

**“GREEN GAS” AS SNG (SYNTHETIC NATURAL GAS)
A RENEWABLE FUEL WITH CONVENTIONAL
QUALITY**

M. Mozaffarian
R.W.R. Zwart
H. Boerrigter
E.P. Deurwaarder
S.R.A. Kersten

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M. Mozaffarian		
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“Green Gas” as SNG (Synthetic Natural Gas) A Renewable Fuel with Conventional Quality

M. Mozaffarian, R.W.R. Zwart, H. Boerrigter, E.P. Deurwaarder
Energy research Centre of the Netherlands, ECN
Westerduinweg 3, P.O. Box 1, 1755 ZG Petten, The Netherlands
S.R.A. Kersten
University of Twente, Department of Chemical Technology
P.O. Box 217, 7500 AE Enschede, The Netherlands

ABSTRACT: “Green Gas” as SNG (Synthetic Natural Gas) can play an important role in the transition process from the present Dutch fossil fuel-based energy supply to a renewable fuel-based economy. Anaerobic digestion and supercritical water gasification have been assessed for SNG production from wet biomass streams. For relatively dry biomass streams steam-blown indirect gasification, pressurised oxygen-blown gasification, hydrogasification, and co-production of both Fischer-Tropsch diesel and SNG have been considered. All cases with upstream gasification are followed, after gas cleanup, by a downstream methanation step. Although upgrading of landfill gas, or biogas produced via anaerobic digestion of wet biomass, will be interesting for the short-term introduction of “Green Gas” in the Dutch energy supply, the supercritical water gasification processes seem to be more promising for conversion of wet biomass to “Green Gas” on the longer term. Based on the modelling results, the upstream-pressurised oxygen-blown CFB and indirect atmospheric steam-blown gasification with downstream methanation routes were identified to be the most promising options for stand-alone SNG production from relatively dry biomass feedstocks. In combination with downstream methanation, SNG production efficiencies up to 70% (LHV) can be achieved. The successful integrated lab-scale demonstration of “Green Gas” production confirmed the potential of the ECN gas cleanup concept to deliver a product gas that can satisfy, among others, the specifications for downstream methanation. For 100 MW_{th} stand-alone systems and biomass costs of 2.3 €/GJ_{wood}, the SNG production costs range from 7.8 to 8.5 €/GJ_{SNG} and the CO₂ emission reduction costs range from 83 to 95 €/tonne. “Green Gas” production via biomass gasification with downstream methanation will become an economic feasible process in the Netherlands, when “Green Gas” receives the same tax exemptions as currently are given to green electricity.

INTRODUCTION

“Green Gas” is a renewable gas from biomass with natural gas specifications. Therefore, it can be transported through the existing gas infrastructure, substituting natural gas in all existing applications.

Using biomass for energy supply will not generally result in a net CO₂ emission. It is even possible to reduce the atmospheric CO₂ by sequestering the CO₂ that is released during the conversion of biomass (negative CO₂ emission). Within the Dutch sustainable energy policy an important role is foreseen for the application of biomass and waste. 10% of the total primary energy demand in 2020 has to be fulfilled by renewable energy sources^{[1][2]}. About 50% of this policy target has to be realised by biomass and waste. For the long term (2040) the Dutch Ministry of Economic Affairs has proposed a Biomass Vision within the Energy Transition activities, declaring that 30% of the fossil fuels in the power and transportation sectors, and 20-45% of the fossil-based raw materials in the chemical industry have to be substituted by biomass^[3].

Compared to other biomass conversion routes, the major advantage of the “Green Gas” concept is the potential to use the existing dense Dutch and European gas infrastructure for large-scale introduction of bio-energy. For Europe this will contribute to the security of gas supply, which will be more and more dependent from import, while for the Netherlands it will save the natural gas resources for a longer period. Furthermore, “Green Gas” is easier to transport and store than electricity or heat. The gas grid losses (<1%) are much less than those of the electricity and heat distribution networks (4% and 15%).

Large amounts of primary fuels are consumed for distributed heat production. The use of centralised produced SNG (economy of scale) for heat production in households and small and medium sized enterprises is economic competitive with alternative options like distributed CHP plants and electrical heating. The buffer function of the gas grid makes continuous operation of “Green Gas” plants possible. This contrary to centralised heat supply options that are dimensioned to maximum heat demand. Moreover, SNG can also be stored in old gas fields for (seasonal) peak shaving.

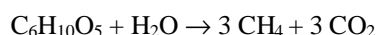
Promising near future applications for “Green Gas” are co-generation at household level (especially in fuel cells), and as alternative fuel for transportation (i.e. CNG, LNG). Concerning the future use of alternative transportation fuels in the EU, the European Commission has a targeted natural gas market share for road transport of 10% by 2020 (based on percentage of the total fuel consumption for transportation). A main driving force for the large-scale introduction of CNG as motor fuel is concern for the security of supply for the transport sector, which currently is solely dependent on oil products^{[4][5]}. Besides, application of CNG will result in fewer emissions of NO_x, CO₂, aromatics, and sulphur compounds, compared to petrol and diesel^{[5][6]}. Similar to CNG, “Green Gas” can also be used as a motor fuel, with the advantage of being an almost CO₂-neutral fuel.

“GREEN GAS” PRODUCTION ROUTES

“Green Gas” can be produced by conversion of biomass via biological or thermochemical processes. The biological route comprises upgrading of landfill gas, or biogas produced from anaerobic digestion of organic wastes (such as vegetable, fruit, and garden waste, organic wet fraction of municipal solid wastes, manure, and sewage). The thermochemical route comprises biomass gasification in supercritical water, co-production of Fischer-Tropsch-SNG from biomass, and biomass gasification with downstream methanation. While anaerobic digestion and supercritical gasification processes are applied for conversion of wet biomass (70-95 wt.% water), the gasification / methanation processes are applied for conversion of relatively dry biomass streams (10-15 wt.% water).

ANAEROBIC DIGESTION

Anaerobic digestion is a biological process in which organic wastes, in absence of air (anaerobic), are converted to biogas, i.e. a mixture of methane (55-75 vol.%) and carbon dioxide (25-45 vol.%). During anaerobic digestion, typically 30-60% of the solid input is converted to biogas. The co-products consist of an undigested residue and various water-soluble substances. Depending on the digestion system (wet or dry), the average residence time is between 10 days and 4 weeks. A simplified stoichiometric reaction for anaerobic digestion of biomass is:



Anaerobic digestion is a proven technology, generally available on a commercial basis, and being applied for small-scale decentralised treatment of “wet” organic wastes at their origin. The produced biogas, either raw or usually after some enrichment in CH_4 , can be used to generate heat and power through prime movers, at capacities up to 10 MW_e, with excess power fed into the grid. In a gas engine, electric efficiencies of 30-35% (on LHV basis), and total efficiencies of 85% can be achieved. Higher electric efficiencies of up to 50% might be reached by using fuel cell systems instead of gas engines. Generally, the produced heat in a prime mover can be used optimally within the digestion process, and for other purposes such as space heating. The simultaneous demand for heat and power is the crucial factor for an efficient use of biogas in co-generation. Otherwise upgrading, injection into the natural gas grid, and transport as “Green Gas” to customers, would be more advantageous.

In order to obtain pipeline quality gas, the biogas must pass through two major processes^[7]:

- (1) A cleaning process, in which trace components (hydrogen sulphide, water, particles, halogenated hydrocarbons, ammonia, oxygen, and organic silicon compounds) harmful to the natural gas grid, appliances, or end-users, are removed.
- (2) An upgrading process (basically separation of methane and carbon dioxide), in which the calorific value, Wobbe-index and other parameters are adjusted in order to meet the pipeline specifications (furthermore, the gas must be odourised before it is added to the natural gas grid).

In 2001, 27 landfill projects in the Netherlands delivered $2 \cdot 10^7 \text{ Nm}^3$ natural gas equivalent to the gas distribution net, while the contribution of biogas from digestion projects was about $3 \cdot 10^7 \text{ Nm}^3$ natural gas equivalent. Compared to annual Dutch gas consumption of $4 \cdot 10^{10} \text{ Nm}^3$, the contribution of landfill gas and digestion gas was, therefore, 0.1%. Taking into account the additional potential for digestion gas, a total contribution of about 0.5% of the annual Dutch gas consumption can be achieved. Although very limited, the short-term exploitation of this potential, as “Green Gas” would be interesting^[8].

If biogas is distributed in a closed biogas network or in a town gas network, only cleaning of biogas is necessary. This option has been demonstrated in Sweden and Denmark^[7]. Utilisation of the natural gas grid, as a transporting system for biogas, plays an important role in promoting the use of biogas as a vehicle fuel, as it will be possible to produce biogas in any place along the gas grid, with the possibility to trade 100% of the gas as vehicle fuel. In Switzerland gas as a fuel for vehicles is becoming more and more popular. Both natural gas and biogas are utilised as vehicle fuel. Also in

Sweden biogas has become very popular as a fuel for vehicles (end 2000 about 4000 vehicles operated on biogas^[5]). During the last years many upgrading plants with capacities between 10-700 m³/hr have been started, producing vehicle fuel mainly from sewage sludge. Biogas as a vehicle fuel is free from fuel tax and thus competitive to the traditional fuels. The Laholm co-digestion plant with a capacity of 250 m³/hr is producing natural gas quality from biogas since 2000, by upgrading biogas and adding propane to correct the heating value and Wobbe-index. In France two upgrading plants, with a capacity of 100 respectively 200 m³/hr are in operation since 1994 respectively 1995, making vehicle fuel from sewage sludge, or landfill gas^[7]. Development of biogas and development of a broader natural gas vehicle market can be mutually supportive. The broader market development creates the basis for broader use of biogas, and development of biogas supplies in areas without natural gas distribution will make it possible to use natural gas vehicles practically anywhere in Europe^[5].

BIOMASS GASIFICATION IN SUPERCRITICAL WATER^{[9][10][11]}

Wet biomass (70-95 wt.% water) may not be converted economically by traditional techniques like pyrolysis, combustion, and gasification, due to the cost and energy requirement for mechanical liquid-solid separation, as well as water evaporation (2.4 MJ/kg at atmospheric conditions). Gasification in hot compressed water is considered as a promising technique to convert such wet streams into medium calorific gas, rich in either hydrogen or methane. At temperatures and pressures above the critical point of water ($T_c = 373.95^\circ\text{C}$, $P_c = 220.64$ bar) there is no distinction between gas phase and liquid phase. Also the behaviour of water will change considerably at these supercritical conditions, and water will even be consumed as a reactant.

Supercritical water gasification (SCWG) is an alternative route for wet biomass streams, which are converted via anaerobic digestion. According to van de Beld *et al*^[10] about 25% of the Dutch biomass-related sustainable energy targets in 2020 could be realised by optimal use of the available wet biomass streams in the Netherlands. Contrary to digestion, supercritical water gasification of biomass can lead to complete conversion of the feedstock. As a result of low reaction rates, large reactors are required in digestion processes. Another aspect of digestion is that the bacteria cannot handle all feedstocks and can loose activity as a result of poisoning. For supercritical water gasification conventional fluid bed technology is identified as the best reactor concept^[9], and the product gas is available at high pressures.

Supercritical water gasification is in an early stage of development. Due to its potential with respect to possible conversion of waste materials to a valuable gas, the laboratory research is developing rapidly. At present there are two pilot plants being operated in the world. The largest plant, in operation since the beginning of 2003, is the one of Forschungszentrum Karlsruhe (FzK) in Germany^[12]. It has a design capacity of 100 l/hr, and was built to demonstrate supercritical gasification of wet residues from wine production. The second one is the process development unit (PDU) at the university of Twente (Enschede, the Netherlands)^[13], with a capacity of 5-30 l/hr, and designed for operating temperatures up to 650°C and pressures of around 300 bar. A simplified scheme of this PDU is presented in figure 1. As first feedstocks "simple" components like ethanol and glycerol have been used, while later trials are intended for the more difficult feedstock types like starch and, eventually, real biomass. The feedstock is pumped to a pressure of about 300 bar. After heat exchange with the reactor effluent in a simple double-walled tube heat exchanger, the feedstock will reach a temperature of 400-550°C, passing the critical point of water. The reactor is operated at a temperature of 600-650°C, and a residence time of 0.5-2 min. for complete carbon

conversion. The two-phase product stream from the reactor arrives in a high-pressure (HP) gas-liquid separator ($P = 300$ bar, $T = 25$ - 100°C) from which the liquid phase is further transferred to a low-pressure (LP) gas liquid separator ($P = 1$ atm, $T = 20^{\circ}\text{C}$). The gas released from the HP is rich in hydrogen, while the LP separator produces a CO_2 -rich gas.

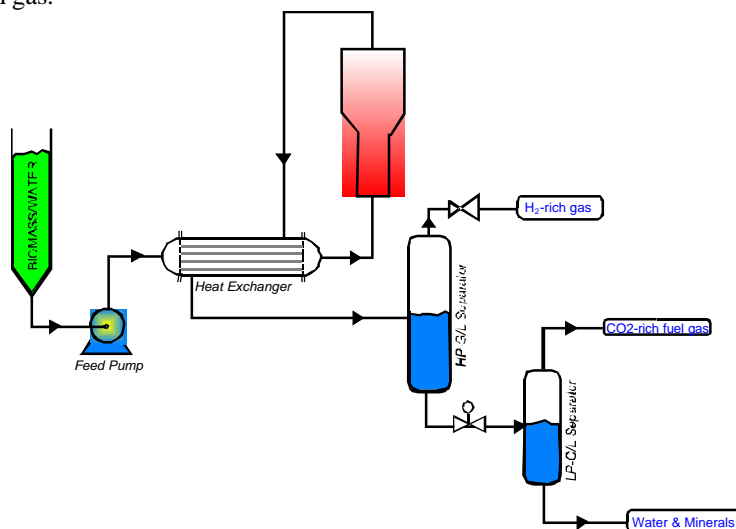


Fig. 1 Simplified scheme of the PDU at Twente University (the Netherlands) for biomass gasification in supercritical water^[9].

Figure 2 shows that, according to thermodynamics, there is a strong shift from methane towards hydrogen and carbon monoxide while increasing the temperature. Methane-rich gas can be produced up to temperatures of about 500°C , higher temperatures favour the production of hydrogen. At relatively low temperatures of about 350°C (just below the critical temperature), methane-rich gases can be produced by using a catalyst.

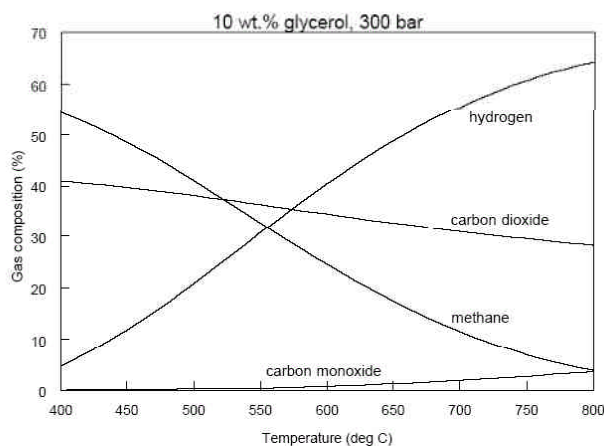


Fig. 2 Equilibrium concentrations H_2 , CH_4 , CO , and CO_2 as function of the temperature (Pressure = 300 bar; feedstock: 90 wt.% water, 10 wt.% glycerol)^[11].

Based on an expected market and technology development, the first commercial products of supercritical gasification of biomass would be electricity (>2008) and SNG (>2010). Later on (>2015), mixtures of CH₄ / H₂ could be added to the natural gas grid. Finally, in long term (>2020), pure H₂ could be produced (requiring infrastructure for storage and distribution of pure H₂), contributing to a potential future hydrogen economy^{[9][10]}.

CO-PRODUCTION OF FISCHER-TROPSCH-SNG FROM BIOMASS

In the co-production FT-SNG concept the off-gases from FT synthesis are used for SNG production through methanation (figure 3a). This concept can be considered as an alternative route to stand-alone FT synthesis, in which large amounts of off-gases would be recycled to the gasification step (figure 3b), requiring a large amount of auxiliary power.

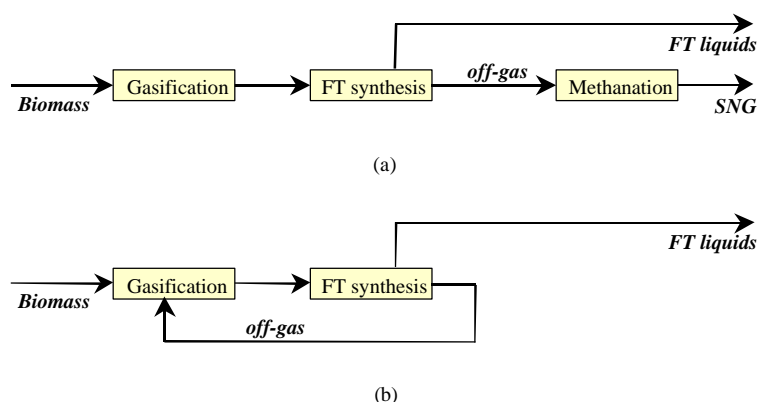


Fig. 3 (a) Co-production of liquid FT transportation fuels and SNG from biomass;
(b) Production of FT liquids from biomass.

Boerrigter and Zwart^{[14][15]} have evaluated the co-production of 50 PJ of Fischer-Tropsch transportation liquids and 150 PJ of SNG per year (*i.e.* 10% of the 2001 Dutch consumption of these energy-carriers^{[16][17]}), leading to an annual CO₂ emission reduction of approximately 12.5 Mtonne. A part of the SNG in these concepts is produced by methanation of the FT off-gas, which already contains significant amounts of C₁-C₄ SNG compounds, however, the amount of SNG produced by methanation of the off-gas is not sufficient to comply with the 150 PJ per year goal. Additional SNG has to be produced either by "integrated co-production", in which a side-stream of the product gas of the gasifier is used for dedicated methanation (figure 4a), or by "parallel co-production", in which part of the biomass is fed to a second gasifier coupled to a dedicated stand-alone methanation reactor (figure 4b). Operating the FT-synthesis at conditions where more SNG is produced at the cost of transportation fuels is not desirable (from both economic and product quality viewpoints).

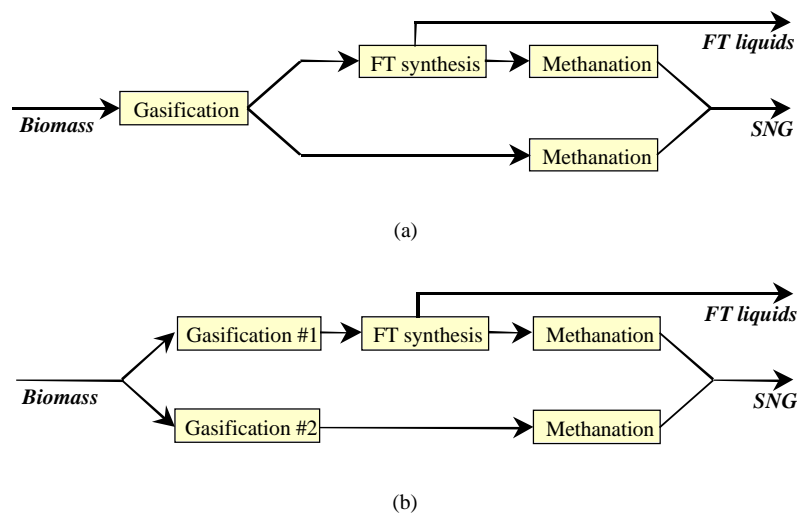


Fig. 4 (a) integrated co-production of FT liquids and SNG; (b) parallel co-production of FT liquids and SNG^[14].

In general, pressurised O₂-blown CFB gasification and atmospheric indirect steam-blown gasification are identified to be the most suitable technologies for co-production (figure 5), with CO₂ reduction costs in the range of the energy tax exemption for “green power” in the Netherlands of 100 €/tonne^[18]. The overall efficiencies (FT liquids plus SNG) are higher for CFB and indirect gasification concepts compared to EF gasification as already much CH₄ and C₂ compounds are present in the product gas. On the other hand, the efficiency to FT liquids is much higher for EF gasification resulting from the presence of all the chemical energy in the gas as syngas compounds (CO and H₂). The integrated co-production concepts have generally higher net energy efficiencies compared to the parallel co-production concepts.

The main overall conclusion of the study is that the co-production of Fischer-Tropsch transportation fuels and Synthetic Natural Gas (SNG) from biomass is economically more feasible than the production of both energy carriers in separate processes. Co-production of “green” FT transportation fuels and “green” SNG will become an economic feasible process in the Netherlands, when both energy carriers receive the same tax exemptions as currently are given to green electricity.

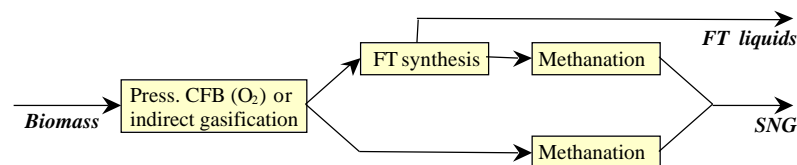


Fig. 5 Optimal system for (integrated) co-production of “green” FT transportation fuels and “green” SNG^[14].

BIOMASS GASIFICATION / METHANATION

Based on comparable assumptions, a technical, economic, and ecological assessment has been carried out for SNG production by combined biomass (hydro)gasification / methanation processes. The objective of the study was to make a selection for future implementation of the promising technologies for the production of SNG from biomass and waste in the Netherlands^[19]. The following gasification-based stand-alone SNG production routes have been considered:

- (1) Pressurised O₂-blown CFB gasification with downstream methanation.
- (2) Atmospheric indirect steam-blown gasification with downstream methanation.
- (3) Pressurised BFB hydrogasification with downstream methanation.

The main pre-conditions for the stand-alone gasification concepts were production of a tar-free, low-nitrogen, and high methane content product gas, and the up-scaling potential of the technology to a commercial scale. Air-blown CFB gasification due to a high nitrogen content of the produced gas, and entrained-flow gasification due to zero methane content of the produced gas have, therefore, been left out of consideration.

Modelling work

A block scheme of the stand-alone SNG production systems is presented in figure 6. In all cases the product gas from gasifier, after a low-temperature cleanup, and passing through a methanation step, is used for the production of SNG as main product.

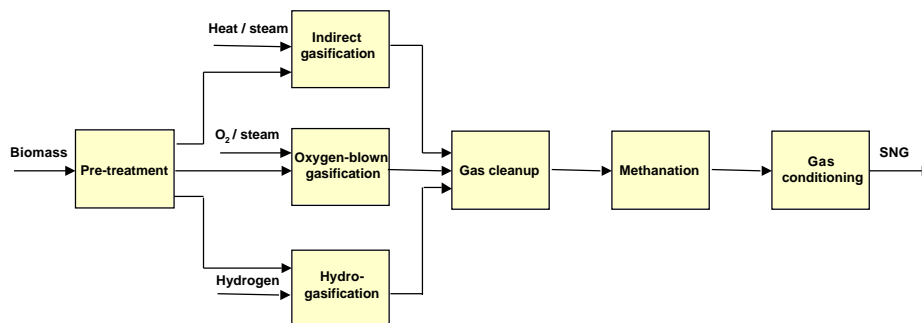


Fig. 6 SNG production by biomass (hydro)gasification / methanation processes.

In order to determine the mass and energy balances of these processes, three Aspen Plus models were developed. The operating temperature of the gasifiers is 850°C. The gasifier pressure is respectively 1 bar for indirect gasification, 15 bar for oxygen-blown gasification, and 30 bar for hydrogasification. In case of indirect gasification, the product gas after cleanup is compressed to 15 bar, before entering the methanation section. In case of pressurised options a CO₂ stream is used as pressurisation gas. The cleanup step consists of a dust filter, deep tar removal with the ECN oil-based gas washer (the OLGA unit)^[20], water scrubbing for removal of NH₃ and halides, and guard beds for final protection of methanation catalyst. The methanation process is based on the inter-cooled methanation process, used within the Lurgi coal-to-SNG process^[21]. The conditioning step consists of gas cooling and

drying, followed by partial removal of CO₂ (if necessary), in order to bring the Wobbe-index of the gas within the Dutch natural gas specification (*i.e.* between 43.46 and 44.41 MJ/Nm³). The heat generated at various points in each process is used for steam and electricity generation in a steam cycle, in order to satisfy the demand within the system.

Some of the modelling results are presented in table 1 and table 2. The results show that the upstream atmospheric steam-blown indirect gasification and pressurised oxygen-blown gasification with downstream methanation routes are the most promising options for SNG production from relatively dry biomass. In combination with downstream methanation, SNG production efficiencies up to approximately 70% (on LHV basis) can be achieved. The specific investment costs of a system with a thermal biomass input of 100 MW are higher for pressurised oxygen-blown gasification compared to indirect steam-blown gasification, mainly due to the requirement of an oxygen plant. The SNG production costs for a 100 MW_{th} system and biomass costs of 2.3 €/GJ_{wood} range from 7.8 to 8.5 €/GJ_{SNG}, while based on the Dutch stimulating measures, valid in 2002, the actual market price for “Green Gas” was calculated to be 8.7 €/GJ_{SNG}. The CO₂ emission reduction costs range from 83 to 95 €/tonne, which is lower than the 100 €/tonne tax exemption for green power.

Table 1 Model-based composition and quality of SNG versus Dutch natural gas (Slochteren quality).

Property		NG	O ₂ -blown gasifier	indirect gasifier	hydro- gasifier
Composition					
CH ₄ (incl. C ₂₊)	vol.%	84.75	87.67	87.62	82.97
H ₂	vol.%	0.00	1.77	1.95	8.02
CO ₂	vol.%	0.89	8.65	8.90	8.37
N ₂	vol.%	14.35	1.84	1.44	0.53
Calorific value, LHV	MJ/kg	38.0	38.41	38.41	39.57
	MJ/Nm ³	31.7	31.26	31.26	30.67
Wobbe-index	MJ/Nm ³	43.46-44.41	43.74	43.74	44.03

Table 2 Evaluation data for gasification-based SNG production processes.

		O ₂ -blown gasification	indirect gasification	hydro- gasification
Thermal input				
biomass	MW	100	100	50
hydrogen	MW			47
Efficiency SNG production	%	66.3*	67.0*	79.1
Carbon conversion	%	93.3	100	80.1
Specific investment costs	€/kW _{th}	482	449	616
SNG production costs	€/GJ _{SNG}	8.5	7.8	5.6
Dutch market price “Green Gas”	€/GJ _{SNG}	8.7	8.7	5.2
Costs CO ₂ avoided	€/tonne	95	83	115

* When the separated tar from the product gas is recycled and converted within the gasifier, SNG production efficiencies up to 70% (on LHV basis) can be achieved.

The up-scaling potential of the indirect gasification technology is expected to be more difficult than the pressurised oxygen-blown gasification, due to the complicated heat exchange between the gasifier and the combustor. This makes the technology mainly suitable for decentralised SNG plants ($< 100 \text{ MW}_{\text{th}}$). The fact that this technology does not require an oxygen plant is another positive aspect of this technology for decentralised applications. In contrary, the pressurised oxygen-blown gasification will be more suitable for centralised applications ($> 100 \text{ MW}_{\text{th}}$).

With respect to biomass hydrogasification, higher SNG production efficiencies (up to 80% LHV) and lower SNG production costs ($5.6 \text{ €/GJ}_{\text{SNG}}$) can be achieved, compared to biomass gasification / methanation routes. However, the limited availability (until 2020), as well as the origin (fossil-based) of the applied hydrogen result in lower SNG production potential and CO_2 emission reduction, and higher CO_2 emission reduction costs (115 €/tonne). Fossil-based hydrogen lowers the market price for SNG from hydrogasification process, as only a part of the produced SNG can be considered green. For hydrogasification, the availability of a sustainable and economically attractive hydrogen source is the key to a successful implementation of the process.

Experimental work

“Green Gas” production via biomass gasification, gas cleaning, and methanation was successfully demonstrated at ECN in December 2003.

Gas cleaning is the major technical challenge in the application of product gases from biomass gasification for SNG production, as the methanation catalysts are very sensitive to impurities, especially sulphur, halides, and tar compounds. In the integrated test, beech wood (1 kg/hr) was converted into a product gas by oxygen/steam-blown gasification in one of the ECN biomass lab-scale (bubbling) fluidised bed gasifiers (figure 7a). The composition of the product gas (main components in vol.% dry basis) is presented in table 3. The product gas was completely de-dusted with a high-temperature ceramic filter (400°C), followed by deep tar removal with the lab-scale OLGA unit (figure 7b), and water scrubbing for removal of NH_3 and halides. In order to achieve the desired H_2/CO ratio for methanation, additional hydrogen was added to the gas. Then the gas was compressed (up to 60 bar) and led through ZnO filters for sulphur removal and active carbon filters for final protection (figure 7c). The clean gas was then used as feed for the micro-flow fixed-bed methanation reactor (figure 7d) with a Ru-based catalyst, operated at 30 bar and 260°C .

Table 3 Product gas composition (beech) of oxygen/steam-blown test in the ECN-WOB gasifier.

Component	Composition vol.%
CO	31
H_2	21
CO_2	29
CH_4	11
C_2H_2	0.2
C_2H_4	3.6
C_2H_6	0.3

The suitability of the cleaned biomass product gas for SNG synthesis was proven by stable catalyst performance during the 150-hours integrated methanation test. The deactivation rate was comparable with a reference case, in which a “clean” synthetic mixed gas was used as feed stream.

The ECN test facilities, as presented in figure 7, were also used during 2001-2003 to prove the technical feasibility of producing Fischer-Tropsch liquids from biomass by integrated biomass gasification (oxygen-blown) Fischer-Tropsch experiments^[22].

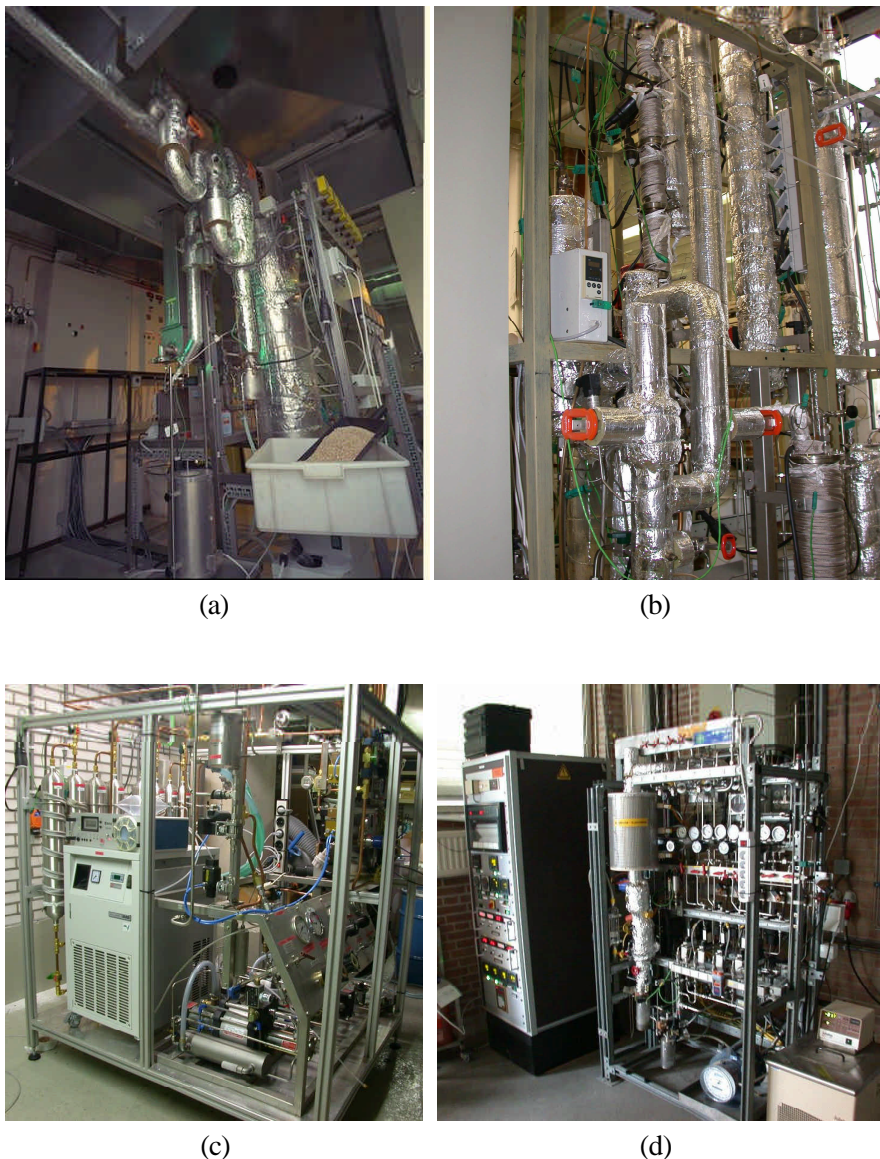


Fig. 7 Lab-scale test facilities for “Green Gas” production: (a) Bubbling fluidised bed test facility for oxygen/steam-blown gasification (WOB); (b) ECN oil-based tar washer (OLGA); (c) Compressor and guard beds; (d) Fixed-bed micro flow methanation reactor (POTTOR).

FUTURE PROSPECTS

The “Green Gas” technology developments at ECN will be continued in 2004-2005, in co-operation with the Dutch Gasunie Trade & Supply (GU T&S) and Gastransport Services (GtS). ECN has recently constructed a bench-scale gasification facility, in order to support the implementation of the selected technologies for conversion of relatively dry biomass streams. The new so-called MILENA gasifier, with thermal inputs up to 25 kW (5 kg/hr biomass), can be operated at direct oxygen-blown gasification mode, as well as at indirect steam-blown gasification mode, as presented in figure 8. In the meantime indirect steam-blown tests have been carried out at T: 750°C-830°C in gasification riser. Typical product gas composition (main components in vol.% dry basis) for beech wood as feedstock is presented in table 4.

Table 4 Typical product gas composition (beech) of indirect steam-blown tests (at T: 750°C-830°C) in the ECN-MILENA gasification facility.

Component	Composition vol.%
CO	42-46
H ₂	15-20
CO ₂	10-12
CH ₄	14-17
C ₂ H ₂	0.2-0.6
C ₂ H ₄	4.4-4.8
C ₂ H ₆	0.3-0.9

The MILENA facility is installed upstream of the already existing gas clean-up infrastructure, followed by a newly to be constructed shift reactor and methanation section, as presented in figure 9. The integrated system enables the proof of production of a gas that can satisfy, among others, the specifications for downstream methanation. The R&D activities are aimed at optimisation of the gasification conditions (agglomeration behaviour, gas composition), gas cleaning (removal of tar and other components) and conditioning, and an extensive methanation test programme. Also an extensive modelling work is foreseen within the programme. The experimental data will be used to fit the models, and the models will be used to predict new tests, as well as to determine the mass and energy balance of the whole process. Another activity concerns analysis and continuous monitoring of the Dutch natural gas market, and potential role that might be played in it by “Green Gas”. The R&D activities should result in a conceptual design for a pilot-scale integrated biomass gasification SNG plant, to be realised and operated in 2005-2008. Commercial units are expected after 2008.

Anaerobic digestion is a proven technology being applied for small-scale decentralised conversion of “wet” organic residues at their origin. SNG production in this sector should always compete with the well-known combined heat and power application. Although upgrading of biogas, produced via anaerobic digestion of wet biomass, will be interesting for the short-term introduction of “Green Gas” in the Dutch energy supply, the supercritical water gasification processes seem to be more promising for conversion of wet biomass to “Green Gas” on the longer term.

Concerning the supercritical water gasification of biomass, the process is in an early stage of development. Recently, different Dutch organisations (Biomass Technology Group, SPARQLE, University of Twente, TNO, and ECN) started

working on possible national co-operation, regarding technology development for the SCWG process^[10]. One of the important aspects for future investigation is the introduction of feedstock in the SCWG process. Regarding the heat balance, an intensive heat exchange between feedstock and products is essential. This heat exchange is a non-trivial matter, as the feedstock will already produce decomposition products like tar and char or coke, while being heated. Non-conventional solutions for the pump, heat exchanger and reactor, as well as for residual carbon combustion, may be required to obtain a practical process. When the biomass concentration in water increases, the product will gradually contain more hydrocarbons and full conversion becomes difficult. Catalysts are then required to improve the conversion. Despite all the problems in the early stage of development, the wet-biomass conversion processes could become an attractive option for the production of clean “Green Gas” from biomass and organic waste^[9]. As mentioned earlier, based on an expected market and technology development, the first commercial products of supercritical gasification of biomass would be electricity (>2008), followed by “Green Gas” after 2010^[10].

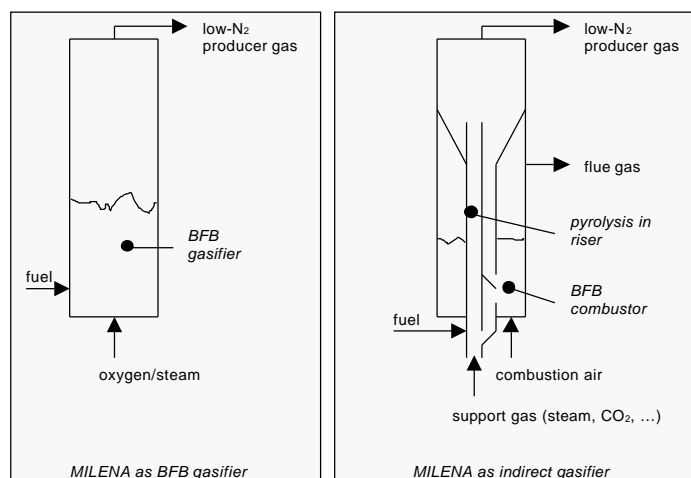


Fig. 8 Two options of MILENA installation for the production of low-N₂ product gas from biomass.

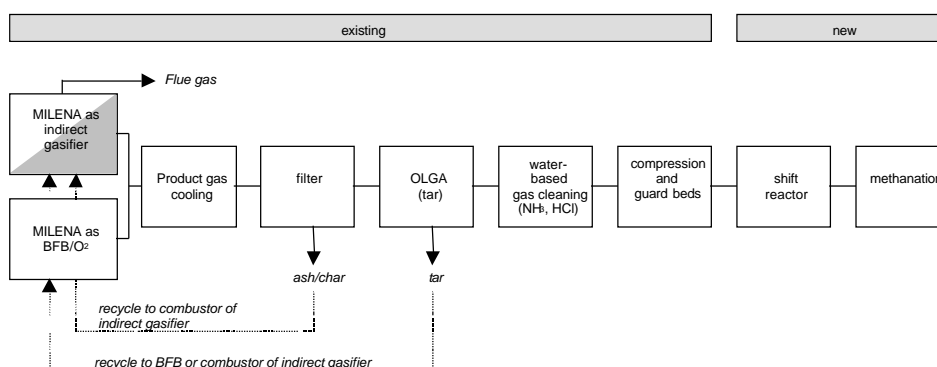


Fig. 9 Existing and new parts of the SNG production facility at ECN.

CONCLUSIONS

- (1) "Green Gas" as SNG (Synthetic Natural Gas) can play an important role in the transition process from the present Dutch fossil fuel-based energy supply to a renewable fuel-based economy.
- (2) Although upgrading of biogas, produced via anaerobic digestion of wet biomass, will be interesting for the short-term introduction of "Green Gas" in the Dutch energy supply, the supercritical water gasification processes seem to be more promising for conversion of wet biomass to "Green Gas" on the longer term.
- (3) Atmospheric indirect steam-blown gasification and pressurised oxygen-blown CFB gasification are the most suitable technologies for co-production of Fischer-Tropsch transportation fuels and SNG from biomass. Co-production is economically more feasible than the production of both energy carriers in separate processes.
- (4) Atmospheric indirect steam-blown gasification and pressurised oxygen-blown CFB gasification with downstream methanation are the most promising routes for stand-alone SNG production from relatively dry biomass feedstocks, resulting in SNG production efficiencies up to 70% LHV. Atmospheric indirect steam-blown gasification is more suitable for decentralised (< 100 MW_{th}) applications, while pressurised oxygen-blown CFB gasification is more suitable for centralised (> 100 MW_{th}) applications.
- (5) The successful integrated lab-scale demonstration of "Green Gas" production confirms the potential of the ECN gas cleanup concept to deliver a product gas that can satisfy, among others, the specifications for downstream methanation.
- (6) For a 100 MW_{th} stand-alone system and biomass costs of 2.3 €/GJ_{wood} the SNG production costs range from 7.8 to 8.5 €/GJ_{SNG} and the CO₂ emission reduction costs range from 83 to 95 €/tonne.
- (7) Both processes of co-production of FT transportation fuels and "Green Gas" from biomass, as well as stand-alone "Green Gas" production via biomass gasification with downstream methanation will become economic feasible processes in the Netherlands, when the produced energy carriers receive the same tax exemptions as currently are given to green electricity. The cost of "Green Gas" production via supercritical water gasification processes should still be determined.

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REFERENCES

1. Ministerie van Economische Zaken: *Derde energienota*. Den Haag, 1995.
2. Ministerie van Economische Zaken: *Duurzame energie in opmars, actieprogramma 1997-2000*. Den Haag, 1997.
3. Ministerie van Economische Zaken: *Biomassa: de groene motor in transitie; stand van zaken na de tweede etappe*. Den Haag, December 2003.
4. Commission of the European Communities: *Communication from the Commission to the European Parliament, the Council, the Economic and Social*

Committee and the Committee of the Regions on alternative fuels for road transportation and on a set of measures to promote the use of biofuels. COM (2001) 547 final, Brussels, November 2001.

5. *Market development of alternative fuels.* Report of the European Commission's alternative fuels Contact Group, December 2003.
6. Hendriksen, P., R.J. Vermeulen, R.C. Rijkeboer, D. Bremmers, R.T.M. Smokers, R.G. Winkel: *Evaluation of the environmental impact of modern passenger car on petrol, diesel, automotive LPG and CNG*, TNO report: 03.OR.VM.055.1/PHE, December 2003.
7. Hagen, M., Polman, E., Myken, A., Jensen, J., Jönsson, O., Dahl, A.: *Adding gas from biomass to the gas grid.* Contract No: XVII/4.1030/Z/99-412, Final report, February 2001.
8. Siemons, R.V.: *Biogas voor bijmenging in het aardgasnet, rapport aan het Team Nieuw Gas.* In "Wegen naar nieuw gas: de eerste stap is een daalder waard", transitiepaden naar een duurzame gasinzet, December 2003.
9. Kersten, S.R.A.: *Biomass gasification in sub and supercritical water: a review.* University of Twente (the Netherlands), November 2003.
10. Beld, L. van de, Penninger, J.: *Vergassing in superkritiek water: status en toekomstperspectief voor Nederland.* Novem-NEO project nr: 0268-03-07-01-0018, April 2004.
11. Mozaffarian, M., Kersten, S.R.A., Deurwaarder, E.P.: *SNG production by supercritical gasification of biomass.* ECN-C--04-081, to be published in 2004.
12. Boukis, N. et al: *Advances with the process of biomass gasification in supercritical water.* 4th International Symposium on High Pressure Technology and Chemical Engineering, Venice, Italy, 2002.
13. Potic, B., Beld, L. van de, Asink, D., Prins, W., Swaaij, W.P.M. van: *Gasification of Biomass in Supercritical Water.* 12th European Conference and Exhibition on Biomass for Energy, Industry and Climate Protection, Amsterdam, 2002.
14. Boerrigter, H., Zwart, R.W.R.: *High efficiency co-production of Fischer-Tropsch (FT) transportation fuels and substitute natural gas (SNG) from biomass.* ECN-C--04-001, ECN, Petten, The Netherlands, February 2004.
15. Zwart, R.W.R., Boerrigter, H.: *High efficiency co-production of substitute natural gas (SNG) and Fischer-Tropsch (FT) transportation fuels from biomass.* ECN-RX--04-042, May 2004.
16. Energieonderzoek Centrum Nederland: *Energie Verslag Nederland 2000.*
17. ECN: *Nationale Energie Verkenningen 1995-2020 – Trends en thema's.* March 1998.
18. Novem: *A strategy for zero-ing emissions: Black Beauty?* March 2002.
19. Mozaffarian, M., Zwart, R.W.R.: *Feasibility of biomass/waste-related SNG production technologies.* Final report, ECN-C--03-066, ECN, Petten, The Netherlands, July 2003.
20. Bergman, P.C.A., Paasen, S.V.B. van, Boerrigter, H.: *The novel "OLGA" technology for complete tar removal from biomass producer gas.* In: *Pyrolysis and Gasification of Biomass and Waste*, Bridgewater, A.V. (ed.), CPL press, Newbury, United Kingdom, 2003.
21. *Catalyst Handbook.* Second edition, edited by M.V. Twigg, ISBN 1874545359, 1996.
22. Boerrigter, H., Calis, H.P., Slort, D.J., Bodestaff, H.: *Gas cleaning for integrated biomass gasification (BG) and Fischer-Tropsch (FT) systems; experimental demonstration of two BG-FT systems.* ECN-RX--04-041, May 2004.