

Hydrogen technologies — Methodology for determining the greenhouse gas emissions associated with the production, conditioning and transport of hydrogen to consumption gate

Annex F

Hydrogen production pathway – Biomass waste as feedstock (with Carbon Capture and Storage – CCS)

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Published in Switzerland

Contents

Annex F (informative) Hydrogen production pathway – Biomass waste as feedstock (with Carbon Capture and Storage – CCS).....1

F.1 Process description and overview.....1

F.1.1 Biomass definition1

F.1.2 Biomass waste definition.....1

F.1.2.1 Determination of waste2

F.1.2.2 Calculation of waste emissions avoidance: equations and examples.....2

F.1.2.2.1 Equation 1:.....2

F.1.2.2.2 Equation 2:.....3

F.1.2.2.3 Example of landfill gas:3

F.1.2.2.4 Equation 3:.....3

F.1.2.2.5 Example of animal feedstock waste and agriculture4

F.1.3 Biomass-Based Hydrogen Routes4

F.1.3.1 General Process Description4

F.1.3.2 Biodigestion / CCS Process Description5

F.1.3.3 Gasification /CCS Process Description7

F.2 Emission sources and inventory9

F.3 Emission Allocation..... 10

F.4 Information to be reported 11

Bibliography 14

Annex F (informative)

Hydrogen production pathway – Biomass waste as feedstock (with Carbon Capture and Storage – CCS)

F.1 Process description and overview

This section provides a definition, description and an overview for hydrogen produced from biomass waste as feedstock with carbon capture.

F.1.1 Biomass definition

Biomass is organic materials derived from plants and animals, excluding material embedded in geological formations and material transformed to fossilized material. Examples of biomass include (not an exhaustive list):

- Conventional food and feed crops
- Food and agricultural waste (e.g., home food waste collection)
- Perennial energy crops (e.g., Miscanthus grass) and short rotation coppice (e.g., willow/poplar)
- Short rotation forestry (e.g., birch) and forest residues (e.g., leftover from logging)
- Marine-based and novel feedstocks (e.g., algae) (BEIS, 2021).

The use of biomass for energy purposes accounts for over 10% of the global energy need, which classifies these feedstocks as the fourth energy source after oil, gas, and coal (World Bioenergy Association, 2020).

Hydrogen from biomass is a carbonless fuel alternative to other high-efficiency biomass secondary energy carriers (e.g., biofuels). Hydrogen production with CCS provides means to sequester and permanently store biogenic CO₂ resulting in a net decrease in atmospheric carbon (IEA, 2017). A wide range of biomass feedstocks can be used for hydrogen production, including wet organic wastes (e.g., sewage sludge, animal wastes, municipal solid waste (MSW)); residues and co-products from agroindustry and the timber industry; dedicated energy crops; and non-food crops (IEA, 2017). The current guidance focuses specifically on the use of waste biomass sources for hydrogen production.

F.1.2 Biomass waste definition

Waste products that could be used for hydrogen production vary widely in composition regionally. **In this document, “waste” is defined as any bio-feedstock that is not deliberately produced and is otherwise unlikely to be valorized in the country of origin.** A non-exhaustive list may include:

- biogenic portion of municipal solid waste (MSW),
- animal waste,
- Sewage sludge,
- food industry residues,
- residue from agriculture,
- forests that would traditionally be left to decompose naturally (ICAO, 2019).

As stated above, this report provides guidance only for waste biomass sources used in hydrogen production. It is worth noting that “waste” is not necessarily a permanent designation for a material. If additional valorized product streams were to emerge for a given type of waste material currently deemed a waste, the competition of its use for hydrogen production could result in upstream emissions impacts.

Additionally, in the context of forestry materials, whether a product is considered a waste or a valorized product is a spectrum versus a clear delineation based on the properties of the material (e.g., corn stover versus corn kernel). A tree that was intended for timber harvest may be thinned because of some perceived defect (e.g., a curved trunk, or relatively diminutive size relative to other trees in the stand). The valorization of the “waste” material which could be considered slash and thinning, may change the decision-making of the forest owner about the allocation of wood material to different end uses. On the margin, this could also result in changes in supply that effect decision-making for other forest owners. Acknowledging that these potential indirect emissions impacts could occur on the margin for certain waste materials over a longer time-frame, issues related to land-use change (LUC)) and other sustainability considerations were outside of the scope of this document, given that the focus is on use of waste.

F.1.2.1 Determination of waste

To determine whether a feedstock is a biogenic waste, stakeholders should rely on analysis specific to the country the feedstock was sourced from. Such analysis should account for the quantity of the respective feedstock that is available in the host country, the approximate size of other markets for that feedstock, and the quantity of the feedstock expected to be used for hydrogen production, to determine whether the feedstock would otherwise have been likely to be valorized. It is worth noting that country’s legislations may encompass this definition.

F.1.2.2 Calculation of waste emissions avoidance: equations and examples

In calculating the emissions associated with biowaste products that would otherwise be disposed of (e.g. MSW that would be disposed of in landfills, or animal waste that would be disposed of in lagoons), stakeholders may attribute credits to the emissions intensity of hydrogen produced based on estimates of GHG emissions of a counterfactual scenario where those wastes would be disposed of.

Regarding hydrogen production, avoided GHG emissions from organic waste feedstock are mainly from CH₄ emissions from decay of organic matter and indirect CO₂ emissions from methane oxidation in the counterfactual scenario.

To determine the value of avoided emissions, stakeholders must first identify an appropriate counterfactual scenario (consequential approach) for the region where the feedstock would likely have been disposed of if it were not utilized for hydrogen production.

F.1.2.2.1 Equation 1:

Equation 1 is an approach to determining the value of a credit for avoided methane emissions that would traditionally be released into the atmosphere. Avoided methane emissions are estimated by subtracting the amount of methane emissions mitigated (e.g., through combustion for power generation, flaring or other oxidation processes) from the amount of methane emissions generated (adapted from (Dong et al., 2006))

$$CH_{4,emission\ credit} = CH_{4,generation} - CH_{4,mitigated} - CH_{4,fugitive\ emission} \quad (F1)$$

where

$CH_{4,generation}$	is the amount of methane generated by the decay of the organic waste feedstock
$CH_{4,mitigated}$	is the amount of the $CH_{4,generation}$ that would likely have been mitigated in the counterfactual scenario (e.g., through combustion for power generation, flaring or other oxidation processes)
$CH_{4,fugitive\ emission}$	is the amount of methane released in the atmosphere

When waste feedstock is being sourced from a region where its disposal would likely have required methane mitigation due to regional regulations, an estimate of the amount of methane generation that would have to be mitigated for regulatory compliance must be accounted for in $CH_{4,mitigated}$.

F.1.2.2.2 Equation 2:

Organic waste feedstock results in carbon dioxide emissions, due partly to decay of the organic matter and partly due to methane mitigation measures at a predefined site in the counterfactual scenario. Carbon dioxide emissions of organic matter are estimated by summing estimates of direct CO₂ emissions with estimates of CO₂ generation from methane oxidation (Lee et al., 2016).

$$CO_{2,emission} = CO_{2,generation} + CO_{2, methane\ oxidation} \quad (F2)$$

F.1.2.2.3 Example of landfill gas:

One traditional approach to the disposal of municipal solid waste is its storage in landfills, where the MSW will eventually decompose to produce GHGs¹. However, landfill emissions may be mitigated, often to comply with regional regulations, e.g., through combustion for power generation, flaring or other oxidation processes (Dong et al., 2006; Lee et al., 2016). Alternatively, this methane can be used for hydrogen production through thermochemical conversion.

F.1.2.2.4 Equation 3:

The quantity of methane generation through the decay of MSW in landfills is typically estimated using first-order decay models, such as Equation 3 (IPCC, 2001). Stakeholders may use such models to estimate the value of $CH_{4,generation}$ in Equation 1.

$$CH_{4,generation\ in\ year\ t} = \sum_x [(A \cdot k \cdot MSW_T(x) \cdot MSW_F(x) \cdot L_0(x)) \cdot e^{-k(t-x)}] \quad (F3)$$

where

x	is the initial year to t
t	Is the years of inventory
X	Are the years for which input data should be added
A	Equals $(1-e^{-k})/k$; normalization factor which corrects the summation. The IPCC recommends values of k
k	Is the methane generation constant (1/year). Countries may have values of k specific to regional waste profiles and conditions at landfills. The IPCC recommends default values of k where region-specific values based on historical data are not available
$MSW_T(x)$	Is the total MSW generated in year x (Gg/year)
$MSW_F(x)$	Is the fraction of MSW disposed at landfill in year X
$L_0(x)$	Is the methane generation potential ($MCF(x) \cdot DOC(x) \cdot DOCF \cdot F \cdot 16/12$ (Gg CH ₄ /Gg waste))
$MCF(x)$	Is the methane correction factor in year x (fraction)

¹ The rate of GHG production from municipal solid waste decay at a landfill depends largely on the composition of the waste (as different waste products will have different carbon content and decay rates), moisture content of the waste, and whether the landfill design is largely aerobic or anaerobic.

DOC (x)	Is the fraction of degradable organic carbon (DOC) in year x (Gg C/Gg waste) The IPCC provides guidance for values of DOC given different types of waste
DOCF	Is the fraction of DOC dissimilated
F	Is the fraction by volume of CH ₄ in landfill gas
16/12	Is the conversion from C to CH ₄

F.1.2.2.5 Example of animal feedstock waste and agriculture

Traditional disposal of animal manure occurs in lagoons. Some lagoons currently capture methane generated and then burn the methane for power generation, but in most cases, methane that is generated is emitted into the atmosphere.

Agriculture waste from large scale agriculture production is normally regulated by local legislation, which may require adopting treatments that results in the production of organic fertilizers and soil conditioners. Agriculture waste treatment includes composting and biodigestion, and both are a mean to promote nutrient recycling and protect the soil against erosion and nutrient loss.

As above, when a credit is being calculated to reflect avoided emissions (consequential approach) from animal or agriculture waste, the value of the credit must account for local regulations that would have mitigated GHG emissions from lagoons or composts in the region the feedstock would likely have been disposed in. CO₂ emitted from biogas formation and agriculture waste incineration are biogenic², thus, do not increase total CO_{2-eq} in the atmosphere.

To estimate avoided emissions from animal waste, it is recommended that stakeholders follow IPCC guidance (Dong et al., 2006).

F.1.3 Biomass-Based Hydrogen Routes

F.1.3.1 General Process Description

Biomass usually has an intricate structure consisting of approximately 6% hydrogen (on a mass basis) in contrast to methane which is 25% hydrogen, for example (Milne et al., 2002). Several highly endothermic processes can be applied to effectively produce hydrogen from different organic matter, leading to significant differences in environmental and energy performances of biomass-to-hydrogen systems (Hallenbeck and Benemann, 2002; Krzysztof J. Ptasiński, 2008; Kalinci et al., 2009).

Biomass-to-hydrogen processes can be divided into two different categories (Hosseini and Wahid, 2016; Nikolaidis and Poullikkas, 2017; Blasi et al., 2020):

1. thermochemical pathways including pyrolysis, liquefaction, or gasification followed by bio-oil upgrading and reforming, or syngas upgrading and biomethane reforming;
2. the biological pathways including water-gas shift reactions promoted by micro-organisms, photo-fermentation and dark-fermentation, anaerobic digestion and biomethane upgrading, and bio-photolysis with photosynthetic organisms (microalgae and cyanobacteria) such as microbial electrolysis cells.

Thermochemical pathways aim to promote cracking reactions under severe thermodynamic conditions, so to breakdown biomass molecules into lower molecular weight polymers and hydrogen-rich gases. Biological routes provide alternative methods of hydrogen production since they can be operated at ambient temperatures and pressures, therefore being less energy-intensive compared to thermochemical processes (Singh and Wahid, 2015).

² It is worth noting that fugitive biomethane emissions cannot be re-absorbed by plants.

The present analysis considers two different hydrogen production routes described as follow and summarized in Figure F.1.

1. Biodigestion route: (a) feedstock pre-treatment, (b) biodigestion and biogas pre-treatment (c) reforming (biomethane or dry reforming), (d) high-temperature shift reactor and (e) pressure swing adsorption (PSA).
2. Gasification route:
 - A. Gasification with combustion: (a) feedstock pre-treatment, (b) gasification and combustion (c) reforming, (d) high-temperature shift reactor and (e) pressure swing adsorption (PSA).
 - B. Gasification without combustion: (a) feedstock pre-treatment, (b) gasification (c) high-temperature shift reactor and (d) pressure swing adsorption (PSA).

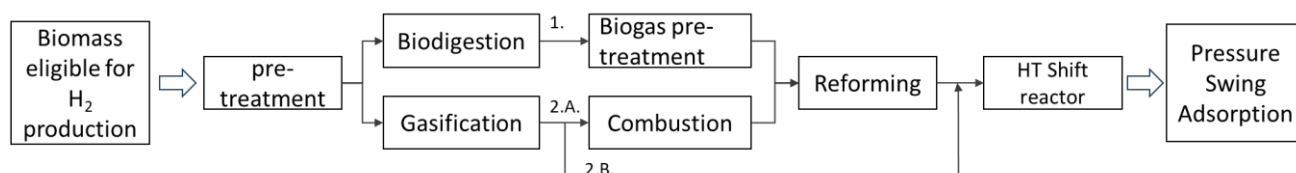


Figure F.1 — An example of hydrogen from Biomass - General Overview

In the biomass-to-hydrogen route, biogenic CO_{2eq} emissions are produced during the gas processing in the pre-treatment phase, the reforming and high-temperature reactions, and the separation in the pressure swing adsorption phase. Non-biogenic CO₂ emissions may be associated with feedstock transport, electric grid energy mix, and other energy inputs for the production system.

As most hydrogen production from biomass is still in the early commercial stage, it is difficult to define standardized production pathways, especially for cases that include CCS. However, due to similarities to coal gasification and SMR processes, their associated carbon capture technologies and processes can be used for biomass-to-hydrogen pathways. Depending on the facility and the biomass conversion process, CO₂ can be captured by different means such as chemical solvents (mono-ethanol amine (MEA), methyl-diethanol amine (MDEA)), physical solvents (Selexol system) and pressure swing adsorption (PSA).

It is worth to mention that hydrogen produced with renewable electricity generated from biomass sources is out of the scopes of the present document as it is treated within the task related to the hydrogen production from electrolysis.

F.1.3.2 Biodigestion / CCS Process Description

Organic feedstock's available for biogas production are mainly agriculture waste, animal manure, sewage sludge and disposed organic waste in landfills. Biogas, which is majorly composed of 40-65% of CH₄ and 35-55% of CO₂, results from the anaerobic digestion of organic feedstock's in absence of oxygen and without energy supply. Other components, such as hydrogen sulfide (H₂S), oxygen, nitrogen, moisture, siloxanes, ammonia, can also be found in minor portions and are removed during the pre-treatment stage. The final desired biogas composition varies according to the reforming technologies utilized. For instance, after the initial upstream system for the biogas mixture (Figure F.2 —), biogas upgrading is required before biomethane SMR (Figure F.3), whereas dry reforming benefits from moisture content in raw biogas (Figure F.4 —).

Module 1 (upstream system) covers upstream activities associated with the pre-treatment of the feedstock, its transport, extraction, and processing until obtaining raw biogas or biogas mixture (Figure F.2). A potential co-product from this process is feedstock for fertilizer, which consists of solid and/or

liquid matter derived from this process. The scope of this work only considers the anaerobic digestion of organic wastes.

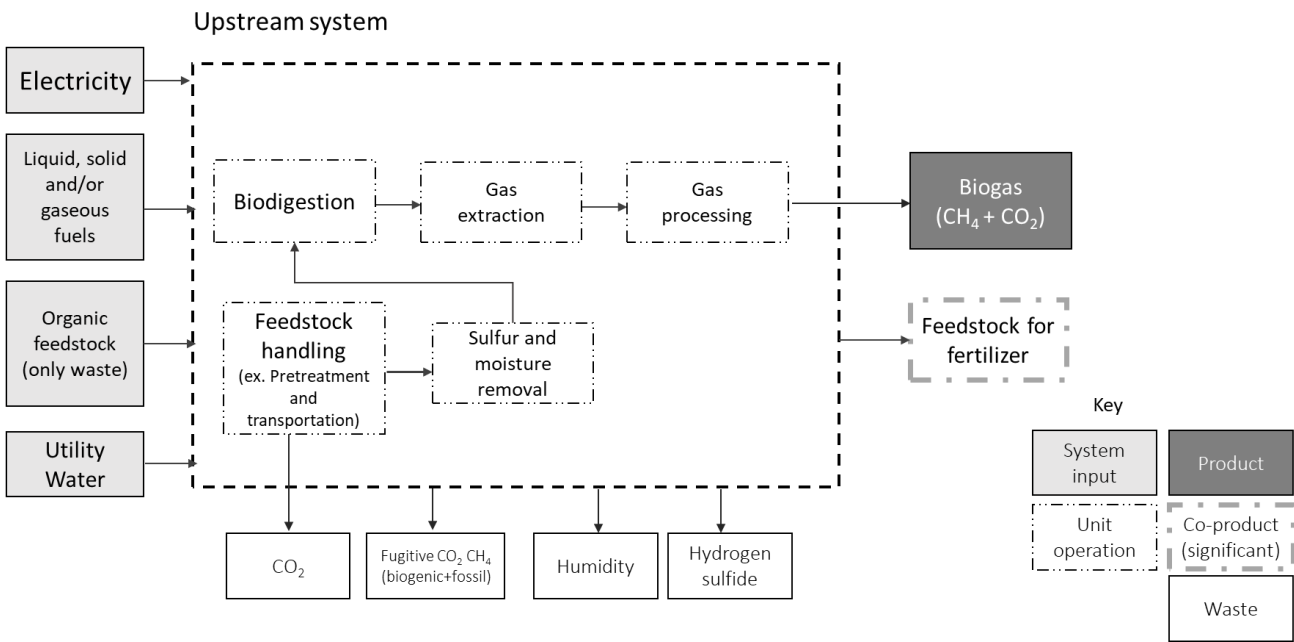


Figure F.2 — An example of process diagram for the upstream system to deliver biogas mixture for upgrading and/or reforming

Module 2 (production system) The base case consists of two different processes.

First (module 2a) biomethane steam methane reforming: (a) biogas mixture heating and pressurization, (b) pre-reformer (desulphurization and moisture removal), (c) primary reformer (SMR), (d) high-temperature shift reactor and (e) pressure swing adsorption (PSA). Carbon capture and storage relates to biogenic CO₂.

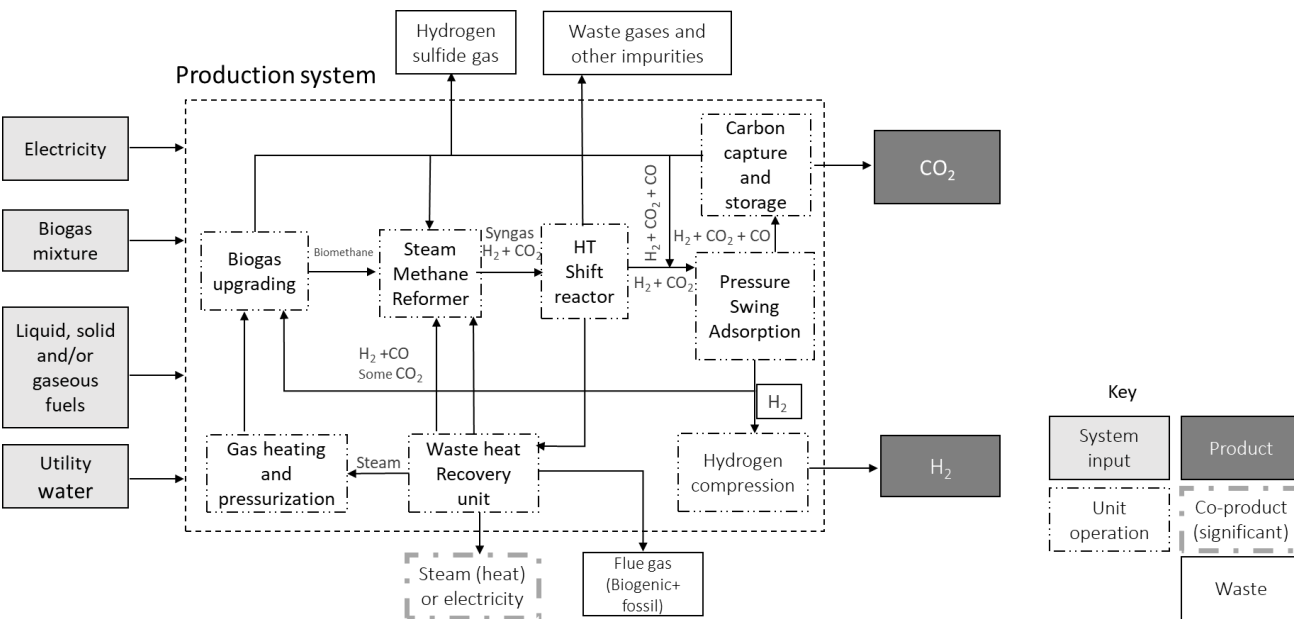


Figure F.3 — An example of process diagram for hydrogen produced from SMR/CCS with biogas

Second (module 2b) Dry reforming: (a) biogas mixture heating and pressurization, (b) pre-reformer (desulphurization), (c) dry reformer (biogas), (d) high temperature shift reactor and (e) pressure swing adsorption (PSA). Carbon capture and storage relates to biogenic CO₂.

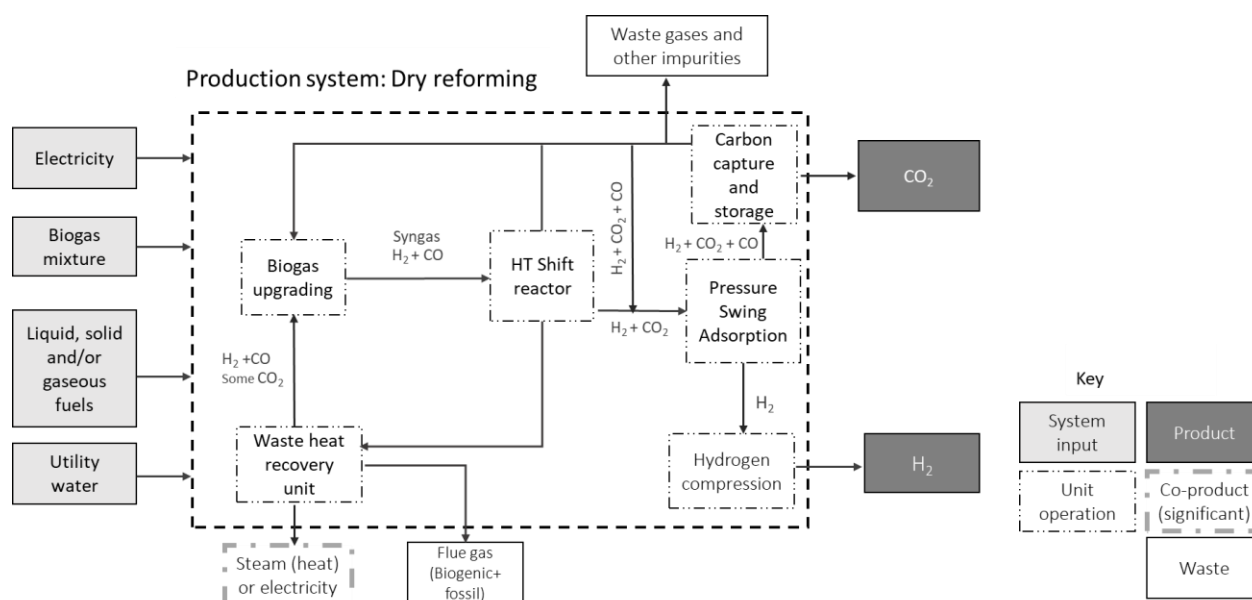


Figure F.4 — Process diagram for hydrogen produced from Dry Reforming/CCS of biogas

For both biogas reforming routes (module 2a and b), co-products can be electricity, steam and/or carbon monoxide (pending the nature of the individual production facility).

F.1.3.3 Gasification /CCS Process Description

Gasification is the thermochemical conversion of a solid fuel into a product gas (also referred to as producer gas) in presence of a specific gasification agent, commonly air. A biogenic carbon-based material, such as biomass and wastes, is partially combusted to generate heat (in general from 700 to 1200°C), which release product gas (e.g., CO, CO₂, H₂, CH₄ and other light HCs), some harmful gases, and other residuals.

Gasification can be performed in either single step, or multi-step processes, based on both fixed and/or fluidized bed reactors. For subsequent steps, gas cleaning and upgrading are necessary in order to remove trace components like H₂S, NH₃, HCl, as well as other residuals (depending on the feedstock and processing conditions). Adding water/steam as a gasification agent is a common practice to increase hydrogen production, enhance char gasification and moderate the reactor temperature. The reforming process is similar to SMR of methane. The major unit operations are a primary reformer to convert methane and the higher hydrocarbons present in the product gas to syngas, plus shift reaction to convert syngas and steam to hydrogen. The purification section is the last conversion step, i.e., Pressure Swing Adsorption (PSA) reactor, which typically requires at least 70 mol% hydrogen in the input stream (Koroneos et al., 2008). Therefore, the flue (tail) gas from the PSA unit is recycled and combusted to provide heat for the gasification and steam reforming processes. More detailed descriptions of biomass gasification-to-hydrogen processes, including detailed LCA studies, are reported in the works of (Moreno and Dufour, 2013; Muresan et al., 2014; Martín-Gamboa et al., 2016). In the present section, the conversion pathways have been elaborated by following the processes layout reported in (Kabir and

Kumar, 2011; Simons and Bauer, 2011; Prussi et al., 2020), based on the gasifiers described in (Binder et al., 2018).

Module 1 (upstream system) covers upstream activities associated with the pre-treatment of the feedstock, its transport, extraction, and processing until obtaining biomass with specifications and moisture content suitable for the next gasification process (Figure F.5). In Module 1, farmed or waste wood is used as the example for biomass feedstock, but in some cases also herbaceous biomass or the organic fraction of MSWs could be considered as feedstock.

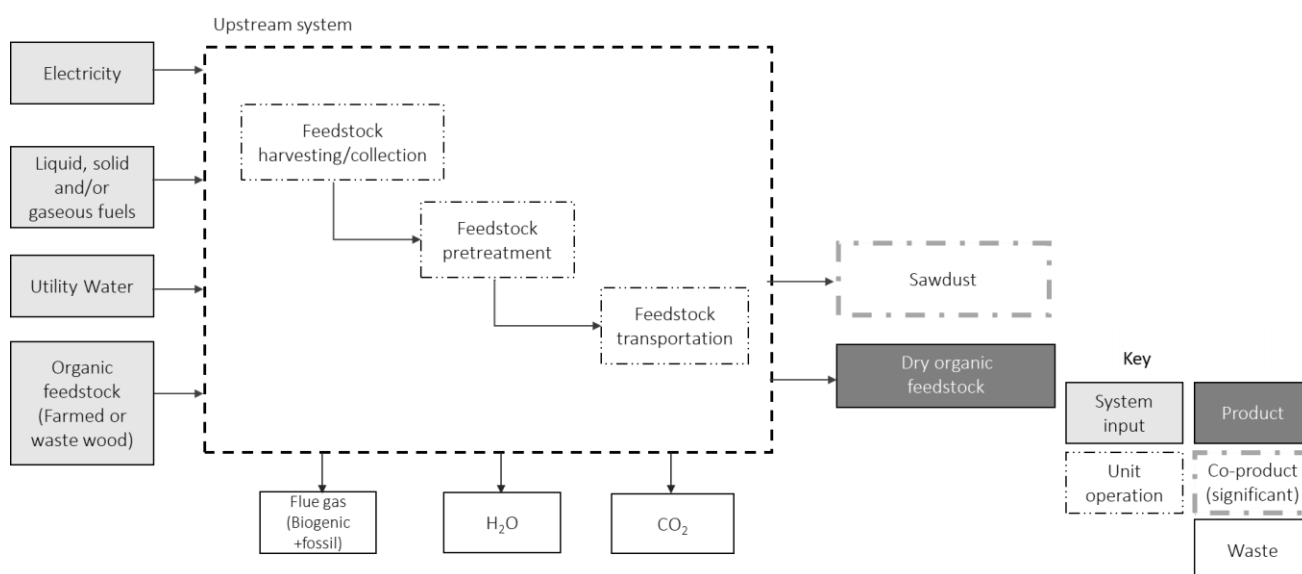


Figure F.5 — Example of process diagram for the upstream system for gasification processes

Module 2 (production system)

Module 2 comprises two different processes layout, based on: traditional gasification (single step unit) [module 2a in Figure F.6], which delivers first the product gas to a steam reformer, followed by a shift reactor and ending with hydrogen purification section in PSA; a double step gasifier based on a fluidized bed [module 2b in Figure F.7], which deliver a cleaner gas (compared to the previous case), i.e., syngas from partial combustion of product gas, directly to the shift reactor followed by the hydrogen purification section. The latter process includes the use of catalysts.

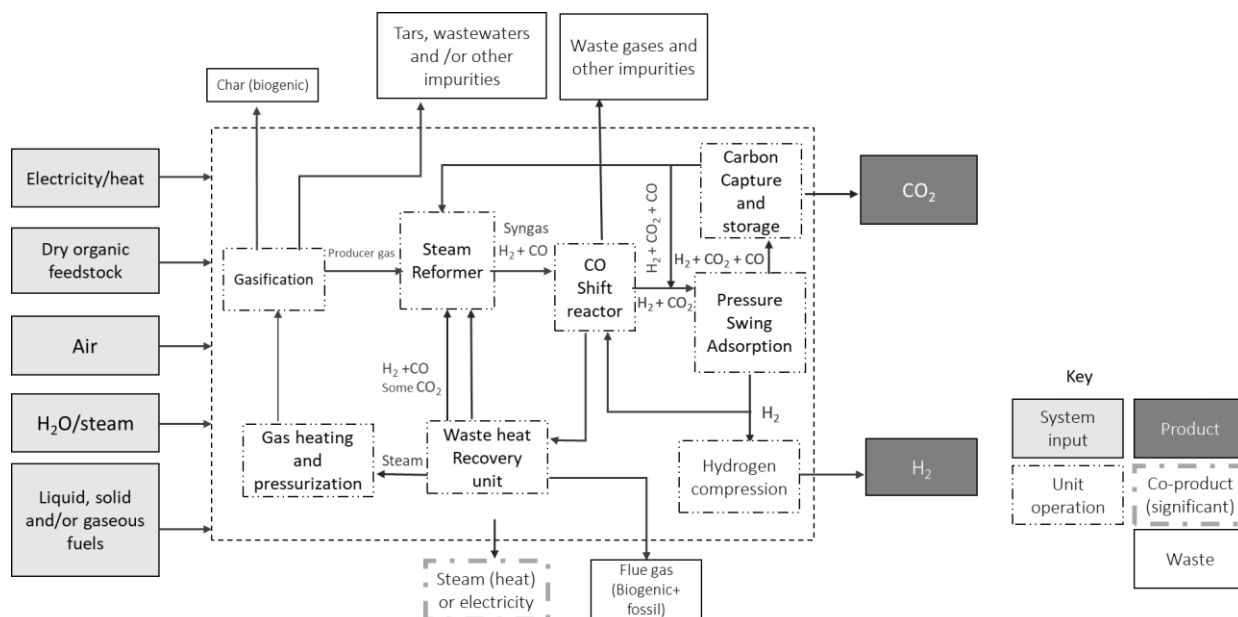


Figure F.6 — Example of production System based on Gasification, Reforming, Shift and PSA

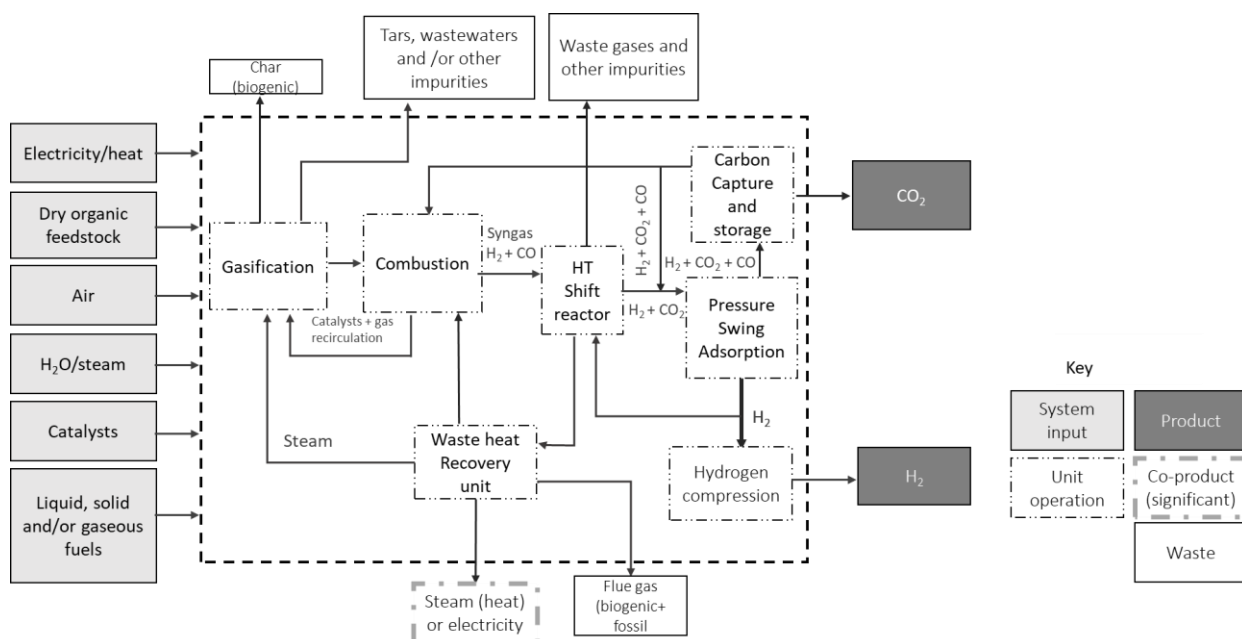


Figure F.7 — Example of production System based on adsorption enhanced reforming (AER) gasification, shift reactor and PSA

F.2 Emission sources and inventory

For biomass-based hydrogen routes with CCS, the main source of GHG emissions is the CO₂ resulting from the gasification and bio digestion processes. However, differently from natural gas SMR or coal gasification, the CO₂ emission from biomass gasification is biogenic. Refer to ISO 14067, article 6.5.2 on biogenic carbon accounting. Other significant emission sources include the emissions of grid electricity, energy used for CO₂ removal process, and energy used for CCS.

Each processing unit or stage in the biomass-based hydrogen routes contains unique emissions sources as outlined in Table F.1.

Table F.1 — GHG emissions summary for biomass-based hydrogen routes /CCUS

Process unit/stage	Key emissions sources	Other emissions sources
Organic feedstock processing	<ul style="list-style-type: none"> Electricity and/or fuel combustion for feedstock extraction, treatment, and movement Fugitive biomethane and/or biogenic carbon dioxide from biogas mixture leakage /decay of organic feedstock 	
Biomass feedstock transport	<ul style="list-style-type: none"> Electricity and/or liquid fuel combustion for materials movement Biomethane leakage 	
Air separation	<ul style="list-style-type: none"> Electricity for air compression (needed for gasification process) 	
Gasification	<ul style="list-style-type: none"> Combustion of dry biomass within the gasifier (biogenic) 	
	<ul style="list-style-type: none"> Gasification of dry biomass within the gasifier (biogenic) 	
	<ul style="list-style-type: none"> Steam for gasification (if purchased from a third party rather than self-generated) 	
Heat recovery for steam or electricity generation	<ul style="list-style-type: none"> No significant emissions other than those covered under common emissions sources 	Potential co-product credits if exported
Hydrogen enrichment	<ul style="list-style-type: none"> Water-gas shift reactions occurring as part of hydrogen enrichment (biogenic CO₂) 	
Syngas purification	<ul style="list-style-type: none"> Electricity and/or heat for operation of the relevant purification units 	
CO ₂ capture and separation	<ul style="list-style-type: none"> Electricity and/or heat for relevant separation units 	
Compression and transport of CO ₂	<ul style="list-style-type: none"> Electricity and/or gaseous fuel combustion for CO₂ compression needed for pipeline transport Liquid and/or gaseous fuel combustion for mobile transport Fugitive CO₂ from mobile transport of CO₂ 	
Storage of CO ₂	<ul style="list-style-type: none"> Electricity and/or gaseous fuel combustion for injection or transformation 	Fugitive CO ₂ from a permanent storage location
Hydrogen compression and storage	<ul style="list-style-type: none"> Electricity and/or gaseous fuel combustion for compression and storage 	

F.3 Emission Allocation

The present analysis showed how existing biomass pathways can be part of hydrogen production with the addition of a final conversion stage in the gas upgrading section. This leads to complex value chains including different technologies at different TRL and commercial maturity. Therefore, the energy and environmental assessments need large life cycle inventory (LCI) and harmonized methodologies for

consistent evaluation. Several studies in the literature investigated the LCA performances of biomass-to-hydrogen pathways, which generally followed the guidance of the ISO LCA methodology, ISO 14040-14067.

The hydrogen production case studies and methods proposed within this document provide the guidelines to a calculation method for production processes with multiple outputs. With regards to the work done in support to IPHE, the main recommendations to perform a full LCA study of biomass-to-hydrogen pathways are reported here below.

1. The need for system boundary definition, which avoids the allocation of GHGs emissions among co-products, wherever possible.
2. When allocation for GHGs cannot be avoided, it should follow 4.3.2.8 (Emissions allocation).
 - ISO guidelines specify that, if allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them (e.g., allocation by energy shares in the various products);
 - When co-products with no-, or negligible, energy content result from the process, other allocation options could be considered, following ISO guidelines;
 - Allocation approaches can be applied in cascade, and no single choice have to be made, in the attempt to cover a very broad spectrum of possibilities.
3. Inclusion of GHG emissions from the use of electricity and energy inputs for hydrogen production in the calculation of hydrogen-related GHG emissions (e.g., including upstream fuel supply chain emissions, emissions from the production of electricity, emissions associated with electricity transmission and distribution losses).

As regards CCS strategies, refer to section 4.3.2.1.

F.4 Information to be reported

Table F.2 — shows the information to be reported for hydrogen produced from hydrogen waste as feedstock with carbon capture.

Table F.2 — Information to be reported for the Biomass/CCS pathway

Category	Matters to be identified
Facility details	<ul style="list-style-type: none"> • Facility identity • Facility location • Facility capacity [Nm³/h, t/h] • Capacity Factor • Commencement of facility operation • Main climatic and meteorological data (Atmospheric pressure, average ambient temperature, average relative humidity)
Production	<ul style="list-style-type: none"> • Feedstock and production technology pathway
Product Specifications	<ul style="list-style-type: none"> • Hydrogen pressure • Hydrogen purity • Contaminants
GHG emissions overview	<ul style="list-style-type: none"> • Emissions intensity of hydrogen batch [kgCO₂e/kgH₂] Refer to ISO 14067, article 6.5.2 on biogenic carbon accounting
Batch details	<ul style="list-style-type: none"> • Beginning and end of batch dates • Batch quantity
Electricity	Location based emissions accounting:

	<ul style="list-style-type: none"> Quantity of purchased grid electricity [kWh] Location based emission factor used [gCO₂e/kWh] Quantity of sold (exported) electricity [kWh] <p>Market based emissions accounting</p> <ul style="list-style-type: none"> Quantity of purchased grid electricity [kWh] Quantity of contracted electricity [kWh] and/or quantity of associated Guarantees of Origins (GO) or Renewable Energy Certificates (REC) Type of GOs or RECs Residual electricity Residual mix emission factor [gCO₂e/kWh] <p>On-site electricity generation</p> <ul style="list-style-type: none"> Quantity of on-site generation [kWh] Emission factor for on-site generation (as applicable) [gCO₂e/kWh]
Other utilities	<ul style="list-style-type: none"> Source/s of water Source/s of steam Catalysts [kg] Quantity of purchased water [kg] Quantity of purchased steam [kg] Quantity of steam exported [kg]
Biomass feedstock conversion	<ul style="list-style-type: none"> Type of biomass feedstock GHG credits from counterfactual scenario (applicable to waste biomass only) Composition and properties of biomass feedstock Quantity of feedstock input [kg] Quantity of biogas mix produced (kg) Composition of biogas mix Types of process fuels combusted Quantities of fuel combusted [L, kg] Relevant emissions calculation or factors used [kgCO₂e/relevant unit of fuel]
Process: Biogas upgrading	<ul style="list-style-type: none"> Biogas mix purification technology Sulphur waste gas processing technology (if applicable) Contaminant removal technology Wastes treatment/storage technology (if applicable) Quantity and type of vented GHG gases [kg] Quantity and type of flared GHG gases [kg] Quantity of biogas mix input [kg] Quantity of purified biogas produced [kg] Composition of produced biogas Type of process fuel(s) used Quantity of process fuel(s) used
Process: Gasification	<ul style="list-style-type: none"> Gasification reactor type Air separation technology (if applicable) Contaminant removal technology Sulphur waste gas processing technology (if applicable) Wastes treatment/storage technology (if applicable) Quantity and type of vented GHG gases [kg] Quantity and type of flared GHG gases [kg]
Process: Hydrogen production	<ul style="list-style-type: none"> Quantity of biogas used for SMR reactions [kg] Quantity of biogas used for heating [kg] Quantity of biogas used for producing steam [kg] (if applicable) Quantity of biogas input [kg] Quantity of hydrogen produced [kg] Type of process fuel(s) used Quantity of process fuel(s) used

	<ul style="list-style-type: none"> Embodied emission factor for biogas [kgCO₂e/kg] (derived from primary and secondary data, provided by the supplier or sourced from relevant source i.e. NGA Factors)
Dry biomass feedstock (wood)	<ul style="list-style-type: none"> Type of wood Particle size [m] Moisture content [%mc] Mass flow [kg/h] Energy flow [MJ/h] Emission factor for wood production Biomass physical pre-treatment technology Biomass dryer or storage technology
Carbon dioxide treatment	<ul style="list-style-type: none"> Type of CO₂ storage Location of CO₂ storage Transport type of CO₂ to storage location (if applicable) Type of CCS energy/fuel(s) used Quantity of energy/process fuel(s) used Quantity of CO₂ captured [kg] Quantity of CO₂ stored [kg] Quantity of CO₂ sold [kg] Quantity of fugitive emissions created during injection of CO₂ into the storage location [kg] Quantity of fugitive CO₂ emissions from storage [kg] (in line with defined timeline)
Waste or co-products	<ul style="list-style-type: none"> Quantity of H₂S produced [kg] (biodigestion only) Quantity of water produced [kg] (gasification only) Quantity sawdust of produced [kg] (gasification only) Quantity of char produced [kg] (gasification only) Quantity of tar produced [kg] (gasification only) Quantity of steam produced Quantity of electricity produced Quantity of flue gas produced Quantity of other wastes or co-products

Bibliography

- BEIS. (2021) Biomass Policy Statement. no.November45.
- Hydrogen from biomass gasification - IEA Bioenergy Task 33 Report (2018, Paris (France)). 2018. Ed. Binder, M., Kraussler, M., Kuba, M., Luisser, M., Rauch Herausgeber, R. Paris (France),
- Blasi, A., Fiorenza, G., Verardi, A. (2020). 3 - Hydrogen from biomass. Ed. Institute on Membrane Technology of the Italian National Research Council (CNR-ITM). Rende, CS, Italy: Elsevier Inc.
- Comparison of Biofuel Life Cycle Analysis Tools - Phase 2, Part 1: FAME and HVO/HEFA (2018, Paris (France)). 2018. Ed. Bonomi, A., Klein, B.C., Chagas, M.F., Souza, N.R.D. Paris (France),
- Comparison of Biofuel Life Cycle Analysis Tools - Phase 2, Part 2: biochemical 2G ethanol (2019, Paris (France)). 2019. Ed. Bonomi, A., Klein, B.C., Chagas, M.F., Souza, N.R.D. Paris (France),
- Borole, A.P., Greig, A.L. (2019) Life-Cycle Assessment and Systems Analysis of Hydrogen Production In Biohydrogen s.l.: s.e.: pp. 485–512.
- Dong, H., Mangino, J., McAllister, T.A., Hatfield, J.L., Johnson, D.E., Bartram, D., Gibb, D., Martin, J.H. (2006) Emissions from livestock and manure management In IPCC Guidelines for National Greenhouse Gas inventories
- Hallenbeck, P.C., Benemann, J.R. (2002) Biological hydrogen production; Fundamentals and limiting processes. International Journal of Hydrogen Energy, 27, 1185–1193.
- Hosseini, S.E., Wahid, M.A. (2016) Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development. 57, 850–866.
- ICAO. (2019) CORSIA Methodology For Calculating Actual Life Cycle Emissions Values. no.March.
- Technology Roadmap: Delivering Sustainable Bioenergy (2017, Paris). 2017. Ed. IEA. Paris,
- International Organization for Standardization. (2006) "ISO 14040:2006 Environmental Management - Life Cycle Assessment - Principles and Framework". In Page. 20.
- IPCC (2001) Waste In Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories Montreal: Intergovernmental Panel on Climate Change (IPCC).
- Kabir, M.R., Kumar, A. (2011) Development of net energy ratio and emission factor for biohydrogen production pathways. Bioresource Technology, 102, 8972–8985.
- Kalinci, Y., Hepbasli, A., Dincer, I. (2009) Biomass-based hydrogen production: A review and analysis. International Journal of Hydrogen Energy, 34, 8799–8817.
- Koroneos, C., Dompros, A., Roumbas, G. (2008) Hydrogen production via biomass gasification-A life cycle assessment approach. Chemical Engineering and Processing: Process Intensification, 47, 1261–1268.
- Krzysztof J. Ptasiński. (2008) Efficiency analysis of hydrogen production methods from biomass. Int. J. Alternative Propulsion, 2, 1601–1608.
- Lee, U., Han, J., Wang, M. (2016) Well-to-Wheels Analysis of Compressed Natural Gas and Ethanol from Municipal Solid Waste. 2016.
- Martín-Gamboa, M., Iribarren, D., Susmozas, A., Dufour, J. (2016) Delving into sensible measures to enhance the environmental performance of biohydrogen: A quantitative approach based on process simulation, life cycle assessment and data envelopment analysis. Bioresource Technology, 214, 376–385.
- Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S.J., Ulgiati, S. (2018) Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. Environments - MDPI, 5, 1–19.

- Hydrogen from biomass: state of the art and research challenges (2002, Golden, CO). 2002. Ed. Milne, T.A., Elam, C.C., Evans, R.J. Golden, CO,
 - Moreno, J., Dufour, J. (2013) Life cycle assessment of hydrogen production from biomass gasification. Evaluation of different Spanish feedstocks. *International Journal of Hydrogen Energy*, 38, 7616–7622.
 - Muresan, M., Cormos, C.C., Agachi, P.S. (2014) Comparative life cycle analysis for gasification-based hydrogen production systems. *Journal of Renewable and Sustainable Energy*, 6, .
 - Nikolaidis, P., Poullikkas, A. (2017) A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, 67, 597–611.
 - JEC Well-to-Tank report v5 | EUR 30269 EN | JRC119036 (2020, Luxembourg). 2020. Ed. Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., Lonza, L. Luxembourg,
 - Reaño, R.L. (2020) Assessment of environmental impact and energy performance of rice husk utilization in various biohydrogen production pathways. *Bioresource Technology*, 299, 122590.
 - Simons, A., Bauer, C. (2011) Life cycle assessment of hydrogen production In *Transition to Hydrogen: Pathways Toward Clean Transportation* s.l.: Cambridge University Press: pp. 13–57.
 - Singh, L., Wahid, Z.A. (2015) Methods for enhancing bio-hydrogen production from biological process: A review. *Journal of Industrial and Engineering Chemistry*, 21, 70–80.
 - Valente, A., Iribarren, D., Dufour, J. (2017) Harmonised life-cycle global warming impact of renewable hydrogen. *Journal of Cleaner Production*, 149, 762–772.
 - _____. (2018) Harmonising the cumulative energy demand of renewable hydrogen for robust comparative life-cycle studies. *Journal of Cleaner Production*, 175, 384–393.
 - Global Bioenergy Statistics 2020 (2020, s.l.). 2020. Ed. World Bioenergy Association. s.l.,
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