

CONCEPT STUDY OF SMALL-SCALE BIOMASS-TO-SNG SYSTEMS WITH EXCESS POWER INTEGRATION

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ABSTRACT: In times of fluctuating renewable energies and overstrained electrical grids, the production of synthetic natural gas (SNG) and thus the utilization of the existing natural gas grid for power distribution is a promising option for future renewable energy systems. Innovative concepts are developed focusing on the integration of an electrolysis unit into the biomass-derived SNG production process (thermochemical pathway). Different system designs and configurations are analyzed containing the following components: Fluidized and entrained flow biomass gasifiers, gas cleaning, methanation and gas upgrading as well as state-of-the-art electrolysis units. Process concepts are modeled using the process simulation software AspenPlus allowing the drafting of the complete process, with the aim to provide feasible solutions and the evaluation and comparison of those concepts among each other. Main focus of the study is on the integration of mass and heat flows and the optimal process design as well as operation conditions. Results show a diverse and complex situation: Methane yields vary from 28.2 to 97.5 % depending mainly on the hydrogen addition from electrolysis with advantages when using entrained flow gasifiers. However, almost complete carbon conversion to SNG can be reached with almost no loss of CO₂ within the process. Cold gas efficiencies vary from 54.2 to 73.8 % which is above the stand-alone systems approving the positive synergy effects. Overall efficiencies are between 68.4 and 75.3 % but show a decreasing trend with increasing hydrogen addition and increasing electrolysis size, respectively. However, performance data, efficiencies and methane yields have to be considered closely and properly before coming to a conclusion because of different scale effects and huge deviations in electrolyzer size between 170 and 2600 kW. Thus, an economic evaluation has to be done in order to give a complete evaluation. Furthermore, all concepts depend largely on a very cheap supply to excess power in the electrical grid.

Keywords: Synthetic natural gas (SNG), biomass, allothermal gasification, catalytic conversion, small scale application, innovative concepts

1 INTRODUCTION

The production of synthetic natural gas (SNG) is a promising option for future renewable energy systems. Today the electrical grid is used for the distribution of energy, but with increasing power feed-in from fluctuating renewable sources like wind and solar, the electrical grid becomes more and more overstrained. Long-term storage regarding seasonal fluctuations cannot be addressed sufficiently with existing technology (PHS, CAES, Batteries, Flywheels, etc.) [1]. Using chemical energy carriers and SNG respectively, the existing natural gas grid can be used for storage and distribution of energy and thus the energy from biomass and excess power can be stored and distributed in an efficient way.

SNG can basically be produced by three different routes:

- Biochemical SNG production (upgrading of biogas from wet agricultural biomass)
- Thermochemical SNG production (gasification of dry biomass with subsequent synthesis and gas upgrade)
- Power-to-Gas concept (electrolysis of water and subsequent methanation of the hydrogen with CO₂).

Today SNG production from biomass slowly develops from research to pilot-scale applications. Appropriate biomass gasifiers (allothermal fluidized bed gasifiers) are nowadays operated in full-scale with thousands of full-load hours per year. However, gas cleaning and the conversion of biogenic synthesis gas to SNG is still not state-of-the-art for (small- to medium-scale) biomass applications but is researched intensively in various projects [2], [3]. In addition, there is increasing interest in entrained flow gasification of biomass (state-of-the-art for coal gasification) but feed preparation (torrefaction,

hydrothermal carbonization or pyrolysis) and the ash melting behavior still have to be addressed and researched properly.

Apart from that, electrolysis units are nowadays commercially available from various suppliers with long-term experience for most technologies but mostly no, to very small experience regarding part load operation or load-change behavior, which is crucial for applications using fluctuating surplus electric power from renewable sources. However, more and more suppliers have realized the new requirements and are adapting to that (see e.g. NEL [4]). Furthermore, different technologies (PEM and Alkaline electrolysis) are on the market or in near-commercial state which have to be adapted and proven for dynamic load change and part load behavior (Alkaline electrolysis) as well as scale-up to the MW-size (PEM electrolysis).

However, the link between the two technologies is still widely disregarded. Conventional electrolysis concepts and pilot projects mostly investigate hydrogen production and the direct utilization of renewable hydrogen or addition of hydrogen to the natural gas grid. But there are some limitations to these concepts e.g. given by the injection specifications (DVGW). Biomass gasification on the other hand suffers from complex and cost intensive gas cleaning and upgrading steps in order to reach injection quality.

Due to the composition of biomass (e.g. CH_{1,37}O_{0,61}) all biomass-based gasification processes supply a synthesis gas with a lack of hydrogen and a surplus of oxygen when compared to the required composition of methane (CH₄). During the SNG production process the appropriate ratio has to be adjusted by separation of CO₂ (standard) or addition of H₂ (see Figure 1).

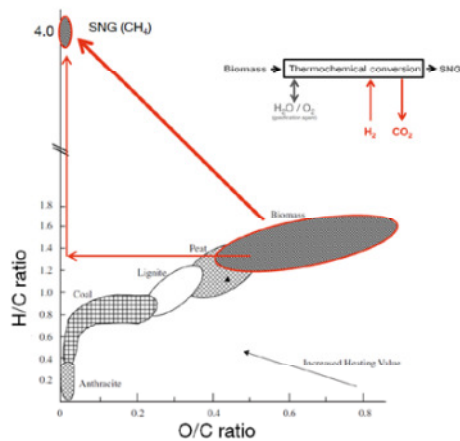


Figure 1: Van Krevelen diagram showing input composition of biomass and target output composition of SNG (adapted from: [5])

The amount of required CO_2 separation is mainly influenced by the gasification technology. Oxygen-blown autothermal gasification produces a higher amount of CO_2 which has to be separated than the steam-blown allothermal gasification (factor of nearly 2.5) [6]. However, for a complete methanation of the carbon contained in the biomass, it is inevitable to add hydrogen to the process.

Therefore, innovative concepts are developed focusing on the integration of an electrolysis unit into the SNG production. Different combinations and system designs are analyzed containing the following components: Fluidized bed or entrained flow biomass gasifiers, fuel preparation, gas cleaning, gas upgrading and methanation units and state-of-the-art electrolysis units. Oxygen and hydrogen from electrolysis are both integrated within different process steps (gasification, methanation, gas cleaning and gas upgrade).

The aim of the study is to provide possible solutions and the evaluation and comparison of those concepts among each other. Main focus of the study is on the integration of mass and heat flows and the optimal process design as well as operation conditions for small-scale units (1 MW_{fuel, input}).

2 STATE OF THE ART

In the following chapter, all process steps are shortly evaluated regarding state-of-the-art in technology and science with focus on important operation parameters, problematic technical issues, limitations and potential future improvements. Starting from the biomass-to-SNG process (see Figure 2) there are four main process steps (gasification, gas cleaning, methanation and gas upgrading). These main steps contain several partial operation steps and side-processes like off-gas post-combustion (from membrane separation), compression and multiple heat exchangers, which are not described in detail here.

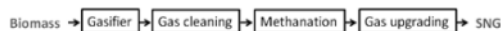


Figure 2: General process steps from biomass to SNG

Furthermore, the integration of an electrolysis unit requires the electrolysis stack with appropriate periphery. Main process steps required for the integrated concepts are briefly described in the following. Fluidized bed and entrained flow gasification are considered within this study.

2.1 Fluidized bed gasification (FBG)

Fluidized bed gasification is a well-known technology for small- to medium-scale biomass applications (~ 0.5 – 50 MW_{th}). Small-scale applications favor bubbling beds whereas larger-scale applications mainly use circulating fluidized beds (see reference plant in Güssing, Austria). Relatively low carbon conversion rates between 90 and 97 % are typical for fluidized beds with some major impact on the cold gas efficiency. The formation of organic impurities (tars) is the other main barrier for FBG technology due to severe problems downstream of the gasifier, where the tars cause blocking and formation of coke which again causes operational interruption. FBGs are known to have tar loads of 2 – 10 g/m³ [7]. Most gasifiers operate under atmospheric pressure but there are experiences even with pressures as high as 20 bar (single bed, e.g. Värnamo) so that a pressurized operation at 5 bar seems to be feasible without major difficulties.

A detailed review of fluidized bed gasification for biomass applications can be found elsewhere [7]. In this study an allothermal fluidized bed gasifier with heat pipes (HPR = Heat Pipe Reformer) developed at the TUM is used as model for the simulations. This gasifier is market ready and available at the required size of about 1 MW_{th} [8].

2.2 Entrained flow gasification (EFG)

The technology of entrained flow gasification is well researched and proven for coal gasification and by far most gasification plants currently under operation are using entrained flow technology [7]. However, the adaption of EFG for biogenic feedstock is still under development because of challenging fuel pre-treatment, ash melting behavior and the poor economics of oxygen supply in small-scale applications by air separation units (ASU).

Fuel pre-treatment can be carried out by drying, torrefaction, HTC (hydro-thermal carbonization), fast pyrolysis and dissolution in organic solvents. Due to various reasons discussed elsewhere in detail [7], torrefaction seems to be a very promising option for the near future when it comes to pre-treatment of relatively dry, woody biomass. However, this technology is not yet state-of-the-art but expected to be on the market in near-commercial scale in the next few years. The torrefied wood has an improved grindability, good storability and enhanced dry feeding ability. At relatively mild temperatures (200 – 300 °C) and atmospheric pressure the fuel properties can be improved while integration in the overall process saves heat demand and improves efficiency. After grinding to typical particle sizes of approx. 30 - 400 μm [7], the pulverized fuel can be fed to the gasifier by pneumatic dense flow feeding.

Entrained flow gasifiers are operated with oxygen/steam mixtures as gasification agents. For small-scale applications, oxygen supply from conventional ASU, cryogenic air separation or pressure swing adsorption (PSA) is not state-of-the-art, not available at the small size or due to poor economics not applied so

far. Entrained flow gasifiers can be designed for slagging or non-slagging operation mode either quite below (< 1200 °C) or above the ash melting temperature (1200 - 1400 °C) depending mainly on the biomass composition. However, slagging operation mode for example at approx. 1300 °C seems to be more likely suited for biomass EFG.

2.3 Gas cleaning, synthesis and upgrading

Gas cleaning can be done by cold (wet) or hot/warm gas cleaning configuration. Whereas cold gas cleaning by scrubbing technology is more or less state-of-the-art for similar processes, hot gas cleaning is not yet applied in a commercial scale. However, due to higher potential efficiency and advantaged in process management, hot gas cleaning seems advantageous for small-scale applications [2]. Process steps include particle removal with cyclone and filter systems, catalytic tar reforming and fixed bed sulphur- and chlorine-adsorption.

After initial gas cleaning, the conversion of synthesis gas to raw-SNG takes place. The reaction of mainly carbon monoxide and hydrogen to methane and water (methanation) is a strongly exothermic, catalytic reaction at temperatures between 250 - 700 °C and pressures around 1 - 80 bar. Catalyst stability, reactor design and especially heat removal and utilization are the most complex issues to be solved. Commercial processes use adiabatic fixed bed reactors in series with intercooling and recycle streams to adjust temperatures and inhibit catalysts degradation (e.g. by Lurgi, Haldor Topsøe, Davy Process Technology) [9]. Also one-stage fluidized bed methanation is being investigated but not market-ready.

The final steps to SNG injection into the NG grid are the raw-gas upgrading steps. Drying and if necessary CO₂ separation has to be applied to fulfill injection requirements. Commercial technology is available for small-scale applications developed for biogas upgrade like pressure swing adsorption (PSA), water scrubbing or chemical as well as physical washes and membrane processes.

2.4 Electrolysis (EL)

In general, there are three main types of cells with two technologies available commercially: High temperature electrolysis (HTEL with solid oxide electrolysis cell (SOEC)), polymer electrolyte membrane electrolysis (PEMEL) and alkaline electrolysis (AEL).

Alkaline electrolysis is by far the most mature technology, features moderate investment costs, high durability and is available over a broad power range (MW). It is a proven technology up to the size of 160 MW_{el} but suffers from low energy densities. AEL systems operate with electrolyte (KOH or potassium carbonate) and at mild temperatures, often below 100 °C. Furthermore AEL proofed sufficient dynamic behavior and by modularization part-load restrictions can be avoided.

PEM electrolysis (polymer electrolyte membrane) is a younger technology which is more and more becoming available commercially. Operating below 100 °C, PEM has the advantage to be favorable for dynamic operation. Electrolysis systems up to 160 kW_{el} are available with significant growth [10].

SOEC's operate at high temperatures, typically around 800 °C but are not available on a commercial scale. However research suggests high potential

especially regarding integration in high temperature processes like gasification.

3 CONCEPT AND METHODOLOGY

As mentioned above, all biomass-based SNG processes have an inherent lack of hydrogen. This can either be compensated by downstream carbon separation (e.g. CO₂ separation by PSA) or hydrogen addition (see Figure 1). Excess energy utilization via electrolysis and subsequent methanation on the other hand needs a carbon source (CO or CO₂). By combining both processes, the synergies like excess oxygen production can be used which enhance the chance for economic investment and operation.

In order to evaluate different concept designs, the process chains are developed for most promising combinations of gasification, methanation, electrolysis and gas cleaning/upgrading. Process parameters are validated by literature and reported data from suppliers. The concepts are modeled and optimized in AspenPlus.

3.1 Integration

There are basically four points in the process from biomass to SNG where either H₂ or O₂ from the electrolysis can be integrated into the process for different reasons:

- Gasifier (O₂ as gasification agent)
- Catalytic tar reforming (O₂ for high-temperature heat supply)
- Methanation (H₂ to suppress carbon formation and/or reach optimal SN number for total stoichiometric methanation)
- Gas upgrading (O₂ for post-combustion of off-gas from CO₂ separation and subsequent utilization of the flue gas as purge gas)

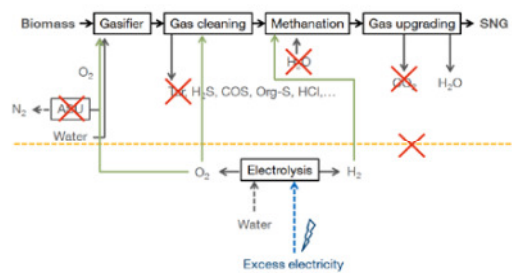


Figure 3: Combination of the Biomass-to-SNG process with an electrolysis unit for excess power integration and possible integration points

Figure 3 shows the possible process designs and integration points by combining these technologies

Overall goal of this study is to examine the efficiency potential, the technical feasibility and whether it is reasonable to think about the direct utilization of surplus power from renewable sources in such a hybrid thermochemical conversion process beyond the oxygen supply for gasification. At the end, all process configurations have to be proven both for technical feasibility and economics (not part of this study).

3.2 Evaluation

For the evaluation and discussion of results, three

parameters are analyzed: the methane yield, which gives a good indication of the yield of carbon from biomass to methane, the cold gas efficiency (CGE) for simple gas efficiency and the overall efficiency, which gives the evaluation of the processes including heat production and extraction (above 130 °C) including auxiliary power demand as well as power demand of the electrolysis unit. Formulas are given below:

$$\eta_{CH_4} = \frac{\dot{n}_{CH_4}}{\dot{n}_{C, fuel}}$$

$$\eta_{CG} = \frac{\dot{m}_{SNG} \cdot LHV_{SNG}}{\dot{m}_{biomass} \cdot LHV_{biomass} + \dot{m}_{H_2} \cdot LHV_{H_2}}$$

$$\eta_{overall} = \frac{\dot{m}_{SNG} \cdot LHV_{SNG} + \dot{Q}_{use}}{\dot{m}_{biomass} \cdot LHV_{biomass} + P_{el} + P_{aux}}$$

Elaborate exergy analysis can perhaps help for a more adequate evaluation but for such small-scale systems, economics are much more important. For reasons of clarity, the efficiency calculations like cold gas and overall efficiency are supposed to be sufficient for a qualitative, comparative study like this. Special focus is on the comparison between the cases and thus the relative evaluation and not the absolute determination of exergetic efficiencies.

4 SIMULATIONS

Process simulations are carried out using ASPEN PLUS V7.3 process simulations software with user-defined subroutines implemented by Fortran and Excel codes. All models are based on already published simulation models with some additional extensions. Validation and verification is carried out according to literature and supplier data (for further information see [7], [11]). Reference plants for validation and verification with experimental data are the biomass gasification plant in Güssing and a modified Choren-type plant for the EF technology (see [7], [11]). For decentralized, small-scale applications a plant size of 1 MW thermal biomass input is modeled. Due to the size, all simulations do not regard elaborate heat utilization (steam cycle, ORC, etc.) and only heat extraction above 130 °C for e.g. district heating systems is considered.

Output specifications are given by the DGWV specification for natural gas injection regulation [12] concerning gas quality and by an injection pressure of 16 bar. Heat losses are considered (determined through heat transfer calculation based on reactor volumes and pressure levels). Uniform biomass composition is assumed for all cases for reasons of comparability with following biomass composition (according to BIOBIB database, TU Wien [13]):

Table I: Biomass composition (from [13])

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

Main components of the process flowsheet are gasifier, gas cleaning, methanation, gas upgrading and electrolysis units.

According to the process description in chapter 2, the modeling of the single process models is carried out. Exact description of the modeling of the single process steps can be found elsewhere [11].

Table II shows an overview of the simulation cases put together containing the single process steps as indicated.

Table II: Simulation cases with associated process configuration and notation

GT	FP	GC	Me	GU	El	No
FICFB	-	CGC: C, F, S, S/Cl-A	FIBM SN=0.46	Co, AS, GD, H ₂ - M	-	FICFB_CGC
HPR	-	HGC: C, CTR, F, S/Cl-A	FIBM SN=0.97	Co, CH ₄ - M, PC	-	HPR_HGC_BC
HPR	-	HGC: C, CTR, F, S/Cl-A	FIBM SN=1.08	Co, CH ₄ - M, PC	HPAE	HPR_HGC_EL- O2
HPR	-	HGC: C, CTR, F, S/Cl-A	FIBM SN=1.15	Co, CH ₄ - M, PC	HPAE	HPR_HGC_EL- H2
HPR	-	HGC: C, CTR, F, S/Cl-A	FIBM SN=3.0	Co	HPAE	HPR_HGC_EL- OM
EF	T	WGC: SS, C, GQ, F, S/Cl-A	FIBM SN=1.0	Co, CH ₄ - M, PC (Air)	HPAE	EF_GQ_EL-GF
EF	T	WGC: SS, C, GQ, F, S/Cl-A	FIBM SN=1.87	Co, CH ₄ - M, PC (O ₂)	HPAE	EF_GQ_EL-H2
EF	T	WGC: SS, C, GQ, F, S/Cl-A	FIBM SN=3.0	Co	HPAE	EF_GQ_EL-OM
EF	T	WGC: WQ, C, S/Cl-A	FIBM SN=1.0	Co, CH ₄ - M, PC (Air)	HPAE	EF_WQ_EL-GF
EF	T	WGC: WQ, C, S/Cl-A	FIBM SN=3.0	Co	HPAE	EF_WQ_EL-OM

Abbreviations:

AS	Amine scrubber
C	Cyclone
CGC	Cold gas cleaning
CH ₄ -M	CH ₄ -membrane
Co	Condenser
CTR	Catalytic tar reformer
EF	Entrained flow gasifier
El	Electrolyzer
F	Filter
FIBM	Fixed bed methanation (quasi-isotherm)
FICFB	Fast internally circulating fluidized bed gasifier („Güssing“)
FIBM	Fluidized bed methanation (PSI)
FP	Fuel pretreatment
GC	Gas cleaning
GD	Glycol dehydrator
GQ	Gas quench
GT	Gasification technology
GU	Gas upgrading
H ₂ -M	H ₂ -membrane
HGC	Hot gas cleaning
HPAE	High pressure alkaline electrolyzer
HPR	Heat pipe reformer (dual stationary fluidized bed)
Me	Methanation
No	Notation
PC	Post-combustion
S/Cl-A	Sulphur-/chlorine components adsorption
S	Scrubber (RME)
SN	Stoichiometric number
SS	Slag separation
T	Torrefaction
WGC	Warm gas cleaning
WQ	Water quench

The main two types of complete flowsheet options (HPR- and EF-based) are described briefly in the following:

4.1 HPR-based models

For the HPR models, no fuel pretreatment is necessary due to fluidized bed characteristics which can handle wide spread fuel particle size with higher moisture content. The feeding system is purged using CO₂ in order to reduce the contamination with nitrogen. The gasifier itself consists of two separated reactors, where the combustion bed provides the heat supply for the gasification bed (via heat pipes). Air or a combination of air and oxygen is used for the combustion process, while steam is used as gasification agent in the gasifier. Both reactors are modeled as equilibrium reactors at 850 °C and 5 bar where the product gas composition is adapted via a restricted equilibrium approach (REA) and further adjusted by external reactors to account for methane and higher hydrocarbons (e.g. tars). The model is based on [11], where a more detailed description can be found. The heat of the flue gas is recovered and used for steam generation.

Hot gas cleaning process is carried out by cyclone separation of large coke and ash particles. These particles are recycled and fed into the combustion reactor. Subsequent catalytic tar reforming is modeled as an equilibrium reactor (RGibbs) at 850 °C (with REA). Oxygen (from the electrolyzer) is used in the reactor for partially oxidizing the gas and maintaining the temperature of 850 °C. After cooling down to 350 °C, a filter separates small dust particles before the trace substances (mainly sulfur and chloride components) are removed in chemical adsorption processes.

The syngas is mixed with steam or hydrogen (or combination of both), before it is fed into the methanation reactor. Steam/hydrogen addition is adapted to avoid carbon formation in the reactor and to adjust the stoichiometric number ($SN = (H_2 - CO_2) / (CO + CO_2)$). The methanation reactor is modeled as a cooled, quasi-isothermal reactor at 300 °C and approx. 4 bar. Heat from the exothermal reactions is used for water evaporation.

The final upgrading of raw-SNG consists at least of a compression and a condensation for water removal. The additional CO₂-removal is modeled using a membrane process. The membrane's permeate contains small amounts of methane and hydrogen which requires post-combustion (using either oxygen from the electrolyzer or air). The upgraded SNG fulfills the grid injection requirements.

Figure 4 shows the process flowsheet of the HPR-cases.

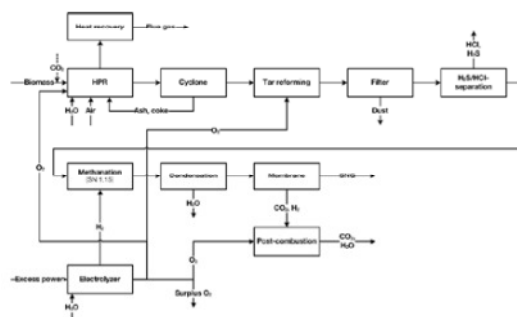


Figure 4: General flowsheet configuration of allothermal fluidized bed gasification (HPR) with hot gas cleaning, membrane upgrade and electrolysis unit for excess power integration (HPR_HGC_EL)

The different configurations only deviate in the final membrane separation step and the amount of supplied hydrogen to the methanation reactor (replacing steam addition).

4.2 EF-based models

Biomass pre-treatment is considered in the EF-based models by combining a torrefaction process with pulverization and dry-feeding system. Torrefaction is modeled in several steps. After heating and drying at 260 °C (until a water content of 3 wt% is reached), the decomposition of the biomass is modeled in a reactor. The energetic loss of biomass during the torrefaction is set to 5 %, based on the LHV. This is in accordance with literature [14]. Pulverization to reach particle sizes of less than 0.5 mm is modeled in a mill with a defined energy demand of 36 kWh/t. The pulverized and sieved fuel is fed into the gasifier with small amounts of purge air. Oxygen from the electrolyzer is fed into the gasifier together with steam as gasification agent, which also homogenizes the temperature distribution within the gasifier. The required, superheated steam is generated internally, using heat from the cooling of the hot product gas. The gasifier is modeled as an equilibrium reactor with restricted equilibrium approach (REA), based on the entrained flow model described in [7].

The gasification is modeled at a temperature of 1350 °C (REA of -300 °C) and a pressure of 20 bar. The resulting gas composition is in close accordance to the data of the reference entrained flow gasifier [7].

Slag is removed from the gasifier by a particle separator and an energy loss for melting the ash is considered by an enthalpy stream. Heat losses through the walls are considered.

The hot product gas from the gasifier is cooled down stepwise to the required temperature of 350 °C. This is done either with a gas quench and a recirculation of cooled product gas or with a water quench.

Trace substances (mainly sulphur and chloride components) are removed in chemical adsorption processes, modeled as separators.

The syngas is mixed with steam, hydrogen or a combination of both before it is fed into the methanation reactor. Again, carbon formation is avoided and the stoichiometric number is adjusted. The reactor itself is modeled as a cooled, quasi-isothermal reactor at 300 °C and 18 bar, considering energy losses.

The upgrading of raw-SNG is modeled similar to the concept described in section 4.1, except for the compression that is not needed, due to the high pressure in the methanation reactor.

Figure 5 shows the process flowsheet of the EF-cases.

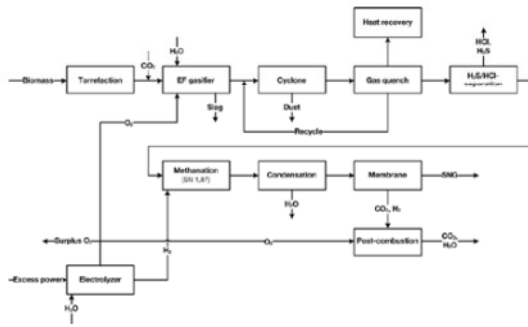


Figure 5: General flowsheet configuration of entrained flow gasification with gas quench and electrolysis unit for excess power integration (EF_GQ_EL)

The different configurations deviate mainly due to the different quench systems (water or gas) and again in the final membrane separation step and the amount of supplied hydrogen to the methanation reactor (replacing steam addition). Electrolysis unit is applied for all cases as replacement for the industrial-scale state-of-the-art ASU.

4.3 Electrolysis

The electrolysis unit is not modeled in detail but considered as “black box” in an excel-sheet. With 4.9 kWh/Nm³_{H₂} and approximately 61 % efficiency (power to hydrogen), the container-based solution is commercially deliverable and thus state-of-the-art [4]. Different scale of hydrogen and oxygen demand is considered by modularization (parallel units).

5 RESULTS AND DISCUSSION

Results are shown in the following chapter regarding methane yield and efficiencies defined in chapter 3. Furthermore, an analysis is given for important performance parameters for a better understanding of the results.

Figure 6 shows the simulation results of the nine configurations (4 x HPR, 5 x EF) for methane yield, cold gas efficiency and overall efficiency.

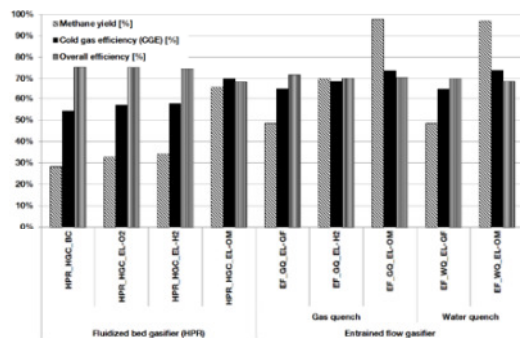


Figure 6: Results for methane yield, cold gas efficiency and overall efficiency of all concepts

For the methane yield, highest values can be reached by the EF-cases (48.3 - 97.5 %), with the absolute best yield for the entrained flow gasifier with gas quench and

optimized hydrogen addition for methanation (EF_GQ_EL-OM, 97.5 %). The HPR-cases only reach lower values (28.2 - 64.9 %) mainly due to the fact that part of the biomass has to be burned in the combustion chamber to supply the required heat for the gasification. This part of the carbon of course is lost for SNG conversion. Also there is a clear trend that by increasing hydrogen addition and increasing electrolysis output respectively, the methane yield increases too. With this, up to 97.5 % of the carbon from the biomass is captured in the energy carrier SNG and nearly no CO₂ is released into the air over the complete process.

Cold gas efficiencies show a similar trend with smaller deviations between the cases. Highest CGE is reached by the entrained flow gasification case with water quench and optimized hydrogen addition for methanation (EF_WQ_EL-OM) with 73.8 % followed by the corresponding case with gas quench (73.7 %). Again, the efficiency increases with increasing hydrogen addition and EF-cases reach slightly higher values (64.5 - 73.8 %) compared to HPR-cases (54.2 - 70.0 %). For all combined processes this findings show, that by combining biogenic SNG production and excess power utilization a synergy effect can be reached. Two stand-alone processes for Biomass-to-SNG and Power-to-SNG reach smaller efficiencies than an optimized combination.

Overall efficiencies however show a slightly different trend with increasing hydrogen addition. Here, the base cases with no or only minimal hydrogen addition reach the best values and the absolute best case is the HPR base case with no electrolysis at all (HPR_HGC_BC, 75.3 %). Also the HPR-cases (68.4 - 75.3 %) in general reach here higher overall efficiencies than EF-cases (68.8 - 71.8 %) but only by little.

To give a better understanding of the results, a further performance analysis is given in the following, showing some more detailed parameters for the overall evaluation. Figure 7 shows some performance characteristics regarding output and input streams.

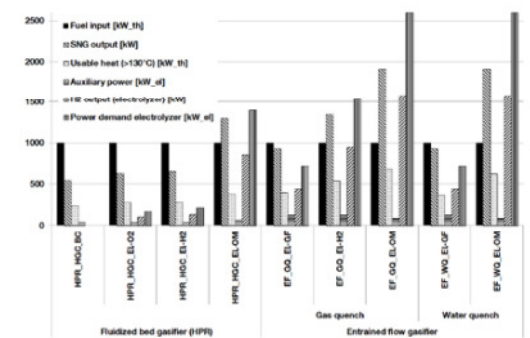


Figure 7: Results for performance parameters (fuel input, SNG output, usable heat, auxiliary power and power demand electrolyzer)

It can be seen from Figure 7, that there is quite a deviation between the cases and configurations regarding e.g. SNG output. Keeping the biomass input constant at 1 MW_{th}, the SNG output varies from 540 kW (HPR_HGC_BC) to 1900 kW (EF_WQ/GQ_EL-OM). Also the size of the electrolysis unit (power demand electrolyzer) compared to the gasifier is quite different for the single cases. The HPR-cases have significantly less power demand of the electrolyzer due to no need of

oxygen supply only in case of optimized methanation the electrolyzer reaches 1.3 MW_{el}. The base case of the EF-cases with only oxygen supply to the gasifier already needs an electrolyzer with nearly 1 MW_{el}.

Summing up, performance data, efficiencies and yields have to be considered closely and properly before coming to an absolute conclusion. Size effects and relative scale of the gasifier and the electrolyzer are varying over a wide range (0.17 – 2.6 MW_{el}) which has to be taken into account when it comes to economics. Only after an elaborate economical study, the best overall concept and configuration can be chosen. This study is still ongoing.

6 CONCLUSION AND OUTLOOK

Following conclusions can be drawn from the findings discussed in chapter 5:

All concepts depend largely on a very cheap supply and local access to excess power in the electrical grid.

The HPR-based cases show more flexibility due to the O₂ utilization at three integration points (gasifier, tar reforming and partial oxidation) instead of two (EF-based concepts). Furthermore, the EF-based cases have huge O₂ surpluses for the H₂-demand driven cases. Economic calculations have to show whether the O₂ surplus can be sold and turned into an economic advantage. However, as cold gas efficiencies and methane yield increase with increasing hydrogen addition, the overall efficiency decreases at the same time, so that the optimal configuration may not be the most efficient and the other way round.

SNG outputs differ significantly (between 0.54 and 1.9 MW) with electrolysis size and methane yields improve due to H₂ input by electrolysis. That is why an elaborate economic evaluation has to show, whether the magnitude of output increase is sufficient for the higher investment in the electrolysis unit. In general, the required sizes of the electrolysis units are substantial larger than the gasification part in many cases. This is enhanced by the fact, that due to fluctuating supply, the electrolyzer has to be designed for about 1500 h/a in comparison to the approx. 7500 h/a of the gasifier (in connection with an adequate buffer storage). However, in case of the EF-based concepts, the electrolyzer unit replaces the cost-intensive ASU which would be necessary otherwise.

Summarizing, up to nearly 98 % of the carbon present in the biomass can be converted and captured in the SNG, which makes these processes carbon-negative. Furthermore, synergies of biomass gasification and electrolysis exist and can be used efficiently. However, local conditions and requirements will in the end determine the best economical concept.

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9 LOGO SPACE

