The potential of small scale SNG production from biomass gasification

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Abstract

Synthetic natural gas (SNG) can be produced from biomass by thermochemical gasification and subsequent synthesis gas methanation and gas processing. For an industrial scale process with high efficiency (up to 74% [1]), the big plant size is connected to a number of disadvantages such as a high biomass transportation volume and local environmental impacts. Small distributed SNG production units would minimize these negative aspects but are expected to cause a lower efficiency.

In order to show the potential of a small scale SNG solution, different process chain configurations are simulated using AspenPlus software. Combined heat and power (CHP) generation via gasification and direct product gas conversion in a gas engine is compared to a SNG route. Different gasification technologies (co-current fixed bed, counter-current fixed bed, and dual fluidized bed) are evaluated. The SNG route is based on a dual fluidized bed gasification, subsequent methanation and injection to the natural gas grid.

As an outcome of the simulations, the efficiencies are calculated with special focus on heat integration and utilization. A maximized utilization of the released process heat results in strong overall efficiency increase. Depending on the local heat utilization, gasification with subsequent methanation has an advantage compared to direct local power generation. Overall efficiency of the SNG option is found to be up to 73.9 % which is in the range of the fluidized bed gasification option. The crucial factor for high efficiency and thus for an economic operation, is the heat demand at the location. With only small constant heat demand, the SNG solution becomes very competitive as some of the - otherwise on-site generated - heat is translated into chemical energy and carried to a power generation location elsewhere.

It is shown, that the SNG production subsequent of a small scale fluidized bed gasifier can very well be efficient in both energetic and economic regards. Most important and crucial parameter is the heat utilization on-site and thus the local heat demand characteristics.

1. Introduction

The urgent demand for greenhouse gas reduction and safe, reliable as well as sustainable energy supply in general promotes renewable energy technologies. In this context, the utilization of biomass for heat and power generation is an option which not only lowers the dependency on fossil fuels but also reduces CO_2 emissions.

Especially the production of synthetic natural gas (SNG) from biomass is a promising option for a future renewable energy production. So far, the electrical grid is used for the distribution of energy. By using the existing natural gas grid, energy from biomass can be stored and distributed in a very efficient way. The production of electricity is independent from direct utilization of biomass and can be adapted to the present power demand. Therefore, SNG is considered as a perfect complement to balance fluctuating electricity production from other renewable sources like solar or wind. Furthermore, the SNG route resolves some of the problems often caused by direct biomass utilization like the localized heat generation and its energy recovery.

While fixed and fluidized bed gasification and combustion became state-of-the-art technology for biomass applications in small and medium scale facilities, the technology of SNG production is still in its research stage [2]. Over the last years, various fixed bed and fluidized bed gasifiers have been coupled to gas engines or gas turbines for direct combined heat and power generation.

The SNG process is also based on the gasification technology and therefore a viable alternative.

2. Concept and methodology

In order to show the potential of small scale SNG production (10 $MW_{th,fuel}$) from biomass, four different process configurations based on biomass gasification are simulated. Process chains are developed for three gasifier types (co-current and counter current fixed bed as well as fluidized bed) and subsequently transformed into simulation models with the simulation software AspenPlus.
Table 1 shows an overview of considered process chain configurations.

Table 1: Process options

	Technology	Application
A	Fixed bed (co-current)	CHP (gas engine)
B	Fixed bed (counter current)	CHP (gas engine)
C	Dual fluidized bed	CHP (gas engine)
D	Dual fluidized bed	SNG (methanation) + subsequent CHP
E	Dual fluidized bed	SNG (methanation) + combined cycle

Power generation is modeled by applying a gas engine in options A-D. In option E SNG is fed to the natural gas grid and converted to electricity in a large combined-cycle plant (co-firing).
The SNG production is mounted downstream of a fluidized bed gasifier with subsequent synthesis gas cleaning, methanation and gas processing as shown in Figure 1.

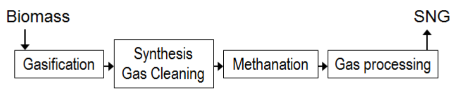

Figure 1: Process steps for SNG production [3]

A broad consensus in literature and industry suggests the allothermal fluidized bed configuration as the most promising gasification option for further SNG production [1, 4-6].
Process parameters for the simulation are validated by literature and show good agreement with reported data from suppliers. Process options are compared by means of energy efficiency and electricity production costs.

3. Process simulation

The simulation software AspenPlus performs material and energy balance calculations. User defined subroutines can be implemented by FORTRAN and Excel based codes.
Gasifiers are designed for a thermal fuel input of 10 MW. This translates to a wet biomass feed (beech wood) of 0.75 kg/s with a lower heating value of 13226 kJ/kg. The outlet product gas stream (synthesis gas) is fixed at 30°C and 5 bar favoring the utilization in a subsequent gas engine and ensuring comparability among each other.
Heat loses are considered for both gasifiers, determined through heat transfer calculation based on reactor volumes and pressure levels for each process and for any process equipment/blocks, respectively.

3.1. Fixed bed gasification

The two fixed bed gasification options (co-current and counter current) are realized using similar components with just small differences in the sequence of process parts caused by the subsiding reaction processes. The simulations further contain a subsequent product gas conditioning section. The power generation is carried out in a gas engine, modeled as “black-box unit” by a typical efficiency factor. Both gasifiers are air-blown and under atmospheric pressure.

The **co-current fixed bed** option (A) is shown in Figure 2. The wet biomass stream is fed to a drying zone, where the moisture is vaporized and separated.

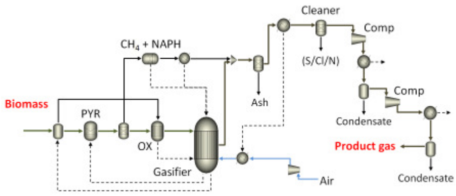

Figure 2: Simplified process simulation flowsheet of co-current fixed bed gasification

The gasifier is simulated by three AspenPlus blocks labeled as PYR, OX and Gasifier. The pyrolysis reactor (PYR) simulated by a RYield reactor decomposes the feed into its elemental composition according to the ultimate analysis of the biomass. Part of the carbon and hydrogen are afterwards separated and externally converted to methane and naphthalene, which is necessary to adjust a realistic gas mixture regarding the tar and methane levels. To simplify, naphthalene is chosen to represent the tar content. The main stream together with the water vapor is further fed to the oxidation reactor (OX) modeled as equilibrium reactor where part of the stream is burned at 1000°C. The actual gasification reactor (Gasifier) is modeled as RGibbs reactor with a restricted equilibrium approach (REA) at 850°C. Chemical equilibrium is assumed for the gas composition but at a different lower temperature which is determined by fitting simulated gas compositions to experimental data (for exact description see [3]).
After the gasifier, ash is removed and the remaining product gas is cooled down to 60°C. The following gas condition part contains the removal of waste substances like tars, sulfur and chloride components as well as the cooling and two-stage compression to the required product gas conditions of 5 bar and 30°C. Excess water is removed by condensation.

The **counter current fixed bed** simulation (B) differs merely in the sequence of the AspenPlus blocks (see Figure 3). In this case, the vaporized water is separated from the biomass stream and merged into the product gas stream after gasification. Thus, the water does not influence the following gasification processes in accordance to the real configuration.

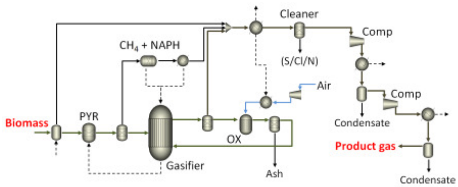

Figure 3: Simplified process simulation flowsheet of counter current fixed bed gasification

Dry biomass enters the pyrolysis zone where the conversion to char and pyrolysis gases occurs. Part of the carbon and hydrogen are separated and externally converted to methane and naphthalene, respectively. The remaining stream is directly fed to the actual gasification reactor (RGibbs) modeled with a restricted equilibrium approach (REA) at 850°C. The residual, not-converted carbon is fed to the oxidation reactor (equilibrium reactor) where it is burned together with preheated air. Recycled to the gasifier, the hot flue gas delivers the heat required for endothermic gasification. The mass flow of combustion air is adjusted to a gasification temperature of 700°C.
The final product gas conditioning unit matches the aforementioned co-current bed option.

3.2. Fluidized bed gasification

The fluidized bed gasification (C) is designed with circulating bed material in two separated fluidized beds. The combustion bed provides the heat supply for the bed material. With this configuration a dilution of the product gas with nitrogen by air is prevented, which guarantees a high caloric synthesis gas. However, the second fluidized bed increases the complexity of the system. For reasons of comparability of the simulation with reality, the simulation is modeled on the basis of the reference plant located in Güssing (Austria), where well-researched data are available in literature [7].

Besides the gasifier, the simulation concept contains a flue gas cooling section, a subsequent product gas conditioning and a process steam production. Figure 4 shows the process configuration with the individual parts of the simulation.

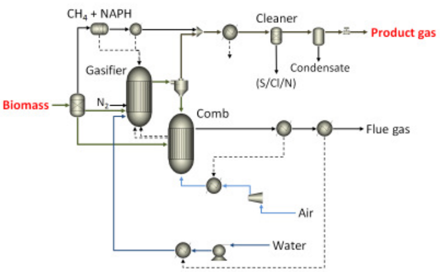

Figure 4: Simplified process simulation flowsheet of fluidized bed gasification

The central gasifier is modeled as equilibrium reactor where the product gas composition is adapted via a restricted equilibrium approach (REA). Biomass feed is connected to a decomposer (pyrolysis) and downstream modified with an external methanation reactor for additional methane generation. Thus the gas composition modeled can be adjusted to real gas data from the reference gasifier (Güssing). In addition, the tar problematic is met by an external tar reactor which produces tar, respectively naphthalene in the same amount literature suggests from the carbon feedstock (about 5 g/Nm^3 wet gas). 90% of the carbon is converted in the gasifier which leaves 10% char for the combustion with preheated air and some additional biomass in the second fluidized bed. For heat generation the mixture is burned under excess air conditions (λ = 1.2). Both reactors are operated at a pressure of 6 bar allowing a pressure loss in subsequent process steps prior to the gas engine. Heat losses for both fluidized beds are considered, too.

The flue gas exits the combustion fluidized bed with a temperature of 850°C. Stepwise cooling in heat exchangers to 100°C provides the required process heat for air preheating and steam production.

Gas cleanup for the product gas is carried out in a cold gas cleaning section. Raw synthesis gas is cooled down to 30°C for the separation of tar and subsequent deposition of miscellaneous contaminations. The cleaning steps are modeled as simple separators. Water is condensed and separated.

3.3. SNG production

The SNG route (options D and E) contains a gas cleaning, methanation and final conditioning part. Figure 5 shows the general outline of the SNG process simulation flowsheet.

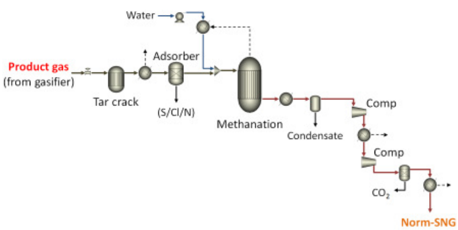

Figure 5: Simplified process simulation flowsheet of SNG production process

Hot gas cleaning is modeled as promising but still challenging technology not yet state-of-the-art. Starting with the product gas at 5 bar from the fluidized bed gasifier, the SNG unit first leads to a tar cracking reactor modeled as RGibbs equilibrium reactor at 800°C with REA (-100°C) so that the main gas composition does not change from the gasifier outlet composition. The naphthalene however is set to chemical equilibrium. After cooling down to 300°C, the synthesis gas is fed to an adsorber, where sulfur and chloride components are removed. The clean synthetic gas is then mixed with some additional water vapor in order to avoid carbon formation in the methanation reactor. The methanation reactor is modeled as near-isotherm at 260°C. The heat produced during the exothermal reaction is used for the vaporization of process water. After methanation, the raw SNG is further conditioned (H_2O and CO_2 removal) to meet grid injection quality before compression.

3.4. Process parameter definition and input specifications

Default state for all educts is ambient condition (15°C and 1bar). Biomass compositions are taken from the Biobib database (TU Wien [8]). Table 2 shows the elementary composition of biomass used for the simulation (beech wood).

Table 2: Biomass composition (BIOBIB, TU Wien 2010 [8])

Element	C	H	O	N	S	Ash
wt% (dry)	47.97	5.78	45.39	0.22	0.03	0.61

The biomass further consists of 80 wt% volatiles and 19.39 wt% bound carbon with a higher heating value of 18659 kJ/kg (dry). Moisture content of the untreated biomass is set to 20 wt%.

Power generation is handled as black-box-unit via CHP as an established and available technology with defined electrical efficiency of 0.4 which is a quite conservative value.

Heat losses and pressure drops are defined according to literature and calculations e.g. for the heat loss through the reactor walls (5.2% fluidized bed and 14.1% fixed bed due to pressure and temperature levels).

4. Results and discussion

In general, simulation results are in good agreement with literature data. Table 3 shows an overview of representative data from simulations (notations A-E are taken from Table 1 in chapter 2).

Table 3: Product gas composition and parameters

	A	B	C	D/E
Composition [mol%]				
H_2O	0.6	0.6	0.6	0.0
H_2	11.1	15.0	44.3	3.8
CO	22.0	21.2	22.8	0.0
CO_2	11.0	12.5	21.3	2.8
CH_4	2.5	2.5	10.4	91.6
N_2	52.9	48.2	0.5	1.8
Mass flow product gas [kg/s]	1.72	1.56	0.53	0.14
LHV product gas [kJ/kg]	4 102	4 506	13 739	45 043
Synthesis gas output [kW]	7 056	7 020	7 220	6 254
Cold gas efficiency	70.6%	70.2%	72.2%	62.5%

Gas compositions strongly depend on the gasification technology. Only the dual fluidized bed technology is suitable for further SNG conversion as there is nearly no dilution with nitrogen from air. Fluidized bed option (C) has a much higher lower heating value (LHV) compared to the fixed bed options (A and B) and the highest cold gas efficiency (72.2%). However, the mass flow (also volume flow) of product gas is much smaller for the fluidized bed.

SNG composition shows only small amounts of unwanted components (3.8% H_2, 2.8% CO_2 and 1.8% N_2). The conversion of synthesis gas to SNG (option D and E) leads to the smallest product gas output (6254.1 kW) due to the second conversion process and various cleaning steps. The output gas meets the German regulations for injection in the natural gas grid [9] and is pressurized to 8 bar.

4.1. Process efficiency

For the base options with combined heat and power generation in a gas engine, simulation results are shown in Figure 6 indicating overall, (net) cold gas and electrical efficiencies.

Efficiencies are defined based on following equations:

$$\eta_{cold\ gas} = \frac{\dot{m}_{product\ gas} \cdot LHV_{product\ gas}}{\dot{m}_{biomass} \cdot LHV_{biomass}}$$

$$\eta_{net} = \frac{\dot{m}_{product\ gas} \cdot LHV_{product\ gas} - P_{\mathrm{int}}}{\dot{m}_{biomass} \cdot LHV_{biomass}}$$

$$\eta_{overall} = \frac{\eta_{el} \cdot \dot{m}_{product\ gas} \cdot LHV_{product\ gas} + \eta_{heat} \cdot \dot{Q}_{use} - P_{\mathrm{int}}}{\dot{m}_{biomass} \cdot LHV_{biomass}}$$

$$\eta_{el} = \frac{P_{electrical,net}}{\dot{m}_{biomass} \cdot LHV_{biomass}}$$

Internal power consumption (P_{int}) is provided by the utilization of product gas with an electrical efficiency of 0.4.

For overall efficiency, heat above a level of 60°C is considered to be usable in any further industrial process or the local heat grid. Gas engines are assumed with an electrical efficiency of 40% and a thermal efficiency of 50%. A heat utilization factor of 0.9 is assumed for the calculation of overall efficiency.

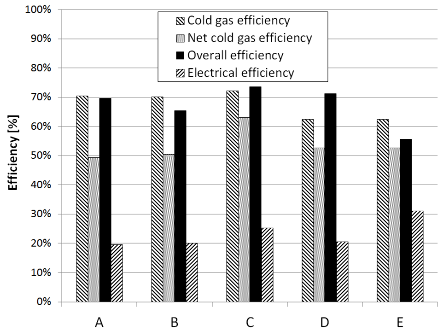

Figure 6: Efficiencies of process options A-E

Highest overall efficiencies are achieved both with fluidized bed gasification (73.7%) and the SNG solution D (71.2%), whereas the small difference is caused by the natural gas grid losses only.

Highest net cold gas efficiency is reached with the fluidized bed option (63.1%). This is mainly caused by higher internal consumption for compressors in the fixed bed options A and B.

The SNG option has lower net cold gas efficiency because of the cleaning and separation steps.

4.2. Importance of heat utilization

A critical factor is the heat utilization on the site of the gasifier. Due to low electrical efficiencies in small scale applications, heat utilization is essential to achieve high overall energetic efficiency and economic profitability.

Besides total efficiencies, more information can be drawn from an overall evaluation including heat utilization and local heat sinks, respectively. Therefore, following scenarios are considered:

- Options A, B and C as described before, with a gas engine (CHP) directly mounted to the gasifier. As the gas engine is directly coupled to the gasifier (operated at full load), a constant heat consumer with high capacity is required on-site. In all these cases, the total amount of heat (process heat and the engine's waste heat) produced at the gasifier location is significantly higher than for the SNG option.

- Option D with the injection of SNG into the natural gas grid and small scale CHP generation (not at the gasifier location), adjusted to local heat demand and heat driven (overall efficiency of 90% from SNG). Waste heat utilization at the gasifier location is variable depending on the consumer.
- Option E, where SNG is injected into the natural gas grid and transferred to an efficient, large scale combined cycle power plant (CCPP). Due to co-combustion of SNG an electrical efficiency of 60% [10] is feasible. Though, only process heat at the gasifier location can be used.

In case of SNG injection (D and E), a gas loss of 1.5% is assumed for transfer through the gas grid. Due to the storage capacity of the grid, power production in option E and heat utilization from the small CHP units (D) can be adjusted to the current demand.

Figure 7 shows the influence of heat utilization at the location of the gasifier on overall efficiencies for the above-mentioned scenarios.

For small amounts of heat demand on-site (< 2.7 MW), the SNG options with injection of SNG in the natural gas grid and power generation in an off-site CCPP or CHP are the most efficient solution by far. The power generation in a CC power plant improves the overall efficiency for small heat utilization factors but stays below the SNG CHP option. That is because both, local process heat of the SNG production as well as gasification waste heat is used.

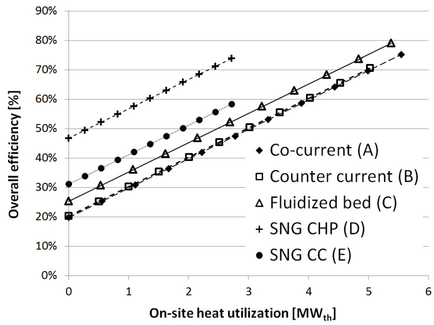

Figure 7: Overall efficiencies of the gasification technologies with varying on-site heat utilization

Figures 6 and 7 also show the efficiencies for mere power generation without the use of any heat (heat utilization = 0).

The SNG CHP option (D) in Figure 7 cannot be considered here, because the engine's waste heat is already included in the calculation as it is not on-site. Highest electrical efficiency is reached with the SNG CC route (31.1 %) due to the high efficient CC power generation.

The fluidized bed route (C) results in an electrical efficiency of 25.3% and fixed bed options are around 20% only (A, B).

If a constant heat consumer with high capacity (> 4MW$_{th}$) is available at the gasifier site, options A-C are promising concepts. In this case, the overall efficiency is in the range or even above the SNG options and lower investment and operation costs are expected. A crucial parameter for the selection of the technology is the potential heat utilization at the location of the gasifier.

Small scale applications vitally need an efficient utilization of waste heat. With increasing heat utilization energetic efficiencies of all options improve strongly.

By using the natural gas grid the heat and power production from SNG is decoupled from biomass gasification and can be adapted to the local demand.

5. Economic considerations

The economic evaluation is based on the German guideline VDI 2067 [11] and realized as a static calculation. The production costs for electricity are calculated depending on the on-site heat utilization.

Selected economic parameters are the interest rate z = 0.06 and the observation period T = 20 years. Following equation is used to calculate the annuity factor 0.0872:

$$a = \frac{z}{1-(1+z)^{-T}}$$

For the annual effort on repairs and servicing, 1.5% of the investment and 1% for insurance and others are assumed respectively. As operational staff for the 10 MW_{th} plant 8 persons (three shifts) - each with 40 000 €/year - are calculated.

The fuel costs are estimated with 90 €/t (2.45 €-Cent/kWh fuel) based on the German fuel market in the years 2010 and 2011.

Full operating hours are assumed to be 7.000 h/year, which correlates with practical experience, e.g. from Güssing [12].

The investment includes the gasifier with all necessary auxiliary components for operation, a gas cleaning unit for particle, H_2S and HCl removal and in the case of a SNG production, additional gas cleaning for tars, a methanation and a CO_2 separation unit, and finally the costs for a CHP or CC power plant.

The costs for the CCPP are assumed to be 500 €/kW_{el} (co-combustion) and for the CHP 430 €/kW_{el}, respectively.

Investment costs are based on [13-16]. Tables 4 and 5 give an overview of the costs.

Table 4: Economic results for fixed bed gasification (options A and B)

Option	A	B
Investment total	4 643 701 €	4 643 701 €
Capital costs (annuity)	404 859 €/a	404 859 €/a
Biomass costs	1 714 787 €/a	1 714 787 €/a
Repairs and servicing	69 656 €/a	69 656 €/a
Personnel costs	320 000 €/a	320 000 €/a
Insurance and others	46 437 €/a	46 437 €/a
Sum annual costs	2 555 738 €/a	2 555 738 €/a
Net power	1 973 kW	2 019 kW
On-site heat utilization	5 548 kW	5 031 kW
Off-site CHP heat utilization	0 kW	0 kW

Table 5: Economic results for fluidized bed gasification and SNG (options C and D/E)

Option	C	D/E
Investment total	11 944 081 €	15 405 427 €/ 16 055 545 €
Capital costs (annuity)	1 041 339 €/a	1 343 115 €/a/ 1 399 796 €/a
Biomass costs	1 714 787 €/a	1 714 787 €/a
Repairs and servicing	179 161 €/a	231 081 €/a / 240 833 €/a
Personnel costs	320 000 €/a	320 000 €/a
Insurance and others	119 441 €/a	154 054 €/a / 160 555 €/a
Sum annual costs	3 374 728 €/a	3 763 038 €/a/ 3 835 971 €/a
Net power	2 526 kW	2 106 kW / 3 111 kW
On-site heat utilization	5 377 kW	2 722 kW
Off-site CHP heat utilization	0 kW	2 593 kW / 0 kW

According the following equation, power production costs are calculated:

$$c_{el} = \frac{c_a - r_{on} - r_{off}}{Q_{el}} \cdot 100$$

c_{el} Power production costs [€-ct/kWh$_{el}$]
c_a Annual costs [€]
r_{on} Revenues on-site heat utilization [€]
r_{off} Revenues off-site heat utilization [€]
Q_{el} Net power generation per year [kWh$_{el}$]

The result depending on the on-site heat utilization is given in Figure 8 for an exemplarily heat revenue of 40 €/MWh heat.

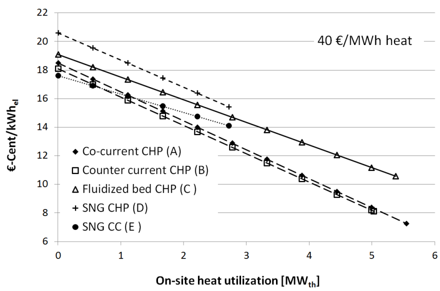

Figure 8: Power production costs with varying on-site heat utilization

The results of the analysis can be summarized by following findings:

- For all concepts and particularly the CHP concepts, the on-site heat utilization is very important, as power production costs can differ by more than 10 €-ct/kWh$_{el}$.
- Due to lower investments, production costs for fixed bed gasifiers are very low (options A and B). But from a technical point of view, an annual operation of 7000 h/a is at least very ambitious for this technology.
- SNG CHP (D) performs worst mainly because of lower power production (compared to (C)) and high investment costs.
- The production of SNG and co-combustion in a high efficient CCPP (E) can be more economic than the application of a SNG CHP (D) or a fluidized bed CHP option (C). However, the economic result is strongly depending on the revenues for heat.
- Further variations of heat revenues show advantages of SNG production at low revenues for the heat.
- In general, the power production costs are in a comparable range for all options, differing by no more than 3 €-ct/kWh$_{el}$.

6. Conclusion and outlook

The concept evaluation and simulation clearly shows a potential of SNG production from biomass gasification both at low revenues for heat or if only low heat utilization on-site is possible. The benefits are related to high conversion efficiency, flexibility in power production, and more efficient heat utilization. In this regard, the SNG pathway is very attractive in comparison to other state-of-the-art technologies like Organic Rankine Cycles or steam cycles [17].

For small scale applications in general, a maximized utilization of the released process heat results in strong overall efficiency increase. Depending on the local heat utilization, gasification with subsequent methanation and grid injection has an advantage compared to local power generation.

Overall efficiency of the SNG option is found to be up to 73.9% (with 100% heat utilization) which is in the range of the fluidized bed gasification option. The crucial factor for high efficiency and thus for an economic operation, is the heat demand at the location of the gasifier. With only small constant heat demand, the SNG solution becomes very

competitive as some of the heat is virtually translated into chemical energy and carried to a power generation location elsewhere.
It is shown, that the SNG production subsequent of a small scale fluidized bed gasifier can be efficient in both energetic and economic regards. Most important and crucial parameters are the local heat demand characteristics.

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