Production of Substitute Natural Gas by Biomass Hydrogasification

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ABSTRACT: Hydrogen, generated from renewable sources, is likely to play a major role in the future energy supply. The storage and transport of hydrogen can take place in its free form (H\textsubscript{2}), or chemically bound, e.g. as methane. However, the storage and transport of hydrogen in its free form are more complex, and probably would require more energy than the storage and transport of hydrogen in chemical form. An additional important advantage of the indirect use of hydrogen as energy carrier is, that in the future renewable energy supply, parts of the existing large-scale energy infrastructure could still be used. Production of Substitute Natural Gas (SNG) by biomass hydrogasification has been assessed as a process for chemical storage of hydrogen. Thermodynamic analysis has shown the feasibility of this process. The product gas of the process has a Wobbe-index, a mole percentage methane, and a calorific value quite comparable to the quality of the Dutch natural gas. With a hydrogen content below 10 mol%, the produced SNG can be transported through the existing gas net without any additional adjustment. The integrated system has an energetic efficiency of 81% (LHV). In the long term, the required hydrogen for this process can be produced by water electrolysis, with electricity from renewable sources. In the short term, hydrogen may be obtained from hydrogen-rich gases available as by-product from industrial processes. Results of thermodynamic analysis of the process and experimental work, application potentials of the process in the Netherlands, and plans for future development are presented.

INTRODUCTION

Hydrogen, generated from renewable sources, is likely to play a major role as an energy carrier in the future energy supply. Due to the finiteness of fossil energy sources, and the global environmental damage caused by them, the world has to switch gradually to other primary energy sources. In the long term, only biomass and other renewable sources such as water, wind, and sun will be available. Most of these energy sources, however, have a fluctuating character, resulting in dissimilarities between energy availability and energy demand. Discrepancies between demand and supply of energy can be solved by temporary storage of the surplus of energy as hydrogen, through water electrolysis.

The storage and transport of hydrogen can take place in its free form (H\textsubscript{2}), or chemically bound as, e.g. methane or methanol. However, the storage and transport of
hydrogen in its free form are more complex, and would probably require more energy \(^1\) than the storage and transport of hydrogen in chemical form. An additional advantage of the indirect use of hydrogen as an energy carrier is that the existing large-scale energy infrastructure for distribution and use can be utilised.

Several routes for chemical storage of hydrogen have been studied \([1]\), from which SNG production by biomass hydrogasification has been identified as the option with the highest energetic efficiency.

As illustrated in figure 1, between the present fossil fuel-based energy supply system and the future hydrogen economy, there would be a long transition phase, during which both fossil and renewable sources of energy would be applied simultaneously. During this phase hydrogen, produced from renewable sources, might be introduced to the energy market by the biomass hydrogasification process. The use of the existing gas infrastructure for transportation of the produced SNG makes a gradual transition to a hydrogen economy possible.

The process of SNG production by biomass hydrogasification has to be developed practically.

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\(^1\) The liquefaction of hydrogen, for instance, takes place at -253°C. Such low temperatures can be obtained by successively compressing the gas and expanding it through a throttle valve or expansion turbine. About 30% of the thermal energy of hydrogen (LHV) is necessary as electricity for compression \([1]\).
Gasification of carbon-containing feedstocks in a hydrogen atmosphere, is called hydrogasification. Hydrogasification of coal has been investigated since the 1930s in Germany, Great Britain and The United States [2]. Generally, the conversion increases with increasing pressure, temperature and residence time. Carbon conversions over 80%, with a selectivity of 90% for methane and ethane, have been obtained in hydrogasification of brown coal, in a 240 tons per day plant in Germany. In the early 1980s, Steinberg et al. [2] carried out flash hydrogasification experiments with wood in an entrained-flow reactor. At pressures between 14-34 bar and temperatures between 800-1000°C, carbon conversions were over 90%. At very short residence times (<1 s) conversion to methane dominated, while at longer residence times the conversion to methane decreased, and the conversion to carbon monoxide increased.

Several processes have been developed for production of methane-rich gases from coal, biomass, or organic solid wastes [3,4,5,6,7,8]. The required hydrogen in these processes is produced within the process [9], e.g. by gasification of residual char from the hydrogasifier (charcoal gasification case in figure 1). The use of an external hydrogen source is new [10], and gives the possibility to apply the hydrogasification process not only for upgrading of biomass and organic wastes to a methane-rich gas, but also as a process for chemical storage of hydrogen.

A simplified flowsheet for SNG production by biomass hydrogasification is shown in figure 2.

![Fig. 2 Simplified flowsheet for SNG production by biomass hydrogasification.](image)

Hydrogen and pre-treated biomass are fed to the hydrogasification reactor. The produced gas passes a high-temperature gas clean-up section for removal of contaminants, followed by a final methanation step for the conversion of residual CO. Removal of H$_2$O from the product gas of the methanation step, results in SNG as the final product.

**MODELLING WORK**

The complete process for SNG production from biomass and hydrogen by hydrogasification has been modelled in the ASPEN$^{\text{PLUS}}$ simulation package. Figure 3 shows a simplified diagram of the developed ASPEN$^{\text{PLUS}}$ model. Biomass (poplar wood) is dried in a steam dryer to the desired moisture content, after which it enters the hydrogasification reactor, together with a hydrogen stream. The reactor is operated at 800°C and 30 bar. A CO$_2$ stream is used to pressurise the biomass to the hydrogasification operating pressure. Both the hydrogen and CO$_2$ streams are assumed to enter the system at atmospheric pressure, and are compressed (within the system) to the hydrogasifier operating pressure.

The product gas of the hydrogasifier is cooled from 800°C to the inlet temperature of the methanation section (about 400°C). It is assumed, that within the temperature
range of 400-800°C, a high-temperature gas clean-up system can be used, in order to remove solid residues as well as gaseous impurities (H₂S, HCl, HF, NH₃) from the product gas. The clean gas is then fed to the methanation section. The methanation is based on the ICI high-temperature once-through process, using a series of inter-cooled reactors operating at successively lower exit temperature [11].

The product gas of the methanation section contains mainly CH₄, H₂, H₂O, and CO₂. Removing H₂O from this stream results in SNG as the final product, which leaves the system at high pressure. The heat released from the hydrogasifier product gas, and the heat generated in the methanation reactors, are used to generate superheated steam (40 bar and 540°C), which enters a steam turbine. A fraction of partly expanded steam is used to dry the biomass, while the remaining part of the steam is used for power generation.

Steady-state integral system calculations have been performed to determine the overall mass and energy balances.

Both the properties of the SNG produced by hydrogasification and the standard Dutch natural gas (Groningen quality) are presented in table 1. As can be seen, the quality of the produced SNG (calorific value and the Wobbe-index²) is comparable with the quality of Groningen natural gas. The hydrogen content of the SNG is below 10 mol%. At these hydrogen concentrations, the produced SNG might be transported through the existing natural gas infrastructure without any adjustment [12].

² Wobbe-index (MJ/Nm³) is defined as the ratio of the gross calorific value to the square root of the relative density of a gas:

\[ W = \frac{HHV}{\sqrt{\left(\frac{\rho_g}{\rho_{air}}\right)}} \]

with HHV (High Heating Value in MJ/Nm³), \( \rho_g \) and \( \rho_{air} \) (gas and air density in kg/Nm³). Wobbe-index is a measure of the amount of energy delivered to a burner via an injector. The energy input is a linear function of W. Two gases of differing composition but having the same Wobbe-index will deliver the same amount of energy for any given injector under the same injector pressure.
Table 1 Properties of standard Dutch natural gas and SNG produced by hydrogasification.

<table>
<thead>
<tr>
<th>Gas composition</th>
<th>SNG</th>
<th>NG</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$ [mol%]</td>
<td>81.6</td>
<td>81.3</td>
</tr>
<tr>
<td>H$_2$ [mol%]</td>
<td>8.7</td>
<td>0.0</td>
</tr>
<tr>
<td>CO$_2$ [mol%]</td>
<td>8.5</td>
<td>0.9</td>
</tr>
<tr>
<td>C$_2+$ [mol%]</td>
<td>-</td>
<td>3.5</td>
</tr>
<tr>
<td>N$_2$ [mol%]</td>
<td>0.8</td>
<td>14.3</td>
</tr>
<tr>
<td>Molecular weight [kg/kmol]</td>
<td>17.4</td>
<td>18.6</td>
</tr>
<tr>
<td>LHV [MJ/kg]</td>
<td>39.0</td>
<td>38.0</td>
</tr>
<tr>
<td>LHV [MJ/kmol]</td>
<td>676.1</td>
<td>708.3</td>
</tr>
<tr>
<td>Wobbe-index [MJ/Nm$^3$]</td>
<td>43.9</td>
<td>44.2</td>
</tr>
</tbody>
</table>

The efficiency of SNG production is defined as the ratio of the thermal energy leaving the system as SNG, and the thermal energy entering the system as biomass and hydrogen. With this definition, and the input/output data presented in table 2, the SNG production efficiency is calculated as 81% (LHV).

Table 2 Energy balance for SNG production by hydrogasification.

<table>
<thead>
<tr>
<th></th>
<th>In [MW]</th>
<th>Out [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>147.3</td>
<td></td>
</tr>
<tr>
<td>H$_2$</td>
<td>171.6</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>SNG</td>
<td></td>
<td>257.7</td>
</tr>
<tr>
<td>Char</td>
<td></td>
<td>20.0</td>
</tr>
<tr>
<td>Total</td>
<td>330.6</td>
<td>289.4</td>
</tr>
</tbody>
</table>

The dry gas composition of the product gas leaving the hydrogasifier is given in table 3. For comparison, also gas compositions produced by direct oxygen-blown gasification (IGT Process) and indirect gasification (Battelle Process) are given [13]. Compared with other biomass gasification processes for SNG production, biomass hydrogasification has the following advantages:

1. The gas produced by hydrogasification has a very high CH$_4$ concentration and a low CO concentration, compared to the gas produced by other biomass gasification processes. Therefore, only a relatively small methanation step will be required to upgrade the produced gas to SNG. As methanation is a highly exothermic process, a small methanation step for hydrogasification means, that less heat will be generated in that step. In other words, a higher percentage of the thermal input would be converted to SNG.

2. The required heat in the gasifier is not delivered by combustion of biomass, which is the case in the direct oxygen-blown gasification. Therefore, less carbon dioxide is produced in the gasifier. Besides, an expensive oxygen plant is not required.

3. Both the gasification reactions and the heat production by the exothermic reactions take place in the same reactor (the hydrogasifier), rather than in two separate reactors, which is the case in the indirect gasification processes, such as the Battelle Process.
(4) The hydrogasification process is more compact, and has fewer components than competing processes.

(5) The presence of excess hydrogen in the hydrogasifier, especially in combination with high operating pressures and temperatures, leads potentially to a reduction in tar formation.

Table 3 Dry gas composition [mol\%] for different gasification processes.

<table>
<thead>
<tr>
<th></th>
<th>Hydrogasifier</th>
<th>IGT O_2-blown gasifier</th>
<th>Battelle gasifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH\textsubscript{4}</td>
<td>50.2</td>
<td>17.8</td>
<td>17.8</td>
</tr>
<tr>
<td>C\textsubscript{2}H\textsubscript{2}</td>
<td>-</td>
<td>1.5</td>
<td>6.2</td>
</tr>
<tr>
<td>CO</td>
<td>4.3</td>
<td>16.0</td>
<td>46.5</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>10.1</td>
<td>39.4</td>
<td>14.6</td>
</tr>
<tr>
<td>H\textsubscript{2}</td>
<td>34.8</td>
<td>25.3</td>
<td>14.9</td>
</tr>
</tbody>
</table>

EXPERIMENTAL WORK

As part of the technical assessment of the biomass hydrogasification concept, an experimental programme was defined in 1999 and performed at Deutsche Montan Technologie (DMT), Germany.

Willow wood, and char produced from willow wood, were used as feedstock. The proximate and ultimate analyses of both feedstocks are listed in table 4. The following types of experiments were carried out:

(1) Lab-scale experiments in a pressurised thermobalance facility, operating up to 50 bar and 1000°C under isothermal as well as non-isothermal conditions.

(2) Bench-scale experiments in a pressurised fluidised bed facility, operating up to 5 bar and 800°C.

Table 4 Proximate and ultimate analyses of feedstocks.

<table>
<thead>
<tr>
<th></th>
<th>willow wood</th>
<th>willow wood char</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximate analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water [wt% ar]</td>
<td>10.0</td>
<td>-</td>
</tr>
<tr>
<td>ash [wt% ar]</td>
<td>3.5</td>
<td>6.0</td>
</tr>
<tr>
<td>volatile [wt% ar]</td>
<td>64.8</td>
<td>5.1</td>
</tr>
<tr>
<td>Ultimate analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C [wt% ar]</td>
<td>45.5</td>
<td>88.0</td>
</tr>
<tr>
<td>H [wt% ar]</td>
<td>5.7</td>
<td>1.0</td>
</tr>
<tr>
<td>N [wt% ar]</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>S [wt% ar]</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Several experiments have been carried out in the DMT pressurised thermobalance facility [14,15,18], from which some of the results will be presented below.

The main parts of the thermobalance are a stainless steel reactor and a microbalance. The reactor, in which the sample is placed, can be heated electrically either to a constant temperature for isothermal runs or with a constant heating rate for non-isothermal runs. First, the sample is weighted and placed within a basket, which is used as sample holder. The reactor is then pressurised and heated up to the requested
pressure and temperature in isothermal runs. After that, the basket, which is connected with the microbalance via a chain, is introduced into the hot reactor by moving down the chain. For chain moving a motor-driven system is used. Reaction of the sample starts with an uncontrolled heat up of the sample, after which it continues at isothermal condition. During the tests the reaction gas is flown through the reactor from bottom to top. The gas stream, including the reaction products, leaves the reactor at the top and is cooled in a heat exchanger where liquid products are condensed and sampled. Thereafter, a part of the gas stream is continuously fed to a gas chromatograph for on-line analysis of gaseous products. A gas meter measures the total gas stream. If reaction occurs too fast for on-line GC-analysis, gas samples can be taken from the gas stream during the run by an automatic gas sampler for later GC-analysis.

Typical amount of feed material was about 500 mg willow wood and 350 mg char. The particle size of the feed material used was less than 0.7 mm. As gasifying agent hydrogen, carbon dioxide, steam, or helium was used.

The tests were run over a period of 3 hours or longer. Only in case of the steam gasification of char the runs were stopped after about 80 minutes, since the gasification reactions finished after about 40-50 minutes. In most other cases, the running time was prolonged (>3 hours) until a high degree of constancy in weight signal was obtained. At the end of the experiments, the concentration of the main gas components produced was always lower than the detection limit of the gas chromatograph (e.g. the detection limit of methane is 40 ppm).

Gasification is a two step process, consisting of pyrolysis of the fuel (through primary as well as secondary reactions), and gasification of the char, originating from pyrolysis. The overall reaction of pyrolysis consists of the conversion of the fuel into char, tar, and gases, especially aliphatic hydrocarbons, CO, CO₂, and water. The gasification reactions of char are slower than the pyrolysis reactions.

During the pyrolysis step of biomass hydrogasification, which took place in the first minutes of the thermobalance experiments, a high percentage of biomass was converted, from which a high fraction to methane and ethane, especially at high pressures. Figure 4 and figure 5 present the biomass conversion, and the release rate of the main carbon-containing components of the product gas at 850°C and two different pressures (1.5 bar and 30 bar). In both cases, a biomass conversion of about 80 wt% (ar) was achieved within a minute. The figures show a shift from carbon monoxide and carbon dioxide to methane, by increasing the operating pressure. This can be explained by a combination of methanation and reversed shift reactions:

\[
\begin{align*}
CO + 3H_2 & \leftrightarrow CH_4 + H_2O \\
CO_2 + H_2 & \leftrightarrow CO + H_2O
\end{align*}
\]

In presence of excess hydrogen, the rate of methane formation through the methanation reaction increases by increasing the operating pressure, while at the same time carbon dioxide will react with hydrogen to produce carbon monoxide through the reversed shift reaction. The same trend is observed for the release rate of ethylene and ethane, i.e. a shift from ethylene to ethane by increasing the operating pressure. This can be explained by hydrogenation of ethylene:

\[
C_2H_4 + H_2 \leftrightarrow C_2H_6
\]

The reaction will shift to ethane formation by increasing the operating pressure, especially in presence of excess hydrogen.
At 850°C and 30 bar, beside 100% formation of the pyrolysis products: C₂H₄, CO, and CO₂, more than 95% of ethane, and about 80% of methane were formed within the first 10 minutes. After that only methane, and in much less extent ethane, continued to be formed, through the hydrogasification of char. Figure 6 presents the mean concentration of the main carbon-containing components in the product gas as a function of pressure. It can be seen how the concentration of CO, CO₂, and C₂H₄ decreases with pressure, while the concentration of CH₄ and C₂H₆ increases with pressure.

The effect of operating pressure on final conversion of biomass and carbon, for different temperatures, is presented in figure 7. Both biomass and carbon conversions
increase with pressure and temperature. At high operating pressures of 30-50 bar, biomass conversions of 92-94 wt% (ar), and carbon conversions of 86-88 wt% were achieved. It should, however, be mentioned that these conversions were achieved after long test runs of about 4 hours. Figure 8 and figure 9 present the conversion of biomass and carbon, as a function of time, for different pressures and temperatures. The test runs begin with rapid biomass conversions of 80 wt% (ar), and carbon conversions of 60 wt%, followed by hydrogasification of the remained char, with a slow reaction rate.

The reactivity of char gasification was studied under three different atmospheres (hydrogen, carbon dioxide, and steam), at 800°C and two operating pressures (5 bar and 30 bar). The required char was prepared by pyrolysing willow wood in a tube kiln under nitrogen atmosphere at a temperature of 800°C, within a period of about 8 hours. The char was cooled down under inert conditions.

![Fig. 6](image.png) Mean concentration of main carbon-containing components in the product gas at 850°C as a function of pressure.

![Fig. 7](image.png) Effect of operating pressure at 800°C, 850°C, and 900°C on biomass and carbon conversions.
Figure 10 presents the weight loss of the char samples under different atmospheres and pressures. It can be seen, that char gasification with steam resulted in the highest conversion rate, followed by CO$_2$ and H$_2$ gasification. Based on this observation, a higher char conversion is expected during the hydrogasification of biomass in a pressurised fluidised bed reactor, because in addition to hydrogen, also the pyrolysis products, CO$_2$ and H$_2$O can take part in the conversion of char, according to the following reactions:

\[
\begin{align*}
C + 2H_2 & \leftrightarrow CH_4 \\
C + CO_2 & \leftrightarrow 2CO \\
C + H_2O & \leftrightarrow CO + H_2
\end{align*}
\]

**Fig. 8**  Biomass and carbon conversions at 850°C as functions of time for different operating pressures.

**Fig. 9**  Biomass and carbon conversions at 30 bar as functions of time for different operating temperatures.
Three experiments were carried out in a bench-scale pressurised fluidised bed gasifier (D=8 cm, H=130 cm), operating at 5 bar and 800ºC [16,17,18]. The experimental time was divided into 2 phases, each of 120 minutes. During the first phase, about 1 kg of the willow wood, together with feeding gas/gasifying agent were fed into the gasifier, while in the second phase no biomass was fed any more. In order to improve the mass and heat transfer, the fluidised bed reactor was filled with approximately 5 kg of bed material (molochite), corresponding to a mean fluidised bed height of 90 cm. Willow wood with a particle size of 0.7-2.5 mm was used. As feeding gas/gasifying agent hydrogen, nitrogen, or carbon dioxide was applied, with purities above 99.99 vol%.

Comparing the pressurised fluidised bed gasification tests in H\textsubscript{2} and in N\textsubscript{2} (pyrolysis) atmosphere, the specific CO formation (m\textsuperscript{3}\textsubscript{STP}/kg\textsubscript{feed maf}) of H\textsubscript{2} gasification is 54% higher than in the case of pyrolysis with N\textsubscript{2}. This can be explained by the reversed shift reaction. This reaction results also in water formation, which can lead to steam gasification. On the other hand, the specific CH\textsubscript{4} formation is 75% higher in the case of H\textsubscript{2} gasification. Besides, the carbon content of the product gas related to the carbon content of the feedstock in the case of H\textsubscript{2} gasification is, with 70%, higher than in case of pyrolysis, with only 59%. This might be explained by a combined gasification of char with hydrogen and with steam, the latter produced during the reversed shift reaction, as mentioned above.

Regarding the PFB gasification of willow wood with CO\textsubscript{2}, the specific CO formation is 60% higher than in the case of H\textsubscript{2} gasification, and 146% higher than in the case of pyrolysis with N\textsubscript{2}. The carbon content of the product gas is with 94% the highest of all PFB test runs. These two points show clearly that the Boudouard reaction has taken place. A part of the CO formed has probably reacted with H\textsubscript{2}O through the shift reaction. With this reaction it can be explained that the specific H\textsubscript{2} formation in the case of CO\textsubscript{2} gasification is 25% higher than in the case of pyrolysis with N\textsubscript{2}.

In summary, the experimental programme has shown the feasibility of biomass hydrogasification as the most important step within the total process of SNG production by gasification of biomass in a hydrogen atmosphere, with respect to the following aspects:

Fig. 10 Weight losing curve of char (prepared from willow wood) at 800ºC, different atmospheres and pressures.
(1) Production of a gas, very rich in methane at the same process conditions (p,T), applied within the previous modelling work.

(2) Conversion of a sufficient amount of biomass to gaseous product, within a reasonable residence time of the biomass feedstock. The remaining char could be used within the process or to generate steam.

The investigation of the autothermal operation of the hydrogasifier requires a detailed examination of the process heat balance. Concerning the thermobalance and PFB tests, neither the input heat of the electric heating system, nor the heat losses, are known. However, based on the experimental results, it seems that the methanation reaction is a major heat source in the hydrogasifier, followed by other hydrogenation reactions.

The product gas in the thermobalance tests, as well as in the PFB tests is highly diluted with hydrogen. This is not desired in practice, due to the following reasons:

(1) In case of a diluted gas, hydrogen should partly be recirculated, resulting in higher costs and process complexity.

(2) Presence of too much hydrogen in the hydrogasifier might result in a process, which cannot be operated autothermally any more.

Therefore, this aspect has to be taken into account when designing a biomass hydrogasifier.

ECONOMIC ASPECTS

According to the Dutch energy policy, presented at the end of 1995 [19], the contribution of renewable energy to total energy consumption should increase from about 1% in 1995 to 10% (288 PJ in) in 2020. With a potential of 75 PJ (avoided fossil fuel use), biomass is, with a contribution of 26%, the most important renewable source to meet the 2020 goal [20].

In an attempt to investigate the potential of the biomass hydrogasification process for the Dutch energy supply in 2020, rough estimations have been made for the SNG production costs [21]. It is concluded, that the hydrogen price plays a dominant role in the SNG production costs, followed (to a much less extent) by the price of biomass. By utilisation of cheap hydrogen, the cost of SNG production would be of the same order as the price of standard natural gas [21]. In other words, the large-scale production of substitute natural gas by hydrogasification might be economically feasible, when in the future, large amounts of cheap electrolytic hydrogen would become available for the energy market. However, in some specific cases, the process might also be applicable in the present and short-term situation. This is especially the case, when hydrogen, or a hydrogen-rich gas, is available as by-product from industrial processes.

For the Netherlands, the hydrogasification process is also an interesting option to import renewable energy from parts of Europe where hydropower or solar energy, and biomass are available to a large extent as natural resources. Another option is to trade in (green) certificates, by converting biomass with hydrogen to SNG, at the location where biomass is produced. This is in accordance with the Kyoto agreements, concerning the recognition of the role of emission trading and other economic flexibility mechanisms.
FUTURE WORK

ECN has defined an RD&D programme for SNG production by biomass hydrogasification process, with the objective to prepare a future demonstration in the Netherlands. The first phase of this programme comprises an assessment of technical and economic prospects of the concept.

For final evaluation of this phase, it is important to integrate the experimental results within the developed ASPEN$\text{PLUS}$ model. Kinetic data obtained from the experiments should be translated into a practical reactor system, in which gasification will have to take place. As a result of exothermic reactions (in particular the methanation), taking place in the hydrogasifier, the gasification process has the potential to be operated autothermally. Modelling studies should show at which process conditions this might be possible. Also, from the modelling studies it should follow, whether the process can be operated in ‘once-through’ mode, or, due to dilution of the product gas from the gasifier, recirculation of hydrogen will be necessary.

Beside attention to the gasification section, also other system components have to be studied in more detail. Important system components are: feedstock pre-treatment (drying and sizing of biomass, compression of hydrogen stream), membrane separation of hydrogen (if necessary), gas clean-up, methanation, and the conditioning section, which is required to bring the product gas from the methanation step to the natural gas quality.

CONCLUSIONS

(1) Based on the thermodynamic and flowsheeting analysis, this work has shown the feasibility of SNG production by biomass hydrogasification. Addition of an external hydrogen stream to the hydrogasification reactor results in a final product gas with a quality comparable to that of standard Dutch natural gas. With a hydrogen content below 10 mol%, the produced SNG can be transported through the existing natural gas infrastructure without any adjustment. The energetic efficiency of SNG production from biomass and hydrogen by hydrogasification is calculated as 81% (LHV).

(2) The experimental programme has shown the feasibility of biomass hydrogasification as the most important step of the total process, with respect to the: a) production of a methane-rich gas, at the same process conditions (p,T), applied in the modelling work; b) conversion of a sufficient amount of biomass to a gaseous product, within a reasonable residence time of biomass feedstock.

(3) For final evaluation of the biomass hydrogasification concept (proof of principle), it is important to integrate the experimental results, within the developed ASPEN$\text{PLUS}$ model.

(4) Large-scale production of SNG by biomass hydrogasification might be economically feasible when, in the future, large amounts of cheap electrolytic hydrogen will become available for the energy market. However, in some specific cases the process might also be applicable in the present and short-term situation. This is especially the case, when hydrogen or hydrogen-rich gases are available as by-product from industrial processes. For the Netherlands, biomass hydrogasification may also be applied to import renewable energy, or to trade in (green) certificates.
ACKNOWLEDGEMENTS

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REFERENCES