Production costs for different green gas qualities based on large-scale gasification of biomass

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Abstract

In the last decades gasification has been regarded as a key technology for the large scale conversion of biomass into green gas (green SNG). By definition green gas is of pipeline gas quality but the current production of SNG contains typically substantial quantities of hydrogen and carbon monoxide. Both components are normally not present in natural gas and only recently limit ranges have been set in the Dutch pipeline gas specifications. In this paper an assessment of the current and potentially near future gas specifications in a Dutch context is presented, from this assessment different process configurations to achieve these specifications were derived and their implication on the production cost were evaluated.

The assessment and evaluation are based on a production unit with an output capacity of 100 MW SNG and injection into the Dutch 40 bar gas grid. This gas grid traditionally transports gas from the well-known Groningen field. The quality specifications (four in total) for the green SNG were based on the relevant developments for the next decade in the Dutch gas transmission grid as well as the current knowledge regarding the implication of the different components on primarily the safety of gas transport and end-users. The different process configurations were derived from the latest technology insights and information from research institutes. Stoichiometric and reaction kinetic modelling were used to determine the flows and reactor sizes with special attention to the methanation. With the methanation the level of hydrogen and carbon monoxide traces can be controlled. Finally the cost prices for four selected green gas qualities were evaluated using a discounted cash flow model (DCF model). The CAPEX and OPEX data in the DCF model were based on publically available literature although accurate figures on economics for this type of green gas production are limited.

The assessment makes clear that the current available technologies are capable to reach the required gas quality specifications. Further our analysis shows that the cost price (excluding the cost for biomass) for green gas production increases with 2,5% if the level of hydrogen decreases from 2 mole % to 0,07 mole % and the level of carbon monoxide decreases simultaneously from 4000 ppm to 200 ppm. Cost prices (excluding the cost for biomass) for green gasses ranges in this study from 0,67 – 0,69 €/m3. From our analysis it becomes clear that the cost price sensitivity towards the different gas product qualities can be judged as moderate and required gas specification can be met by green SNG producers.

Introduction

Green gas can play a significant role in achieving the climate targets of the Netherlands. The use of green gas is a generally accepted method to decrease greenhouse gas emissions by substituting natural gas from fossil origin. Gasification is one of the crucial technologies to convert dry-biomass into green gas (green SNG). It is expected that gasification can reach the required scale to produce significant amounts of green gas, but technical challenges in scaling up the technology still lay ahead. Another potential challenge is whether the technological chain can produce green gas that can meet the specification set by the stakeholders of the gas system. By definition green gas is of pipeline gas quality, but the produced green SNG may contain hydrogen and carbon monoxide. The composition of the green SNG to be injected in the natural gas system is a key quality parameter for its acceptance.

The requirements for the green gas injection are derived from the pipeline gas specifications as developed over the last decades. Hydrogen and carbon monoxide are normally not present in natural gas and only recently limit ranges have been set in the Dutch pipeline gas specifications (Ministry of Economic Affairs, 2014). Although these specifications are still developing to reflect the growing demand to inject gases from renewable sources, the current technology developers still might need to focus on the current status. To reach the required specifications additional technological steps are to be considered.

The present work assesses the current pipeline specifications and the anticipated developments. Based on the assessment a matrix of allowable components levels was derived. These levels also represent the green gas qualities to be produced. A detailed description of the total SNG process is given. The process configurations were derived from the latest technology insights and information from research institutes. From the process configurations a model is

made to calculate the mass- and energy balance based on process and conversion efficiencies. Further the economics are included to compare the economic performance of the different configurations. Goal was to analyze the impact of gas specifications on the production cost of green SNG.

Natural gas pipeline specifications

The Dutch gas system can be divided into two qualities. The first system is based on the natural gas quality coming from the Groningen field. This quality differs substantially from other qualities due to the relatively large amount of nitrogen. As for this reason a second system was developed for high calorific gas. For both systems specifications have been developed and are incorporated in the Dutch gas law. Recently these specifications have been update and cover amongst conditions for Wobbe index, oxygen, hydrogen sulfide, alkythiols, total sulphur, water, hydrocarbons and dust (Ministry of Economic Affairs, 2014). Components like hydrogen and carbon monoxide which are an important part of green SNG are also covered.

Table 1 Current Groningen gas specifications for pipeline specification and anticipated development for hydrogen and carbon monoxide (Ministry of Economic Affairs, 2014)

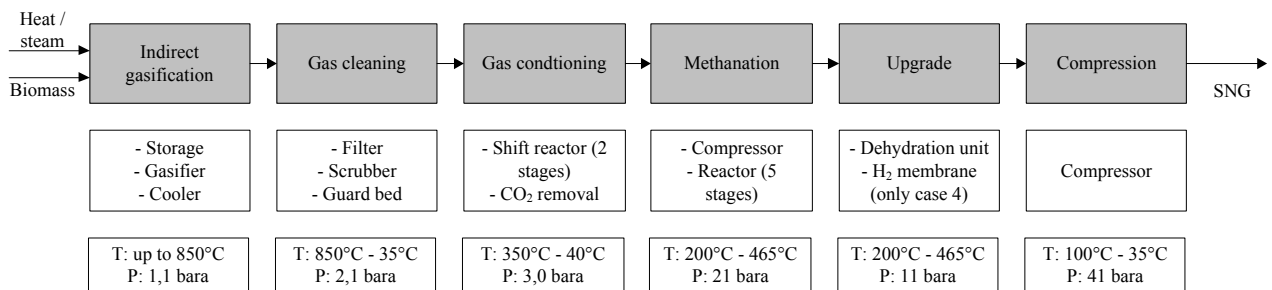| Component	Current specification	Anticipated development
Hydrogen	≤ 0,02 mol% (high pressure network) ≤ 0,1 mol% (distribution network)	Increase to < 0,5 mol%
Carbon monoxide	2.900 mg/m^3 (n)	No changes

Table 1 shows the current specifications for hydrogen and carbon monoxide as well as the anticipated developments after 2021. For hydrogen a further increase to < 0,5 mol% is foreseen due to the growing demand to inject gases from renewable sources. Allowing more hydrogen in

natural gas still needs more research to further determine the impact of hydrogen on gas appliances and transport systems. The limit range for carbon monoxide is based on the health risk for humans at a free outflow of gas. A further increase is not foreseen in the near future.

Production process

In the process of converting dry-biomass into green gas (green SNG) there are two major steps. The first step is the gasification of the dry-biomass which is an endothermic process where the main components like cellulose, hemi-cellulose and lignin are converted into simple molecules like hydrogen, carbon monoxide and carbon dioxide, but also hydrocarbons, tar and ash (Gassner & Maréchal, 2009). There are many different gasification technologies but for the production of green SNG the dual fluidized bed gasifier has received great attention. This type of gasifier has a separate gasification and combustion reactor/zone. The heat required for the gasification is not supplied by the flue gas but transferred from the combustion reactor/zone by a fluidizing agent. Additional heat may be supplied by steam. An important advantage is that the produced syngas is not diluted by flue gases. Some main developments in the last decades were done by (Corella, Toledo & Molina, 2007; Kirkels & Verbong 2011). After the gasification the produced syngas needs to be further cleaned and components like ash, tars and sulphur compounds have to be separated. The produced syngas may not have the right stoichiometry between hydrogen and carbon monoxide (3:1), to adjust for this a shift reactor is necessary. After the shift reactor the excess of CO_2 is separated. The second major step is the methanation which is an exothermic process. At methanation primarily hydrogen and carbon monoxide react to form methane and water. The water can be separated and the green SNG is finally compressed to the required pressure. Methanation was investigated in 1960s and 1970s for the conversion of coal

6

into synthetic natural gas, but only one commercial plant was build. Mostly fixed bed reactors are applied but also fluidized bed reactors are considered (Kopyscinski, Schildhauer, & Biollaz, 2010). Nowadays with the growing interest in green gases also methanation receives new and more attention. Major players delivering methanation processes are Haldor Topsoe and Johnson Matthey. An overview of the different process step and their main characteristics are given in Figure 1.

Heat / steam →	Indirect gasification	Gas cleaning	Gas condtioning	Methanation	Upgrade	Compression	→ SNG
Biomass →							
	- Storage - Gasifier - Cooler	- Filter - Scrubber - Guard bed	- Shift reactor (2 stages) - CO_2 removal	- Compressor - Reactor (5 stages)	- Dehydration unit - H_2 membrane (only case 4)	Compressor	
	T: up to 850°C P: 1,1 bara	T: 850°C - 35°C P: 2,1 bara	T: 350°C - 40°C P: 3,0 bara	T: 200°C - 465°C P: 21 bara	T: 200°C - 465°C P: 11 bara	T: 100°C - 35°C P: 41 bara	

Figure 1 Overview of the process chain

Cases

The methanation processes are not converting fully hydrogen and carbon monoxide. From the literature a wide range of residual amounts of hydrogen and carbon monoxide can be found (Gassner & Maréchal, 2009; Kopyscinski, Schildhauer, & Biollaz, 2010). Based on expert consultation with ECN is was agreed that the current technology should be able to produce SNG with a residual amounts of hydrogen of 2 mol% and carbon monoxide of 4.000 ppm without any additional measures. If these values are compared with the current specifications then additional measures are required. It is believed that the available technologies are capable of achieving the required levels but they have to be adapted. To investigate the impact four cases have been

modelled with the final goal to attain the required specifications as can be found in Table 1. Especially for hydrogen this proved to be challenging. To get below 0,5 mol% hydrogen optimizing of the methanation process is not enough and hydrogen membranes are required. Furthermore the Wobbe index is also still above the required level of 44,41 MJ/m3 but by adding carbon dioxide or nitrogen this can easily be adjusted. In Table 2 the final calculated values are presented.

Table 2 Four cases for calculated values for H_2 and CO

Case	H_2 [mol%]	CO [ppm]	CH$_4$ [mol%]	CH$_4$ [mol%]	Inerts [mol%]	Wobbe index [MJ/m^3]
1	2	4000	88,4	5,4	3,8	45,66
2	1	1000	88,9	6,2	3,7	45,25
3	0,6	200	89,3	7,1	3,0	44,42
4	0,07	200	89,8	7,1	3,0	44,67

Approach

The modelling was based on the "Cold Gas Efficiency" of the different process steps. The "Cold Gas efficiency" is the energy output divided by the energy input. The efficiency of the gasifier can for example be defined as follows:

$$\eta_{CGE} = \frac{M_{gas} \cdot Q_{gas}}{M_{biomassa} \cdot Q_{biomassa}}$$

$M = \text{kg/s}$

$Q = \text{kJ/kg}$

The processes with the lowest efficiency are the gasifier and the methanation. The overall process efficiency based on data from the literature (Gassner & Maréchal, 2009; Meijden, van

der, Veringa, Rabou, 2010) was estimated to be 57%. Also the main chemical compositions from the different gas streams were derived from the literature. With these compositions a mass balance could be modelled. The design production capacity is 100 MW based on the caloric value of the produced green SNG. This equals a production of approximately 80 mln m^3(n) natural gas per year. It was assumed that the biomass used for gasification is softwood, a dry and clean biomass. Furthermore the softwood entering the gate of the production plant is already debarked and pelletized.

Methanation

To investigate the impact of the required limit ranges for hydrogen and carbon monoxide the methanation was modelled based on the reaction-kinetics. As indicated before the main reaction is the conversion hydrogen and carbon monoxide into methane and water. Besides this reaction two other reactions play an essential role. The following three reactions are the main reactions for methanation and are the inverse of methane steam reforming (Xu & Froment, 1989):

$$3H_2 + CO \leftrightarrow CH_4 + H_2O$$

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

$$4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O$$
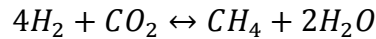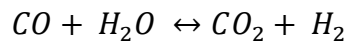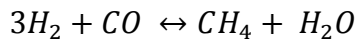
In their work to investigate the kinetics of methane steam reforming Xu and Froment (1989) found the following reaction kinetics for the three respective reactions.

$$r_1 = \frac{k_1}{P_{H_2}^{2,5}} \left(P_{H_2O} P_{CH_4} - \frac{P_{H_2}^{3} P_{CO}}{K_1} \right) /(DEN)^2$$

$$r_2 = \frac{k_2}{P_{H_2}} \left(P_{CO} P_{H_2O} - \frac{P_{H_2} P_{CO_2}}{K_2} \right) /(DEN)^2$$

$$r_3 = \frac{k_1}{P_{H_2}^{3,5}} \left(P_{CH_4} P_{H_2O}^2 - \frac{P_{H_2}^4 P_{CO_2}}{K_3} \right) /(DEN)^2$$

$$DEN = 1 + K_{CO}P_{CO} + K_{H_2}P_{H_2} + K_{CH_4}P_{CH_4} + K_{H_2O}P_{H_2O}/P_{H_2}$$

The values of the different constants are among other given in Elnashaie and Elshishini (1993). The overall reaction rate for the disappearance and formation of hydrogen can be obtained from:

$$r_{H_2} = r_1 + r_3 - r_2$$

Resulting in a rate kmol/(kg cat·hr). To be able to solve this equation a mass and energy balance was derived for a given conversion rate. Once the overall reaction rate is determined the amount of catalyst and size of the reactor can be determined which are important parameters for the investment cost in the methanation process. As discussed previously in four different steps the residual amount of hydrogen and carbon monoxide were lowered to finally reach the required levels as set the specification. The results are already given in Table 2.

Results cost price

Finally, the CAPEX and OPEX are calculated for the four cases. The CAPEX was obtained from the separate units' hardware costs and costs for installation. The hardware costs depend on the size of the units and if necessary the cost were estimated by the general scaling rules. The OPEX were derived from the separate units' size for energy, personnel and commodities or fix percentages from the investment cost for maintenance. Using the CAPEX and OPEX the production cost prices have been calculated with a discounted cash flow model. The results are presented in Figure 2.
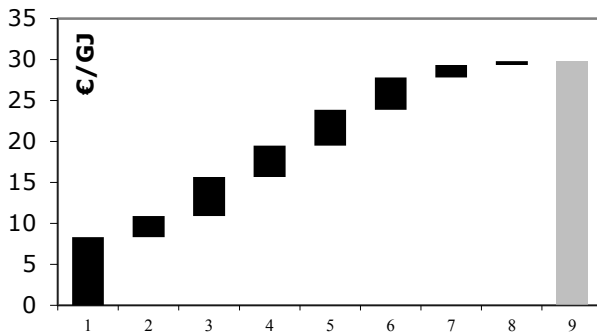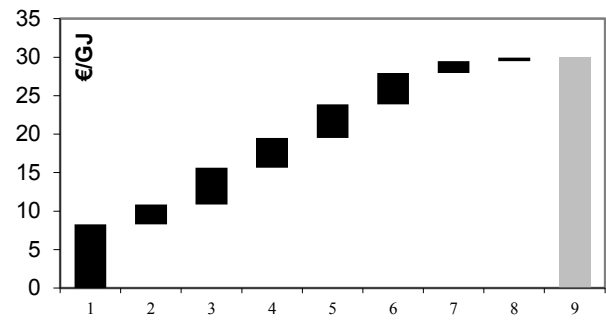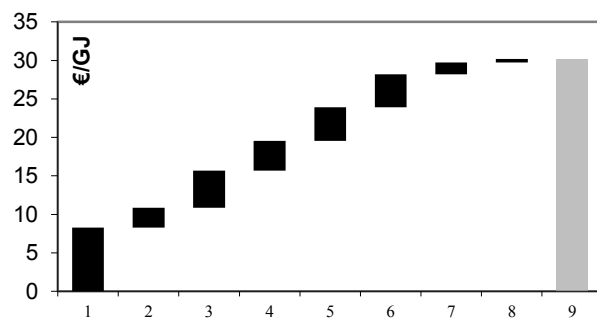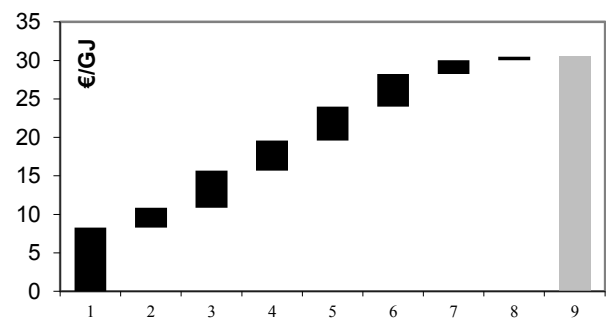
Figure 2 Results cost price production in €/GJ for four cases

The four cases are the same cases as in Table 1. The numbers on the x-axis correspond to the process steps as presented in Figure 1 and are 1) wood pellets, 2) pellet transportation, 3) gasification, 4) gas cleaning, 5) gas conditioning, 6) methanation, 7) upgrade, 8) compression and 9) total of all the previous steps. In all cases the wood pellet price and transportation of pellets was kept constant. As to be expected the cost methanation is increasing from case 1 till case 4, 3,98 €/GJ up to 4,26 €/GJ. The cost for upgrading increases substantially in case 4 due to the application of membranes to separate the final amount of hydrogen.

Conclusion

The analysis shows that the cost price (excluding the cost for biomass) for green gas production increases with 2,5% if the level of hydrogen decreases from 2 mole % to 0,07 mole % and the level of carbon monoxide decreases simultaneously from 4000 ppm to 200 ppm. Cost prices (excluding the cost for biomass) for green gasses ranges in this study from 0,67 – 0,69 €/m3. From our analysis it becomes clear that the cost price sensitivity towards the different gas product qualities can be judged as moderate and required gas specification can be met by green SNG producers. The assessment makes clear that the current available technologies are capable to reach the required gas quality specifications.

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