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Biomass gasification for synthesis gas production and applications of the syngas

Reinhard Rauch,^{1*} Jitka Hrbek² and Hermann Hofbauer²

Synthesis gas from biomass can be produced and utilized in different ways. Conversion of biomass to synthesis gas can be done either in fluidized bed or entrained flow reactors. As gasification agent oxygen, steam, or mixtures are used. The most common use of biomass gasification in the last decades has been for heat and/or power production. Nowadays, the importance of transportation fuels from renewables is increased due to environmental aspects and growing fossil fuels prices. That is why the production of Fischer–Tropsch (FT) liquids, methanol, mixed alcohols, substitute natural gas (SNG), and hydrogen from biomass is now in focus of view. The most innovative and interesting ways of synthesis gas utilization and projects, BioTfuel or GoBiGas, BioLiq, Choren, etc. are discussed here. Further the microchannel technology by Oxford Catalysts and distributed production of SNG in decentral small scale are presented. The synthesis platform in Güssing, Austria is also presented. The FT liquids, hydrogen production, mixed alcohols, and BioSNG, these are the projects associated with the FICFB gasification plant in Güssing. Also the principle and examples of sorption-enhanced reforming to adjust H₂/CO ratio in product gas during the gasification is described. Finally, in the conclusion also an outlook for the thermochemical pathway to transportation fuels is given. © 2013 John Wiley & Sons, Ltd.

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SPIRIT AND PURPOSE OF BIOMASS GASIFICATION FOR SYNTHESIS GAS PRODUCTION

Synthesis gas is one important intermediate to produce fuels for transportation and chemicals. Currently, synthesis gas is produced mainly from natural gas, coal or by-products from refineries. The usage of synthesis gas is about 50% to ammonia, 25% to hydrogen, and the rest is methanol, Fischer–Tropsch (FT) products and others.^{1,2}

Owing to the global warming problem, caused by fossil CO₂ emissions, and also due to issues

related to security of energy supply, much R&D on the production of synthesis gas from biomass was carried out in the past decade. The main investigated applications of the synthesis gas was to produce transportation fuels over FT synthesis, methanol synthesis or others, like mixed alcohol synthesis.

TECHNOLOGIES FOR PRODUCTION OF SYNTHESIS GAS FROM BIOMASS

In the past decades much R&D was done to develop special gasification systems to convert biomass to synthesis gas, or to adapt coal gasification technology for biomass. These systems can be divided into several groups according to Ref 3:

- Producing and transport of the heat into the gasification reactor: allothermal–autothermal

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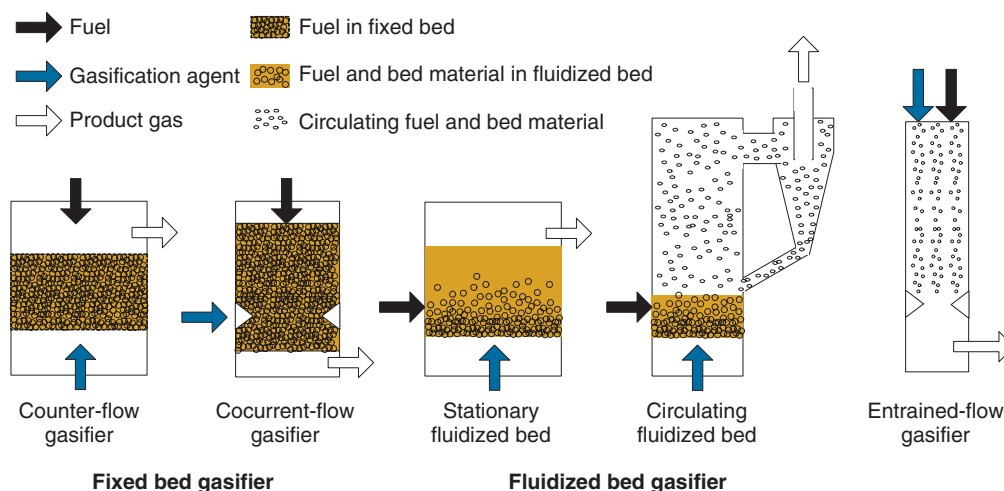


FIGURE 1 | Different types of gasifiers.

- Type of reactor: fixed bed-fluidized bed-entrained flow
- Type of gasification agent: oxygen-steam-mixtures of steam and oxygen

Allothermal–Autothermal

Autothermal gasifiers provide the necessary heat of reaction by means of partial oxidation within the gasification reactor. If air is used as oxidizing agent during the process, the product gas contains a high amount of nitrogen. So for synthesis gas production either pure oxygen (in entrained flow reactors) or mixtures of oxygen and steam (in fluidized bed reactors) are used as gasification agent.

The great advantage of the autothermal gasification is the direct heating of the reactants and therefore more efficient energy utilization. The process is simpler as by allothermal gasification and it is easier to operate it under pressurized conditions.

Allothermal (or indirect) gasification is characterized by the separation of the processes of heat production and heat consumption.⁴ The allothermal gasification facility almost always consists of two reactors, connected by an energy flow. Biomass is gasified in the first reactor and the remaining solid residue (char) or product gas is combusted in the second reactor to produce the heat for the first process. The transport of the heat can be done either by circulating a bed material or by heat exchangers.

Allothermal gasifiers generally produce two gas streams: a medium calorific product gas (gasification reactor) with little or no nitrogen and a flue gas (combustion reactor). The production of an N₂-free gas without the need of pure oxygen is one

of the advantages over autothermal gasification processes. Another important advantage is the complete carbon conversion and that there is no problematic waste produced. All carbon containing streams from the product gas cleaning (e.g., dust, tars) can be recycled to the combustion zone and there converted to heat, which is used for the gasification reactions.⁵

Fixed Bed–Fluidized Bed–Entrained Flow

According to the design of the fuel bed, the gasifiers can be divided into fixed bed, fluidized bed, and entrained flow. The differences in the design of the gasification reactor are shown in Figure 1.

The composition of the gas and the level of undesirable components (tars, dust, ash content) produced during biomass gasification process are dependent on many factors such as feedstock composition, reactor type, and operating parameters (temperature, pressure, oxygen fuel ratio).

Oxygen Blown–Steam Blown

Typical composition of a dry gas produced during the biomass gasification process is shown in Table 1. As can be seen, the concentration of the gas compounds during oxygen and steam gasification is completely different.

During oxygen gasification, the combustion products (CO₂, H₂O) are in the product gas and take part in the chemical reactions, mainly in water-gas shift reaction.

On the other hand, higher amount of hydrogen in the product gas can be found during the steam gasification. The hydrogen found in the product gas

TABLE 1 | Typical Composition of Dry Gas During the Oxygen and Steam Gasification of Biomass

Compound	Oxygen Gasification (Entrained Flow)	Oxygen Gasification (Fluidized Bed)	Steam Gasification
CO (vol %)	40–60	20–30	20–25
CO ₂ (vol %)	10–15	25–40	20–25
H ₂ (vol %)	15–20	20–30	30–45
CH ₄ (vol %)	0–1	5–10	6–12
N ₂ (vol %)	0–1	0–1	0–1
LHV (MJ/Nm ³)	10–12	10–12	10–14
Tar content (g/Nm ³)	<0.1	1–20	1–10

does not originate only from the fuel as in the case of oxygen gasification but also from the steam (H₂O).

The tar content depends not only on the type of gasifier but also mainly on the operation temperature. In entrained flow gasification, where the temperature is above 1000°C, there is no tar produced, whereas in fluidized bed gasification, where the temperature is below 1000°C, tar is produced and has to be removed from the product gas.

Requirements on the Gasification Reactor

To use the product gas from a biomass gasifier as synthesis gas, there are several properties, which have to be taken into account:

- H₂:CO ratio
- Amount of inerts, like nitrogen
- Amount of methane and higher hydrocarbons
- Catalyst poisons like sulfur-, nitrogen-, and chlorine components
- Operation pressure

Synthesis gas consists mainly of hydrogen and carbon monoxide, in some cases small amounts of carbon dioxide (methanol synthesis) or methane (BioSNG) are also present. For most synthesis a H₂:CO ratio of 2 is required. This ratio is normally adjusted in a separate catalytic reactor before the synthesis reactor, where some CO is converted to hydrogen by the water-gas shift reaction. If the gasifier produces the correct H₂:CO ratio, the exothermal water-gas shift reaction can be avoided, which reduces investment and operation costs and also increases the efficiency.

Impurities like nitrogen act as inert during the synthesis and their concentration have to be as low as possible. The inerts reduce the partial pressure and by this effect reduce the conversion. Especially for synthesis reactions, where the product is separated as a liquid and where a recycle of remaining unconverted gas is done (e.g., methanol), the inerts have to be bled off as they would otherwise be accumulated. Also for production of BioSNG the inerts have to be below 1 vol%, as otherwise the heating value of the BioSNG will not fulfill the requirements of natural gas.

Methane and higher hydrocarbons normally act as inert during the synthesis reaction, so they have to be treated similar to inerts. These components are mainly present in fluidized bed reactors and not in high temperature gasification (Table 1). As the heating value of the hydrocarbons is much higher than that of H₂ and CO, a small amount of hydrocarbons already present in the gas can contain most of the energy of the synthesis gas. So the overall conversion from biomass to final product (e.g., FT liquids) is reduced by the small amounts of hydrocarbons that are already produced in the gasifier. So in most cases the hydrocarbons are converted to H₂ and CO in a reformer to maximize the conversion from biomass to the final desired product. The only exemption is the production of BioSNG. Here a high content of methane and nontar hydrocarbons in the synthesis gas are favored, as then the highest conversion efficiency to BioSNG is achieved.

Catalyst poisons deactivate the synthesis catalyst and have to be removed to very low levels. The most well-known poison is sulfur, which can be in form of H₂S, COS, mercaptans, or thiophenes in the synthesis gas. The organic sulfur components are mainly present in fluidized bed gasifiers, and not in high temperature gasification. So the removal technology has to be adapted to the type of the sulfur components, e.g., thiophenes cannot be removed by ZnO adsorbers.

Almost all synthesis reactions are under elevated pressure and the synthesis gas has to be compressed during the gas treatment. By the choice of a pressurized gasifier, the electricity consumption of the compressor can be reduced or avoided. Until now only oxygen or oxygen–steam blown gasifiers were operated under elevated pressure, in which case the investment and operation costs for an air separation unit have to be taken into account. For this reason in small scale (<100 MW fuel input), mainly indirect atmospheric gasifiers are discussed to avoid the costs of the oxygen production.⁶

The choice of the gasification reactor is not easy, as it influences the whole conversion chain, e.g., the gas treatment has to be adjusted to the type of gasifier

and the synthesis should also fit to the properties of the synthesis gas (e.g., $H_2:CO$ ratio, amount of inerts). Up to date no single 'winner' has been identified and R&D on the different types of conversion chains from biomass to transportation fuels and chemicals is going on.

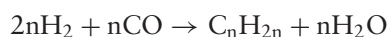
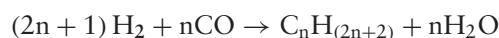
APPLICATIONS FOR SYNTHESIS GAS FROM BIOMASS

R&D on applications for synthesis gas from biomass was in the past decade mainly focused on transportation fuels and less on chemicals. Most of the R&D was done on FT, hydrogen, methanol (including MtG, MtD, MtO, DME), ethanol, mixed alcohols, and SNG. Therefore, below, there are short descriptions of the different synthesis routes.

FT Synthesis

The FT synthesis is based on the conversion of a mixture of carbon monoxide and hydrogen into liquid hydrocarbons.⁷

The FT synthesis can be represented by following chemical reactions:



The process, a key component of gas to liquids technology, produces synthetic fuels and chemicals from mainly natural gas and coal at a large scale, and in the near future also from biomass. This process is best known for being used in South Africa by Sasol and in the gas to liquid (GTL) plant operated and built by Shell in Bintulu, Malaysia.⁸

Depending on the reaction temperature, the process can be divided into low-temperature (LTFT, 200–260°C) and high-temperature (HTFT, 300–350°C) FT synthesis.⁹

During LTFT (up to 260°C) a higher fraction of higher-boiling hydrocarbons (above 360°C) is produced.¹⁰ Also the total distillate yield is higher than during HTFT. Higher temperature leads to faster reactions and higher conversion rates, also tends to favor shorter chains and methane, olefin, and aromatics production. Typical pressures range from one to several tens of atmospheres. Increasing the pressure leads to both higher conversion rates and formation of the much-desired long-chained alkanes. Even higher pressures would be favorable, but the benefits may not justify the additional costs of high-pressure equipment and costs for pressurizing.

A variety of catalysts can be used for the FT process, but the most common are the transition metals such as cobalt, iron, and ruthenium. Nickel could also be used, but tends to favor methane formation. In LTFT cobalt- or iron-based catalyst are mostly used, whereas in HTFT only iron-based catalysts are used.

The advantage of the cobalt-based catalysts is a much longer lifetime. Less unsaturated hydrocarbons and alcohols are produced compared with the iron-based catalysts. On the other hand, iron-based catalysts are more tolerant to sulfur and can be also used to adjust the $H_2:CO$ ratio, if it is lower than 2 by means of water-gas shift reaction.

Hydrogen

Hydrogen can be produced from the gasification product gas through the steam reforming and water-gas shift reaction. Using a dual fluidized bed (DFB) gasification system with CO_2 adsorption along with suitable catalysts, it is possible to achieve a hydrogen yield up to 70 vol% direct in the gasifier.¹¹

Furthermore, the costs of hydrogen production by biomass gasification in very large scale are competitive with natural gas reforming.¹²

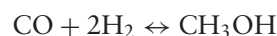
Hydrogen is one of the most promising future energy carriers.¹³ Therefore, it is expected that biomass gasification process will be available for large-scale hydrogen production.

Series of investigations on hydrogen production methods have been conducted over the past several decades.¹⁴ Biomass is potentially a reliable energy source for hydrogen production. It is renewable, abundant, easy to use, and CO_2 neutral.

Methanol

Methanol, also known as methyl alcohol, wood alcohol, or wood spirits, is often abbreviated as MeOH. It can be produced from fossil or renewable resources and can be used either directly as a transportation fuel or can be converted further to hydrocarbons.¹⁵

Methanol is produced from synthesis gas by the hydrogenation of carbon oxides over a suitable (copper oxide, zinc oxide, or chromium oxide-based) catalyst:



The first reaction is the primary methanol synthesis reaction. A small amount of CO_2 in the feed

(2–10%) acts as a promoter of this primary reaction and helps maintain catalyst activity. The stoichiometry of both reactions is satisfied when R in the following relation is 2.03 minimized.¹⁶ H_2 builds up in the recycle loop, this leads to an actual R value of the combined synthesis feed (makeup plus recycle feed) of 3 to 4 typically.

The reactions are exothermic and give a net decrease in molar volume. Therefore, the equilibrium is favored by high pressure and low temperature. During production, heat is released and has to be removed to keep optimum catalyst life and reaction rate; 0.3% of the produced methanol reacts further to form side products such as dimethyl ether, formaldehyde, or higher alcohols.¹⁷

The catalyst deactivates primarily because of loss of active copper due to physical blockage of the active sites by large by-product molecules; poisoning by halogens or sulfur in the synthesis gas, which irreversibly form inactive copper salts; and sintering of the copper crystallites into larger crystals, which then have a lower surface to volume ratio.

Conventionally, methanol is produced in two-phase systems: the reactants and products forming the gas phase and the catalyst being the solid phase. The production of methanol from synthesis gas was first developed by the company BASF in Germany already in 1992. This process used a zinc oxide/chromium oxide catalyst with poor selectivity, and required extremely vigorous conditions—pressures ranging from 300 to 1000 bar, and temperatures of about 400°C. In the 1960s and 1970s, the more active Cu/Zn/Al catalyst was developed allowing more energy-efficient and cost-effective plants, and larger scales. Processes under development at present focus on shifting the equilibrium to the product side to achieve higher conversion per pass than the currently achieved 20–30% in tubular- or quench-type reactors. Examples are the gas/solid/solid trickle flow reactor, with a fine adsorbent powder flowing down a catalyst bed and picking up the produced methanol; and liquid phase methanol processes where reactants, product, and catalyst are suspended in a liquid. Fundamentally different could be the direct conversion of methane to methanol, but despite a century of research this method has not yet proved its advantages.

Methanol to Diesel

The methanol to diesel (MtD) process first converts methanol into propylene, this is followed by olefin oligomerization (conversion to distillates), then product separation-plus-hydrogenation.¹⁸

The process would yield mostly kerosene and diesel, along with a small yield of gasoline and light

ends. The near-zero sulfur/polyaromatics diesel fuel resulting from this process would differ from more conventional FT diesel only in cetane number (>52 via ‘Methanol-to-Synfuel’ vs >70 cetane for FT diesel). The incidental gasoline stream not only would be near-zero sulfur but also have commercial octane ratings (92 RON, 80 MON) and maximally 11% aromatics.

Methanol to Gasoline

In the 1970s, Mobil developed and commercialized a methanol to gasoline (MtG) process. A plant was built in Montunui, New Zealand in 1985 and sold to Methanex. It produced gasoline until 1997 when the plant was permanently idled. If the gasoline is to be sold without additional blending, then further treating is necessary to reduce the amount of benzenes.¹⁹

Methanol to Olefins

Methanol to olefin (MtO) synthesis is a commercially attractive process because of the high demand of propylene and ethylene in the market. Nowadays, these compounds are produced mainly through noncatalytic steam cracking of fossil fuels (naphtha).¹⁹

The MtO process, however, uses zeolite-based catalysts that efficiently convert methanol into propylene and ethylene.

Dimethyl Ether

Dimethyl ether (DME) or (CH_3OCH_3) is generally produced by dehydration of methanol. In recent R&D projects, the methanol production and dehydration processes are combined in one reactor, such that DME is produced directly from synthesis gas slightly more efficient than methanol. In addition, the direct synthesis of DME allows $H_2:CO$ ratios of about 1, which is an advantage for oxygen blown gasifiers.

Like methanol, DME has promising features as fuel candidate with both the otto and the diesel engine (www.biodme.eu). With adaptations to engine and fuel system, DME can be used in diesel engines, leading to higher fuel efficiency and lower emissions. In otto engines, DME can be used with liquefied petroleum gas (LPG). Since DME is as easily reformed as methanol, it has a big potential as fuel for fuel cell vehicles.²⁰ DME has similar physical properties as LPG and can be handled as a liquid, using the same infrastructure as LPG.²¹

Mixed Alcohols

The catalytic conversion of synthesis gas to mixed alcohols is nowadays of great importance because

mixed alcohols are valuable additives to gasoline to increase the octane number and reduce the environmental pollution. Furthermore, a great benefit of the mixed alcohol synthesis is the high resistance of the catalysts against sulfur poisoning and the fact that the gas cleaning facilities can be simpler as in other syntheses. Mixed alcohols can also be converted to high-quality fuels via dehydration and oligomerization.

Normally, the alkali-doped oxides (zinc and chromium oxides) and alkali-doped sulfides (molybdenum sulfides) are used as catalysts for mixed alcohols synthesis (MAS).

Depending on process conditions and catalysts, the main primary products are generally methanol and water. Ethanol, propanol, butanol, etc. are gradually including methanol synthesis followed by its successive homologation.²² The reaction mechanism of the MAS is following.²³

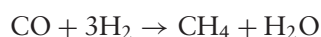


Owing to reaction stoichiometry the proposed CO/H₂ ratio is 2, but the optimal ratio is in practice closer to 1 because of water-gas shift reaction that occurs in parallel with the alcohol formation.

BioSNG

Natural gas that is produced from coal or biomass is known as 'synthetic natural gas' or 'substitute natural gas' (SNG),^{24,25}

The typical catalyst for methanation is nickel and the main reaction is



Ni-based catalysts are also active in water-gas shift and hydration of higher hydrocarbons, like olefins. Normally a H₂:CO ratio of 3 is necessary, which is obtained by a water-gas shift reactor before methanation. In some types of reactors, e.g., fluidized beds, the water-gas shift can be carried out also in parallel with the methanation, so no external adjustment of the H₂:CO ratio is necessary.

Methanation can be done at atmospheric pressure, although according to the thermodynamics higher pressure is preferred.

As Ni-based catalysts are sensitive to sulfur poisoning, gas treatment is quite important before the methanation, and sulfur compounds have to be removed to below 0.1 ppm.

There is one main difference in the synthesis gas treatment compared with other synthesis. Almost all gasifiers have some methane in the product

gas, depending on the operation temperature. As methane has not to be converted in the methanation, high methane content in the synthesis gas is a big advantage for the production of BioSNG (if the overall efficiency is higher, the higher the methane content in the product gas is). Thus especially indirect gasifiers are advantageous for methanation, which have a syngas with a methane content of 10 vol% or more.

EXAMPLES OF SYNTHESIS GAS UTILIZATION

In the following chapter some examples of gasification systems for production of synthesis gas are described. They were selected, as there are some innovative aspects included, like:

- Innovative consortium as here forest industry works together with a refinery (Neste Oil–Stora Enso)
- Concept of decentral biomass upgrading by pyrolysis to increase the energy density for transport and central gasification in extremely large scale (Bioliq process)
- Using coal gasification technology and adjusting the biomass properties by torrefaction (BioT-fuel)
- Synthesis gas platform, where R&D on different synthesis is performed, taking slip streams of synthesis gas from a commercial biomass CHP (biomass CHP Güssing)
- Dual fluidized bed gasification optimized for SNG (ECN)
- Sorption-enhanced reforming, to adjust the H₂:CO ratio direct inside the gasifier
- Microchannel reactor technology (Oxford Catalysts, Velocys)
- Decentral small scale methanation for production of BioSNG (Distributed SNG)
- Large-scale FT synthesis (Choren)
- Large scale of alcohol synthesis (Range Fuels)
- Large-scale BioSNG production (GoBiGas)

There are several other projects going on which are not described in this paper, like the UPM Andritz-Carbona project on FT synthesis in Stracel, the Ajos BTL project in Finland, the Woodspirit project (Methanol) in Oosterholm (the Netherlands), or the Ethanol demonstration project from Enerkem, the TIGAS Project from Haldor Topsoe at GTI in

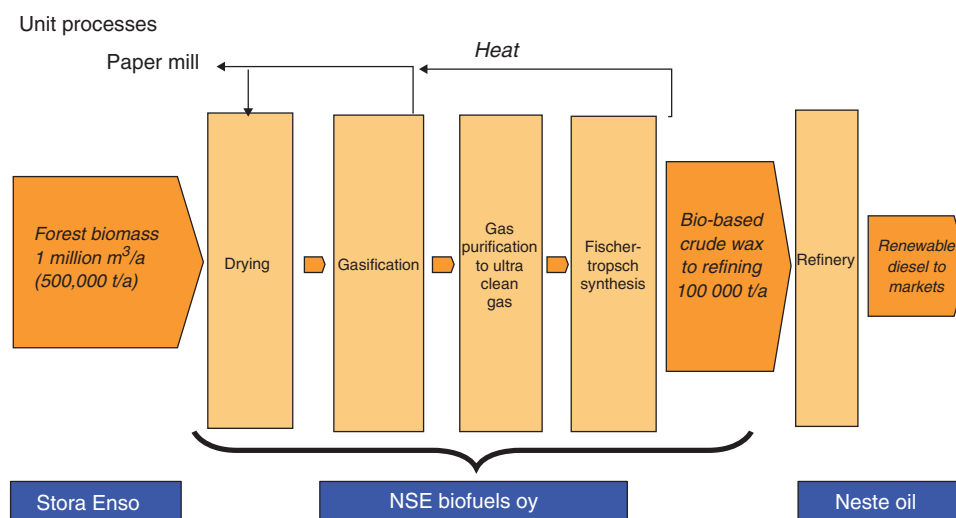


FIGURE 2 | Stora Enso–Neste Oil joint venture.

Chicago, or Ineos Bioenergy who are doing syngas fermentation.

The reason for selecting the above projects for this review, was on the one side, that they have an interesting concept, on the other side, that there was information available. This is one main problem in commercial and large demonstration projects, that there is almost no information available.

Innovative Consortium as Here Wood Industry Works Together with a Refinery (Neste Oil–Stora Enso)

Neste Oil Corporation is a refining and marketing company concentrating on low-emission, high-quality traffic fuels. The company produces a comprehensive range of major petroleum products and is the world's leading supplier of renewable diesel (NextBTL).²⁶

Stora Enso is a forest industry and procures most of its wood from private forest owners, state forests and companies in Finland, Sweden, the Baltic states, Continental Europe, and Russia.

Stora Enso and Neste Oil have joined forces to develop the technology for, and later produce, new-generation biofuel from forest industry residues.

NSE Biofuels Oy, is owned by Neste Oil Oy and Stora Enso Oy. It combines competencies of two different industries: forest industry and oil refining industry.²⁷

The goal is an implementation of the first commercial biomass-to-liquids (BtL) plant and further to develop profitable businesses based on experiences and on market demands (NOSE-Project).

The objectives of NOSE-project are to develop and verify BtL technology based on biomass

gasification route, further to provide the overall commercial technology concept and evaluate the technoeconomic feasibility of the production concept.

Project partners are VTT, Foster Wheeler, NesteJacobs, Stora Enso, and Neste Oil.

The biomass gasification technology being employed was initially developed as part of the Ultra Clean Gas project, which was led by VTT Technical Research Centre of Finland, acting as the main research and testing partner for the joint venture. Gasification equipment is being supplied by Foster Wheeler, a leader in the field of fluidized bed reactors.

The demonstration process is based on the use of FT synthesis and covers the entire chain from drying wood-based biomass to test the FT catalysts needed to produce bio-based crude wax that can then be refined into premium-quality renewable diesel by Neste Oil. Much of the development effort has focused on ensuring good syngas output from of an oxygen blown CFB gasifier and that it can be reformed and cleaned catalytically to a sufficiently high level of purity to yield the best results from the latest generation of FT synthesis (Figure 2).

High energy efficiency, the ability to handle different types of feedstock, and the potential for integration in existing pulp and paper mills have also been prioritized in the design.

The demonstration plant will start using sawmill by-products, shavings, and sawdust before testing the main feedstock intended for a commercial-scale plant: forest residues, such as logging waste, stumps, and small-dimension logs that cannot be used as pulpwood.

The tests of BtL have been completed and technology verified in Varkaus test plant at the end

of August 2011. The plan was to build a full-scale commercial facility at one of Stora Enso's mills capable of producing in the order of 100,000 t/annum of bio-based crude wax for final refining into renewable diesel by Neste Oil.

Unfortunately the consortium decided not to continue at the moment with this development, as they pronounced by a press release from 17th August 2012: 'We have calculated the cost of the project very carefully and realistically. It would have represented a very significant investment and we concluded that we would not have gone ahead in any case, even if we had won public funding,' according to Neste Oil's President & CEO, Matti Lievonon, and Stora Enso's CEO, Jouko Karvinen.²⁸

Concept of Decentral Biomass Upgrading by Pyrolysis to Increase the Energy Density for Transport and Central Gasification in Extremely Large Scale (Bioliq Process)

The Karlsruhe BtL concept²⁹ combines decentralized production of energy-rich bioSynCrude® by means of rapid pyrolysis of biomass (straw, wood) and central processing with final industrial-scale refinement.

Since the volumetric energy density of bioSynCrude® is by more than one order of magnitude higher relative to straw, it is clear that the method's efficiency is enhanced by decentralized energy densification and conversion in a central large-scale unit. The process technology can be seen in Figure 3.

The dry, comminuted biomass is mixed with hot sand at ambient pressure in the absence of air in a twin-screw mixing reactor. Pyrolytic conversion of the biomass particles at approximately 500°C, and condensation of the pyrolysis vapors take a few seconds only. Depending on the operating conditions and on the biomass selected, one obtains 40–70% of liquid pyrolysis oil and 15–40% of pyrolysis char as well as a fraction of noncondensable pyrolysis gas whose combustion heat can be used for heating or drying. In the pilot plant, 500 kg/h (2 MW) of biomass are converted by rapid pyrolysis into bioSynCrude®.

Pyrolysis char and pyrolysis oil are mixed to obtain a slurry (bioSynCrude®). The rapid and efficient conversion of the mixture during gasification essentially depends on the size distribution of the coke particles. Rapid pyrolysis enables a pyrolysis condensates/pyrolysis char mixing ratio that is ideal for the slurry and contributes to optimizing product yields.

The bioSynCrude® is atomized with hot oxygen in an entrained flow gasifier and is converted above 1200°C into a tar-free, low-methane raw synthesis gas. The gasifier used is particularly suited for the high

amounts of biomass ashes that are produced during gasification. The process is performed at pressures that are determined by the subsequent synthesis. There is no need for complex gas compression procedures. While FT syntheses require process pressures of up to 30 bar, methanol or DME syntheses are carried out at up to 80 bar. The bioliq pilot gasifier is designed for 5 MW (1 t/h) and two pressure stages of 40 and 80 bar.³⁰

Cleaning of raw synthesis gases: particles, alkaline salts, H₂S, COS, CS₂, HCl, NH₃, and HCN are removed to avoid catalyst poisoning during fuel synthesis. The pilot plant is equipped with an innovative hot-gas cleaning system for particle filtration, pollutant decomposition, and adsorption at 500°C.³¹

The clean syngas is finally converted over methanol/DME to gasoline.

Using Coal Gasification Technology and Adjusting the Biomass Properties by Torrefaction (BioTfuel)

The aim of the BioTfuel project is to develop market and end-to end chain of technologies to produce second-generation biodiesel and biojet fuel. The biodiesel and biojet fuel produced will be suitable for use in all types of diesel and jet engines, either pure or in blends.³²

The BioTfuel project will develop technologies for converting lignocellulosic biomass—such as straw, forest waste, and dedicated crops—into synthetic fuel, by validating their technical and economic feasibility in demonstration units and optimizing their energy efficiency and environmental impact.

The whole process chain, which can be seen in Figure 4, includes R&D (CEA, IFP Energies nouvelles³³), licensors of the technology (Axens, Uhde), and fuel producers (Sofiprotéol, Total).

BioTfuel project is planned for 7 years (2010–2016) and total funds allocated is 1127 M€.

The BioTfuel project uses torrefaction as first step, to convert biomass into a product similar to coal. Afterward a coal gasifier (PRENFLO) is used to produce the synthesis gas. The biomass pretreatment and torrefaction take place at Sofiprotéol site in Venette and gasification, purification, and synthesis at Total site in Dunkirk.

The biomass will be pretreated during the torrefaction process, pulverized and afterward injected under pressure into the gasifier with direct quench.

The syngas must be very pure and have the correct chemical composition to be converted into liquid fuel. Thus, the technological developments will

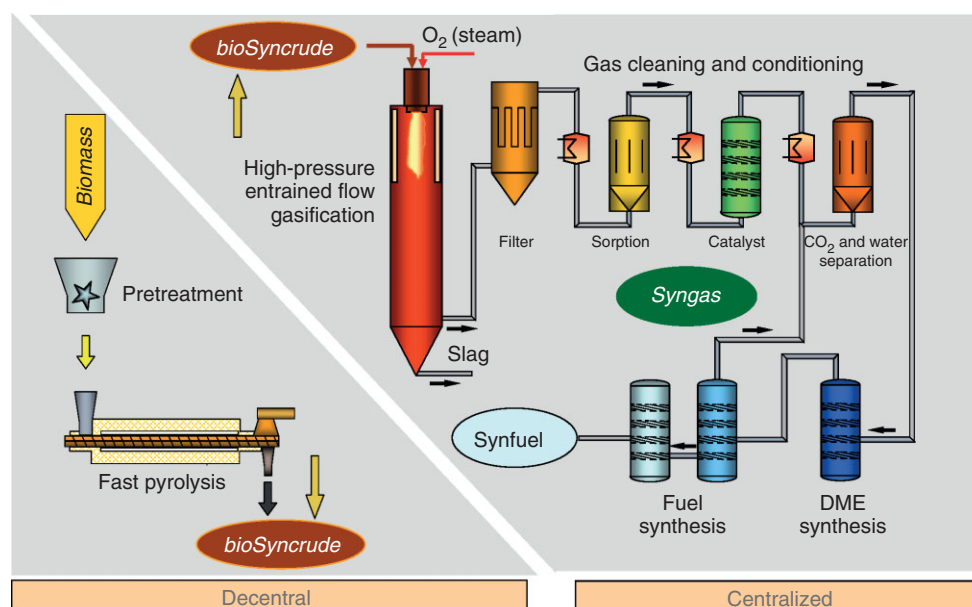


FIGURE 3 | Bioliq process. (Reprinted with permission from Ref 29. Copyright 2012 Karlsruhe Institute of Technology)

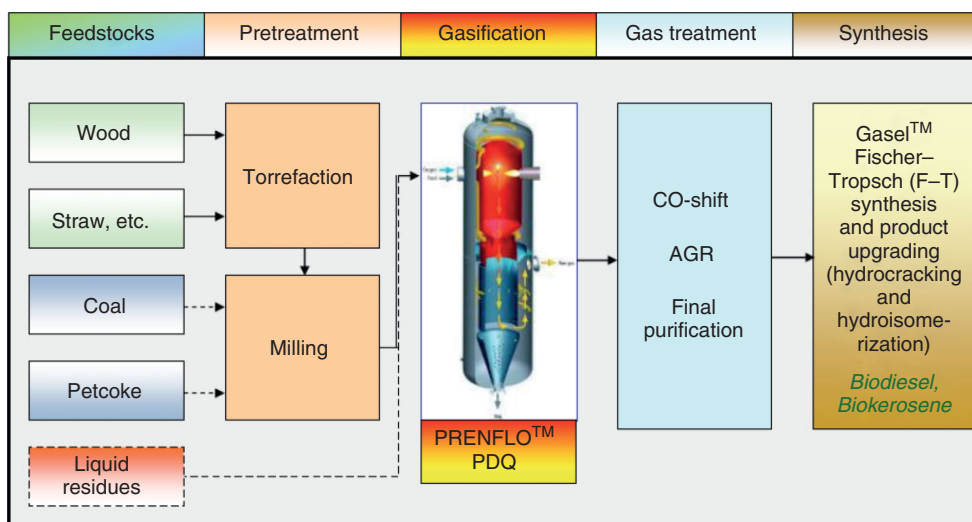


FIGURE 4 | BioTfuel concept.

focus mainly on the final stages of the syngas cleaning and conditioning, when the gas is pretreated for FT synthesis.

The FT process will convert purified syngas into a mixture of hydrocarbons at low temperature, using a cobalt-based catalyst. No R&D work will be carried out on the FT process because it is already available commercially.

The opinion of the BioTfuel consortium is that second-generation biofuel production requires large industrial units to be profitable and a continuous supply of feedstock. The biomass used in BioTfuel project will be forest and plant waste, straw, and

other lignocellulos materials sourced from different locations. The availability of these materials is subject to seasonal variations. Thus, a process chain will be developed that works with a wide range of biomass feedstock as well as with liquid and solid fossil fuel feedstock.

The BioTfuel objectives are to develop, demonstrate, and commercialize a full XTL chain (XTL: X to liquids, where X can be gas, coal, waste, or biomass). First industrial XTL plants will have a capacity of 5000 barrels (bbls)/day (200kt/year) in one single train. The market launch of the process chain is planned by 2020.

Synthesis Gas Platform, Where R&D on Different Synthesis Is Performed, Taking Slip Streams of Synthesis Gas from a Commercial Biomass CHP (Biomass CHP Güssing)

In 2002 an 8 MW CHP FICFB steam blown gasifier producing heat and power (4.5 MW_{th}, 2 MW_{el}) with a gas engine started its operation in Güssing, Austria.³⁴ Renet-Austria, a competence network on energy from biomass, consisting of experts from Universities and industry started to develop this process further to a commercial stage. The flow diagram of the gasification process can be seen in Figure 5.

Owing to the excellent performance that was reached during the last years and the high availability, several additional research projects could be started in Güssing.

The producer gas from the DFB gasifier is nearly free of nitrogen and has a high hydrogen content. For this reason, it is well suited as synthesis gas. Therefore, projects aiming at the development of processes for the production of BioSNG, FT liquids, mixed alcohols, and hydrogen are currently carried out. The picture of the synthesis platform can be seen in Figure 6.

BioSNG

BioSNG was the first synthesis, investigated at the biomass CHP Güssing.³⁵ In 2003, a first test rig was moved to Güssing in order to use a real synthesis gas from biomass. Later, a 10 kW unit

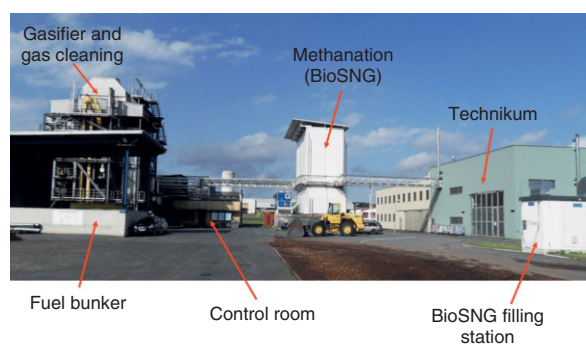


FIGURE 6 | Synthesis platform Güssing. (Reprinted with permission Ref 34. Copyright 2012 BTG Biomass Technology Group BV)

was installed and successfully operated for more than 1000 h without deactivation of catalyst. Within the BioSNG demonstration project the construction and operation of a 1 MW demo unit was realized. The purpose was to prove the concept of preprocessing of the product gas, the methanation, and upgrading of the raw BioSNG to final BioSNG ready for use (e.g., feed-in into a gas grid).

A slip stream of the product gas from the gasifier was taken before entering the gas engine and transported to the BioSNG demonstration unit. The product gas is already cleaned from particles and tars to the extent required for gas engine operation. In the BioSNG demonstration unit, additional cleaning of the gas is carried out to avoid the poisoning of the methanation catalyst. The conditioned product gas enters the fluidized

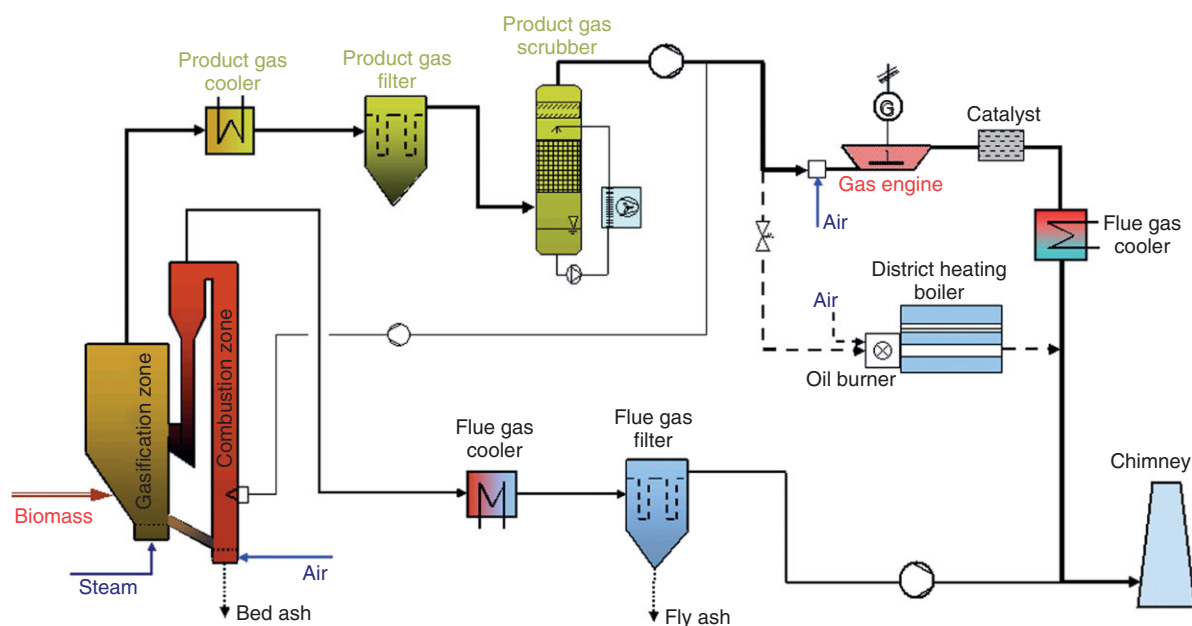


FIGURE 5 | Güssing gasification plant.

bed methanation reactor, where the methanation, hydration of olefins and CO-shift takes place in parallel. Then the raw SNG passes several purification steps (CO₂ removal, drying) to increase the methane content to meet the regulations for feeding into the natural gas grid.

The PDU was operated for several weeks and a high-quality gas as required by the gas grid was produced. The plant was able to operate at design process parameters. A number of parameters were tested, varying pressure, temperature and capacity of the plant and also varying the recycle flow from hydrogen separation.

With this project it was possible to demonstrate the production of pipeline ready BioSNG from wood using the Güssing BioSNG demonstration unit. It was also shown that the chemical efficiency of more than 60% from wood chips to BioSNG could be reached in practice, which is excellent.³⁶

FT Synthesis

Within the EC project RENEW the second synthesis, which was synthetic diesel production via FT synthesis was investigated.³⁷ A laboratory scale Fischer–Tropsch-Reactor (slurry reactor) in a side stream of the existing allothermal fluidized bed gasifier was designed and installed. During the experiments different combinations of the gas cleaning devices, different catalysts, and operation parameters were tested.

The FT liquids produced during operation were collected, analyzed, and used for further processing, like hydrotreating, or are used direct in diesel engines for testing.

The FT synthesis (Figure 7) consists of a gas treatment, where catalyst poisons are removed to

below 10 ppb and the gas is dried and compressed. The FT reaction takes place in a slurry reactor (three phases: catalyst, gas, waxes) with a volume of 20 L. The gas and the FT product leaves the reactor over sintered metal filters. After the FT-reactor, the FT products are separated from the tailgas and collected.³⁸

The collected FT products are distilled. The fraction up to 180°C is used as naphtha, from 180°C to 320°C as diesel and the fraction above 320°C are waxes.

Furthermore, investigations on hydrotreating of FT-biowaxes for generation of bio-products from lignocellulosic biomass were carried out with the industrial partner OMV.³⁹

Schablitzky et al. investigated the ability of bifunctional catalysts for cracking and hydrogenation of paraffinic feedstocks with aim to obtain second-generation biofuels in the diesel bowling range in a pilot scale hydroprocessing unit.

Analytical data from the produced diesel is given in Table 2

Mixed Alcohols

Another synthesis investigated in Güssing is MAS. For that purpose a pilot plant was built to produce mixed alcohols from synthesis gas generated in commercial CHP gasification plant. The synthesis gas used for the MAS is also taken after the gas cleaning system from the biomass CHP (particle and tar removal).⁴⁰

To adjust a H₂:CO ratio from 1.8:1 of the synthesis gas from gasification plant to a ratio of 2:1 a steam reformer is used. It consists of two electrically heated tubes. In the first one the gas is heated up to 900°C. The second tube is filled with a catalyst and acts as reforming reactor, followed by air cooling

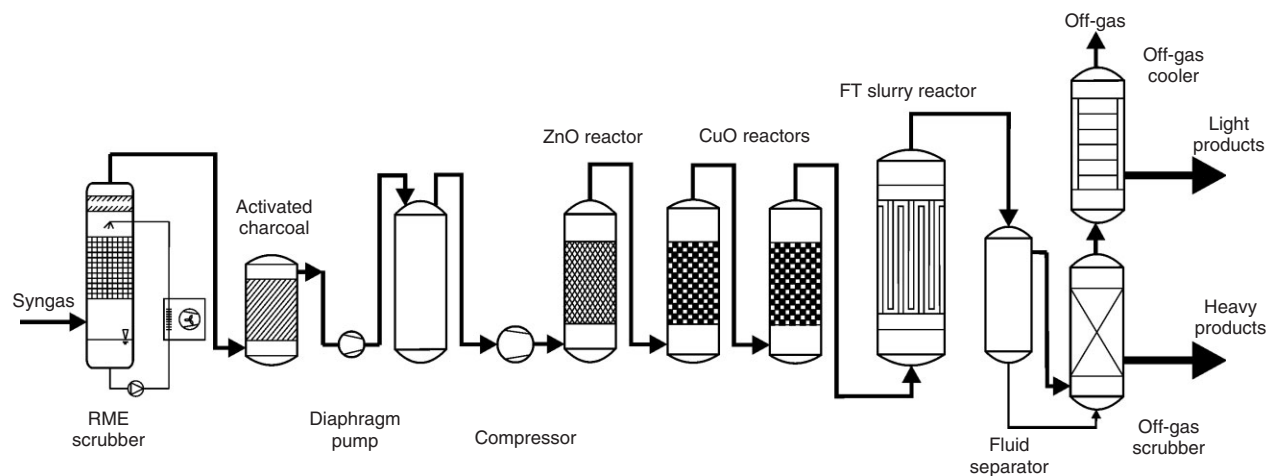


FIGURE 7 | Flow sheet of the FT test rig in Güssing.

TABLE 2 | Properties of FT Diesel

Properties	EN 590:2004		Hydroprocessed	
	Min	Max	FT Diesel	FT Diesel
Cetane number (—)	51.0	—	75–85	75–80
Density at 15°C (kg/m ³)	820	845	770–790	760–780
Total aromatics content % (m/m)	—	—	<1	2.6
Flash point (°C)	>55	—	87–91	75–80
Viscosity at 40°C (mm ² /second)	2.00	4.50	2.3–2.5	2.0–2.1
Cold filter plugging point (CFPP, °C)	—	–20	–5 to 0	–16 to –58

and glycol scrubber. After the drying, compression up to 300 bar is done before the MAS reactor. The condensation of the mixed alcohols takes place immediately after the reactor at the same operation pressure.

At the MAS pilot plant in Güssing a MoS₂ catalyst is used, as this type of catalyst is resistant against sulfur poisoning. So the gas treatment is much simpler which reduces the operation and investment costs. For this reason the MAS is from the economics favorable, as also work by NREL in the US showed.⁴¹

Hydrogen from Biomass

‘Hydrogen from biomass for Industry’ is the most recent project within the synthesis platform.⁴²

The common method for hydrogen production is natural gas steam reforming, but if hydrogen should be produced from renewable, biomass gasification is

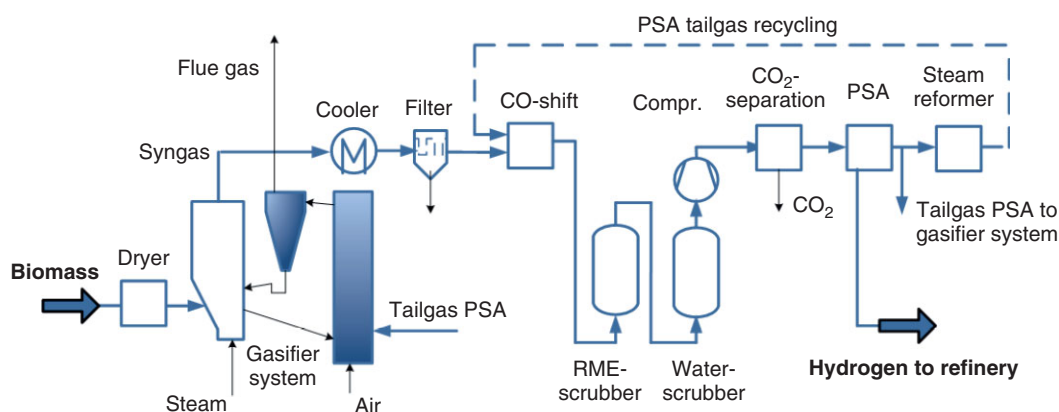
probably the most economic option. The aim of the project was the production of hydrogen with high purity for the direct integration in a refinery. First, a simulation of the whole process was done. The hydrogen production was based on steam gasification, a CO-shift step, CO₂-separation with a pressurized water scrubber, a PSA system, a steam reformer, and advanced gas cleaning components (Figure 8). The results showed that 30 MW of hydrogen can be produced from 50 MW of wood chips.

Based on the simulation results, the laboratory unit for hydrogen production is now under construction.

Dual Fluidized Bed Gasification Optimized for SNG (ECN)

The Energy Research Centre of the Netherlands (ECN) has demonstrated SNG generation from biomass.⁴³ In this process, indirect gasification is used, and both gasification and methanation are carried out at atmospheric pressure.⁴⁴ The biomass is gasified in the riser of a DFB and the remaining char is circulated to the combustor (downcomer of DFB). In this process, the heat required for gasification is supplied by char combustion in the combustor. Steam is used for gasification and air is used for char combustion. The lab-scale gasifier, developed in 2004, has a biomass capacity of 5 kg/h and operates at temperatures of 750–900°C.

Based on the experiments, a SNG system was optimized which consists of an indirect gasifier, a solvent scrubber tar removal system which recycles tar to the gasifier, a gas cleaning reactor including CO-shift, and a methanation combined reactor. The indirect gasifier that is working at 850°C produces nearly nitrogen-free syngas and a high amount of methane. Tars are recycled to the gasifier in order

**FIGURE 8** | Process design for hydrogen production from biomass.

to increase efficiency, whereas the tar-free syngas is cleaned from other contaminants (e.g., sulfur and chlorine). The clean syngas is fed to a combined shift and methanation process, converting the syngas into SNG. After methanation, further upgrading (e.g., CO₂ and H₂O removal) is required in order to comply with the desired SNG specifications. The overall net thermal efficiency is reported as 70% based on low heat value (LHV). Forty percent of the carbon of the biomass becomes part of the SNG and an equal amount of carbon can be captured as CO₂. The remaining 20% of the carbon is part of the flue gas from the process.

Sorption-Enhanced Reforming, to Adjust the H₂:CO Ratio Direct Inside the Gasifier

The composition of the syngas from gasification processes or syngas production technologies are generally not suited for direct use in the downstream synthesis system. In several cases, H₂/CO syngas ratio adjustment techniques such as downstream shift reactors, membrane separators or pressure swing adsorption are employed to meet the ratio requirements. This adds costs and complexity to the overall process.

In the sorption-enhanced reforming process, hydrocarbon reforming, water-gas shift, and CO₂ separation reactions occur simultaneously in a single reaction step over a reforming catalyst mixed with a CO₂ sorbent. Depending on reaction conditions, the product gas may contain as much as 98% H₂ and only ppmv levels of CO and CO₂, thereby minimizing the final H₂ purification process or even eliminating it for some applications.⁴⁵

There is a number of CO₂ sorbents such as Ca-based oxides, HTC (hydrotreating catalysts, which are double-layered hydroxides) and mixed oxides of Li and Na. Limestone and dolomite are the precursors for Ca-based oxides. These have the advantage of good availability and are not expensive. They offer high CO₂ capacity and react rapidly over a wide range of temperatures and pressures. Their disadvantage is associated with the high temperature required for sorbent regeneration. High temperature promotes sorbent sintering that leads to rapid deactivation. Another disadvantage is the high attrition of the adsorbents, so much R&D was done to improve the mechanical properties.

The concept of sorption-enhanced hydrogen production in the presence of Ca-based sorbent is not new. The first description of this process was published already in 1867 by DuMotay and Marechal who used limestone to enhance the gasification of carbon with steam.⁴⁶ Later, Curran et al.⁴⁷ developed

the 'CO₂ acceptor process', utilizing the carbonation reaction for the gasification of lignite coal to produce a H₂ rich gas.

The carbon capture reaction for the specific case of CaO sorbent is



HTCs are members of the family of double-layered hydroxides that, when doped with K₂CO₃, can serve as high-temperature CO₂ sorbents. They react rapidly but have much lower CO₂ capacity than Ca-based sorbents and are also considerably more expensive. But their advantage is regeneration at lower temperature so that sorbent durability can be improved. The HTC-CO₂ complex may be regenerated by pressure swing, temperature swing, or a combination of the two.

Recently, mixed metal oxide sorbents of Li and Na such as Li₂ZrO₃, Li₄SiO₄, and Na₂ZrO₃ have become subject of great interest. They have a higher CO₂ capacity than HTC and lower temperature is needed for regeneration as by the Ca-based sorbents.

In situ CO₂ capture involves suitable reaction conditions under which the whole process can be carried out. This requirement limits the available techniques for CO₂ capture, e.g., membrane and cryogenic separation process require high pressure or low temperature for efficient CO₂ capture,⁴⁸ adsorption of CO₂ with carbon based adsorbents is limited to low temperatures (150–250°C)⁴⁹ and hydrotalcite compounds have a significantly diminished capacity for CO₂ capture beyond 300°C.⁵⁰

Although many metal oxides react with CO₂ to form carbonates, not all metal oxides are suitable for CO₂ capture under conditions for biomass gasification.⁵¹

CaO is capable of scavenging CO₂ to very low concentrations at moderate temperatures (450–750°C) and atmospheric pressure. Furthermore, it is low cost and abundant because it can be derived from naturally occurring precursors including limestone, dolomite, and calcium hydroxide. The enhanced output from biomass gasification when coupled with CO₂ capture using CaO is demonstrated based on thermodynamic equilibrium modeling.⁵²

The increase of H₂ concentrations corresponding to the capture of CO₂ by CaO is shown in Figure 9. As can be seen operating window for temperature is 460–600°C. In this temperature range the highest H₂ yield was achieved. With rising temperature H₂ content is decreasing because of deactivation of CaO sorbent. When the sorbent reaches its ultimate conversion, it can be regenerated to produce CO₂ and

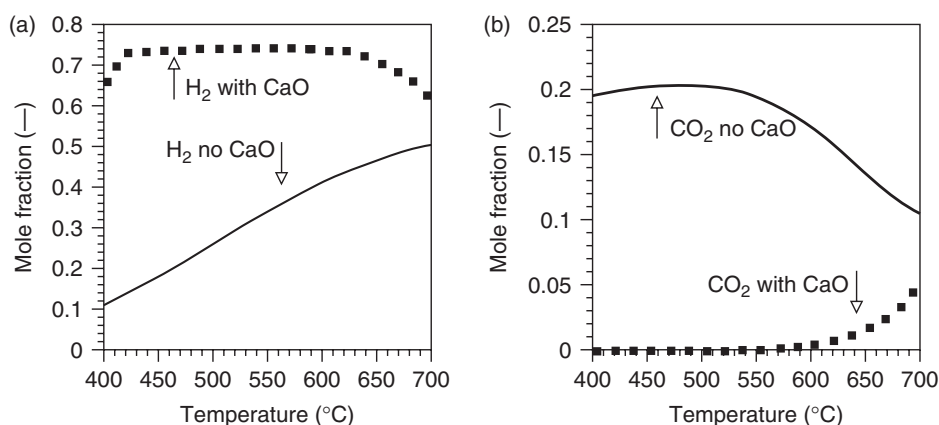


FIGURE 9 | Predicted H₂ and CO₂ molar concentrations in sorption-enhanced reforming.

CaO by heating to 700–950 °C, depending on the CO₂ partial pressure. Although the regeneration process requires the input of energy, the heat generated by the exothermic absorption reaction partially offsets this demand.

The application of CO₂ capture to enhance H₂ production from biomass coupled with the production of a highly concentrated stream of CO₂ represents a suitable and renewable pathway for hydrogen production. Furthermore, if the process is combined with CO₂ storage a negative balance of CO₂ in the atmosphere can be achieved.

Demonstration of this process was already done at the biomass CHP Güssing,⁵³ but the demonstration plant in Germany was not realized for different reasons.

Microchannel Reactor Technology (Oxford Catalysts, Velocys)

Oxford Catalysts Group PLC⁵⁴ is the leading technology innovator for clean synthetic fuel production. Their two operating subsidiaries, Oxford Catalysts Ltd and Velocys, Inc. design, develop and commercialize technology for the production of synthetic oil from waste gas (which would otherwise be flared or reinjected), stranded gas, renewable sources such as waste biomass, as well as coal via FT synthesis.

Microchannel technology is suited for carrying out highly exothermic catalytic reactions, such as FT synthesis or highly endothermic, such as methane reforming.

Microchannel reactors are compact reactors that have channels with diameters in the millimeter range (Figure 10). These small channels dissipate heat more quickly than conventional reactors with larger channel diameters in the 2.5–10 cm range,

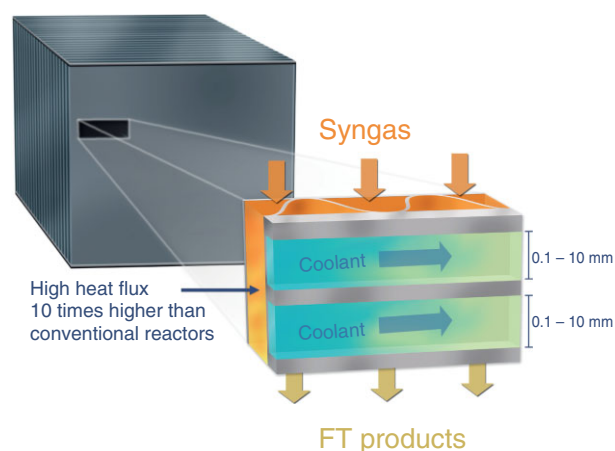


FIGURE 10 | Velocys microchannel reactor. (Reprinted with permission from Ref 54. Copyright 2012)

so more active catalysts can be used. Mass and heat transfer limitations reduce the efficiency of the large conventional reactors used for FT, steam reforming reactions and hydroprocessing. The use of microchannel processing makes it possible to greatly intensify chemical reactions enabling them to occur at rates 10 to 1000 times faster than in conventional systems.

These reactors exhibit conversion efficiencies in the range of 70% per pass, and are designed for economic production in a small scale. A single microchannel reactor block produces some 30 bbls of synthetic fuel per a day. In contrast, conventional FT plants are designed to work at minimum capacities of 5000 bbls/day, and function well and economically at capacities of 30,000 bbls/day or higher. They typically exhibit conversion efficiencies in the range of 50% or less per pass.

Microchannels are claimed to have a smaller footprint, can be scaled up or down more flexibly

as they can be 'numbered up', and have efficiencies superior to those achievable using conventional process technology. Microchannel reactors therefore have the potential to unlock the distributed production of fuels and other materials on a small, decentralized scale.

Velocys did already a demonstration program over 4000 h with a 0.3 bbls/day FT microchannel reactor, using the synthesis gas from the biomass CHP Güssing.⁵⁵

Decentral Small Scale Methanation for Production of BioSNG (Distributed SNG)

A conversion of woody biomass into SNG is a promising alternative to other applications of synthesis gas. The main advantage of the production of SNG against other technologies like the conversion of biomass into power or liquid fuels is high energy efficiency in particular in case that waste heat of the process is used for combined heat and power production—that are 'polygeneration' applications. Furthermore, the necessary technologies for the upgrading of the methanized syngas require the same technologies, which are used for the feeding of biogas into the pipelines.

Steam gasification is advantageous for this process because of the high content of methane in the product gas, which gives a higher overall efficiency for the process. Agnion uses in the distributed SNG concept no cold gas cleaning, because of the heat loss. As the heat pipe reformer is operated at 5 bars, the condensation of the steam in the product gas can be done at a temperature level, where additional district heat can be provided. In this way the overall efficiency is quite high, as also the condensation heat of the steam can be used. So the chemical efficiency from biomass to SNG is up to 70% and the overall efficiency above 90%.⁵⁶

A fixed bed methanation process, suitable for decentralized SNG production was studied by Kienberger et al. In this process,⁵⁷ catalytic methanation and catalytic tar-reforming was combined within one reactor. The influence of the gasifier operation parameters (temperature, residence time, input steam content) on syngas quality and composition was discussed. Actually the gasification technology of heat pipe reformer is demonstrated only for CHP in Germany.

Large-Scale FT Synthesis (Choren)

On January 31, 1990, UET Umwelt- und Energietechnik Freiberg GmbH (later the Engineering division of

CHOREN Industries GmbH) was formed. The portfolio included process technology for steam fluidized bed drying, analysis services for optimizing power plant equipment and many other energy processes.⁵⁸

The construction and commissioning of a 1 MWth Carbo-V[®] pilot plant in 1998 marked an important milestone. The plant's objective was to demonstrate the effectiveness of Carbo-V[®] technology for the production of fuel gas and synthesis gas from carbonaceous feedstocks. The process was then thoroughly tested from 1998 to 2004. The Carbo-V[®] pilot plant was successfully operated with a wide variety of feedstocks (such as untreated wood, various types of waste timber, 'dry stabilate' material from waste processing, meat and bone meal, hard coal, and lignite). In 2001, a 150-kW gas engine successfully ran under load on Carbo-V[®] gas for 600 h, thus verifying the potential of the Carbo-V[®] process for electrical power production from biomass.

R&D activities for production of renewable transport fuels began in 2000. A FT test rig for fuel production was built. In September 2001, a joint research project with DaimlerChrysler was started with funding from ZIP, an innovation program from the German Federal Ministry for the Environment. Subsequently, Volkswagen joined the research activities being pursued by CHOREN and DaimlerChrysler in September 2002. One objective was the physical use of the raw gas from Carbo-V[®] gasification to produce renewable synthetic fuels. A synthesis pilot plant was thus built, initially for methanol synthesis and later for FT synthesis, as an extension of the already existing Carbo-V[®] pilot plant. The Carbo-V[®] pilot plant with FT synthesis was later named the α -Plant. By the end of 2004, the plant had been operating successfully for more than 22,500 h.

In November 2002, the foundation stone was laid for the construction of the first industrial-scale Carbo-V prototype plant (β -Plant) with a capacity of 45 MWth at the Freiberg site.

It was planned to produce 18,000 m³ of FT fuel per year. Investment costs were more than 100 M €. ⁵⁹

Choren Industries filed for insolvency in July 2011. Choren's biomass gasification technology was sold to Linde Engineering Dresden, who will further develop the Choren Carbo-V[®] technology used to produce syngas.⁶⁰ The β -Plant in Freiberg is still not in operation and here also no investor was found till now, who takes over this demonstration plant for FT synthesis. Recently, it was announced by Linde that they had licensed the project to the Finish Forest Biofuels project, one of the NER 300 contractors.

Large Scale of Alcohol Synthesis (Range Fuels)

Range Fuels tried to develop a technology that converts woody biomass into ethanol over the thermochemical pathway. The technology was based on staged pressurized gasification of biomass, syngas purification, and its catalytic conversion. The aim was to produce up to 100 million gallons of biofuel per year as well as green power.⁶¹

The Soperton site, where the technology should be installed is located in a region rich in biomass resources in the United States. Test plots of high-yield energy crops on the plant site demonstrated the potential this feedstock has to supplement the woody biomass already available in the region.

Woody biomass was delivered by trucks to a wood yard, where the biomass was processed and stored prior to conversion. The biomass passed through a pressurized gasifier, where it was converted to a gas and residual char and minerals. The product gas from gasification passed through a reforming section where it was converted to syngas. Finally, the syngas was cleaned and compressed before injection into a catalytic converter that performed the final transformation into ethanol.

Unfortunately, Range Fuel was officially closed down in late 2011 with a foreclosure sale of its plant held on January 3, 2012. In 2012, LanzaTech NZ Ltd took over the facilities and will use it probably with their enzymatic conversion of syngas to ethanol.⁶²

Large-Scale BioSNG Production (GoBiGas)

Göteborg Energi, the energy company in the western part of Sweden, has the goal to convert to renewable energy long term. One step is to replace fossil natural gas by renewable gas. Here much R&D, demonstration and also commercial plants on upgrading biogas to natural gas quality was done in the past. Also, to convert wood into methane the GoBiGas project was initiated.⁶³

The goal of the GoBiGas project is to produce biomethane (BioSNG) by thermal gasification of forest residues such as branches, roots, and tops. The gasification plant is scheduled to be built in two stages, the first stage (about 20 MW_{gas}) is planned to be operational in 2013. The second stage (about 80–100 MW_{gas}) is scheduled to be in service in 2016. How and when to implement stage 2 will be decided after an evaluation of the stage 1 plant.

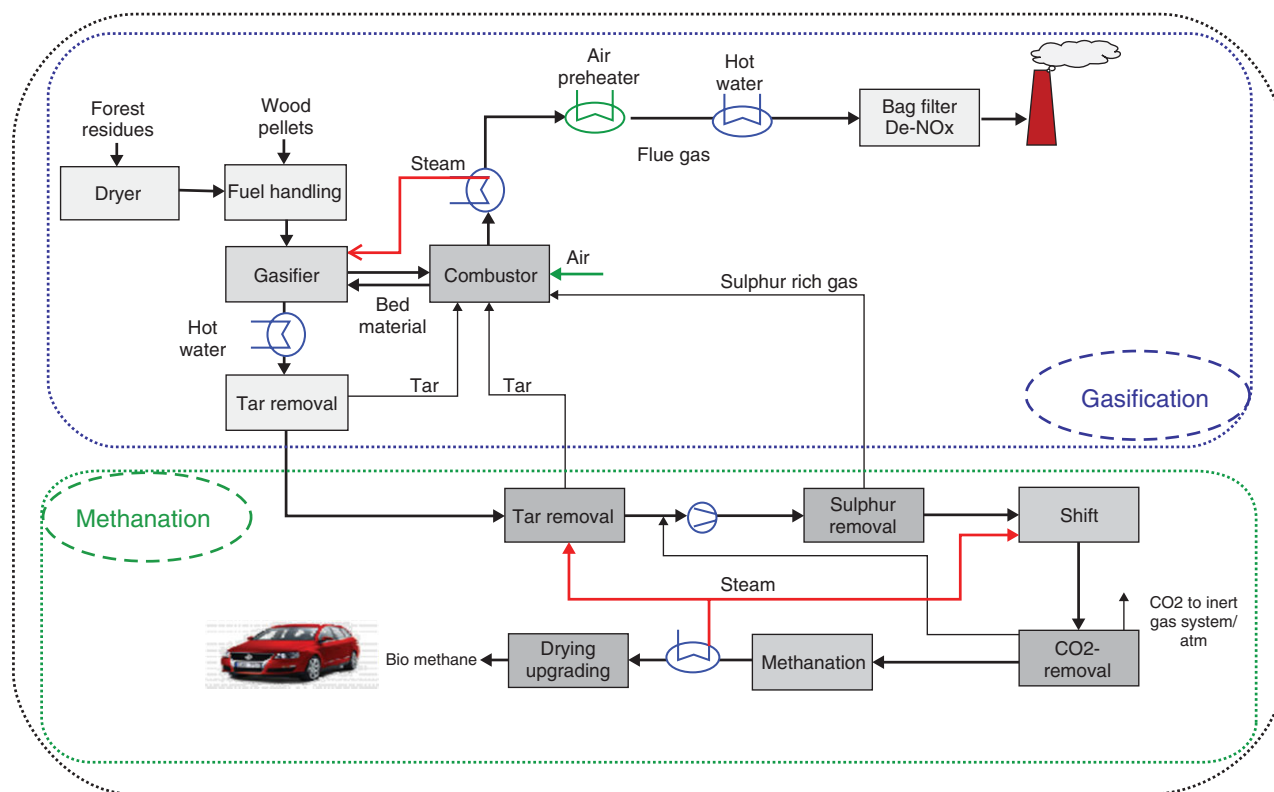


FIGURE 11 | Flow chart of GoBioGas project

The biomass is converted to a synthesis gas in the gasification plant. This so-called synthesis gas is purified and then upgraded in a methanation plant to BioSNG with a quality comparable with natural gas to enable the two types of gases to be mixed in the gas network.

As gasifier, a dual fluidized bed system, based on the principle of the Güssing biomass CHP was selected. The methanation is supplied by Haldor Topsoe and here fixed bed methanation is used. Details about the flow chart can be seen in Figure 11.

The 20 MW BioSNG plant is actually under construction and start-up is planned for 2013. For the second stage grants from the NER300 program of the EC will be received with high probability. There appear to be good chances that also in near future also the second stage of 80–100 MW BioSNG production will be realized.⁶⁴

CONCLUSION

The product gas from thermal biomass gasification processes is an outstanding energy carrier. It can be used as a stand-alone fuel (heat and power applications) or it can be further treated and transformed into another energy carrier by chemical upgrading and synthesis. The energy density of synthesis gas is only about 30% that of natural gas and is therefore not suitable for distribution as-is, unless converted to transportation fuels and other chemical products such as synthetic natural gas, methanol, and synthetic petroleum fuel. In a purified state, the hydrogen component of synthesis gas can also be used directly for industrial applications (e.g., oil refineries) or to power hydrogen fuel cells for electricity generation.

In this review, different biomass-based synthesis gas applications are described. The processes for alternative fuels production from synthesis gas as well as other applications are presented here. The heat and power applications were developed in the last decades, but more recently the interests for transportation fuels production (trucks, jet) have come more into the focus, explaining the intensive R&D work performed and planned in this area. The reasons are both the climbing prices of fossil fuels and also the climate change issue in combination with an increasing energy demand in transportation sector. These factors are reflected in policy measures to increase the use of advanced biofuels such as from the second and third generation.

Recently, there are several projects going on to produce advanced biofuels for transportation. An

overview about ongoing projects can be found in several databases like:

- IEA Bioenergy Task 33 Thermal Gasification of Biomass (<http://www.ieatask33.org>)
- IEA Bioenergy Task 39 Liquid Biofuels (<http://demo-plants.bioenergy2020.eu/projects/mapindex>)
- US DOE Bioenergy Technologies Office (http://www1.eere.energy.gov/biomass/integrated_biorefineries.html)

Several different gasification technologies are used for production of synthesis gas from biomass, but there is only the DFB steam gasification technology in commercial operation (for CHP, not for synthesis gas). All others have done extensive R&D and also demonstration, but no commercial plant is at the moment in operation.

There are several demonstration plants in the planning or construction phase (GoBiGas, BioTfuel, Stracel BTL or Ajos BTL, Woodspirit, Enerkem demo on Ethanol, or TIGAS), where different gasification technologies are used and also different products are produced. It looks like, that the United States focuses more on ethanol (as blending component for gasoline) and Europe more on diesel substitutes. This is logical, looking at the market shares of the gasoline and diesel in these countries. Europe has a high share of diesel and the United States a high share of gasoline in the transportation sector, so their focus of R&D is according to the fuels used in the countries. In general, the impression is that so-called drop-in fuels are the focus of demonstration in the near future.

Some projects focus also on gaseous fuels like BioSNG or hydrogen. Here the main advantage is the high conversion efficiency of up to 70%. The main disadvantage in case of hydrogen is that the infrastructure still has to be developed.

On the long term there is no alternative to advanced biofuels. Some sectors like heavy transport or aviation will depend also in future on hydrocarbons, as they need fuels with high energy density. In the private transport sector there is a trend to electric cars and hydrogen, but a change in this sector needs decades, so also here hydrocarbons will be the main fuel for the next decades. So it is necessary to develop this technology further, although there were some drawbacks and failures of companies in the past.

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