] Buffi M., Prussi M., Scarlat N. (2022) Energy and environmental assessment of hydrogen from biomass sources: Challenges and perspectives. - Biomass and Bioenergy, Volume 165, 2022, 106556, ISSN 0961-9534, https://doi.org/10.1016/j.biombioe.2022.106556. (https://www.sciencedirect.com/science/article/pii/S0961953422002185)

[11] Pareek A.; Dom R.; Gupta J.; Chandran J.; Adepu V.; Borse P.H.; Insights into renewable hydrogen energy: Recent advances and prospects. Mat. Sci. Energy. Technol. 2020, 3, 319.

[12] Bock S.; Stoppacher B.; Malli K.; Lammer M.; Hacker, V. Techno-economic analysis of fixed-bed chemical looping for decentralized, fuel-cell-grade hydrogen production coupled with a 3 MWth biogas digester. Energy Conv. and Management. 2021, 250:114801. DOI: 10.1016/j.enconman.2021.114801

[13] Luo M.; Yi Y.; Wang S.; Wang Z.; Du M.; Pan J.; Wang Q. (2018). Review of hydrogen production using chemical-looping technology. Renew. and Sust. Energy Reviews. 2018, 81:3186–3214. DOI: 10.1016/j.rser.2017.07.007



(without claiming to be exhaustive), MEC | microbiell electrolyse cells, AEL | alkaline electrolysis, PEM | Polymer electrolyt membrane, HT | high temperature water steam

Figure 1: Overview on pathways for renewable hydrogen with focus on hydrogen from biomass

Thermochemical pathways for hydrogen production have the advantage of being already available at industrial scale, since they are based on current well-established technologies for fossil fuels conversion. Conversion efficiencies of thermochemical pathways are in the range of 35-70%, depending on the used technology. However, also these processes release carbon dioxide (CO2) and to achieve negative GHG emissions[14], require the coupling of bioenergy generation with carbon capture concepts (Bioenergy with carbon capture and storage BECCS, Bioenergy with carbon capture and utilization, BECCU).

In general, bio-chemical/biological routes are less energy intensive, as they usually operate under mild conditions (ambient temperature and pressure). However, these methods suffer from slow conversion rates and low hydrogen yields, requiring larger reactor volumes.

In terms of efficiency, dark fermentation (~ 80%) can compete with the above-mentioned processes.[14] Consequently, biomass can contribute mainly in large scale generation facilities through thermochemical pathways of gasification and pyrolysis, whereas biological processes may be used in more small-scale hydrogen production facilities which are flexible enough to adapt to local available resources.

---

[14] Lepage T.; Kammoun M.; Schmetz Q.; Richel A. Biomass-to-hydrogen: A review of the main routes production, processes evaluation and techno-economical assessment. Biomass and Bioenergy 2021,144, 105920.

Depending on the process and its design, hydrogen could be the main product or a by-product. Table 1 lists relevant hydrogen production technologies with the respective technology readiness level (TRL), hydrogen quality and possible application perspectives, without claiming to be exhaustive.[15] Furthermore, the compliance with the purity requirements defined in the standards ISO/DIS 14687 or DIN EN 17124 is essential for hydrogen utilization, which may require the coupling of hydrogen purification units in the production processes.

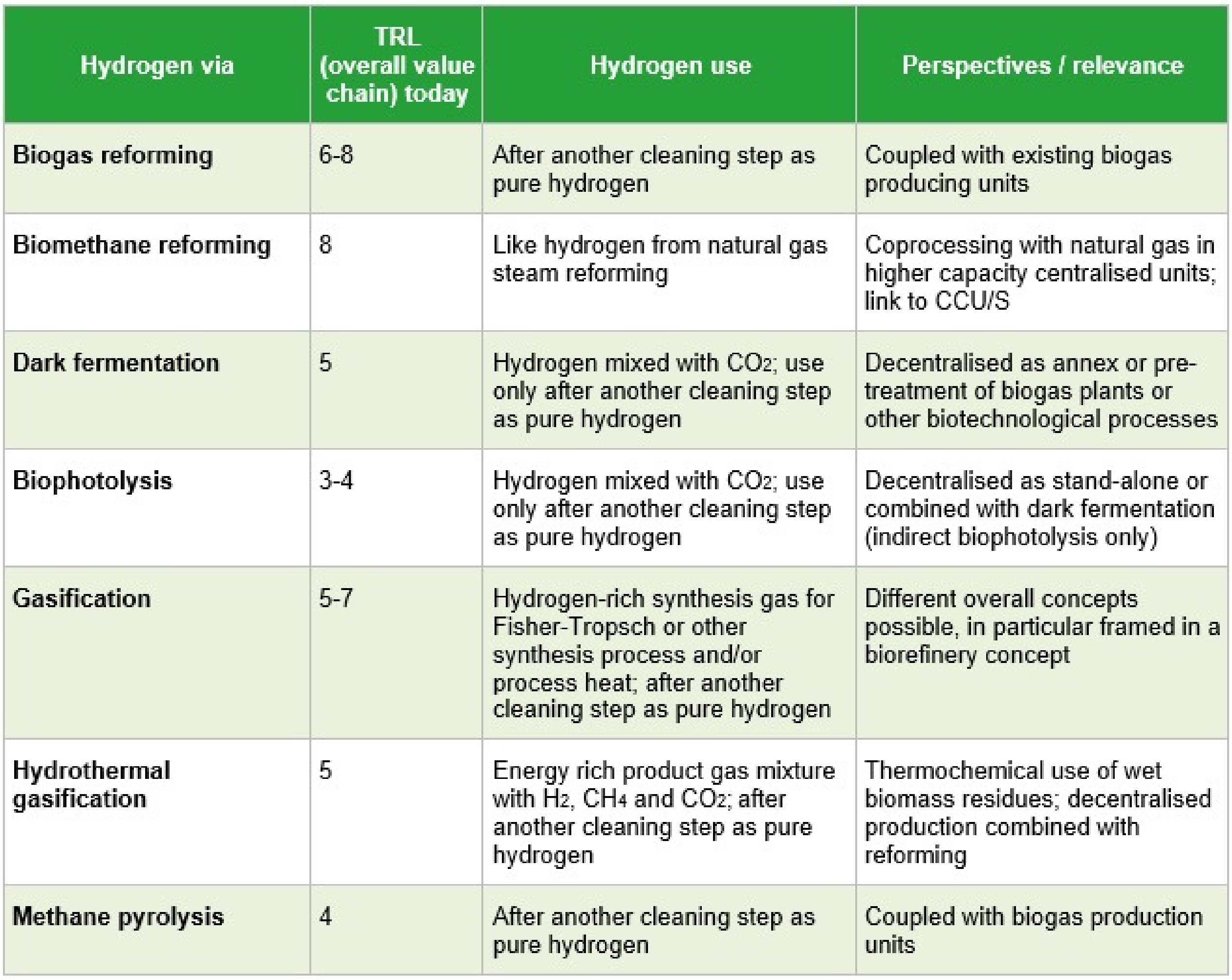
The first decentralised or small-scale hydrogen production plants based on biogas/biomethane processes are under construction; hence experience in commercial operation has yet to be gained. In the short term, co-refining of biomethane from the natural gas grid could be implemented in the classic commercially established steam reforming processes in large-scale plants.

Research and development projects which are based on thermochemical gasification and biotechnological dark fermentation are being pursued more with the aim of producing hydrogen as a by-product or synthesis gas component, usually integrated in a biorefinery process in which various products (e.g. fuels, chemicals) are obtained. Projects on biomass steam gasification aim to produce a hydrogen rich syngas (> 40 vol%). Its hydrogen content can further be increased by sorption enhanced reforming (SER) up to 70 vol%. Further research and demonstration are also needed on BECCS and BECCU concepts for processes in which CO2 or carbon is produced as a result of the process.

---

[15] Mueller-Langer, F., Kretzschmar J, Kornatz, P. et al.: Wasserstoff aus Biomasse. In: FVEE-Themenheft: Mit Wasserstoff zur Klimaneutralität – von der Forschung in die Anwendung Beiträge zur FVEE-Jahrestagung 2021, Online: https://www.fvee.de/wp-content/uploads/2022/07/th2021_fvee.pdf

Table 1 - Comparison of technology options for biohydrogen



Hydrogen via	TRL (overall value chain) today	Hydrogen use	Perspectives / relevance
Biogas reforming	6-8	After another cleaning step as pure hydrogen	Coupled with existing biogas producing units
Biomethane reforming	8	Like hydrogen from natural gas steam reforming	Coprocessing with natural gas in higher capacity centralised units; link to CCU/S
Dark fermentation	5	Hydrogen mixed with CO_2; use only after another cleaning step as pure hydrogen	Decentralised as annex or pre-treatment of biogas plants or other biotechnological processes
Biophotolysis	3-4	Hydrogen mixed with CO_2; use only after another cleaning step as pure hydrogen	Decentralised as stand-alone or combined with dark fermentation (indirect biophotolysis only)
Gasification	5-7	Hydrogen-rich synthesis gas for Fisher-Tropsch or other synthesis process and/or process heat; after another cleaning step as pure hydrogen	Different overall concepts possible, in particular framed in a biorefinery concept
Hydrothermal gasification	5	Energy rich product gas mixture with H_2, CH_4 and CO_2; after another cleaning step as pure hydrogen	Thermochemical use of wet biomass residues; decentralised production combined with reforming
Methane pyrolysis	4	After another cleaning step as pure hydrogen	Coupled with biogas production units

As with all biomass-based products, **sustainability indicators** such as costs and greenhouse gas emissions for biohydrogen are strongly dependent on the respective overall concept and on the nature of the resources used, the technology and the scaling of the plant. Compared with renewable hydrogen from electrolysis, there is currently no advantage per se for biohydrogen.

Advantageous or even negative greenhouse gas balances for biohydrogen usually result from the use of biogenic waste and residual materials and/or if additional process-related CO2 or waste carbon is used. Compared to green hydrogen from electrolysis, only concepts with organic residues or waste materials (e.g. liquid manure) and/or CO2 utilisation have an advantage[16].

Available studies on the production of biohydrogen are mainly limited to steam reforming and gasification, and show high variability in the results, e.g., in terms of production costs, ranging from 16 to 93 EUR/GJ (normalised to 2020, average 5 to 8 EUR/kg), and in terms of GHG emissions varying from -100 to 60 kg GHG/MJ (acc. RED methodology).

---

[16] Dögnitz, N.; Hauschild, S.; Cyffka, K.F.; Meisel, K.; Dietrich, S.; Müller-Langer, F.; Majer, S.; Kretzschmar, J.; Schmidt, C.; Reinholz, T.; Gramann, J. (2022): Wasserstoff aus Biomasse (DBFZ-Report, 46). Leipzig: DBFZ. 102 S. ISBN: 978-3-946629-88-7. DOI: 10.48480/b4wn-c154

To qualitatively assess the **costs** derived from each hydrogen production route, variables such as the energy source, feedstock used, capital investment (CAPEX) and operational costs (OPEX) must be taken into account.[17]

Plant size and capacity influence the CAPEX. The larger the facilities the higher the CAPEX, but production costs are lower. The CAPEX can be potentially also reduced, if already existing infrastructure can be used, for example, if biomethane is used in existing steam reforming plants, substituting natural gas.

Regarding OPEX, the price of the biomass feedstock, which is directly related to its availability and transport, is the main factor in the production costs. The price for biomass should be as cheap as possible to decrease overall hydrogen production costs. Biomass gasification and pyrolysis offer viable approaches with production costs in the range of 1.25 – 2.2 USD/kg H2 (based on 2004 values).[18] According to a 2014 study, (dark- & photo)-fermentation can produce H2 prices between 2.5 and 2.8 USD/kg, but significant barriers to a full industrial implementation are the low H2 yields and the larger reactors needed.

Other renewable hydrogen processes, as for example water electrolysis, do not directly cause carbon emissions, but have a high electrical consumption (4.5 – 56.0 kWh/m3 (STP) H2).14 This technology has a high TRL, but the industrial production is currently at a small scale. Felgenhaur and Hamacher compared the process efficiencies and determined that for a similar productivity (90 kg/h), the CAPEX of water electrolysis (4 M EUR) is lower than gasification (9.9 M EUR).[18] Electrical consumption is the main reason for the high OPEX, especially when renewable electricity is use. The H2 production cost is expected to decrease in the future with technology development lowering costs from 5.0 EUR/kg H2 to 2.3 EUR/kg H2 for alkaline electrolysis. [19]

---

[17] Nikolaidis P.; Poullikkas A. A comparative overview of hydrogen production processes. Renew. Sustain. Energy Rev. 2017, 67, 597.

[18] Felgenhauer M.; Hamacher T. State-of-the-art of commercial electrolyzers and on-site hydrogen generation for logistic vehicles in South Carolina, Int. J. Hydrogen Energy 2015, 40, 2084.

[19] Proost J.; State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings, Int. J. Hydrogen Energy 2019, 44, 4406.

Our position:

- Biohydrogen can **contribute to build-up a hydrogen economy**, but the availability of biomass and the process life cycle emissions need to be taken into account.

- Biohydrogen is a very relevant source for renewable hydrogen, but much R&D efforts are still needed to **reduce costs**.

- With adequate consideration of the cost factors for biomass and the value of biogenic carbon, biohydrogen processes can be an economical viable treatment option for the treatment of biogenic **waste/residues**.

- Thermochemical **pyrolysis and gasification** technologies for hydrogen production provide very high potential to become competitive on a large scale in the near future.

- **Fermentative hydrogen** production is still in infancy, and thus needs significant research and development before reacting commercial scale.

- Common to all processes is the importance of H2 **purification** according to the quality requirements for the subsequent application.

- In the short term, biohydrogen could be produced mainly by known processes via **reforming of methane-rich gases**. For the future, **fermentative** and **thermochemical processes** are promising options.

3.2 Hydrogen from solar energy

Solar energy can be used for photo-electrochemical, photocatalytic and thermochemical pathways of hydrogen production.

Hydrogen production by **photo-electrochemical water splitting** uses photo-electrochemical cells (PEC) in which special materials are used for direct light-induced water splitting. A photoelectrochemical cell consists of two electrodes (made of metal or semiconductor) bathed by a aqueous electrolyte solution in which the water electrolysis happens with the help of solar photons. **Photocatalysis** differs from photo-electrochemical water splitting mainly because no counter electrode is applied to the photochemically active semiconductor. Hydrogen production by water splitting in a photo-electrochemical cell was first reported in 1972. In this process, a photo-anode made of TiO2 was used under UV illumination[20].

In recent years, there have been promising advances, for example through **nano-structuring**. A hybrid photo-electrochemical-photovoltaic (PEC-PV) tandem device for light-driven water splitting was developed under the European project PECDEMO (Photoelectrochemical Demonstrator Device).

The photo-electrochemical as well as the photocatalytic processes are still in the experimental phase and have a TRL of 2 to 4. Thus, although these technologies represent promising approaches for the production of hydrogen from solar energy, in particular at small scale and local level, further research efforts are needed to reach practical implementation. Efficiencies between 5% and 15% have already been achieved using the best available materials and catalysts[21]. Significant research and development remain necessary to identify suitable long-term stable materials for the semiconductor layers[22]. The decisive factors will be the levels of efficiency that can be achieved in long-term operation and whether and how the hydrogen can be effectively collected and cleaned on a large scale. In the PECDEMO project, techno-economic considerations were carried out in which a system efficiency of 8% was assumed. This would result in hydrogen production costs of 9 EUR/kg[23]. If higher efficiencies are achieved in the conversion of sunlight into hydrogen, significantly lower production costs can be achieved.

---

[20] A. Kay, I. Cesar, M. Gratzel, New benchmark for water photooxidation by nano structured α-Fe2O3 films, Journal of the American Chemical Society, 2006, 128, 15714-15721.
[21] Erneuerbarer Wasserstoff, https://www.fvee.de/fileadmin/publikationen/Programmbroschuere/fz2019/fz2019_03_03_02.pdf (13.01.2020).
[22] Hydrogen implement Agreement – Task 35 in Annual Report, http://ieahydrogen. org/pdfs/2014-Annual-Report-Task-Reports/2014-Annual-Report_Task35.aspx (10.01.2020).
[23] A. Maljusch, M. Wullenkord, Technoeconomic Analysis of PEC Water Splitting at Various Scales in Advances in Photoelectrochemical Water Splitting: Theory, Experiment and Systems Analysis, Royal Society of Chemistry, 2018.

In addition to photo-electrochemical pathways for hydrogen production, **thermochemical pathways that use heat provided by solar thermal energy** to produce renewable hydrogen can be exploited. Water splitting by heat promises particularly high efficiencies and thus low hydrogen production costs. Two paths for water splitting have emerged in research that are particularly promising in terms of efficiency: metal oxide redox and sulphur cycle processes.

In the **metal oxide redox cycle** process, a redox material is typically first reduced cyclically and then oxidized in a further process step. The redox material is in contact with water vapor and oxidizes the oxygen and reduces the hydrogen, generating gaseous oxygen and hydrogen. In these cyclic processes the redox material assumes different states, but is not consumed itself. The reduction step is endothermic and usually takes place at high temperatures above 1,000°C. In addition to two-step processes, there are a number of other processes that consist of a higher number of process steps, which allows lower maximum temperatures. The required process temperatures are mainly determined by the catalysts used. A distinction can be made between systems in which the redox material undergoes a phase transition in the process and those in which this is not the case.

The generation potential in Europe and worldwide depends mainly on the solar radiation and the availability of suitable areas for solar fields. Capital costs, which can differ from region to region, are one of the main cost factors for hydrogen generation. In a recent study, hydrogen costs of 3.20 EUR/kg of hydrogen were predicted (in comparison to cost of kerosene of 1.90 EUR/l).

In a nutshell, solar thermochemical metal oxide redox cycle processes represent a promising opportunity to produce hydrogen on a large scale and in an economically viable way. The processes, components and materials required have been developed in several national and international projects in recent years. The wide range of possible catalysts and process concepts suggests that further increases in efficiency and associated cost reductions are likely in the future.

Two **sulphur cycle** processes are known, which are thermochemical processes based on the thermal cracking of sulfuric acid. One is the **sulfuric acid-iodine process**, for which initial investigations of the reaction mechanisms promised a possible thermal efficiency of 47%[24].

---

[24] H. Norman, G. E. Besenbruch, L. C. Brown, D. R. O'Keefe, C. L. Allen, Thermochemical water-splitting cycle, bench-scale investigations, and process engineering. Final report, February 1977-December 31, 1981, United States, 1982.

The other is the **sulfuric acid hybrid cycle**, a combination of thermochemical and electrochemical processes. The latter process, also known as the Westinghouse process, uses a special electrolyser to which sulphur dioxide (SO2), the reaction product of sulfuric acid splitting, is added to water. As a result, the decomposition voltage theoretically required for water splitting is 0.17 V for SDE (sulphur dioxide depolarized electrolysis), which is significantly lower than conventional electrolysis (1.23 V). Even with less favourable assumptions, the electrical energy requirement is only up to 35% of conventional electrochemical water splitting[25].

Our position:

- Photo-electrochemical, photocatalytic and thermochemical hydrogen production are future technologies that have a **high potential** as they are based on renewable resources: water and sunlight.

- The **competitiveness** of hydrogen from solar thermal energy will steadily increase. The current economic disadvantage of producing hydrogen using these approaches will be reduced by continued research and increasing costs of fossil fuels and electricity.

- As these technologies have low values of **TRL**, large public and private investment in research and development is needed for their further development

---

[25] L. E. Brecher, S. Spewock, C. J. Warde, The Westinghouse Sulfur Cycle for the thermochemical decomposition of water, International Journal of Hydrogen Energy, 1977, 2, 7-15.

3.3 Heat recovery from hydrogen production

As stated above, hydrogen can be produced from biomass through different conversion processes as well as from solar energy. Besides this, it can also be produced in water electrolysers with renewable electricity. In all processes **heat is released** that should be used to increase the overall process efficiency and to minimize conversion losses. Furthermore, existing heat of other industries can be also used in some processes to increase the efficiency of hydrogen production.

Surplus heat from biohydrogen production could be used from thermochemical process routes, especially from reforming, but also from gasification and pyrolysis. The quality and quantities of heat generated depends highly on the specific concept design and its integration in existing infrastructures.

Also, in the hydrogen generation processes using **solar irradiation**, heat that cannot be used for the hydrogen generation process may be further used for other purposes.

Hydrogen production by **electrolysis** is implemented by two leading technologies, namely alkaline electrolysis and polymer electrolyte membrane electrolysis (PEM). The efficiency of electrolysers transforming electricity into hydrogen is in the range of 55-70%. The remaining part of energy is released as heat. If this heat is used, the overall efficiency of hydrogen production can increase up to 86%, as an example in Ibbenbüren[26], Germany, shows. Another planned project[27] estimates an efficiency increase of up to 90% if the electrolyzer is installed in a city and the heat generated is used for district heating. Projections of the overall waste heat potential in Europe could cover up to 64% of the projected district heating supply in 2040[28].

To increase the efficiency of electrolysis, also high-temperature electrolysis (HTE) can be applied using **waste heat from industrial processes**. The GrInHy project[29] claims that the HTE can increase the electrical efficiencies, resulting in an electricity demand of <40 kWh instead of 51-60 kWh per kg hydrogen in state of the art low-temperature electrolysis. This is due to the fact that a significant share of energy input is provided as heat – preferably from waste heat from industrial processes. For instance, the GrInHy2.0 project focusses on using the waste heat from steel annealing processes.

---

[26] https://www.bdew.de/energie/effizienzsteigerung-bei-der-wasserstofferzeugung/
[27] https://www.energie-bau.at/heizen-kuehlen/3335-der-elektrolyseur-der-wasserstoff-und-dessen-nutzung
[28] https://www.nefi.at/files/media/Bilder/News/NEFI%20Konferenz%202022/NEFI2022%20Conference%20Proceedings/NEFI_Conference_2022_Proceedings.pdf
[29] https://www.green-industrial-hydrogen.com/project/grinhy-project#:~:text=Green%20Industrial%20Hydrogen%20via%20reversible%20high-temperature%20electrolysis%20As,Oxide%20Cell%20technology%20in%20a%20relevant%20industrial%20environment.

Our position:

- The production of hydrogen usually leads to the release of heat. To increase the overall efficiency, **this heat should be further used**, for example in district heating.

- Hydrogen production units should be operated **close to heat consumers**. Cities and industrial clusters are suitable to use the heat from the hydrogen production process, based on several types of heat demand (e.g. district heating).

- Some processes can also use **industrial waste heat** in the hydrogen production process to increase its efficiency. There should be incentives to generally use industrial waste heat.

- In the EC Hydrogen Strategy there are only very limited **linkages** included between the hydrogen production and the heating and cooling sectors. These linkages need to be highlighted and further strengthened to increase the overall **efficiency** of the energy sector.

4 STORAGE AND TRANSPORT OF HYDROGEN

Hydrogen is an energy carrier that can be used either directly for energy applications (e.g. in the hard to abate industry) or used as a chemical for further chemical reactions, such as for the production of syngas, methane, or LPG. Hydrogen can be also injected directly into the natural gas grid, however, only up to certain limitations that are regulated by legal and gas quality aspects.

If hydrogen is used directly, its specific characteristics need to be considered. As hydrogen is so light, it is a challenge to store and transport it. It is typically stored as a cryogenic liquid, which requires a significant amount of energy to produce and maintain.

There are a few different methods that are commonly used to store and transport hydrogen, each of which has its own set of trade-offs. One method is to store hydrogen as a compressed gas in high-pressure tanks. This method is relatively cheap and easy, but it is not very energy efficient, because a large portion of the energy stored in the hydrogen is used up in the compression process.

Another method is to store hydrogen as a cryogenic liquid, which requires cooling the gas to extremely low temperatures (-253°C) in order to turn it into a liquid. This method is more energy efficient, because it allows for a much higher density of hydrogen to be stored in a given volume. However, it is also more expensive and requires more specialized equipment.

When it comes to transporting hydrogen over long distances, the most common method is to ship it by truck, train, or boat. However, these methods can be expensive and may not be practical for certain locations. An alternative method is to transport hydrogen via pipelines, similar to the way natural gas is transported. This method can be more cost-effective and energy efficient, but it requires a well-developed infrastructure of pipelines, which can be expensive to build and maintain and, given the recent developments in connection with the Ukraine crises (see e.g. the recent explosion in the Nordstream gas-pipe in the North Sea), also associated with considerable risks.

As this document will make clear, we do not deny that hydrogen may have a development potential for certain sectors that are difficult to abate given its special characteristics, but even more important is to recognize that other, much more mature and developed RHC technologies are ready to decarbonize other, much more widespread and representative heating and cooling sectors with just a fraction of the cost of deployment of vast and very expensive hydrogen infrastructure.

Our position:

- It is important to consider hydrogen production and use in the energy sector always **in comparison with other renewable energy technologies** that may be more competitive and applicable in the short term.

- The characteristics of hydrogen pose **challenges on the storage and transport of pure hydrogen**, especially if it is in large volumes and in the long-term. Therefore, the general focus should be placed on short hydrogen transport as well as on direct use or on only short storages.

- Hydrogen can be used for further chemical processes to produce further energy carriers, which can be considered as **indirect storage**.

5 USE OF HYDROGEN

Wherever it is possible, different forms of energy (heat, electricity, kinetic energy) and energy carriers (biomass) should be **directly used to fulfil the final energy demand**. The conversion of renewable energy sources to hydrogen could add value, as hydrogen has special features, such as the fact that it is a standardized fuel that can be used e.g. in transport or in the chemical industry. It can also contribute to balance the intermittent energy from photovoltaics or wind turbines and the corresponding imbalances between supply and demand. However, any further conversion step along the value chain reduces the overall efficiency. Therefore, it is necessary prioritize value and conversion chains which are as short as possible.

For example, in the renewable heating and cooling sector, it generally makes more sense from the energetic viewpoint to directly combust logwood, pellets, or woodchips than to use this biomass to produce hydrogen and then use it for heating. However, some buildings may not be suited for these combustion systems (e.g. as there is not enough space available for biomass storage) and in these cases, the use of hydrogen for domestic heating and cooling purposes could be a solution if the building is connected to a gas grid and if the boiler is suitable for hydrogen use. Similarly, it makes more sense to directly use to use electricity in heat pumps for domestic heating instead of using electricity to produce hydrogen and then to use it for heating.

Currently, hydrogen is a rather expensive, but very valuable energy carrier. So, it should be used very wisely, especially in energy sectors which are **hard to-decarbonize**, such as for high temperature industrial processes and in the maritime and aviation transport sectors, as well as in the chemical industry as a commodity.

The widely discussed challenges related to storage and transportation of hydrogen, likewise technically as well as economically, can potentially be overcome, if hydrogen is stored in liquid or gaseous energy carriers, such as FT-liquids, alcohols, or SNG.

Our position:

- Wherever it is possible, different forms of energy (heat, electricity) and energy carriers (biomass) should be directly used to fulfill the final energy demand.

- Hydrogen should be used in those energy sectors which are hard-to-decarbonize, such as for high temperature industrial processes and in some transport sectors.

5.1 Transport

Overall, hydrogen is in competition with other energy options within the RED framework. Especially biohydrogen competes with advanced biofuels on the minimum quotas in the EU Member States, depending on the specific national regulations and goals. The main competition is with biomethane from residual and waste materials, which is already produced at commercial scale.

In the future, further competition with lignocellulose-based bioethanol and paraffinic fuels produced via the Fischer-Tropsch (FT) process from residual and waste materials, or hydrotreatment routes from forest residues, tall oil and palm oil wastewater can be assumed. In EU Member States with a GHG mitigation quota (e.g. Germany, Sweden), those fulfilment options have the best chances of being counted towards the quota, which have low GHG emissions at low costs, and thus high GHG savings.

In general, the use of pure hydrogen in transport allows a CO2 neutral mobility in a TTW (tank-to-wheel) perspective. To push its use, an efficiency factor is foreseen in the RED for fuel cell electric vehicles (FCEV) like for battery electric vehicles (BEV). A FCEV with hydrogen compared to vehicles based on combustion engines, e.g. used with renewable fuels like Bio-LNG, PTL or other renewable diesel, shows that under current conditions the FCEV overall costs per kilometre are significantly higher than for BEVs due to very high investment costs for a FCEV. This might change if hydrogen can be counted within a GHG quota trading system, among other incentives to use a FCEV. However, this can only be done with a backbone of a hydrogen infrastructure, e.g., for dedicated fleet applications.

Our position:

- Hydrogen in the transport sector will be mainly used for maritime, aviation and heavy-duty transport. Within these sectors, the hardest-to-decarbonize sector is probably the aviation sector, for which large amounts of hydrogen may be needed in the future, especially for the e-fuel production for conventional aircrafts, but also as liquid hydrogen in new aircrafts. Thereby, economic and environmental aspects of the use of renewable hydrogen in **hydrogen aircrafts** must be compared with the direct production of sustainable aviation fuel (SAF) from biomass for conventional aircrafts.

- For light-duty vehicles (i.e. passenger cars), other technologies, such as **electric vehicles (EV)** and **plug-in hybrid electric vehicles (PHEV)** will play a major role. Hydrogen will only play a minor role in the short- to medium term for light-duty vehicles due to economics and infrastructure requirements.

5.2 Industries

Achieving climate neutrality in industry requires a far-reaching conversion of the current fossil energy and raw material management to a renewable basis. Renewable hydrogen has a special role to play in the decarbonization of major energy-intensive industrial sectors, also called **hard-to-decarbonize sectors**, both as a raw material feedstock and as a gaseous energy carrier. The decarbonization potential of renewable hydrogen lies on the one hand in the substitution of fossil fuels and of fossil-based hydrogen in existing applications, and on the other hand in new hydrogen applications.

In the **chemical industry**, hydrogen is currently used in numerous processes, in some cases in large quantities. However, the hydrogen used is currently produced almost exclusively by steam reforming of fossil natural gas, and it needs to be replaced by renewable hydrogen. In the future, the gas demand in the chemical industry will largely depend on process requirements for the production of the basic chemical feedstocks. Important examples are ammonia (or urea) and methanol.

There is significant potential in the iron and steel industry to achieve substantial reductions in greenhouse gas emissions through the change of industrial processes to renewable hydrogen.

By converting the currently used fossil-based (coke) process route with blast furnaces and LD converters (Linz-Donawitz converters) to direct reduction iron electric arc furnace (DRI-EAF) production, renewable hydrogen can be used as a reducing agent and energy carrier, reducing GHG emissions by over 90%. Significant quantities of renewable hydrogen will be required for this transformation.

Furthermore, hydrogen can be important also for many **other industries**. In some important industrial applications, a significant demand for gaseous energy carriers will remain in the future, which cannot be substituted by alternatives such as heat pumps, due to high temperature requirements, process designs, radiation requirements, and quality demands. These applications are primarily industrial furnaces for high-temperature processes, which currently use natural gas as energy source. In most cases, this can be replaced by renewable hydrogen or renewable methane without major intervention in the process control, thus enabling the decarbonization of existing plants and processes. For a successive replacement of natural gas, an increasing blending of renewable hydrogen, through synthetic gas or biomethane, can also play an important role in the future.

Other important gas-consuming sectors, which will continue to have a demand for gas in the future, are the **cement, refractory** and **glass industries**. A large demand also comes from the **non-ferrous metals sector**, followed by the **pulp and paper industry** and the **manufacturing of metal products**.

CO2 capture and utilization (CCU) opportunities may also represent a future application area for renewable hydrogen. In this process, CO2 from industrial processes is captured by different capture technologies and used in combination with hydrogen to produce intermediates for the chemical industry and possibly for synthetic fuels (e.g. in biorefineries or SynBioPTx hybrids using synergies of biomass and power based technologies). In this way, emissions can be reused in further applications and, if necessary, bound in the long term, while contributing to further develop an increasingly more circular economy. In general, point source-based carbon capturing is energetically, as well as economically, far superior to atmospheric carbon capturing – unless this is inherently done by growing biomass.

Our position:

- **Industrial transformation** to renewable hydrogen use in several sectors represents a considerable infrastructural, technical and economic challenge.

- In order to make renewable hydrogen in energy-intensive processes competitive, **further development** and **new instruments** for supporting the operating costs will be necessary in the future.

- In order to tackle the technical challenges of the transformation processes at an early stage and to accelerate technological learning curves, it is important to support **pilot and demonstration projects**.

- **European and international cooperation partnerships** for renewable hydrogen and its derivatives must be established.

- For the coordinated use of hydrogen in industrial processes, it is also necessary to ensure **uniform international technical norms** and **standards** for plants, equipment and products, as well as harmonized national and European safety and environmental standards for renewable hydrogen.

5.3 Domestic heating and cooling

Priority in Europe's domestic heating and cooling sector should be given to the improvement of the **energy standard of buildings**. New buildings should be constructed with very high energetic standards, such as the passive house standard or as Net Zero Energy Buildings (NZEB). However, a main challenge is the existing building stock which needs to be refurbished and insulated to get a higher efficiency standard. Besides measures to increase the energy efficiency of buildings, the heat demand needs to be supplied with renewable energies.

In general, direct use of energy in the heating and cooling sectors, such as the **direct use** of biomass, geothermal, solar thermal energy or electricity through heat pumps should be prioritized – for both district heating as well as individual heating solutions.

The implementation of **district heating and cooling**, at different scales, is urgently needed at large scale in Europe. This would provide the opportunity to take up waste heat from hydrogen production processes, as well as from electricity generation through hydrogen.

The EC Hydrogen Strategy mentions that a dedicated hydrogen infrastructure can use hydrogen not only for industrial and transport applications as well as for electricity balancing, but also **for the provision of heat for residential and commercial buildings**. It further mentions that pilot projects are ongoing to analyse the potential to replace natural gas boilers with hydrogen boilers, and the injection of hydrogen combined with natural gas in the gas grid. Besides the potential, the life cycle emissions should also be investigated in comparison to other heating concepts such as district heating. In general, the direct use of hydrogen for heating purposes as substitute of natural gas is considered as expensive and critical from a lifecycle perspective. Alternatively, the existing natural gas infrastructure and existing end-use facilities could stay in place if just natural gas is substituted by biomethane or Bio-SNG. The latter would also allow for an efficient large-scale and trans-seasonal storage of hydrogen if converted to Bio-SNG and stored in the existing gas storage facilities. A critical question is to which extend biomass-hydrogen pathways could be used to substitute natural gas, as biomass is available in Europe on the one hand in large quantities, but on the other hand limited if a certain critical point is reached.

Our position:

- The increase of the **energetic status of buildings** as well as the **direct use of renewable energies** for domestic heating and cooling must get a very high priority in Europe.

- **Waste heat** of hydrogen production and from the use of hydrogen for electricity generation should be fed into district heating systems, wherever possible.

- Natural gas substitution by hydrogen in boilers in domestic heating systems is unfavourable due to economic and life cycle reasons. It should be **avoided to use hydrogen directly in the domestic heating and cooling sector** at large scale, instead the accelerated deployment of direct renewable energy technologies, district heating and cooling, and heat pumps that are operated with renewable electricity needs to be fostered.

5.4 Power generation

The International Energy Agency estimates a hydrogen demand of about 530 Mio. tonnes annually by 2050[30]. In the same report 102 Mio. tonnes are estimated to be used for power generation. It might look inefficient to use a precious energy carrier like hydrogen for electricity production, as only less than 40% of incoming energy from sun and wind can be converted to electrical energy and more than 60% of energy is lost during electrolyses and re-electrification either by fuel cells or by direct burning of hydrogen. By 2050 IEA estimates an installed power capacity of more than 1,800 GW of hydrogen power plants.

Currently, the **installation of renewable energy production from wind and solar** is often limited by the alternating demand (load) in the power grid and the grid performance, besides other limitations. However, for the decarbonisation of the electricity sector, and as result of fluctuating and unstable power generation of renewable energies, power capacities of PV and wind need to increase on a global scale by factors of 20 and 11, respectively. This leads to almost 3.8 times more installed power when compared to today [31]. These huge investments can be improved if excess energy can be stored for periods with less solar and wind power. It can be assumed that the volumes which are currently used for the storage of natural gas will be in a similar range for hydrogen in the future in order to build the bases for **sector coupling** and **sector integration** covering two essential functions: short term power grid stabilisation (grid balancing) and transferring energy from summer to winter.

In several countries, the use of gas driven combined heat and power (CHP) plants is considered as an important bridging element supporting the energy transition phase towards full decarbonisation. If new gas CHP plants will be installed, they should be even today **hydrogen ready**. Also, the conversion of existing CHP plants from natural gas to hydrogen is considered as a viable option, and first demonstrator projects are implemented already.

Besides combined heat and power plants running on hydrogen, also **fuel cells** are a future option to produce electrical energy. Due to higher investment costs of fuel cells, it is expected that they will operate more likely in mobility applications or at local scale coupled with local hydrogen production. An advantage of fuel cells compared to combustion technologies is that they are emissions free. The combustion of hydrogen will always lead to some NOx emissions.

---

[30] IEA 2021, Net Zero by 2050
[31] IEA 2021, Net Zero by 2050

In terms of stationary applications solid oxide fuel cells (SOFC) seem to be the preferred option, as they operate at high temperatures of around 800°C, and therefore can provide waste heat which can be used in industrial processes or district heating. Such SOFC-CHP systems reach high overall efficiency levels of more than 90%.

Although the energy supply of many industrial processes can be converted to hydrogen in the future, some processes like ammonia production and even steel production will still require huge amounts of methane[32]. Biomass gasification or anaerobic digestion in biogas plants can be a competitive route for renewable CH4 to cover these huge demands. Additionally burning biomass in CHP processes provides stable renewable electricity and heat throughout the year. Converting biomass into hydrogen can make sense if available biomass exceeds the demands for renewable CH4, electricity and heat. In such cases, same as for PV and wind, hydrogen production from biomass for repowering applications could be a sensible option.

Our position:

- Hydrogen production of **excess renewable energy** (PV, wind) supports short term grid stabilisation and energy transfer from summer to winter.
- New installations of CHP plants need to be **hydrogen ready**.
- Electricity production from stationary fuel cells should be **combined with heat utilisation**.
- Biogas production is important for **industrial methane demands**.

---

[32] Austrian Energy Agency 2021, Erneuerbares Gas in Österreich

ABBREVIATIONS

BECCS	Bioenergy with carbon capture and storage
BECCU	Bioenergy with carbon capture and use
BEV	Battery electric vehicles
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CCU	Carbon capture and use
CHP	Combined heat and power
CLH	Chemical looping hydrogen
DH	District heating
DHC	District heating and cooling
EC	European Commission
ETIP	European Technology and Innovation Platform
EU	European Union
EV	Electric vehicles
FCEV	Fuel cell electric vehicles
FT	Fischer Tropsch
GHG	Greenhouse gases
HTE	High-temperature electrolysis
LNG	Liquified natural gas
NZEB	Net zero energy buildings
OPEX	Operating expenses
PEC	Photo-electrochemical cells
PEM	polymer electrolyte membrane electrolysis
PTL	Power to liquid
PV	Photovoltaics
R&D	Research and development
RED	Renewable Energy Directive
RHC	Renewable heating and cooling
SCWG	Supercritical water gasification
SER	Sorption enhanced reforming
SNG	Synthetic natural gas
SOFC	Solid oxide fuel cell
TRL	Technology readiness level