Synergies of green hydrogen and biobased value chains deployment

Report WP2: Case studies on hydrogen produced from biomass

Contribution of IEA Bioenergy Tasks 33, 36, 39 and 44 to Inter-Task Project
(ITP) Synergies of green hydrogen and biobased value chains deployment

IEA Bioenergy: Task 33

July 2025

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Report WP2: Case studies on hydrogen produced from biomass

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Contribution of IEA Bioenergy Tasks 33, 36, 39 and 44 to Inter-Task Project (ITP) Synergies of green hydrogen and biobased value chains deployment

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Index

Preface

According to the International Energy Agency (IEA), fuels in the form of hydrogen, hydrogen-based fuels, and bioenergy will meet 24% of global final energy demand in 2070 in the Sustainable Development Scenario (SDS), particularly in the areas where direct electrification is difficult (IEA, 2020). The statistics show that all these fuels need to ramp up quickly to meet the targets. Bioenergy is a limited but a very diverse energy carrier and required for various applications (industry, transport, high-temperature heat, negative carbon emissions etc.). The future scenarios typically see bioenergy in combination with carbon capture and storage/utilization (CCS/U).

The SDS describes that 20% of hydrogen use in 2070 will be in the production of synthetic fuels from hydrogen and CO_2 for the aviation and further 10% used for ammonia production (IEA, 2020). While most of the hydrogen is produced from natural gas today, the demand for renewable hydrogen is increasing. The main interest has so far been in electrolytic hydrogen from wind and solar electricity (IEA, 2021).

In addition to electrolytic hydrogen, there is also great opportunities to convert biomass to renewable hydrogen, so-called biomass-based hydrogen or biohydrogen. This option is currently a rather overlooked opportunity for providing renewable hydrogen and there is a need to make information and data available on biohydrogen production and utilization options. Furthermore, there are many biobased processes either in demand for renewable hydrogen (e.g. synthetic renewable fuels, biorefining) or that could benefit from renewable hydrogen integration for improving the quality of products (e.g. boosting biomethane production). In addition to process level synergies between hydrogen and biobased value chains, system level synergies and services are expected to take place, such as increased flexibility, use of joint infrastructure and provision of long-term storage options. Different synergies could benefit the economic deployment of both bioenergy and renewable hydrogen-based fuels, and the overall energy system demands.

Biohydrogen and renewable hydrogen in biobased processes

Biomass-based hydrogen or biohydrogen pathways should be considered as an important complement to water electrolysis as many of the biogenic pathways may provide great benefits such as:

- Non-intermittent, fossil-free, large-scale hydrogen production, i.e. 24/7.
- Mitigation of the demand for fossil-free power.
- Process integration opportunities to reach more energy efficient production systems.
- Co-production of other value-added commodities such as biocarbon, biochar, biomethane etc.
- Carbon dioxide removal (negative CO_2-emissions) if CCS is applied or biochar produced.

Adding renewable hydrogen to biobased value chains represents another strong link between hydrogen and biomass/bioenergy. In principle, renewable hydrogen integration into biobased value chains can be done to 1) replace conventional, fossil hydrogen use, 2) upgrade the quality of products, or 3) produce (additional) products and by-products.

Within the IEA Bioenergy strategic Inter-task project "Synergies of green hydrogen and biobased value chains deployment" the focus is on the value chains directly linked to bioenergy, i.e., biomass as a source of hydrogen production (biohydrogen) and biobased processes utilizing renewable hydrogen. Representative examples are showcased to describe the potential role biobased value chains linked to the hydrogen economy, and to create a clearer overall picture of the promising value chains and their potential for future applications.

In this report, we provide an overview of prominent projects (case studies) reflecting on the production of hydrogen from biomass. We provide a concise presentation of the different projects looking into the production of biohydrogen in different parts of the world and put the results into a broader context their technological and economic performance and finally discuss further research needs for realizing biohydrogen projects.

In section 1, we present a general overview on biohydrogen technologies and describe the selection and basic characteristics of the technologies based on exemplary case studies. This is followed by individual presentations of each of the case studies in section 2. Thereby a uniform template has been used for presenting the different first-of-its-kind projects. Section 3 concludes with a forward-looking discussion into issues on the need of further research.

Summary

Over the duration of the IEA Bioenergy triennium 2022 to 2024, a consortium of IEA Bioenergy Tasks – 32, 33, 34, 36, 37, 39, 40, 42, 44 and 45 – collaborated on an inter-task project called Synergies of green hydrogen and biobased value chains deployment. Hydrogen is a very cross-cutting topic and the strategic inter-task project is a collaborative effort of the IEA Bioenergy TCP Tasks and also in collaboration with the Hydrogen TCP.

The objective of the project was to identify and assess technologies for producing hydrogen from biomass as well as synergies in the deployment of green hydrogen and biobased value chains that can enhance the use of biobased value chains in the energy system.

The descriptions of technologies and concepts - including 1) technology readiness and economic fundamentals and 2) climate effects and role in the energy system - are done through case studies. This serves to increase visibility and share state-of-the-art knowledge of promising applications. The report on hand looks into types of technologies for producing biohydrogen and their respective technology readiness level. It summarizes the findings of the work package 2 "Case studies on hydrogen from biomass" and provides a synthesized view on promising biomass technologies, major drivers and barriers for their deployment, and measures to overcome potential barriers.

The considered case studies and their respective findings show that, there are various activities and projects in different parts of the world that look into the production of biomass-based hydrogen. The project developers mainly come from the fuel industry. Early stage concepts and their development is driven by research. All the presented production concepts are still under development and none of them has reached commercialization. The presented concepts are in the TRL level range of 4-7 and many of them show the "weakest link" in complete integrated operation for hydrogen production. For consistently evaluating the status of development a methodological framework has been developed addressing the TRL of key process components: feedstock handling, conversion processes, upgrading, and integrated operation. Each component is given a weight based on its relative importance in the overall technology resulting in an overall weighted average of technology development.

Project/Developer	Country	Technology	Products/by-products	TRL - weakest link	TRL - weighted average
Torrgas Technology BV	NL	Medium/large-scale gasification	A tar and nitrogen free syngas for production of methanol, H2, SNG, SAF and biochar as soil improvement or in the (chemical) industry	5	7

Cortus AB	SE	Small-scale gasification	Biochar, H_2, SNG	5	7
RISE & Indienz AB	SE	Anaerobic digestion	H_2 and methane	5.8-6.7	4
Hytron/NEA	BR	Alcohol reforming	H_2	6-7	7.2-7.8
Nissan	BR	Onboard alcohol reforming	H_2, electricity	6-7	6.5-7.3
Hycamite Oy	FI	Thermo-catalytic decomposition (or pyrolysis)	H_2, solid carbon in different forms for wide range of applications, e.g., graphitic carbon for battery storage	6	6.7

With regards to the techno-economic performance of the different biohydrogen pathways first results show that biohydrogen production prices are competitive with production prices for power-based hydrogen. From a system perspective several of the biomass-based hydrogen production concepts also generate additional value-added commodities such as biochar, biocarbon, biomethane etc. This adds flexibility, resilience and likely also improved economic performance. Many of the concepts also generate a stream of CO_2, what opens for opportunities to obtain negative CO_2-emissions. Hence, biohydrogen can add to the portfolio of renewable hydrogen provision while at the same time allowing for additional energy and climate system services as carbon capture and storage. This makes it a relevant concept for further consideration within scenarios for reaching climate-neutrality.

Introduction

Renewable hydrogen has been identified as key to reach fossil-free societies and industries as it offers a variety of ways to defossilize a range of sectors – including long-distance transport, chemicals, and iron and steel – i.e., so-called hard-to-abate sectors.

The most discussed alternative for low-emission hydrogen production is water electrolysis using fossil-free electricity. Less focus is however put on biomass-based hydrogen production pathways. These pathways should be considered as an important complement to water electrolysis as many of the biogenic pathways may provide great benefits such as:

- Non-intermittent, fossil-free, large-scale hydrogen production, i.e. production 24/7.
- Mitigation of the demand of fossil-free power.
- Process integration opportunities to reach more energy efficient production systems.
- Co-production of other value-added commodities such as biocarbon, biochar, biomethane etc.
- Negative CO_2-emissions if CCS is applied or biochar produced.

There are numerous production pathways to convert different types of biomass feedstocks to biohydrogen as illustrated in Figure 1. The pathways can be divided into two main groups, biological and thermochemical technologies, respectively (Buffi et.al 2022).

- Thermochemical technologies include pyrolysis, hydro- and solvothermal liquefaction, and gasification followed by required downstream upgrading such as reforming, separation etc.
- Biological processes include water-gas shift reactions promoted by micro-organisms, photo-fermentation and dark fermentation, anaerobic digestion followed by biogas/biomethane reforming, fermentation to alcohols followed by reforming, and bio-photolysis with photosynthetic organisms (microalgae and cyanobacteria) such as microbial electrolysis cells.

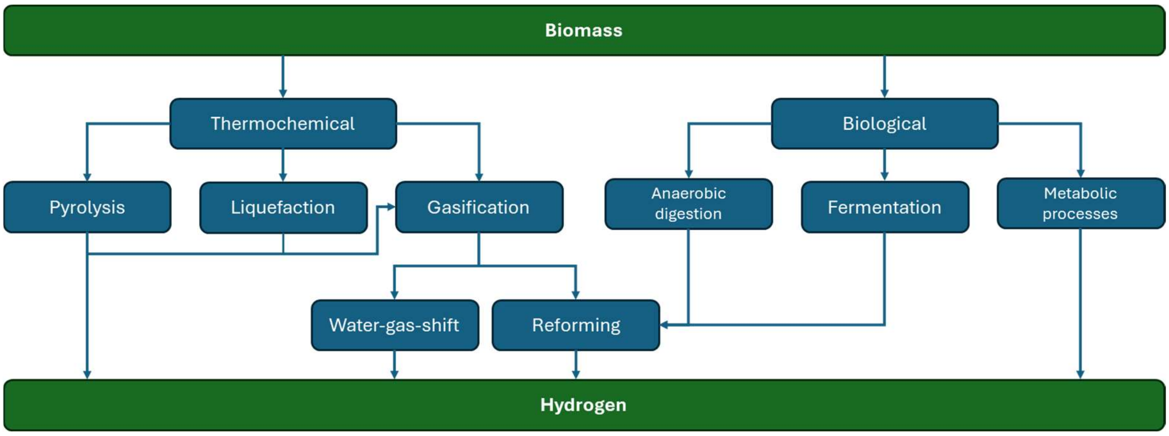

Figure 1. Main conversion processes to produce hydrogen from biomass sources (based on Buffi et.al 2022)

In the following, the different biomass-based conversion technologies to hydrogen are described briefly.

BIOLOGICAL CONVERSION PROCESSES

Biohydrogen produced via biological methods commonly involve microorganisms that can produce hydrogen through metabolic processes, some light-dependent and some non-light-dependent process.

The production pathways depending on light include photo-fermentation and bio-photolysis (direct or indirect) using algae or microalgae, while dark fermentation is a light-independent process using bacteria.

Biological conversion normally takes place at lower temperatures in the range of 30-60°C and low pressures (1 atm). These processes are most suited to convert residues like agricultural waste, agri-food effluents, sewage sludge and municipal solid waste into hydrogen (Lepage et al.,2021)

Photo-fermentation

Photo fermentation is a novel hydrogen production process that utilizes light energy to convert biomass into hydrogen (Ahlström, 2021). Various types of photosynthetic and non-photosynthetic microorganisms such as green algae, cyanobacteria, anoxygenic photosynthetic bacteria, and nitrogen-fixing bacteria, etc. can converted to hydrogen. Different types of nanomaterials can be used as photocatalysts to boost the hydrogen production (Pandey et.al, 2023). The hydrogen yields of photo fermentation is in the range of 0.004-0.049 kg H_2 per kg biomass (Lepage et.al, 2021).

Dark fermentation

Via dark fermentation (or acidogenesis), biomass is decomposed by anaerobic bacteria in the absence of light and oxygen to form hydrogen. The substrates can be lignocellulosic biomass, carbohydrate materials like wastewater from industry, sugar-containing crop residues, and municipal solid waste. Two different hydrogen-producing enzymes (hydrogenase and nitrogenase) are involved in acetate and butyrate pathways of dark fermentation, leading to the production of hydrogen.

Lepage et al. (2021) reports that the hydrogen yield for dark fermentation is in the range of 0.004-0.044 kg H_2 per kg biomass.

Biological electrolysis

Microbial electrolysis cell (MEC) can produce hydrogen from organic waste assisted by various bacterial strains. In the process, organic matter oxidises at the anode while proton reduction takes place at the cathode under the nominal external voltage supply. The technology is still under development and the performance (efficiency and operating costs) of MEC needs to improve before implementation can occur in any larger-scale applications (Gautam et.al, 2023)

THERMOCHEMICAL CONVERSION PROCESSES

Pyrolysis

Pyrolysis takes place in the temperature range of 400-800°C in absence of oxygen. Pyrolysis technologies can be divided into three different categories: slow pyrolysis, fast pyrolysis and flash pyrolysis.

The pyrolysis process decomposes the feedstock into three different fractions a liquid fraction, as solid charcoal fraction and a gas fraction mainly consisting of H_2, CO, CO_2 and CH_4. The share of the different fractions depends on the type of pyrolysis reactor, with the highest gas shares reached for flash pyrolysis reactors.

The gas and liquid fractions can be converted to hydrogen in different ways. The most common approach is to react the water-soluble fraction of the liquid fraction in reforming reactors (catalytic steam reforming or steam reforming). The non-soluble fraction can potentially be cracked into other smaller hydrocarbons, e.g. BTX, whereas hydrogen can be separated from the gas fraction. The charcoal fraction is typically used to provide the process with heat (Ahlström, 2021). Figure 2 illustrates a generic process scheme of the production pathway.

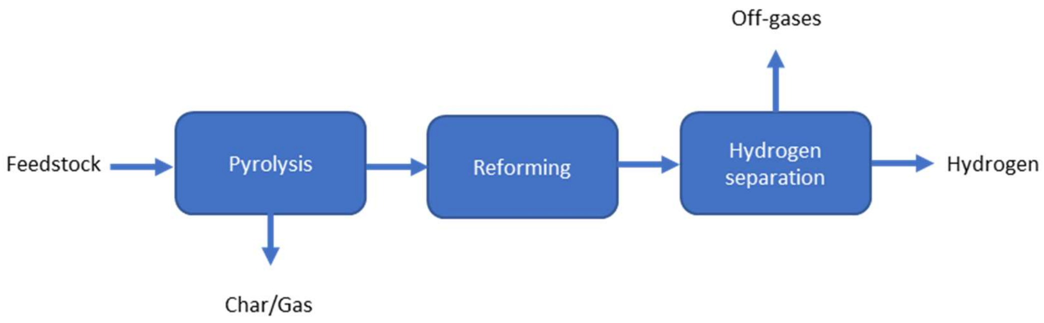

Figure 2. Simplified process scheme for hydrogen produced via pyrolysis of biomass

Gasification

Thermal gasification processes convert solid or liquid feedstocks into transportation fuels, chemicals, heat and/or electricity. The process takes place at high temperatures, exceeding 700 °C, and with a controlled amount of an oxidant (in form of air, oxygen and/or steam). The produced gas consists of varying levels of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), hydrogen (H_2), water and normally lower concentrations of light hydrocarbons ($\geq C_2$) and tar. Following several gas cleaning and conditioning steps, a high-purity hydrogen stream can be obtained via Pressure Swing Adsorption (PSA).

A generic process scheme of biomass gasification for hydrogen production is shown in Figure 3.

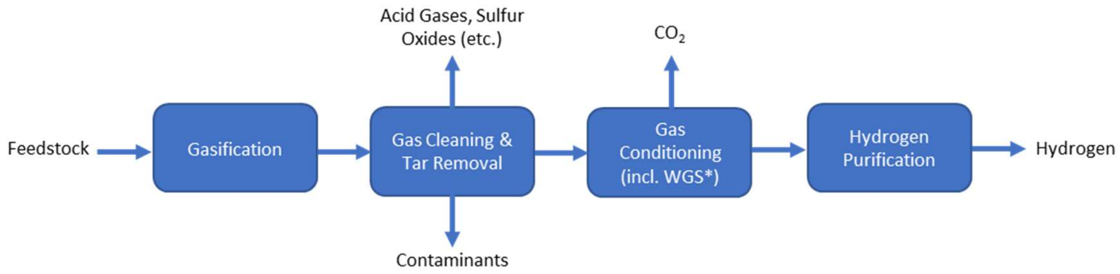

*Figure 3. Generic process scheme of hydrogen production via biomass gasification (From https://task33.ieabioenergy.com/biomass-and-waste-gasification-for-the-production-of-hydrogen/). *WGS – Water Gas Shift.*

Hydrothermal liquefaction

Biohydrogen can be produced via hydrothermal liquefaction of various types of wet biomass. The conversion process normally takes place in the temperature range of 250-370°C at elevated pressures (4-22 MPa). The main product is a liquid biocrude along with a gaseous stream, an aqueous phase, and a solid residue by-product. The aqueous phase can be recirculated to the hydrothermal unit to enhance the liquid yield, but it can also be used to produce a hydrogen-rich syngas via steam reforming (Megía et.al, 2021).

CASE STUDY OVERVIEW

As examples on the different technology options, six different biohydrogen production pathways are explored via case studies in which the process and the overall concept are explained. The case studies also include assessments of the techno-economic performance as well as the technology readiness level (TRL). Table 1 shows an overview of the covered case studies.

Table 1. Overview of the described biohydrogen production case studies

Technology	Project/Company	Country	Feedstock
Medium/large-scale gasification	Torrgas Technology BV	The Netherlands	Torrefied biomass
Small-scale gasification	Cortus AB	Sweden	Woody biomass
Anaerobic digestion	RISE & Indienz AB	Sweden	Waste-water
Alcohol reforming	Hytron/NEA	Brazil	Ethanol
Onboard alcohol reforming	Nissan	Brazil	Ethanol
Thermo-catalytic decomposition (or pyrolysis)	Hycamite OY	Finland	Methane

Each case study includes a process description with a block scheme, the main mass- and energy balances, the current development status, principal feedstock(s) and its specifications, the potential applications and by-products, as well as feasible production capacities. The mass and energy balances are used to calculate a variety of key performance indicators (KPI) to illustrate the techno-economic characteristics of the production pathways.

METHODS AND LIMITATIONS

A strong prerequisite during the selection of the case studies was that a promotor or technology developer could contribute with technology descriptions and relevant key data. It was also important to obtain a case study portfolio that involves different types of biogenic feedstocks at different scales and technological readiness levels (TRL). It should be noted that the report does not cover all the biohydrogen production technologies available.

Different technical key performance indicators (KPI) were assessed based on the established mass and energy balances with data provided by the developer or promotor. The economic parameters were also provided by the case study promotor.

The European Clean Hydrogen Joint Undertaking (CH-JU, 2021) has proposed KPIs for a broad range of hydrogen production technologies comprising both state-of-the-art as well as future targets, see Table 2. These KPIs were, when possible, estimated for the case studies presented in this report.

Table 2. KPIs for biomass-based hydrogen production technologies proposed by the European Clean Hydrogen Joint Undertaking

Parameter	Unit	State-of-the art 2020	Targets	
			2024	2030
Hydrogen production via biomass gasification				
System carbon yield	kg H_2/ kg C	0.15	0.22	0.32
System capital cost	€/(kg/d)	1 806	1 514	1 264
System operational cost	€/kg	0.013	0.011	0.009
Hydrogen production from raw biogas				
System energy use	kWh/kg	64	60	57
System capital cost	€/(kg/d)	1 250	1 150	1 000

Parameter	Unit	State-of-the art 2020	Targets	
			2024	2030
System operational cost	€/kg	1.35	1.32	1.28
Hydrogen production from biological production				
System carbon yield	kg H_2/kg COD	0.012	0.015	0.021
Reactor production rate	kg $H_2/m^3/d$	7.5	15	>15
Reactor scale	m^3	3	10	100
System capital cost	€/(kg/d)	450	400	450
System operational cost	€/kg	3.2	3	2.5

Input data to be able to calculate the CH-JU KPIs are in some cases missing. Therefore, other, relevant KPIs were assessed for them, but also for other cases to reflect their system characteristics in a more complete manner.

It is very important to point out that the production pathways described and assessed in this report should not and cannot be compared. There are many reasons for this, but one is that they are at different stages of technology readiness level (TRL) in their development curve. This means that:

- there is a lack of validated key technical data such as product yields and conversion efficiencies in published literature for those cases that are at a comparably early stage of R&D.
- the economic estimations have a high level of uncertainty, as component costs and other assorted capital expenditure (CAPEX) costs figures are hard to source, especially from the public domain. It is also, for understandable reasons, difficult for companies to reveal crucial economic data.

The technical analyses in this report also cover assessments of the technology readiness levels (TRL). The TRL-levels were assessed according to a framework described in Jafri et.al (2020). Here, each sub-process of the pathway was assessed and assigned a TRL score with the aid of definitions from the European Union Horizon 2020 program (European Commission, 2015)and the United States Department of Energy Clean Coal Program (Clausing and Holmes, 2010). The overall score for the technology was determined from the component scores using two complementary approaches: (a) the weighted average approach, (b) the weakest link approach.

In the weighted average approach, each of the components was assessed for importance and given a weight, which was used to calculate a weighted average TRL score. In the weakest link approach, the entire technology was assigned the TRL of the lowest scoring component to account for the possibility that some key components and sub-components may be significantly lagging in development compared to others. The integrated operation, i.e. the demonstration of all parts of the process configuration in an integrated assembly is treated as an independent, separate step. The results of the assessment are provided in tabular form following the structure presented in Table 3.

Table 3. Tabular format used for the presentation of technology readiness assessment results.

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

CASE 1: THE TORRGAS CONCEPT - HYDROGEN PRODUCTION VIA GASIFICATION OF TORREFIED BIOMASS

Background

The Dutch company Torrgas Technology BV provides a concept for converting torrefied biomass residues in a patented two-stage gasification technology for production of biochar, and a tar and nitrogen free syngas that can be used to produce hydrogen. Table 4 presents a brief overview of the Torrgas concept and process.

Table 4. Technology profile for the Torrgas gasification concept

Designation	
Developer/Promotor	Torrgas Technology BV
Conversion technology	Two-stage gasification process
Feeding System	Vacuum transport with hopper and sluicing system
Principal Feedstock(s)	Torrefied biomass, such as forestry residues, woody plantations, and agricultural wastes
Principal Application(s)	A tar and nitrogen free syngas for production of methanol, H_2, SNG, SAF and biochar as soil improvement or in the (chemical) industry
Scale	From 30 up to 100 MW_{th} input (LHV basis)
Development Status	Technical testing in demonstration scale; pending commercialization.

Process description

A process scheme including a simplified energy balance of the Torrgas concept[1] is shown in Figure 4.

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[1] https://www.torrgas.nl/technology/

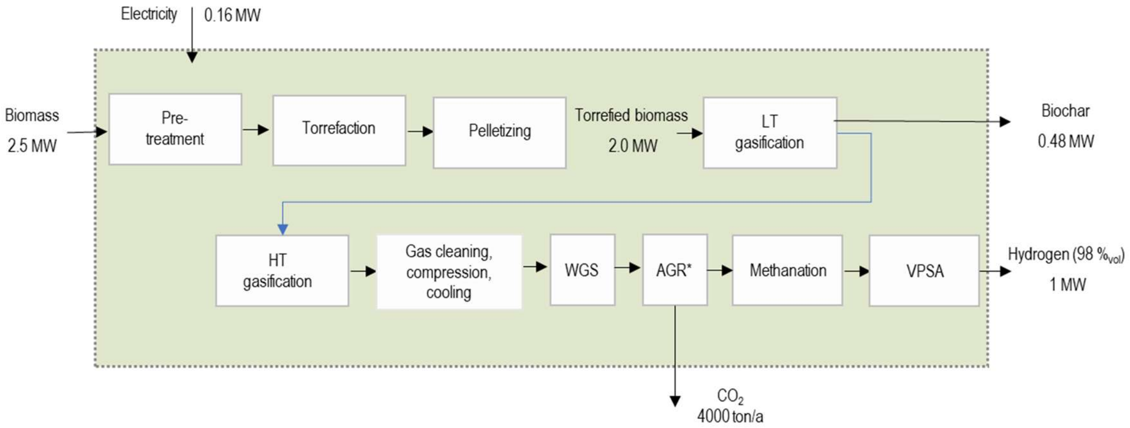

Figure 4. Process scheme including energy balances across the system boundary for production of 1 MW of hydrogen gas. AGR – Acid Gas Removal.*

Torrefied biomass is used as feedstock for the gasification process. Torrefaction is a thermal treatment process in which the biomass is heated to a temperature in the range of 250 to 280 °C under atmospheric pressure and in the absence of oxygen. The formed gases are burnt in a combustion chamber to provide heat to the drying and the torrefaction processes. The final product is a solid, dry, and blackened biomass product. This pre-treatment process severely improves the fuel quality properties (energy density) making it better suited for longer transport distances as well as for thermal conversion applications (increased homogenity). This also means that the pre-treatment process can be carried out close to the location of the feedstock origin.

The fuel conversion takes place in a pressurised two-stage gasification process. In the first stage (low temperature gasifier, LTG), the fuel is heated up to approximately 600-700 °C with a blend of steam and oxygen as oxidants. This stage generates a producer gas for further processing in a high temperature gasification (HTG) step. A co-product of this first stage is biochar which can be applied as soil improver or in the (chemical) industry. In the second stage (HTG), the producer gas is further heated to 1200 °C with pure oxygen as oxidation agent. The producer gas is a tar-free (<0.1 mg/m^3_n dry basis) and contains mainly CO, CO_2 and H_2 and water. For the Torrgas gasification, no external heat sources are required (other than for start-up).

Dust, hydrochloric acid and ammonia are removed using wet scrubbing in an alkaline/acid scrubber system. Traces of hydrogen sulphide (H_2S) are removed in a zinc oxide (ZnO) bed. Downstream of the sulphur removal unit, a compressor, water-gas-shift (WGS) and synthesis reactors are situated. In the case of producing hydrogen, CO_2 is removed downstream the synthesis step using an absorber-stripper system. The produced hydrogen gas contains approximately 80 % (m/m) of H_2 with the remaining part being Argon and Nitrogen originating from the Vacuum Pressure Swing Adsorption (VPSA) oxygen feed stream. This quality corresponds with the European anticipated network quality for hydrogen of 98 % (v/v).

Development status, applications, and production scale

Torrgas currently develops a project titled HyCarb[2] to produce biohydrogen from torrefied biomass. A plant is projected in Delfzijl in the Netherlands with a production capacity of 100 MW_{th} fuel input and is envisaged to include an on-site torrefaction plant.

Also, in the Netherlands, a 10 MW demonstration plant is planned to be constructed on the Brightlands Chemelot Campus to produce biomethanol by gasifying torrefied biomass, based on technology developed by Torrgas (project BrigH2).

In the Torrgas gasification system a co-product biochar is produced. The biochar contains approx. 85-90 % (m/m) of carbon, while the remaining part being minerals originating from the original biomass. The biochar includes e.g. nitrogen, phosphorous and potassium, which are all important elements for soil improvement. By returning this biochar to the soil carbon depletion in (agricultural) soils as well as the demand for synthetic fertilizers are reduced whilst obtaining a carbon negative value chain.

Assessment of the technology readiness

The assessment of the technology readiness level of the biohydrogen concept developed by Torrgas, is described in Table 5.

Table 5. Assessment of the technology readiness level of the Torrgas concept

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	9	25	Covers the conveyance of the prepared feedstock to the gasifier. The feedstock handling system has successfully been demonstrated in pilot scale in Groningen. The system applied is a proven system for pellet transport. The hopper/sluicing system has been demonstrated in the Choren-plant in Freiberg, Germany, (45 MW wood chips input operating at 5 bar(a)) as well as in the pilot plant
Gasification reactor with	6-7	25	The gasification system is proven on pilot scale (500 kW input) in Groningen. The

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[2] https://www.torrgas.nl/projects/

Process steps	TRL	Weight [%]	Comments
heat supply			system is based on a combination of individual reactors, which was proven by Choren in the in Freiberg on 45 MW scale on 5 bar(a)
Product gas conditioning, cleaning, and purification	8	25	This concerns off-the-shelf technology bought from third parties. Commercial for coal gasification. (-1 TRL-level because not validated with biomass feedstocks in relevant scale)
Integrated operation	5	25	No integrated operation has yet been carried out by Torrgas. However, integrated operation at the Choren plant was (partially) carried out in the mid 2000's
Overall “Weighted Average”	7-7.3		
Overall “Weakest Link”	5		Integrated operation to be proven

Key Performance Indicators

Different KPIs have been calculated based on the data provided by the developer as well as own assumptions. Table 6 shows the indicators proposed by Clean Hydrogen Joint Undertaking (CH-JU, 2021) and

e It can be noted that the values are surprisingly low (around a factor 10), which means that they should be used with caution.

Table 7 the additional KPIs assessed in this case study. It can however be noted that the CH-JU KP presented in Table 6 regarding system capital cost is not clearly defined.

Table 6. KPIs of the Torrgas concept based on the indicators proposed by Clean Hydrogen Joint Undertaking

KPI parameter	Unit	Torrgas concept	SoA 2020	Targets	
				2024	2030
System carbon yield [a]	kg H_2/kg C	0.23	0.15	0.22	0.32
System capital cost	€/(kg H_2/d)	2 000-2 500 [b]	1 806[c]	1 514[c]	1 264[c]
System operational cost[c]	€/(kg H_2)	-0.4 to -0.5 [d]	0.013[e]	0.011[e]	0.009[e]

[a] Based on the composition of dry raw synthesis gas and 98% hydrogen output

[b] CAPEX considered includes complete investment costs for the chemical plant (2025 basis). The value also includes the plant start-up expenses as 10% of the investment cost. Capital cost includes all the cost related to all the equipment necessary for the normal operation of the plant relative to the hydrogen production (so excl. biochar co-product). Including torrefaction and on-site oxygen generation. If the oxygen generation is excluded, the value reduces to 1,600-2,100 €/kg H_2/day

[C] It is not clear if these values include contingency, civil work and financing costs.

[d] Operation and maintenance cost averaged over the first 10 years of the system. Routine maintenance and "wear and tear" (rotating parts, cleaning of equipment...), labour, utility and chemical costs considering a plant life of 20 years. Feedstock and electricity costs are not included in O&M cost. In this particular case revenues from biochar including CO_2 credits are considered.

[e] It can be noted that the values are surprisingly low (around a factor 10), which means that they should be used with caution.

Table 7. Additional KPIs of the Torrgas concept

KPI parameter	Torrgas concept	Unit
Hydrogen yield	70	kg H_2 per ton of dry biomass
Fresh biomass to hydrogen efficiency[a]	45	%

KPI parameter	Torrgas concept	Unit
Energy efficiency excl. co-products [b]	43	%
CO_2 sequestration potential, carbon captured	>100[c]	%
Production capacity	30-100	MW_{th} input (LHV basis)

[a] including torrefaction

[b] Calculated as energy in hydrogen output over energy in biomass and electricity energy inputs. The energy efficiency including biochar co-product equals 65%

[c] Negative carbon emissions can be obtained both via CCS and by biochar applications

Developer Feedback

Torrgas has provided technical information, techno-economic data as well as given feedback on the assessments with corrections and clarifications on various aspects.

CASE 2: THE CORTUS CONCEPT - HYDROGEN PRODUCTION THROUGH BIOMASS GASIFICATION VIA THE WOODROLL® PROCESS

Background

The Swedish company Cortus Energy AB is the owner of the patented WoodRoll® gasification technology that converts low-grade biomass to ultra clean syngas with a high concentration of hydrogen (about 55 – 60 %). The technology is currently being demonstrated in the 6 MW WoodRoll® plant in Höganäs, Sweden, where the produced syngas is used to replace fossil natural gas at the Höganäs steel plant. Figure 5 shows the WoodRoll® plant in Höganäs.

Figure 5. The WoodRoll® plant in Höganäs, Sweden (Photo from Cortus, 2024)

The WoodRoll-technology is well suited to also upgrade the syngas to renewable hydrogen applying additional separation and upgrading steps, which is described in the following.

Table 8 shows the technology profile of Cortus WoodRoll®.

Table 8. Technology profile for WoodRoll® for hydrogen production.

Designation	
Developer/Promotor	Cortus AB and partners
Conversion technology	WoodRoll®, two-stage gasification process
Feeding System	Conventional screw feeding system
Principal Feedstock(s)	Wood chips, bark, forestry residues

Designation	
Principal Application(s)	Biochar, H_2, SNG
Scale	Up to 50 MW syngas output
Development Status	Technical testing in industrially relevant demonstration scale (6 MW gasifier)

Process description

The core of the technology concept is the indirectly heated WoodRoll® gasifier - a refractory-lined entrained flow gasifier, in which gasification of biochar takes place at a temperature around 1,100˚C. Superheated steam is used as oxidizing agent to produce a clean syngas made up primarily of hydrogen, carbon monoxide, carbon dioxide and methane.

The synthesis gas is cooled in the integrated steam boiler before passing through a particle filter. The synthesis gas continues to a condensation step before being compressed. The synthesis gas is free of tars (incl. BTX) and traces of H_2S. HCN is removed in the condensation step (ending up in syngas condensate). Figure 6 shows an illustration of the gasification concepts and its sub-processes.

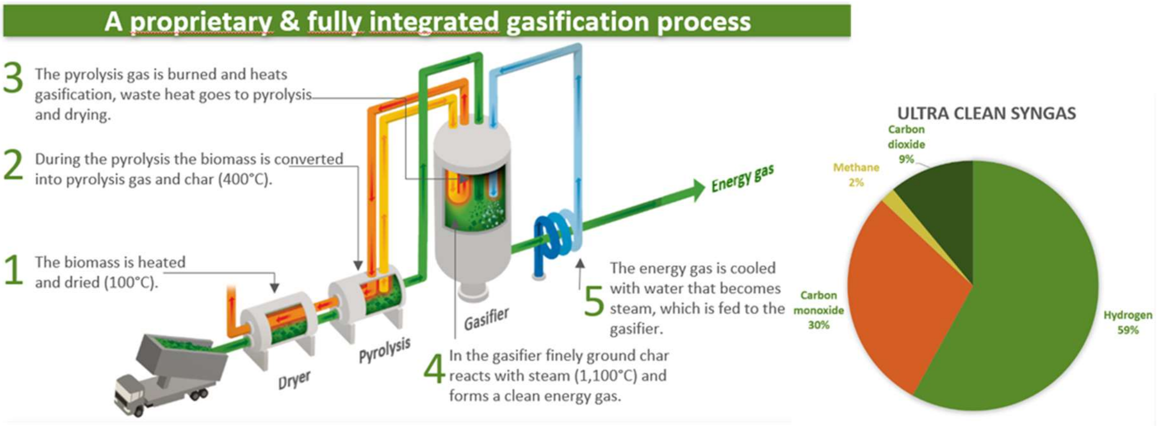

Figure 6. Schematic of the WoodRoll® gasification concept and producer gas composition.[3]

To separate the hydrogen from the synthesis gas with as high hydrogen yield as possible, dual separation stages are applied. In the first, a Pressure Swing Adsorption (PSA) unit separates the hydrogen from the original synthesis gas stream. The tail gas from the PSA passes a water-gas shift reactor, to shift the remaining part of the CO in the gas. The gas is then supplied to a second PSA-stage, where the hydrogen is extracted from the shifted tail-gas.

A simplified process scheme including the main mass and energy balances (normalized to approx. 1 MW of hydrogen output) of the WoodRoll® gasification concept with steam addition for hydrogen production is shown in Figure 7.

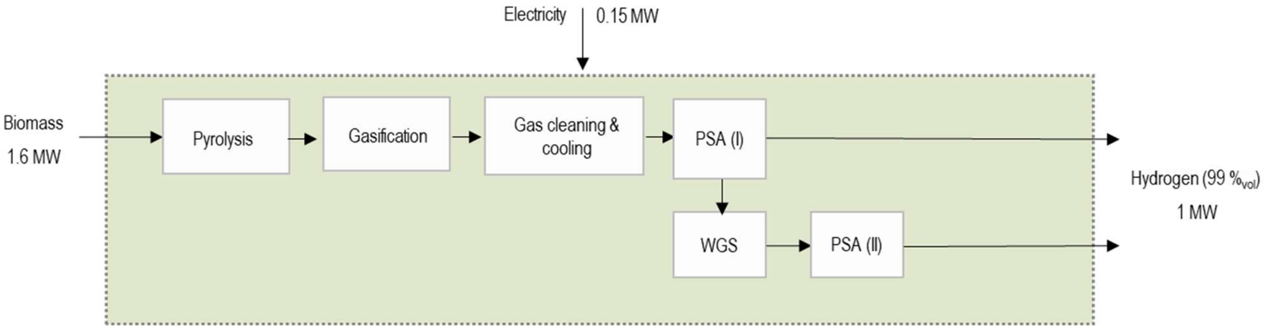

Figure 7 Process scheme with an energy balance across the system for production of 1 MW of hydrogen via WoodRoll® gasification.

Development status, applications, and production scale

The biomass gasification demonstration plant in Höganäs has been in validation phase since 2020 with increased number of operational hours each year. In the end of June

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[3] https://cortus.se/wp-content/uploads/2020/04/woodroll_process.pdf; https://task39.ieabioenergy.com/wp-content/uploads/sites/37/2022/10/Cortus-Energy-and-WoodRoll.pdf

2024, the gasification plant delivered synthesis gas to the belt furnace 11 out of its 20 days of operation.[4]

Cortus has currently no plans for producing hydrogen, but the technology is well suited for the purpose. The opportunities to demonstrate hydrogen production at Höganäs site in the future is good as an installation of a high-pressure syngas storage (150 bar) exists and sub-streams of synthesis gas can be utilized.

Assessment of the technology readiness

An assessment of the technology readiness level of the WoodRoll® process with dual PSA for hydrogen production is provided in Table 9.

Table 9. Assessment of technology readiness of the WoodRoll® gasification process and Dual-PSA for hydrogen production

Process steps	TRL	Weight [%]	Comments
Feedstock handling system incl. drying	9	25	Conventional metal/stone separation and conveying system for feeding. Exists in many biomass boilers around the world since many years. The WoodRoll® Dryer is commercial.
Thermal conversion incl. the pyrolysis and gasification	7	25	The gasification system is proven on pilot scale (0.5 MW thermal input) in Köping, Sweden. Demonstration phase of 6 MW with accumulated operation of > 2000h (sub-processes in heated operation > 10 000 h). Maximum continuous operation of about 250 h.

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[4] During the ITP Synergies project work Cortus Energy AB unfortuanetly filed for bankrupcy and that the presented project will most likely not be pursued for the time being. It therefore remains to be seen how and if the project will proceed (https://www.qcintel.com/carbon/article/swedish-biochar-producer-files-for-bankruptcy-38091.html)

Process steps	TRL	Weight [%]	Comments
Product gas conditioning, cleaning, and purification	8	25	Syngas cooling system is commercial. Syngas compression and gas separation by PSA incl. heat exchange are commercial technologies but not validated with biomass-based syngas.
Integrated operation	5	25	Maximum continuous operation of about 220 h. No tests with hydrogen production.
Overall "Weighted Average"	7.3		
Overall "Weakest Link"	5		Fully integrated gasification with hydrogen production via WoodRoll® still to be proven

Key Performance Indicators

Several KPIs have been calculated based on the data provided by the developer in combination with own assumptions. Table 10Table 6 shows the indicators proposed by Clean Hydrogen Joint Undertaking (CH-JU, 2021) for hydrogen produced via biomass gasification and

Table 11 shows the additional KPIs assessed in this case study.

Table 10. KPI’s of the Cortus concept based on the indicators proposed by Clean Hydrogen Joint Undertaking

KPI parameter	Unit	Cortus concept	SoA 2020	Targets	
				2024	2030
System carbon yield	kg H_2/kg C	0.24	0.15	0.22	0.32
System capital cost[b]	€/(kg H_2/d)	N.A	1 806	1 514	1 264
System operational cost[c]	€/(kg H_2	N.A	0.013	0.011	0.009

[a] Based on the composition of dry raw synthesis gas and 98% hydrogen output

[b] CAPEX considered includes investment costs for the chemical plant of a double bed fluidised gasifier. The value also includes the plant start-up expenses as 10% of the investment cost. Capital cost includes all the cost related to all the equipment necessary for the normal operation of the plant. It is however not clear if these values include contingency, civil work and financing costs.

[c] Operation and maintenance cost averaged over the first 10 years of the system. Routine maintenance and "wear and tear" (rotating parts, cleaning of equipment...) was estimated considering a plant life of 20 years. Feedstock and electricity costs are not included in O&M cost. It can however be noted that the SoA and target values are surprisingly low (around a factor 10), which means that they should be used with caution.

Table 11. Additional KPIs of the Cortus concept

KPI parameter	Torrgas concept	Unit
Hydrogen yield	99	kg H_2 per ton of dry biomass
Biomass to hydrogen efficiency	63	% (LHV basis)
Energy efficiency excl. co-products	57	%
CO_2 sequestration potential, carbon captured	>100[b]	%

[a] Calculated as energy in hydrogen output over energy in biomass and electricity energy inputs

[b] Negative carbon emissions could be obtained both via CCS and by biochar applications

Developer Feedback

Cortus Energy has provided with techno-economic data and provided feedback on the assessments with corrections and clarifications on various aspects.

CASE 3: THE BIOFLEX CONCEPT - TWO-STEP BIOLOGICAL PROCESS FOR BIOHYDROGEN AND METHANE PRODUCTION

Background

Biological hydrogen can be produced from various waste streams such as industrial process water. The combination of biohydrogen and methane production was tested in pilot scale in the Bioflex project, led by RISE Research institutes of Sweden (RISE). The aim of this project was to study the generation of two biobased gas products to establish a more flexible and robust production system. Process water from the sugar industry was used as carbon and energy substrate. This water stream is currently used as substrate in a 20 000 m^3 biogas reactor.

In the Bioflex concept, microorganisms produce hydrogen in the absence of oxygen (anaerobic conditions). The hydraulic retention time (HRT) is lower for hydrogen production than for methane (biogas) production. The combination of methane and biohydrogen production offers faster degradation rates of organic compounds and lowers the hydraulic retention time (HRT) requirements resulting in smaller reactor vessels. In addition, this combined process results in higher carbon utilization, leading to lower Chemical Oxyged Demand (COD) in the effluent and therefore less GHG emissions from the digestate. Finally, this flexible production pathway can switch from methane to biohydrogen depending on the market demand and offers higher energy output in a shorter time.

Even though the combined process requires two sets of tanks (bioreactors), it is expected that the total volume of the bioreactors will be smaller than using only one methane bioreactor. This is due to the higher production rates as previously explained. Table 12 gives a general overview of the concept.

Table 12. Technology profile for the two-step anaerobic bioprocess concept

Designation	
Developer/Promotor	RISE/Indienz
Conversion technology	Two-stage anaerobic digestion
Feeding System	Peristaltic pump

Designation	
Principal Feedstock(s)	Carbohydrate-rich wastewater streams
Principal Application(s)	Biohydrogen and methane
Scale	5L reactor for biohydrogen and 60L reactor for methane
Development Status	Technical testing in small pilot scale in industrial settings

Process description

A process scheme of the two-step bioprocess concept is shown in Figure 8.

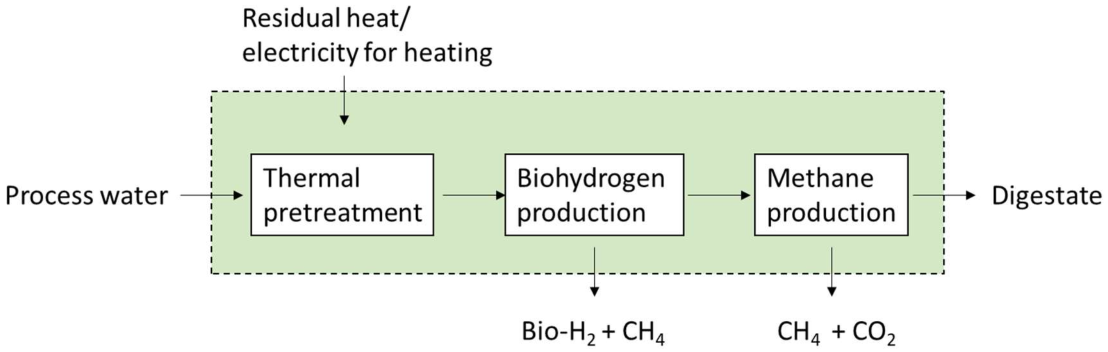


Figure 8. Process scheme for the two-step bioprocess for production of biohydrogen and biogas

The process water is heat-treated at 90 °C for 3 - 5 min, to minimize methane production and favour biohydrogen production in the first reactor. On a bigger scale, the pre-treatment can consist of a water tank where water heated by electricity is flowing around the tank, heating the content to 90 °C, for 30 minutes. The heat can also be harvested from residual streams to increase process profitability and resource efficiency. The prolonged heating of the process water is suggested due to continuous loading of methanogens that are present in the process water.

The pre-treated process water is then pumped into the first biohydrogen reactor, where microorganisms specialized in hydrogen production are dominant. The microorganisms feed on the carbohydrates from the process water and produce biohydrogen, volatile fatty acids, carbon dioxide and methane. The formed gas is led out from the upper part of the reactor. When the process is run in a continuous mode, the effluent from the biohydrogen reactor is pumped into the methane reactor, where methanogens are dominant in a mixed anaerobic culture. The volatile fatty acids produced in the biohydrogen reactor along with residual nutrients are converted into methane and carbon dioxide. The effluent liquid of the two-stage process has low COD/BOD levels, and it can be transported for further storage or treatment for other applications. Process control is performed by adjusting pH, temperature inside the reactors, HRT of the process water and removing the produced gases out of the reactors to avoid product inhibition. The gas production rate for biohydrogen and methane was 1.57 L/Lr/d and 0.91 L/Lr/d, respectively. Out of the 0.91 L/Lr/d production of methane, approximately 0.7 L/Lr/d were produced in the biohydrogen reactor and 0.21 L/Lr/d in the methane reactor.

The scaled-up two-step bioprocess can be integrated with a 5 MW electrolyser which not only produces hydrogen but also utilizes heat to the biohydrogen reactor. The electrolyser is an alkaline electrolyser which matches the temperature requirement of the bioprocesses better compared to the other available technologies (e.g. Proton exchange membranes). Figure 9 illustrates the potential interactions between the reactors and the electrolyser including mass and energy balances when the electrolyser and the reactors are operating at the same time. The excess heat from the electrolyser is used for pre-treatment of the process water before it enters the biohydrogen reactor. The operating temperature in the pre-treatment upstream of the biohydrogen reactor is 90 °C, which is higher than the temperature of the stack of the electrolyser. Therefore, a heat pump is required to supply the heat at the desired temperature.

It can be noted that even if the water supply is interrupted consequently stopping the operation of the biological reactors, the electrolyser could still produce hydrogen, and the excess heat could potentially be utilized in a district heating network.

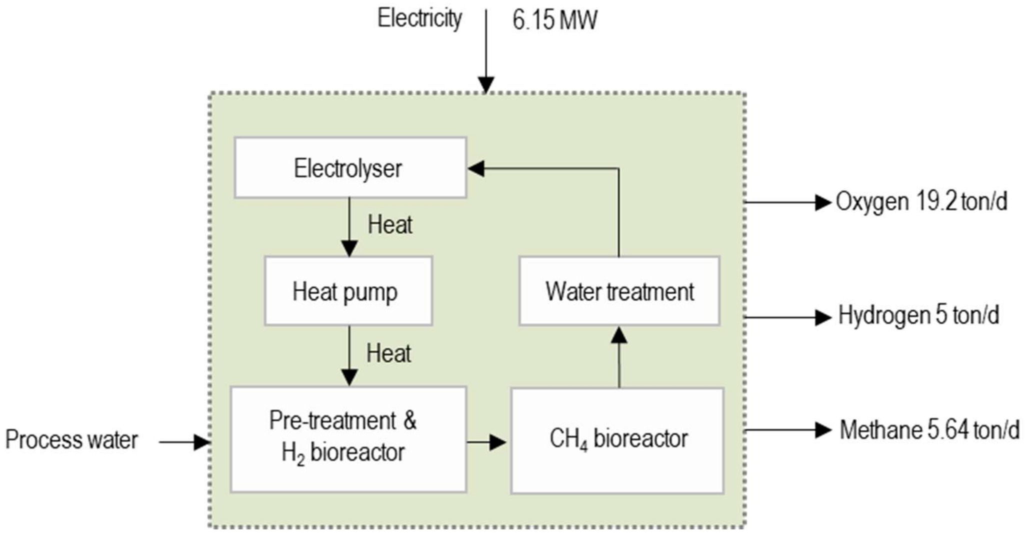


Figure 9. Potential interactions between the biological reactors and the electrolyser. Of the produced 5 ton/day of hydrogen, approx. 2.6 ton/day is produced via water electrolysis. Of the 6.15 MW power input, the electrolyser requires 5 MW, the heat pump 0.3 MW and compressors and pumps 0.85 MW.

Development status, applications, and production scale

The process has been tested in lab scale and small pilot scale in industrial settings. The process needs to be scaled up more and first tested in a large pilot scale, preferably in connection with an existing biogas plant.

Assessment of the technology readiness

An assessment of the technology readiness of the two-step bioprocess concept is provided in Table 13.

Table 13. Assessment of technology readiness for the Bioflex concept

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	9	10	Same system as biogas system, which is available in full scale.
Pre-treatment system	6-7	10	Efficiency of the pre-treatment system is required to get an economical viable process.
Hydrogen reactor	4-5	40	The hydrogen bioreactor for larger scale needs to be developed further for maximum hydrogen production efficiency. A pilot scale reactor is under development at RISE.
Biogas reactor	9	10	Commercial scale reactors for biogas/methane production are available.
Product gas separation	7-9	20	To separate the biohydrogen and methane produced in the first reactor, gas separation system, such as membrane separation need to be installed and developed. Several solutions are commercially available.

Process steps	TRL	Weight [%]	Comments
Integrated operation	4	10	The optimal process integration of hydrogen and methane production in series needs to be optimized in respect to (Hydraulic Retention Time) HRT and volume of reactors
Overall "Weighted Average"	5.8-6.7		
Overall "Weakest Link"	4		Integrated operation to be proven

Key Performance Indicators

Several KPIs have been calculated based on the data provided by the developer in combination with own assumptions. Table 14Table 10Table 6 shows the indicators proposed by Clean Hydrogen Joint Undertaking (CH-JU, 2021) for hydrogen produced via biological production.

Table 14. KPIs of the RISE/Indienz concept for hydrogen production via anaerobic digestion

Parameter	Unit	BioFlex concept	SoA 2020	Targets	
				2024	2030
System carbon yield	kg H_2/kg COD	0.0055	0.012	0.015	0.021
System capital cost	€/(kg/d)	N.A	450	400	450
System operational cost	€/kg	3.5	3.2	3	2.5

The system carbon yield of the Bioflex-concept is approximately half of the claimed state-of-the art value. Here, it must be noted that also biomethane is produced, which is not taken into account in the KPI defined by Clean Hydrogen Joint Undertaking.

Table 15 shows the additional KPIs assessed in this case study.

Table 15. Additional KPIs of the RISE/Indienz concept combined with the electrolyser

KPI parameter	BioFlex concept	Unit
Hydrogen yield	34.2	kg/MWh electricity
Energy efficiency	86-88	%
Selling price hydrogen	7.3-8.2	€ per kg H_2
Selling price methane	2.5-3.1	€ per kg CH_4

Developer Feedback

There is still no industrial technology developer of this technology in place, so no feedback could be taken into consideration for this case.

CASE 4: THE HYTRON/NEA CONCEPT - HYDROGEN FROM ETHANOL THROUGH ONSITE REFORMING

Background

Ethanol is a well-established biofuel, produced from various renewable raw materials and widely used in vehicles world-wide, either as pure ethanol or in fuel blends with gasoline. The global production of ethanol as motor fuel was 121 Mm^3 in 2023 (Statista, 2024).

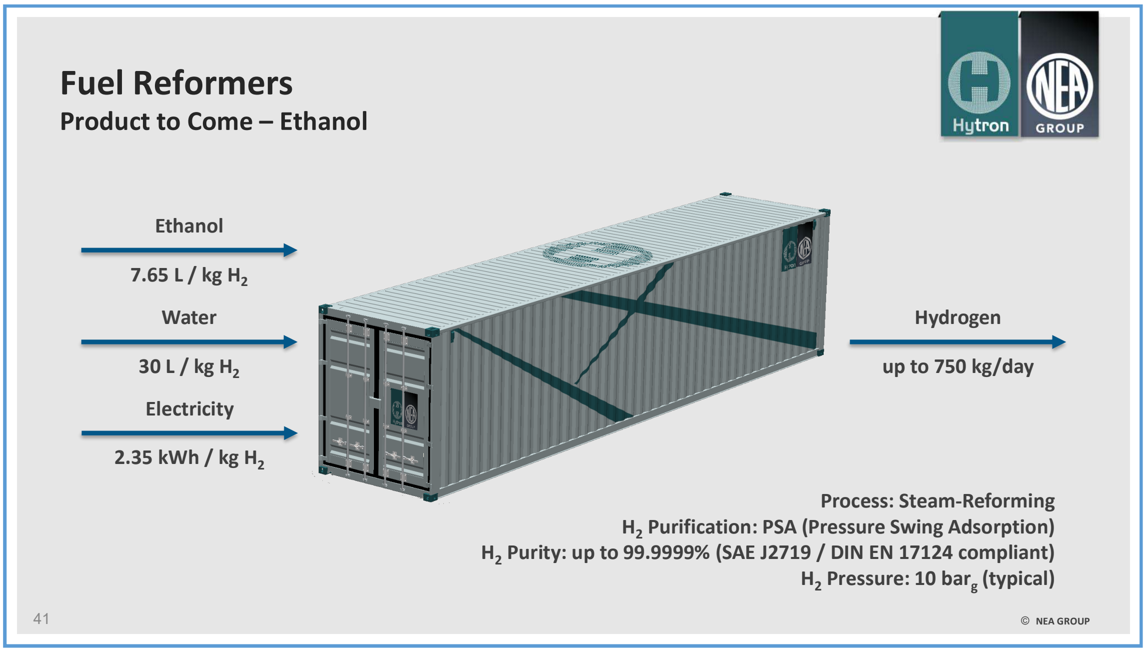
Ethanol can also be used to produce hydrogen via catalytic reforming. The hydrogen production can take place both on board the vehicle or at the gas station. This case study concerns onsite hydrogen production, which has been studied and developed in Brazil since 2010 by Hytron/NEA. Table 16 gives an overview of the technology profile.

Table 16. Technology profile for hydrogen production, purification, and delivery for vehicular use in an onsite unit.

Designation	
Developer/Promotor	Hytron/Neuman & Esser
Conversion technology	Hydrous ethanol catalytic reforming to produce hydrogen for vehicular use
Feeding System	Hydrous ethanol specified as fuel motor is available in all 42,000 gas stations in Brazil
Principal Feedstock(s)	mainly corn and sugarcane (considering the current global ethanol production)
Principal Application	Deliver fuel to existing hydrogen fleet of light vehicles (Toyota Mirai II, Hyundai Nexo and others) and in the future to other hydrogen vehicles such as buses.
Scale	This technology will be available in containers with a nominal output up to 750 kg H_2/day
Development Status	Prototypes are produced and tests are planned to start in 2025.

Process description

The ethanol conversion process is endothermic and in the presence of suitable catalysts and water, the chemical energy of the process makes it possible to maintain reactors (reformers) at temperatures in the range of 600 and 900 °C, producing a gaseous stream rich in hydrogen. After purification, the hydrogen can be used in fuel cell vehicles. Figure 10 illustrates the production system and its balances.



Fuel Reformers

Product to Come – Ethanol

Hytron

GROUP

Ethanol

7.65 L / kg H_2

Water

30 L / kg H_2

Electricity

2.35 kWh / kg H_2

Hydrogen

up to 750 kg/day

Process: Steam-Reforming

H_2 Purification: PSA (Pressure Swing Adsorption)

H_2 Purity: up to 99.9999% (SAE J2719 / DIN EN 17124 compliant)

H_2 Pressure: 10 bar_g (typical)

41

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Figure 10. NEA Hytron proposed hydrogen production system by steam ethanol reforming[5]

Development status, applications, and production scale

The company Hytron, based in Sumaré, State of São Paulo, was founded in 2003 as a spin-off from the Hydrogen Laboratory of the State University of Campinas, Unicamp, supported by the São Paulo Research Foundation, FAPESP. The company focused on technologies for production, purification, and use of hydrogen.

In 2020, Hytron was incorporated by the German company NEA Neuman & Esser Group, reinforcing its expertise in systems integration. Hytron offers a line of hydrogen production reformers for ethanol and biomethane with a rated capacity of up to 750 kg H_2/day at 10 bars with purity up to 99.9999%.

The reformers are offered in integrated and autonomous solutions (turn-key basis), including feed treatment, reforming and shift conversion, PSA gas purification, purity supervision, thermal management and utilities, controls, and containers for outdoor installation. Its deployment in conventional gas stations, where ethanol is readily available, offers an immediate fuel dispenser unit for hydrogen vehicles.

Applying this concept, Shell Brazil, Raízen (sugarcane processing company), Hytron, University of São Paulo (USP) and SENAI (technical education and innovation for industry institution) signed in September 2023 a cooperation agreement for practical validation of hydrogen production from ethanol, through the construction of two plants (5 kg/h and, later, 44.5 kg/h of hydrogen). The project, depicted in Figure 11, includes a hydrogen refueling station on the main campus of USP, in the city of São Paulo, to

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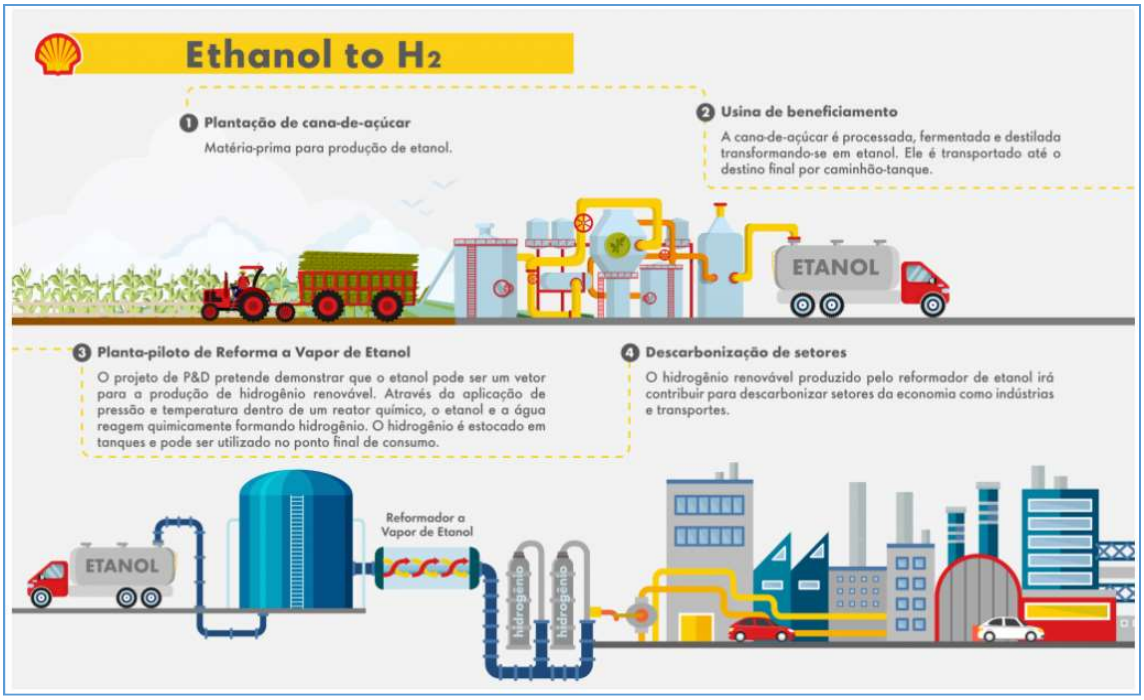
[5] https://task44.ieabioenergy.com/wp-content/uploads/sites/12/2023/03/Lopes_Synergies-ITP-WS_Hytron_NEA-Group-.pdf

supply fuel to three buses used by students and visitors to the campus. These buses, currently burning diesel in conventional ICE, will be equipped with fuel cells.



Ethanol to H_2

❶ Plantação de cana-de-açúcar

Matéria-prima para produção de etanol.

❷ Usina de beneficiamento

A cana-de-açúcar é processada, fermentada e destilada transformando-se em etanol. Ele é transportado até o destino final por caminhão-tanque.

❸ Planta-piloto de Reforma a Vapor de Etanol

O projeto de P&D pretende demonstrar que o etanol pode ser um vetor para a produção de hidrogênio renovável. Através da aplicação de pressão e temperatura dentro de um reator químico, o etanol e a água reagem quimicamente formando hidrogênio. O hidrogênio é estocado em tanques e pode ser utilizado no ponto final de consumo.

❹ Descarbonização de setores

O hidrogênio renovável produzido pelo reformador de etanol irá contribuir para descarbonizar setores da economia como indústrias e transportes.

Figure 11. Conceptual scheme of Shell Brazil, Raízen, Hytron, USP and SENAI project for HYDROGEN production system by catalytic ethanol reforming in USP campus. Illustration by Shell (https://h2businessnews.com/brasil-construira-la-primera-planta-mundial-de-hidrogeno-producido-a-partir-de-etanol/, https://www.shell.com.br/energia-e-inovacao/pesquisa-e-desenvolvimento/ethanol-to-h2.html).

Assessment of the technology readiness

An assessment of the technology readiness of an electric vehicle with fuel cells fed with hydrogen produced by onsite reforming of ethanol is shown in Table 17, for the main process steps.

Table 17. Assessment of technology readiness for hydrogen from ethanol through onsite reforming

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	9	10	Ethanol fuel distribution is a mature and commercial activity in Brazil and other countries

Process steps	TRL	Weight [%]	Comments
Ethanol catalytic reforming on site	6-7	40	This technology is well-known, however its adaptation to vehicular application requires developing efforts, considering thermal balance, efficiency, compactness, and robustness requirements.
Hydrogen separation	9	20	Adopting Pressure Swing Adsorption (PSA) systems, this process is well known, although the vehicular application imposes additional development to assure the required purity.
Hydrogen refueling station	9	10	This technology is available and adopted in gas stations abroad.
Process integration	6-7	20	The system components must be integrated and optimized for efficiency, reliability, and cost/size/weight reduction
Overall “Weighted Average”	7.2-7.8		
Overall “Weakest Link”	6-7		

Key performance indicators

Table 18 shows KPIs of the onsite ethanol reforming concept. It can be noted that Clean Hydrogen Joint Undertaking has not specified KPIs for hydrogen production via reforming of alcohols.

Table 18. KPIs of the onsite ethanol reforming concept for biohydrogen production promoted by Hytron/ Neuman & Esser

KPI parameter	Hytron concept	Unit
System carbon yield	0.32	kg H_2/kg C
System energy use [a]	46.8	kWh/kg H_2
Energy efficiency[b]	57	%
Production rate [c]	11.2-15.3	kg H_2 per ton sugarcane
Production rate	132	kg H_2 per 1,000 liters anhydrous ethanol
Levelized Cost of Hydrogen (LCOH) [d]	4.2-6.3	€ per kg H_2

[a] Energy supply in the form of ethanol and electricity. Energy efficiency for producing the required electricity assumed to be 40%.

[b] Calculated as energy in produced hydrogen (LHV) over supplied energy in ethanol and electricity

[c] Fresh weight sugarcane. Lower range value valid for conventional process of ethanol production (1G), higher range value valid for sugar & cellulose ethanol production (1G/2G)

[d] Estimated cost range. Currency conversion, 1 $ = 0.90 € and Brazilian ethanol price (August, 2024)

Making an economic comparison of this concept with for example hydrogen produced via electrolysis depends primarily on the direct costs of inputs i.e. electricity and ethanol. Figure 12 illustrates the cost relations at two different hydrogen yields to reach break-even situations and when one production pathway is more economic beneficial than the other. In Brazil, the price of ethanol is normally in the range of 0.45-0.55 USD/liter and the electricity price in the range of 0.150 to 0.200 USD/kWh, indicating that hydrogen production via ethanol reforming would be highly competitive against electrolytic hydrogen in the country (Nogueira, 2022).

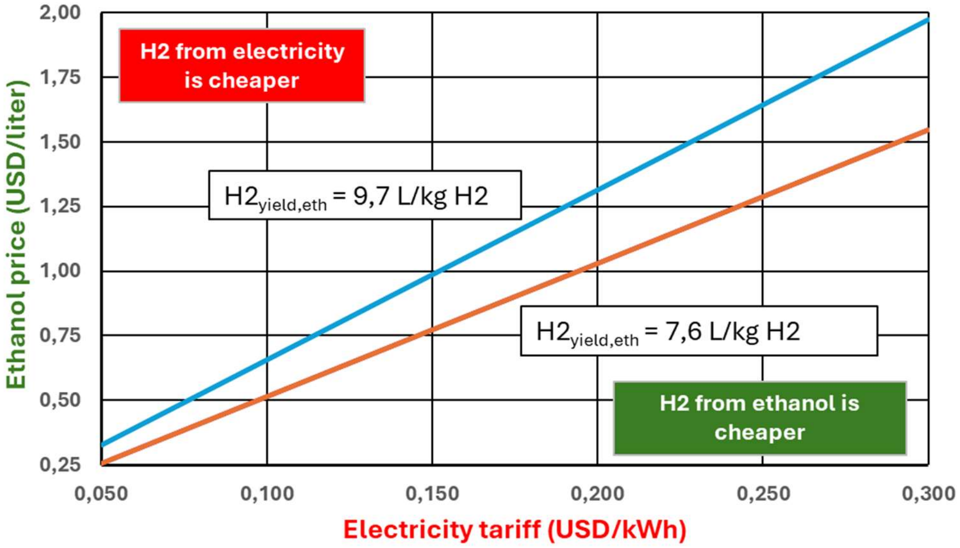


Figure 12. Parity curve for hydrogen production from ethanol and electricity at different hydrogen yields. The electrolytic hydrogen yield is assumed to be 50 kWh per kg hydrogen and that CAPEX and other OPEX are similar for both production pathways (Nogueira, 2022).

Developer feedback

Hytron NEA has provided data and feedback on the assessment of this technology.

CASE 5: THE NISSAN CONCEPT - HYDROGEN FROM ETHANOL THROUGH ONBOARD REFORMING

Background

Ethanol is a well-known biofuel, produced from various raw materials and widely used in transport, fuelling light vehicles either as pure ethanol or in fuel blends with gasoline.

Catalytic reforming of ethanol to produce hydrogen is an endothermic process, in which, in the presence of suitable catalysts and water, the chemical energy of the process makes it possible to maintain reactors (reformers) at temperatures between 600 and 900 °C, to produce a gaseous stream rich in hydrogen, which can be purified for use in fuel cells. Fuel cells efficiently convert the chemical energy of hydrogen into electricity, used to drive electric motors and move the vehicle.

Considering mobility applications, the production of hydrogen from ethanol can be done essentially in two conditions: on board the vehicle or at the gas station. This case refers to onboard hydrogen production, which has been studied and developed in Brazil since 2016 by Nissan. The main conceptual advantage of this onboard route is simplicity: hydrogen is produced and used directly, not requiring gas compression and storage. Table 19 shows the technology profile of the onboard biohydrogen provided by Nissan.

Table 19. Technology profile for onboard H2 production, purification and use in fuel cells.

Designation	Electric vehicle with SOFC feed with hydrogen produced by onboard reformer
Developer/Promotor	Nissan Motor Corporation
Conversion technology	Hydrous ethanol catalytic reforming to produce hydrogen and SOFC (Solid Oxide Fuel Cell) to generate electricity
Feeding System	Hydrous ethanol specified as fuel motor is available in all 42,000 gas stations in Brazil
Principal Feedstock(s)	Considering the current global ethanol production, mainly corn and sugarcane
Principal Application	Currently in Light Duty Vehicles (LDV) and in the future probably in all road vehicles
Scale	This technology has been experimentally implemented in a Nissan NV-299 mini-van
Development Status	Prototypes were produced and tests have been conducted

Process description

Electricity is generated in a Solid Oxide Fuel Cell (SOFC), fed with hydrogen produced onboard through the catalytic reforming of ethanol. This technology neither requires compression or hydrogen storage and is favored by the nationwide ethanol availability in the existing gas stations in Brazil.

The generated electricity is stored in the vehicle battery, which supplies electricity to an electric motor to drive the vehicle. The heat generated during power generation in the SOFC is recycled to the reformer to improve the hydrogen production. Figure 13 shows the process scheme of the Nissan on-board hydrogen production concept.

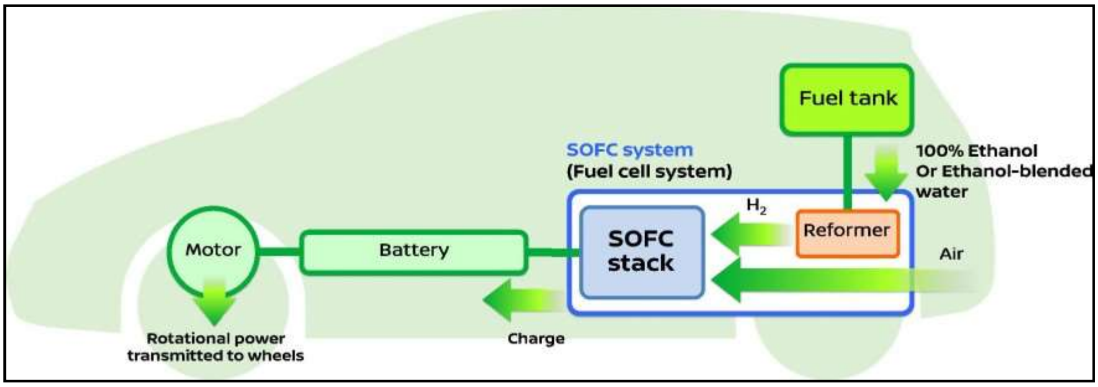


Figure 13. Scheme of the Nissan e-bio SOFC electric vehicle (Illustration from automobilesreview.com)

Development status, applications, and production scale

The automaker Nissan Motor Corporation has been developing this concept since 2016. Tests were carried out in the Nissan e-bio Fuel Cell prototype, with the set of reformer and fuel cell mounted in a Nissan NV-299 mini-van (see Figure 14), which showed promising technical viability in particular regarding the fuel economy. The tests showed that the car could be operated 30 km per liter of ethanol, which is more than twice the driving distance for a conventional vehicle fueled with ethanol.

After this successful proof of concept, the objective of Nissan is to improve performance and integrate fuel cells and reformers to reduce the volume occupied by this system and verify durability, reliability, and performance. Other automakers have shown interest in this solution for the electrification of their models.

Figure 14. Prototype of Nissan e-bio SOFC electric vehicle (Nissan Motor Corporation, 2016).

Assessment of the technology readiness

An assessment of the technology readiness level of electric vehicles with SOFC feed with hydrogen produced by onboard reforming of ethanol is shown in Table 20, for the main process steps.

Table 20. Assessment of technology readiness for the Nissan onboard ethanol reforming concept.

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	9	10	Ethanol fuel distribution is a mature and commercial activity in Brazil and other countries
Ethanol catalytic reforming onboard	6-7	30	This technology is well-known, however its adaptation to vehicular application demands efforts, considering thermal balance, compactness, and robustness requirements, as well as starting up time.

Process steps	TRL	Weight [%]	Comments
Hydrogen separation	8	10	Adopting Pressure Swing Adsorption (PSA) systems, this process is well known, although the vehicular application imposes additional development to assure the required purity.
Hydrogen use in vehicular SOFC	6-7	20	This type of fuel cell operates at temperature in the range 500-1,000 C and issues of thermal balance and starting conditions are in progress.
Process integration	6-7	30	The system components must be integrated and optimized for efficiency, reliability and cost/size/weight reduction
Overall “Weighted Average”	6.5-7.3		
Overall “Weakest Link”	6-7		

Key performance indicators

As an innovative technology under development, there is still limited data on economic viability, especially on capital cost. The operating cost seems attractive, as in Internal Combustion Engines (ICE's) ethanol is currently competitive with gasoline, as the reformer/SOFC route is more efficient and, therefore, also more economical.

Table 21 shows assessed KPIs of the Nissan onboard ethanol reforming concept.

Table 21. KPIs of the onboard ethanol reforming concept promoted by Nissan

KPI parameter	Nissan concept	Unit
System carbon yield	0.25	kg H_2/kg C
Energy efficiency[a]	59	%
Production rate	8.8-12.0[b]	kg H_2 per ton sugarcane
Production rate	103	kg H_2 per 1,000 liters anhydrous ethanol
Levelized Cost of Hydrogen (LCOH)	5.1-7.6[c]	€ per kg H_2

[a] Defined as energy in produced hydrogen over energy in supplied ethanol

[b] Fresh weight sugarcane. Lower range value valid for conventional process of ethanol production (1G), higher range value valid for sugar & cellulose ethanol production (1G/2G)

[c] Estimated cost range. Currency conversion, 1 $ = 0.90 € and Brazilian ethanol price (August 2024)

CASE 6: METHANE SPLITTING BY THERMAL CATALYTIC PROCESS TECHNOLOGY BY HYCAMITE TCD OY

Background

The company Hycamite TCD Technologies Oy in Karleby, Finland develops a technology for energy-efficient production of fossil-free hydrogen and solid carbon from methane (biomethane or natural gas). With heat supply and a catalyst, the methane molecules are split into hydrogen and carbon. No carbon dioxide is formed during the conversion as no oxygen is available. The technology is based on long-term research in applied chemistry at the University of Oulu.

Methane splitting is a well-known technology and typically done via thermal, thermo-catalytic, molten catalytic or plasma-based processes. Thermo-catalytic decomposition (TCD) of methane by catalytic process possess certain advantages over thermal, molten and plasma technologies such as low energy requirements. Methane splitting over solid heterogeneous catalysts operated at moderate temperatures can deliver different types of carbon allotropes and pure hydrogen.

The type of carbon allotrope solely depends on the type of metal catalyst and its composition. For example, TCD of methane over Ni based catalysts produces carbon nanofibers (CNFs), whereas over Fe-based catalysts typically produces highly graphitised carbon nano onions, platelets, and carbon nanotubes (CNTs). The main challenges concern catalyst, reactor, and overall process scale-up. There are few companies in the world, who are commercialising the TCD technology e.g., Hycamite.

Table 22 summarizes the technology profile of the Hycamite TCD concept.

Table 22. Technology profile for the Hycamite TCD concept

Designation	Hycamite TCD Technology Oy
Developer/Promotor	Hycamite TCD Technology Oy
Conversion technology	Methane splitting by catalytic pyrolysis
Feeding System	LNG/biomethane pipeline
Principal Feedstock(s)	LNG, biomethane
Principal Application(s)	H_2, solid carbon in different forms for wide range of applications, e.g., graphitic carbon for battery storage
Scale	1 000 tons of hydrogen & 3 000 tons of carbon annually (CSF plant)
Development Status	In the process building commercial scale methane splitting plant for 3 000 ton of carbon and 1 000 ton of hydrogen production. The plant is expected to be in full operation by November 2024.

Process description

The Hycamite process is a disruptive technology that will help defossilize the industry. It is a thermo-catalytic process i.e., methane splitting by using a catalyst into H_2 and solid carbon. Figure 15 shows a process scheme including simplified energy balances normalized to production of 1 MW hydrogen.

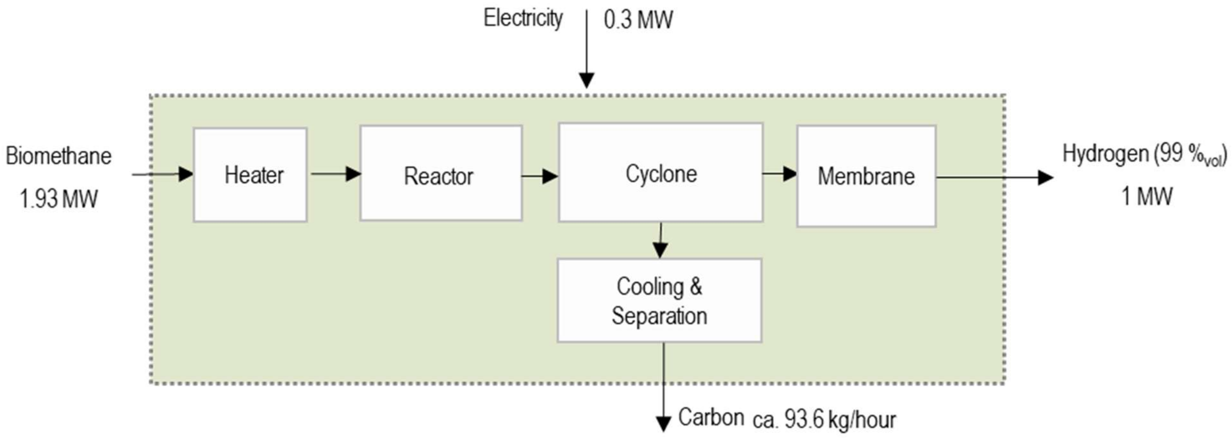


Figure 15. Process scheme including energy balances across the system boundary for production of 1 MW of hydrogen gas.

The process converts LNG or biomethane in a fluidised bed reactor (FBR) *via* external heating elements. The feed gas is pre-heated up to the reaction temperature in the range of 600°C-750°C before the reactor inlet. In the FBR, the catalyst and bed materials undergo fluidisation via feed gas inlet. The carbon growth is initiated over the active metal particles and the carbon nanoparticles are collected in the cyclone separator. The collected carbon is discharged after a certain time on stream operation (>24 h). The cyclone carbon is cooled down and separated and collected in the silo storage tanks. The H_2 and the unreacted CH_4 is separated in a membrane system and the H_2 permeates with 99.9% purity and is sent via pipeline.

Development status, applications, and production scale

Hycamite TCD has currently a smaller test facility in the city of Karleby in Finland. At the same industrial site, Hycamite is currently taking a scaled-up demonstration facility (a so-called Customer Sample Facility (CSF)) into operation. The plant is expected to be in full operation by November 2024. This plant's production capacity is designed for production of 2,000 tons of hydrogen gas and 6,000 tons of high-quality biocarbon per year at full operation.

Assessment of the technology readiness

An assessment of the technology readiness of the Hycamite TCD concept is provided in Table 23.

Table 23. Assessment of technology readiness for the Hycamite TCD concept

Process steps	TRL	Weight [%]	Comments
Feedstock handling system	9	10	Biomethane, LNG gas supply from gas grid terminal is agreed and all certifications and contracts are made
Hycamite process (reactor & catalyst)	6	40	Pilot scale is successfully deployed and produced more than 20 kgs of solid carbon with more than 6 kg of Hydrogen.
Product gas separation cleaning	8	20	Off-the shelf membrane separation with CH_4/H_2 and cyclone separators (-1 point for not tested in commercial scale with biomethane)
Integrated operation	6	30	Successfully demonstrated in pilot scale.
Overall “Weighted Average”	6.7		
Overall “Weakest Link”	6		To be tested in demonstration scale

Key Performance Indicators

Table 24 shows estimated key performance indicators of the biohydrogen production concept based on thermochemical decomposition of biomethane developed by Hycamite OY.

Table 24. Calculated KPIs for the Hycamite TCD-concept

KPI parameter	Hycamite concept	Unit
Hydrogen yield	0.24	ton H_2 per ton of methane
System energy use[a]	74	kWh/kg H_2
Total energy efficiency[b]	45	%
Levelized Cost of Hydrogen (LCOH)	4.1-5.9	€ per kg H_2
CO_2 sequestration potential, carbon captured	>100	%

[a] Energy use includes methane and power supplies

[b] Calculated as energy in hydrogen output over energy in methane and electricity energy inputs

CONCLUDING DISCUSSION

This report shows that renewable, biomass-based hydrogen can be produced via several different conversion technologies, from a variety of biogenic feedstocks and in a wide capacity range. Feedstocks can be of

- Lower grades, such as wastewater, forestry and agricultural residues, which may improve the economic performance of a plant.
- Higher quality feedstock such as bioethanol and biomethane, which allows convenient feedstock distribution and storage.

Many of the biomass-based hydrogen production concepts also generate additional value-added commodities such as biochar, biocarbon, biomethane etc. This adds flexibility, resilience and likely also improved economic performance. Many of the concepts also generate a stream of CO_2, what opens for opportunities to obtain negative CO_2-emissions.

All the presented production concepts are still under development and none of them has reached commercialization. The presented concepts are in the TRL level range of 4-7 and many of them show the “weakest link” in complete integrated operation for hydrogen production.

Table 25 shows a summary of the estimated hydrogen production costs without taking potential credits of selling valuable co-products into account for the technologies included in the case studies.

As part of the techno-economic assessments made for the presented concepts, relevant KPIs defined by the European Clean Hydrogen Joint Undertaking are calculated. These KPIs present the state-of-the-art values as well as indicator targets of the future, which is valuable. The defined KPIs are, however, strongly focused on the system hydrogen yield and the economic performance but miss important features that biomass-based production systems possess, like that other value-added products are simultaneously produced. It can also be noted that KPIs are missing for important conversion technologies for hydrogen production, such as reforming of biogenic alcohols. Therefore, the KPI's defined by the European Clean Hydrogen Joint Undertaking can be considered incomplete and should be revised by adding more production pathways and adding targets that reflect the whole production system and its key characteristics. Furthermore, the definitions of some of the KPIs are a bit unclear. For example, the system capital cost is said to include the complete investment costs and plant start-up expenses. But does it include contingency, civil works and financing costs as well?

A methodological approach aiming at a consistent evaluation of the development status of the different emerging technologies is applied. The approach is centered on the assignation of distinct technology readiness level (TRL) scores to the essential process sub-steps of technologies, namely, feedstock handling, conversion processes, required upgrading and integrated operation, of which relative importance is weighted. Weightings still entail an individual assessment of not only how each step compares against the others in the same process chain, but also of how it measures up against equivalent technical processes. In this context, identifying the step with the lowest score i.e., the "weakest link" and providing it as a complement to a weighted score is motivated and serves to direct attention to the focal points for future development work.

Table 25. Estimated hydrogen production costs

Technology	LCOH €/kg H_2
Biomass gasification (w.o credits for CO_2 and biochar)	3-4
Anaerobic digestion (w.o credits for CH_4)	7-8
Ethanol reforming (onboard/onsite)	4.2-7.6
Thermocatalytic decomposition (w.o credits for C)	4-6

Even though the economic assessments have a high level of uncertainty largely due to the low TRLs, the economic performance for biomass-based hydrogen in general seems promising. The production costs may be equal or even lower than the costs foreseen for hydrogen produced via renewable power in many world regions by 2025, in which also larger volumes of biomass resources may be available, see Figure 16.

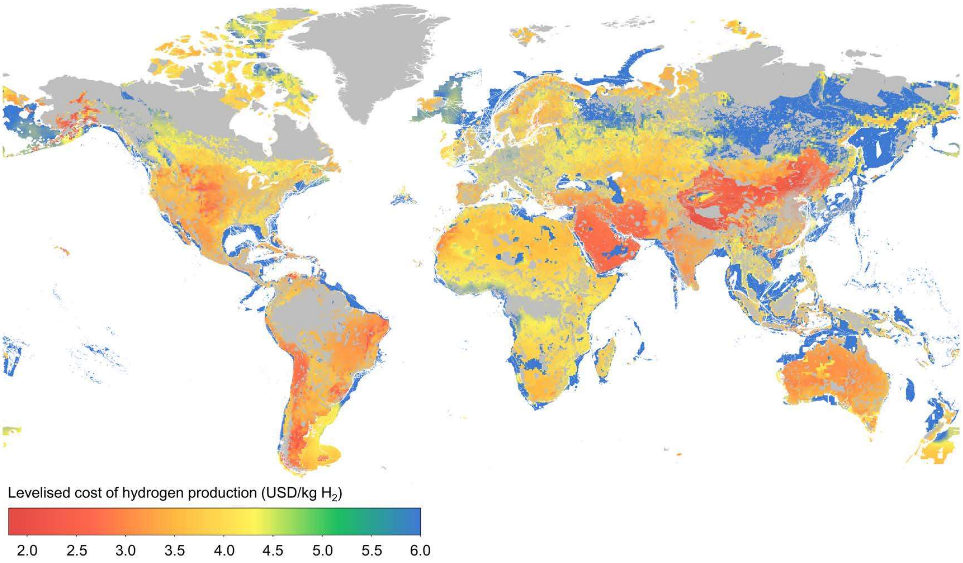


Figure 16. Hydrogen production cost from hybrid solar PV and onshore wind, and from offshore wind in the Net Zero Emissions by 2050 Scenario, 2030 (IEA, 2024)

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