

PROCESS EFFICIENCY OF SMALL SCALE SNG PRODUCTION FROM BIOMASS

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ABSTRACT: Biomass can be converted to synthetic natural gas (SNG) by thermochemical gasification and a subsequent methanation. For a multi megawatt process the conversion efficiency of biomass to SNG is up to 74 % based on the LHV [1]. However, a big plant size is connected to a high biomass transportation volume and other local environmental impacts. Using small distributed SNG production units would minimize these negative aspects. However, it is expected that a decrease in plant size results in lower efficiency. An overall process is simulated with the software package AspenPlus based on a thermal biomass input of 500 kW. The gasification is based on the Biomass Heatpipe-Reformer[®] of the Technische Universität München.

As an outcome of the simulation the conversion, net and overall efficiency is calculated. The base case simulation using conservative parameters results in a net efficiency (conversion efficiency) of 65.2 % (67.3 %). As a by-product heat is released from the process in the range of 140 kW. A complete usage of the heat released results in an overall efficiency of 90.4 %. The influence of single process parameters is evaluated and optimized. By using ambitious process parameters the net efficiency can be increased by 4.6 percent points.

Keywords: allothermal gasification, synthetic natural gas (SNG), biomass, modelling, small scale application

1 INTRODUCTION

Using biomass for energy recovery is an option to lower the dependency on fossil fuels like natural gas and to reduce CO₂ emissions. Today the electrical grid is used for the distribution of bioenergy. Biomass is converted to electricity in multi megawatt power plants with electrical efficiencies up to 30%. In order to achieve an optimum biomass use, the production of heat within the process is essential. This requires an appropriate heat consumer (industry, heat grid). Due to the limited heat consumer that are capable of using heat in the megawatt range also the locations for a biomass power plant are limited. On the other hand a downscaling to the particular needs of the heat consumer reduces the efficiency and increases specific investment costs.

An alternative solution for the distribution of bioenergy is the usage of the natural gas grid. Biomass can be converted to synthetic natural gas (SNG) via a thermochemical gasification and a subsequent methanation process. After gas conditioning the SNG can be fed to the existing natural gas grid. The conversion efficiency of such a process is up to 74 % based on the Lower Heating Value (LHV) for multi megawatt process [1]. Bioenergy in the form of SNG can be stored using the full developed natural gas storage technique. The gas grid itself can compensate small fluctuations between SNG production and utilization and SNG can be stored in existing natural gas storage facilities. SNG production offers several possibilities for further utilization and enlarges the application spectrum for biomass. It can be used for electricity production, heat production, as a transportation fuel and for domestic heating and cooking systems.

The target plant size of centralized SNG production is 10 to 100 MWth [1, 2, 3, 4] that is connected to a high biomass transportation volume and other environmental impacts that complicate the selection of a appropriate plant location. In contrast the SNG production in small distributed systems is a way to minimize the local

environmental impacts. A small scale process can be based on an indirect gasification via the Biomass Heatpipe-Reformer[®] (BioHPR[®]) [5, 6]. The first commercial facility of this kind with a thermal input of 500 kW is installed near Munich.

The objective of the work presented here is the process simulation of the SNG production based on the BioHPR[®]. The process is simulated using the AspenPlus software, a commercial available software package that is used for numerous chemical processes. However, simulations done on biomass gasification are limited (e.g. [7, 8, 9]). Only one simulation is known to the authors that couples biomass gasification with methanation, however for a large scale process [10].

The simulation presented here is based on experimental gasification data. The influence of process parameters on the process efficiency is evaluated and achievable net and overall efficiencies are presented. For an overall SNG system evaluation it is assumed that the SNG is transported to a small scale combined heat and power generation system (CHP). Due to the storage capacity of the natural gas grid the CHP power load can be adapted to the present heat demand.

2 PROCESS DESCRIPTION

The overall process consists of four process steps that are shown in Figure 1.

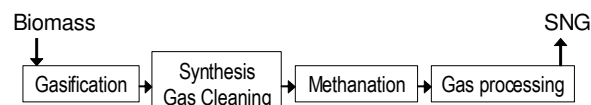


Figure 1: Process steps from biomass to SNG

2.1 Gasification

In the first step biomass is converted to synthesis gas in an allothermal gasifier. In the work presented here the

Biomass Heatpipe-Reformer[®] (BioHPR[®]) is used for the gasification step. The system consists of two fluidized beds, combustor and reformer, that are interconnected via heatpipes. In the lower bed biomass is burned with air in an exothermic reaction. The heat released in the combustor is transported via heatpipes to the reformer. This second bed is fluidized by steam and biomass is converted to synthesis gas in endothermic gasification reactions. The reformer can be operated at increased pressure. Char that is produced in the gasification zone can be fed to the combustor. For further information about the BioHPR[®] please see [5]. The BioHPR[®] can be replaced by any other allothermal steam biomass gasifier that is designed for a small scale process.

2.2 Synthesis Gas Cleaning

Synthesis gas cleaning is essential for the process since the methanation catalyst is sensitive to poisoning. Gaseous halides and sulphur components result in a deactivation of the catalyst and therefore have to be removed after the gasification reactor. For small scale processes a suitable gas cleaning process is dry adsorption in fixed beds. Halides are removed with $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$ at an operation temperature around 400°C [11]. Sulphur removal can be done with a ZnO fixed bed at around 400°C and has the potential to decrease sulphur concentration below the limit for methanation [12](i.e. 1 ppm [13]). For tar removal there are several options (e.g. water or organic scrubbers, catalytic reforming). However, it is possible that tar removal is not required for the SNG process. If the synthesis gas temperature never falls below the tar condensation temperature before the entering the methanation reactor tars can be converted at the methanation catalyst. Recent investigations demonstrated the ability to simultaneously reform light tars as the water gas shift reaction and the methanation reactions take place in a fluidized bed reactor [14]. However, carbon formation reducing the performance of the catalyst is possible and there is the need for further research in that field.

2.3 Methanation

The methanation of synthesis gas from coal gasification is a well developed process. A lot of research was performed in the United States in the early 1970s due to oil shortcomings. In the 1980s most of the research was stopped due to the low oil prices, but a 900 MW SNG-plant was constructed in North Dakota in 1984 and is still in operation [15]. The principal reactions within the methanation process are shown in Table 1 [16].

Table 1: Principle reactions within the methanation process

		$\Delta H_{R(300^\circ\text{C})}$ [kJ/mol]
$\text{CO} + 3 \text{H}_2$	$= \text{CH}_4 + \text{H}_2\text{O}$	(1) -217.1
$\text{CO} + \text{H}_2\text{O}$	$= \text{H}_2 + \text{CO}_2$	(2) -39.2
$\text{CO}_2 + 4 \text{H}_2$	$= \text{CH}_4 + 2 \text{H}_2\text{O}$	(3) -177.9
2CO	$= \text{C} + \text{CO}_2$	(4) -173.6
$2 \text{H}_2 + \text{C}$	$= \text{CH}_4$	(5) -82.7

The enthalpies of reactions were calculated with FactSage software package [17] at 300°C, a typical methanation temperature.

For operation of the methanation process it is essential to avoid both reaction (4) and the reverse of reaction (5)

since carbon formation would deactivate the catalyst. In the methanation reactor carbon formation is mainly dependent on the Steam-to-Biomass-Ratio SB and the temperature. SB is the mass flow of water related to dry ash-free biomass within the system. If the water content of the synthesis gas from the gasification is too low steam has to be added before the methanation process.

All methanation reactions are exothermic. Hence a cooling of the reaction zone is necessary. The combination of fluidized bed and heatpipes that was developed for the BioHPR[®] can be adapted to the methanation reactor. The methanation catalyst is used as bed material. That enables a homogeneous temperature distribution within the reactor and prevents the occurrence of hot spots during exothermic reaction. The heatpipes that remove heat from the reaction zone can be operated with water as the working fluid. The heatpipes are back cooled in a pressurized boiler at e.g. 1.0 MPa and 180°C. With that system the reaction heat of the methanation is used to produce pressurized steam.

As the number of molecules decreases during methanation the chemical equilibrium shifts towards methane at higher pressure. The reformer of the BioHPR[®] is operated at increased pressure. Hence, it is possible to operate the methanation reactor at increased pressure without an additional compression.

2.4 SNG Processing

After methanation the raw SNG consists mainly of methane, steam and CO_2 . Before feeding to the natural gas grid a gas processing is required to remove H_2O and CO_2 . For the removal of H_2O a combination of a condensation at ambient temperature and an adsorption process seems to be economically reasonable. For CO_2 removal a small scale process can be equipped with a Pressure Swing Adsorption (PSA) that is operated at approximately 0.8 MPa [18]. Finally SNG is compressed to grid pressure and fed to the natural gas grid.

3 PROCESS SIMULATION

All process steps were simulated using the AspenPlus software, a modelling tool performing material and energy balance calculations. User defined subroutines can be implemented into the simulation by using FORTRAN codes.

In the simulation the principle of the Biomass Heatpipe-Reformer[®] (BioHPR[®]) is selected for the gasification step. The BioHPR[®] can be replaced by any other biomass steam gasifier that is designed for a small scale process (< 1 MW).

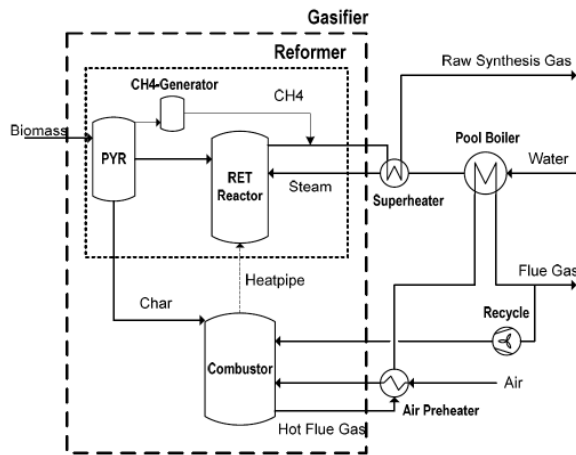


Figure 2: Simulation Process Flow Sheet of the gasification

Table 2: Composition of spruce wood

Element	C	H	O	N	S	Cl	Ash
Mass.-% (mf)	49.8	6.3	43.2	0.13	0.015	0.005	0.55

Spruce wood (composition see Table 2, higher heating value 20.2 MJ/kg, moisture 25 %) is selected as representative biomass. Figure 2 shows the simulated process flow sheet for the gasification. The reformer of the BioHPR[®] is simulated by three Aspen blocks (PYR, RET Reactor and CH₄-Generator). The pyrolysis is simulated by an Aspen RYield block (PYR) that decomposes the feed into its simple components carbon, hydrogen, oxygen, nitrogen, sulphur, chlorine and ash according to the wood ultimate analysis. Ash and partly carbon leaves the pyrolysis block and enters the combustor. The main feed stream and steam as gasification medium is fed to an Aspen RGibbs reactor (RET Reactor). The endothermic gasification reactions are simulated by a restricted equilibrium temperature approach. Chemical equilibrium is assumed for the composition of the synthesis gas, but at a temperature that differs from the real gas temperature. By fitting simulated synthesis gas compositions to experimental data from a 150 kW facility ([5]) by a variation of the restricted equilibrium temperature (RET) a linear dependency between RET and the Steam-to-Biomass-Ratio SB is determined (see Figure 3).

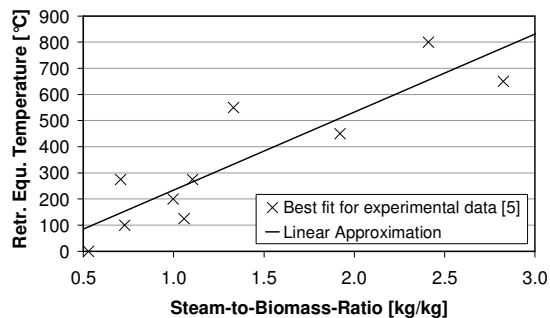


Figure 3: Restricted Equilibrium Temperature (RET) fitted to experimental data

In the simulations SBs between 0.5 and 1.0 are used

which results in restricted equilibrium temperature (RET) around 100°C to 250°C. However, using positive RETs leads to chemical equilibrium compositions at high temperatures and consequently to an underestimation of CH₄ in the synthesis gas. That is compensated by producing methane in an external RYield block (CH₄-Generator) from C and H that was separated after the pyrolysis block (PYR) and mixing the methane to the raw synthesis gas after the gasification block (see Figure 3). The amount of methane in the raw synthesis is adjusted to experimental gas measurements and is in the range of 9 to 11 Mol.-% in dry synthesis gas. Simulated dry synthesis gas compositions compared to the experimental gas composition of two data sets with SB = 0.53 and SB = 0.73 from [5] are shown in Table 3.

Table 3: Simulated dry synthesis gas compositions compared to experimental data

gas components [Mol.-%]	data set 1 (SB = 0.53)		data set 2 (SB = 0.73)	
	experiment	simulation (RET = 94°C)	experiment	simulation (RET = 154°C)
H ₂	39.8	39.7	40.8	40.7
CO	23.5	27.2	23.5	24.2
CO ₂	19.4	15.5	20.4	17.4
CH ₄	10.2	10.1	9.2	9.7
N ₂	7.1	7.4	7.1	8.0

Heat that is required for the endothermic gasification reactions in the RET Reactor is produced by burning char in the combustor (Aspen RGibbs block) and transported via heatpipes between the two blocks. For the supply of the required heat amount about 80 % of the biomass total char have to be fed to the combustor. Saturated steam for the indirect gasification is produced by cooling the flue gas from the combustor. The steam is superheated by cooling raw synthesis gas. For better heat integration and variability of heat released via heatpipes and in the pool boiler the systems is equipped with an air preheater and a flue gas recycle.

The process flow sheet of gas cleaning, methanation and gas processing used for the simulation is shown in Figure 4. The gas cleaning is modelled by separation reactors that remove any chlorine and sulphur components. A removal of tars is not implemented since there is the possibility that tars are converted at the methanation catalyst. The methanation is performed in a fluidized bed reactor that is internal cooled by heatpipes. Due to the catalytic reaction chemical equilibrium is assumed at the exit of the methanation reactor. The heat of methanation is transported to a pressurized pool boiler and steam is generated. That steam is partly mixed to the entrance of the methanation reactor to prevent carbon formation. Excess steam is superheated by raw synthesis gas and can be used for industrial processes or heating purposes. Raw SNG leaving the methanation reactor is cooled to 60°C in order to produce hot water for heat production. After removing the condensate the gas is further cooled to 5°C. Pressure Swing Adsorption (PSA) at 0.8 MPa is modelled for the upgrading of the SNG to grid quality.

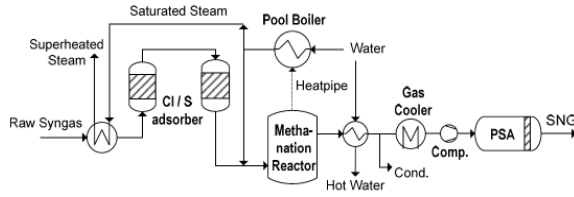


Figure 4: Simulation process flow sheet of synthesis gas cleaning, methanation and gas processing

For the evaluation of the efficiency of the system the simulation is run with base case parameters from Table 4. The values represent state of the art values that result from operation experience of the gasifiers (150 kW and 500 kW facilities) and manufacturer information.

Table 4: Process parameters for the base case simulation

Parameter	base case value
thermal biomass input	500 kW
<i>Temperatures:</i>	
reformer outlet	700°C
combustor outlet	900°C
flue gas exit	130°C
synthesis gas cleaning	400°C
methanation	270°C
<i>Heat losses:</i>	
reformer	7 kW
combustor	3 kW
methanation reactor	3 kW
<i>Pressures:</i>	
reformer	0.4 MPa
combustor	0.1 MPa
methanation water boiler	1.0 MPa
pressure swing adsorption	0.8 MPa
<i>Pressure drops:</i>	
fluidized beds	0.02 MPa
synthesis gas cleaning	0.02 MPa
heat exchangers	0.005 MPa
air to fuel ratio (lambda at combustor)	1.2
steam-to-biomass ratio (reformer)	0.7
<i>Pressure swing adsorption (PSA):</i>	
CO ₂ removal efficiency	96 %
methane loss	2 %
<i>Pump efficiencies:</i>	
isentropic	0.6
mechanical/electrical	0.9
<i>Compressor efficiencies:</i>	
isentropic	0.6
mechanical/electrical	0.9

4 EFFICIENCY DEFINITION

The efficiency of the SNG process is evaluated on basis of the conversion efficiency, the net efficiency and the overall efficiency. The definitions are as follows.

The conversion efficiency relates the chemical enthalpy of the SNG to the thermal biomass input on a LHV basis. As there are no electrical consumption and by-products

taken into account the conversion efficiency is inappropriate for the comparison to other processes.

$$\eta_C = \frac{\dot{m}_{\text{SNG}} \cdot \text{LHV}_{\text{SNG}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

The net efficiency incorporates furthermore the electrical own consumption of the process and is therefore a measure if SNG is the only product.

$$\eta_{\text{net}} = \frac{\dot{m}_{\text{SNG}} \cdot \text{LHV}_{\text{SNG}} - P_{\text{own, SNG}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

In the overall efficiency heat that is produced in different steps of the process and can be used in an industrial process or heat grid is added as a product. For the calculation of the heat produced, \dot{Q}_{SNG} , only the heat from cooling the raw SNG to 60°C and steam produced by cooling the methanation reactor is taken into account. A heat loss of 10 % during transfer to the heat consumer is assumed.

$$\eta_{\text{overall, SNG}} = \frac{\dot{m}_{\text{SNG}} \cdot \text{LHV}_{\text{SNG}} + \dot{Q}_{\text{SNG}} - P_{\text{own, SNG}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

SNG can be seen as an intermediate product of the biomass process chain. To evaluate the system efficiency from biomass to the end product it is assumed that SNG is converted to electricity $P_{\text{el, CHP}}$ and heat \dot{Q}_{CHP} in a combined heat and power generation system (CHP). In that case the electrical efficiency is defined as

$$\eta_{\text{el, CHP}} = \frac{P_{\text{el, CHP}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

and the biomass to heat and power overall efficiency

$$\eta_{\text{overall, CHP}} = \frac{\dot{Q}_{\text{SNG}} + \dot{Q}_{\text{CHP}} + P_{\text{el, CHP}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

5 RESULTS

For the base case the net efficiency η_{net} is calculated to be 65.2 %. The heat produced, \dot{Q}_{SNG} , is 114 kW. That results in an overall efficiency $\eta_{\text{overall, SNG}}$ of 90.4 %.

The composition of the SNG produced is shown in Table 5. The gas consists of methane, hydrogen and carbon dioxide. A small amount of nitrogen comes from the feeding system of biomass to the gasifier. It can be reduced if carbon dioxide from the SNG processing system is used as biomass carrier gas. Sulphur and chlorine compounds are not present in the SNG since these are removed prior to methanation.

The Wobbe Index evaluates the applicability of fuel gases. Gases with the same index cause the identical heat load of a burner. The Wobbe Index of the SNG produced in the small scale process is 46.4 MJ/m³. For the injection into the German natural gas grid the Wobbe Index has to be in the range 46.1 MJ/m³ to 56.4 MJ/m³ and hydrogen and carbon dioxide concentrations are limited to

maximum 5 Vol.-% and 6 Vol.-%, respectively [19]. The SNG produced in this small scale process meets the requirements for injection into the natural gas grid.

Table 5: Composition of SNG derived from the process simulation

Component	Vol.-%
CH ₄	88.6
H ₂	4.9
CO ₂	3.0
N ₂	3.5

6 SENSITIVITY ANALYSES

In order to evaluate the influence of single process parameters a sensibility analysis is performed. The simulation is run with a variation of each one parameter in the range -50 % to 50 % from the base case parameter value. The influence on the net efficiency of the SNG process is shown in Figure 5. The values in brackets behind each parameter denote the base case value. The lines intersect at the net efficiency of the base case (65.2 %). A variation of Steam-to-Biomass ratio, flue gas exit temperature and lambda over the full range is not reasonable due to process limitation.

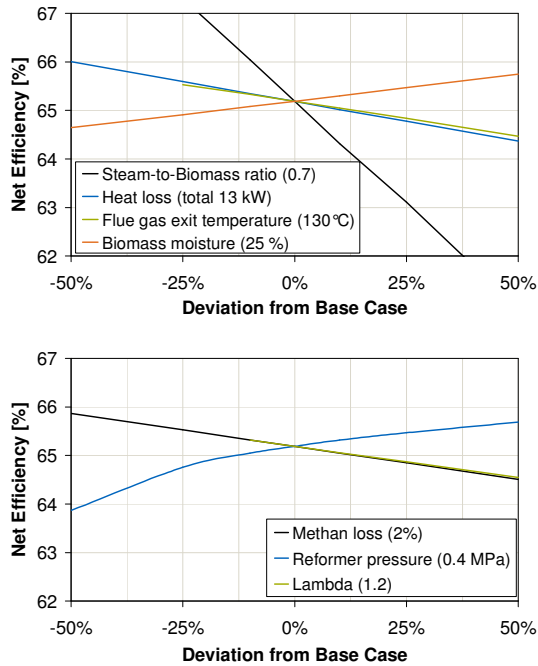


Figure 5: Influence of process parameters on the net efficiency η_{net} (sensitivity analysis)

The Steam-to-Biomass-Ratio of the reformer has the largest influence on the net efficiency. If more steam is fed to the reformer a bigger amount of char has to be fed to the combustor in order to produce heat for steam generation. A smaller carbon content of the synthesis gas lowers the amount of SNG produced. The increasing net efficiency with increasing biomass moisture content is caused by the fact that the efficiency calculation is based on the LHV of biomass.

The results of sensitivity analysis for the overall efficiency are shown in Figure 6.

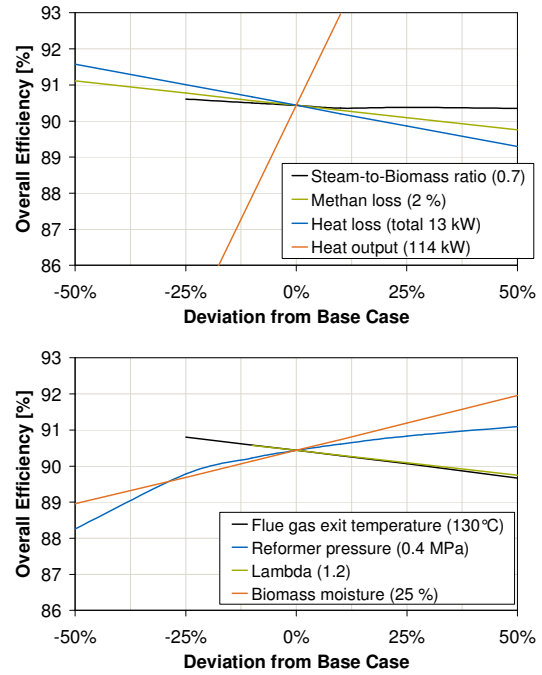


Figure 6: Influence of process parameters on the overall efficiency $\eta_{overall, SNG}$ (sensitivity analysis)

The heat output (heat transferred to an external heat grid or industry) is an important parameter for the overall efficiency. Only small variations of this parameter can strongly influence the overall efficiency. The Steam-to-Biomass-Ratio has a smaller influence on the overall efficiency than on the net efficiency since steam is condensed from the raw SNG and adds to the heat output.

7 PROCESS OPTIMIZATION

A process optimization was performed on basis of the sensitivity analysis. The optimized parameters are summarized in Table 6. The optimized simulation results in a net efficiency η_{net} of 69.8 % and an overall efficiency $\eta_{overall, SNG}$ of 96.2 %. These values show the potential of a small scale SNG production from biomass.

Table 6: Optimized Parameters for the process simulation

Parameter	Optimized value
Steam-to-Biomass ratio	0.53
methane loss	1 %
total heat loss	6,5 kW
flue gas exit temperature	110°C
reformer pressure	0.6 MPa
lambda	1.08

8 OVERALL SNG SYSTEM EVALUATION

For the overall SNG system evaluation it is assumed that the SNG is injected into the natural gas grid and consumed by a combined heat and power generation

system. Due to the storage capacity of the natural gas grid the power load of the CHP system can be adapted to the present heat demand. With this operation mode 5250 full load hours per year for the CHP system can be achieved [20]. Assuming 8000 full load hours per year for the SNG production the consumption of a standard gas engine (electrical load 190 kW, electrical efficiency 36 %, thermal efficiency 54 % [20]) is equal to the amount of SNG produced. Natural gas grid losses are assumed to be 1.5 %. This configuration results in an electrical SNG efficiency (biomass to electricity) $\eta_{el, CHP}$ of 23.1 % for the base case and 24.7 % for the optimized case. The overall SNG efficiency (biomass to heat and electricity) $\eta_{overall, CHP}$ is 80.0 % for the base case and 83.0 % for the optimized case. The CHP parameters are not changed for the optimized case.

9 SUMMARY AND CONCLUSION

Biomass can be converted to synthetic natural gas (SNG) by a thermochemical gasification and a subsequent methanation process and distributed in the existing natural gas grid. In order to minimize transportation efforts and other environmental impacts connected to large scale plants a small scale process was developed for the production of SNG. The gasification is based on the allothermal Biomass Heatpipe-Reformer[®] (BioHPR[®]). All process steps are simulated with the software package AspenPlus. Using technical reasonable parameters a base case simulation is developed. The conversion, net and overall efficiency are summarized in Figure 7. The influence of important process parameters is evaluated by a sensitivity analysis that results in optimized input parameters. The efficiencies are improved by about 3.5 percent points (see Figure 7).

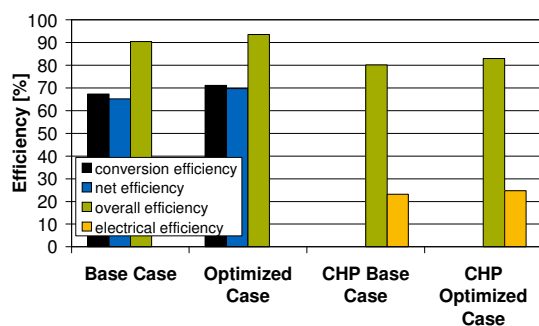


Figure 7: Summary of efficiencies for the production of SNG from biomass (Base Case and Optimized Case) and for the subsequent combined heat and power production from SNG based on the primary biomass input (CHP Base Case and CHP Optimized Case)

Since SNG can be seen as an intermediate product from biomass an additional process step is required to evaluate the efficiency of the biomass application. It is assumed that SNG is transported by the natural gas grid and consumed by a combined heat and power generation system. The engine power of the CHP system is adapted to the annual production of SNG in the small scale process. The overall biomass to CHP efficiencies are presented in Figure 7. For the CHP optimized case the electrical efficiency is 24.7 % and the overall efficiency is 83.0 %. Both values are in the range of efficiencies for

state of the art biomass multi megawatt power plants. Hence, the small scale production of SNG achieves high efficiencies, benefits from the small scale application and enlarges the application spectrum of biomass.

10 REFERENCES

- [1] S. Rönsch, M. Dreher, A. Vogel, and M. Kaltschmitt, "Synthetic Natural Gas from Solid Biofuels - A Technical Analysis," *VGB Powertech*, vol. 5, pp. 110–116, 2008.
- [2] M. Seiffert, F. Müller-Langer, and M. Kaltschmitt, "Demonstration of the production and utilization of Synthetic Natural Gas (SNG) from solid biofuels - Presentation of the European project "Bio-SNG"," in *16th European Biomass Conference & Exhibition, Valencia*, 2008.
- [3] H. Hofbauer, R. Rauch, S. Fürsinn, and C. Aichernig, "Energiezentrale Güssing," Technische Universität Wien, Report, 2005.
- [4] M. Mozaffarian and R. Zwart, "Feasibility of biomass/waste-related SNG production technologies," ECN, Tech. Rep., 2003.
- [5] T. Metz, "Allotherme Vergasung von Biomasse in indirekt beheizten Wirbelschichten," Ph.D. dissertation, TU München, 2007.
- [6] J. Karl, "Distributed generation of Substitute Natural Gas from biomass," in *16th European Biomass Conference & Exhibition, Valencia*, 2008.
- [7] M. B. Nikoo and N. Mahinpey, "Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS," *Biomass and Bioenergy*, vol. 32, no. 12, pp. 1245 – 1254, 2008.
- [8] K. Panopoulos, L. Fryda, J. Karl, S. Poulou, and E. Kakaras, "High temperature solid oxide fuel cell integrated with novel allothermal biomass gasification: Part I: Modelling and feasibility study," *Journal of Power Sources*, vol. 159, no. 1, pp. 570 – 585, 2006.
- [9] L. Shen, Y. Gao, and J. Xiao, "Simulation of hydrogen production from biomass gasification in interconnected fluidized beds," *Biomass and Bioenergy*, vol. 32, no. 2, pp. 120–127, FEB 2008.
- [10] M. Jurascik, A. Sues, and K. J. Ptasinski, "Optimization of biomass to-Synthetic Natural Gas conversion technology based on exergy analysis," in *16th European Biomass Conference & Exhibition, Valencia*, 2008.
- [11] R. Newby, T. Lippert, R. Slimane, O. Akpolat, K. Pandya, F. Lau, J. Abbasian, B. Williams, and D. Leppin, "Novel Gas Cleaning/Conditioning for Integrated Gasification Combined Cycle," National Energy Technology Lab, Report, 2001.
- [12] S. van Paasen, M. Cieplik, and N. Phokawat, "Gasification of Non-woody Biomass," ECN and TU Delft, Report, 2006.

- [13] S. Fürnsinn and H. Hofbauer, "Synthetische Kraftstoffe aus Biomasse: Technik, Entwicklungen, Perspektiven," *Chemie Ingenieur Technik*, vol. 79 No.5, pp. 579–590, 2007.
- [14] M. Seemann, T. Schildhauer, S. Biollaz, S. Stucki, and A. Wokaun, "The regenerative effect of catalyst fluidization under methanation conditions," *Applied Catalysis A: General*, vol. 313, no. 1, pp. 14 – 21, 2006.
- [15] Dakota Gasification Company. Great Plains. 23.12.2008. [Online]. Available: www.dakotagas.com
- [16] L. Seglin, *Methanation of Synthesis Gas*, Advances in Chemistry Series ed., L. Seglin, Ed. American Chemical Society, 1975, vol. 146.
- [17] FactSage, *Version 5.5*, Thermfact and GTT-Technologies Std., 2008, Thermfact and GTT-Technologies.
- [18] S. Ramesohl, M. Kaltschmitt, W. Althaus, and F. Burmeister, "Analyse und Bewertung der Nutzungsmöglichkeiten von Biomasse," Fraunhofer Institut Umsicht, Report Band 3: Biomassevergasung, Technologien und Kosten der Gasaufbereitung und Potenziale der Biogaseinspeisung in Deutschland, 2005.
- [19] DVGW, *Technische Regel Arbeitsblatt G 262 - Nutzung von Gasen aus regenerativen Quellen in der öffentlichen Gasversorgung*, DVGW Std., November 2004.
- [20] W. Urban, K. Girod, and H. Lohmann, "Technologien und Kosten der Biogasaufbereitung und Einspeisung in das Erdgasnetz," Fraunhofer UMSICHT, Report, 2008.