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Heat Recovery Aspects of Importance for the Product Mix and GHG Emission Reductions in a Bio-SNG System

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This paper presents the impact of adjusted operating parameters (superheating temperature and backpressure or condensing mode) for the heat recovery steam cycle (HRSC) by external conditions on the product mix (SNG; power and heat) in a commercial scale gasification-based bio-SNG (biomass derived synthetic natural gas) production system. The GHG reduction potentials for a case with a condensing HRSC and for a case with the HRSC in backpressure mode producing heat for CO_2 separation of the flue gases are evaluated. Pinch technology was used to identify the potential for heat recovery and process integration. Small changes in the operational parameters of the HRSC can result in significant changes of the conversion efficiencies of heat and power. With an HRSC in back-pressure mode, reducing the power production by 4 MW compared to the condensing case, it is possible to produce ~60 MW of heat for district heating. This study shows that approximately one third of the carbon input to the gasifier ends up in the SNG, whereas one third is separated prior to methanation and one third is emitted as CO_2 in the flue gases from the combustor of the indirect gasifier. If infrastructure for CO_2 storage is available, and CO_2 separated from the process and from the flue gases is stored, the GHG emission reductions from the bio-SNG system can be doubled compared to a case without CO_2 storage possibility.

1. Introduction

In this study, the impact of adjusted operating parameters for the heat recovery steam cycle (HRSC) by external conditions on the product mix (i.e. SNG, power and heat) for a gasification-based bio-SNG production plant is investigated. The product mix, described by partial conversion efficiencies of the products (biomass to SNG, power and heat respectively) is a key factor for the further analysis of the environmental impact and also for the economic performance of the system. Focus in this study is on how operating parameters, e.g. superheating temperature, condensing or backpressure mode and size of the HRSC is dependent on external factors, such as the presence of heat sinks (e.g. district heating networks or industrial processes) and whether the biomass is dried on or off-site. Many previous studies of bio-SNG systems have focused on overall efficiencies and on the impact of different technology choices for the main processes in the SNG production chain. An overview of process configurations and efficiencies is given by Gassner and Maréchal (2012). Gerber et al. (2011) concluded that the reduction of the environmental impact cannot be translated directly by an increase of process efficiency for processes producing several products. This is logical since the different products replace services with different environmental burdens. Knowledge of how different parameters impact the product mix is important for identifying resource efficient systems.
This study investigates how the on-site energy balance is impacted by importing dry biomass (which can be assumed to be transported longer distances, for instance by ship and hence, reducing the dependency on the local biomass resource). Future studies should also analyse how the environmental burden is impacted by long distance transportation and technology and resource use for off-site biomass drying.

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In a study of process design for systems cogenerating bio-SNG, heat and power Gassner and Maréchal (2012), concluded that the steam turbine inlet temperatures of the HRSC is positively correlated with process efficiency and cost, but other operating conditions of the steam cycle need to be optimised for each process configuration and is dependent on whether or not excess heat can be delivered to a district heating net. In the current study the impact on the partial conversion efficiencies of using some of the produced SNG for superheating the steam in the HRSC was investigated. Two uses of excess heat are considered in this study; one for district heating and one for an industrial process. Previous studies have not differentiated between these uses of the excess heat, but this is important since there will be differences in the number of operational hours, the environmental burden of the replaced services and the localisation of the bio-SNG plant. Steubing et al. (2011) concluded that the efficient use of process heat is crucial for the GHG performance of gasification based bio-SNG systems and Steubing et al. (2014) concluded that for these systems the most important driver of the environmental performance is the substitution of non-renewable energy. CO_2 sequestration was not included in their evaluation. The current study evaluates the GHG emission reduction potential for two configurations with on-site biomass drying; one with a condensing HRSC and one where the backpressure produced heat is used for CO_2 separation from the flue gases of the combustor in the indirect gasifier. A single configuration, based on the work of Heyne et al. (2011), of a tentative commercial scale (430 MW_{th} biomass input) SNG-process is used for the evaluations in this study.

2. Methodology

2.1 Partial conversion efficiencies

Pinch technology and specifically split GCCs, as described by e.g. Smith (2005), was used for analysing the excess heat of the bio-SNG process and the size and steam data for the heat recovery steam cycle. The product mix of the SNG-production system is described by the partial conversion efficiencies ($\eta_{biomass \to p_i}$) for the products (p_i) (i.e. SNG, power and useful heat), defined according to Equation 1, where biomass is the input (MW_{LHV}):

$$\eta_{biomass \to p_i} = \frac{output_i\ [MW_{LHV}]}{input\ [MW_{LHV}]} \tag{1}$$

2.2 Greenhouse gas emission reductions

A consequential LCA methodology with system expansion was used for estimating the GHG emission reductions; see Holmgren et al., (2014) for a thorough description of the methodology. In this study the accomplished reductions are presented as the sum of three factors, described by Equations 2-4:

$$\text{Emission reductions by substitution} = SNG * E_{subst} - B * E_B \tag{2}$$

where SNG is the amount of produced SNG (MWh y^{-1}) and E_{subst} is the emission factor (kg $CO_{2\ eq.}$ MWh^{-1}) for the substituted fuel (1 MWh_{SNG} replaces 1 MWh_{fuel}); B is the amount of biomass (MWh y^{-1}) needed to produce the SNG and E_B is the emission factor for the biomass (kg $CO_{2\ eq.}$ MWh^{-1}).

$$\text{Emission reductions of net power production} = P * E_{ref\ power} \tag{3}$$

Where P is the net power production (MWh y^{-1}) and $E_{ref\ power}$ is the emission factor for the reference power production technology.

$$\text{Emission reductions of } CO_2 \text{ storage} = CO_{2\ stored} - P_{compression} * E_{ref\ power} \tag{4}$$

Where $CO_{2\ stored}$ is the amount of stored CO_2 and $P_{compression}$ is the amount of power needed for compressing the separated CO_2 to storage conditions.

3. The SNG production system and data for calculations

The SNG production system is assumed to be located at an industrial site (in Gothenburg) with a natural gas grid and a district heating network or industry with low pressure steam demand nearby.

3.1 The SNG process

The analysis in this study is based on the process configuration, Figure 1, and modeling by Heyne et al. (2011) The process was adjusted to a stand-alone gasification unit, scaled to 430 MW_{th} biomass input at 50 % moisture content and the final pressure of the SNG was set to 30 bar. The char produced in the gasifier is used in the combustor to drive the gasification process. The biomass is dried to 20 % moisture content by a steam dryer with a heat demand of 802 kJ kg^{-1} H_2O evaporated at 180 °C and a power demand of 29 kJ_{el} kg^{-1} H_2O evaporated based on Heyne et al. (2011).

3.2 The heat recovery steam cycle

A heat recovery steam cycle with four pressure levels was used in this study. The different cases of operational parameters for the HRSC are presented in Table 1. Backpressure at 0.95 bar represents heat delivery to a district heating net (90/45 °C), whereas 2.5 bar represents utilisation in an industrial process. The heat exchanging with syngas for superheating steam was limited to a temperature of 450 °C since higher temperatures will damage the heat exchangers (Martelli et al., 2012). In Case S4 some of the SNG was used for additional superheating, thereby allowing for higher steam data. The tolerable amount of water at turbine outlet was set to 12 %. The number of annual operational hours was set to 8,000 for the SNG and power production and 8,000 or 5,500 for the heat delivery to the district heating net, representing base load or middle load production.

3.3 The GHG emission reductions

The impact of the differences in product mix on the GHG emission reduction potential is illustrated through evaluation of two cases; S1 and S3. In Case S1 the HRSC is operated in condensing mode maximizing the net power production, whereas in Case S3 the backpressure heat is used for separating the CO_2 from the flue gases of the combustor. The fuel emission factors used in the GHG emission evaluation were; 21.8 kg $CO_{2\,eq}$ MWh^{-1} for forest residues, based on the scenario of wood

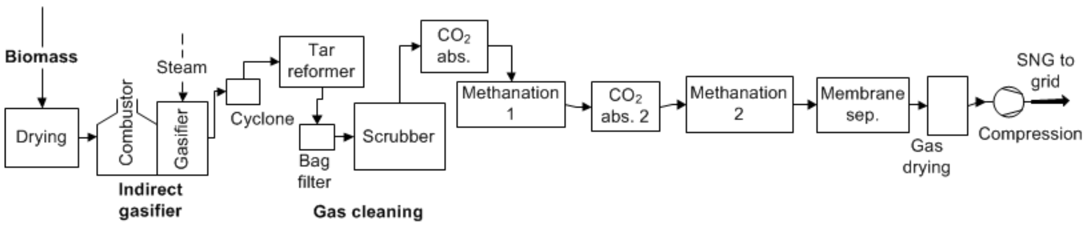

Figure 1: Flow sheet of biomass gasification based SNG production and final upgrading to grid quality

Table 1: Case description

Case	Turbine inlet data (T, P)	Mode	Biomass drying
S1	450 °C, 60 bar	Condensing	Process integrated steam drying
S2	450 °C, 60 bar	Backpressure 0.95 bar,	
S3	450 °C, 60 bar	Backpressure 2.5 bar	
S4	600 °C, 115 bar	Condensing	
O1	450 °C, 60 bar	Condensing	Off-site drying
O2	450 °C, 60 bar	Backpressure 0.95 bar	

chips in southern Sweden by Lindholm et al. (2010b) for soil carbon impact, and Lindholm et al. (2010a) for production and distribution (with an updated transportation distance to 100 km) and Gode et al. (2011) for combustion; 285.8 kg $CO_{2\,eq.}$ MWh^{-1} for gasoline and 249.5 kg $CO_{2\,eq.}$ MWh^{-1} for natural gas based on Gode et al. (2011). The emission factors used for the reference power production were: 925 kg $CO_{2\,eq.}$ MWh_{el}^{-1} for coal condensing power without CCS and 295 kg $CO_{2\,eq.}$ MWh_{el}^{-1} with CCS and 417 kg $CO_{2\,eq.}$ MWh_{el}^{-1} for NGCC production based on Axelsson and Pettersson (2014). All emission factors have been updated with the GWP_{100} factors from IPCC, (2007). The CO_2 sent for storage is pressurized to 75 bar and the power demand for compression is 0.11 MWh $kton^{-1}$ CO_2 based on Heyne and Harvey (2014). Emissions during transport or storage of the CO_2 were not considered. The MEA absorption unit employed for the flue gas separation has the same specific heat demand, 3.7 MJ kg^{-1} CO_2 at 115 °C, as the unit used in the syngas section, but with a separation efficiency of 90 % instead of 95 % due to the lower CO_2 concentration in the flue gases.

4. Results

The pinch analyses, Figure 2, show that there is a significant difference in high temperature excess heat, 78 MW and 87 MW for the cases of onsite and off-site biomass drying respectively. This increases the power production in the HRSC by 5.4 MW (15 %) compared to the steam drying case (Case S1 and O1 in Figure 3). By using 38 MW of the SNG (total production 298 MW) for additional superheating, the power

production can be increased by over 50 % (S1 and S4 in Figure 3), corresponding to a marginal power production efficiency of 55 %. With only a slight reduction, 4 MW, in power production ~ 60 MW of heat for district heating can be produced (which means either 350 or 500 GWh depending on whether it is middle load or base load production).
In the cases with off-site biomass drying (O1 and O2) the energy demand for drying was ignored. This is justified by the assumption that the biomass is dried by excess heat with no alternative use.

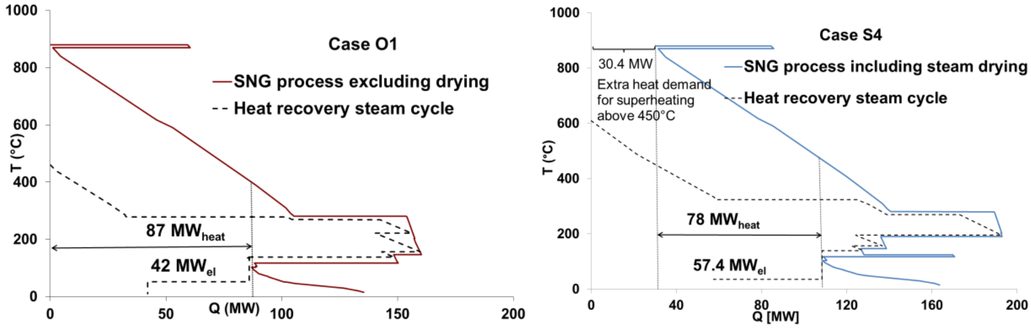

Figure 2: Left; split GCC for the SNG process (without biomass drying) and an HRSC. Right: split GCC for the SNG process with steam drying. Extra heat is used for superheating the steam in the HRSC

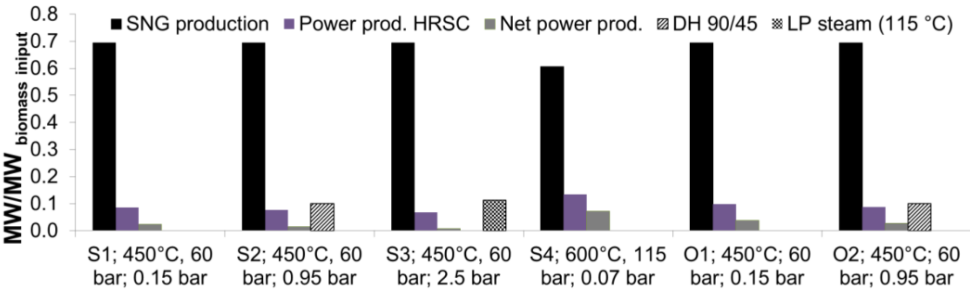

Figure 3: Conversion efficiencies for products in the SNG production system for cases with different operating parameters of the HRSC and biomass drying alternatives

The analysis shows that one third of the carbon input to the gasifier ends up in the SNG (Table 2). In Case S3 where the backpressure is at a higher level, the available heat 48 MW (Figure 3), matches the demand (46 MW at 115 °C) for separating the CO_2 from the flue gases well. Figure 4 shows the contribution to reduced GHG emissions by product for Case S3 (with) and Case S1 (without CO_2 storage). Total GHG emission reductions differ only slightly with reference power production technology, mainly because the net power production in each case is small. In the case without CO_2 storage, the main contribution to reduced GHG emissions is provided by the SNG substituting fossil fuels. CO_2 storage has the potential to double the GHG emission reduction of the system. Systems with CO_2 storage show GHG reductions of the same magnitude as for biomass replacing coal in condensing coal power plants.

5. Discussion and conclusions

The electricity production potential of the HRSC is in line with the estimate for a similar system given by Heyne et al. (2010) based on Carnot representation. The district heating production potential of ~60 MW identified for the system in this study could be compared to the base load of a large district heating system such as at the suggested localisation in Gothenburg, which has a summer time (June-August) base load production of ~70-120 MW. If the excess heat from the gasification system cannot outcompete other base load production units, industrial use of the excess heat will mean a higher number of annual delivery hours and even if requiring higher temperatures (as in our case) the total amount of delivered heat will be higher. This will result in higher revenues and most likely also greater reduction in GHG emissions since industries importing the steam will save fuel. The carbon analysis in this study shows a higher amount of input carbon ending up in the flue gases (29 %) compared to the results by Carbo et al. (2011) (20 %) in their analysis of a 500 MW$_{th}$ BioSNG plant. Storage of separated CO_2 can, under the conditions of this study, double the GHG emission reductions from the bio-SNG production systems. However, separating the CO_2 from the flue gases will require additional investments in equipment whereas the CO_2 separation from the process stream is necessary in any case. From a systems perspective it will be less important for the total GHG reductions if the SNG replaces natural gas or gasoline when CO_2 from the system can be stored. Currently there is no infra-

Table 2: Distribution of carbon in the gasification system products (percentage of total input)

Carbon in SNG-product	Carbon in flue gases	Carbon in separated CO_2 before methanation	Carbon lost in scrubber or gas-cleaning membranes
34.8 %	29.4 %	35.4 %	0.5 %

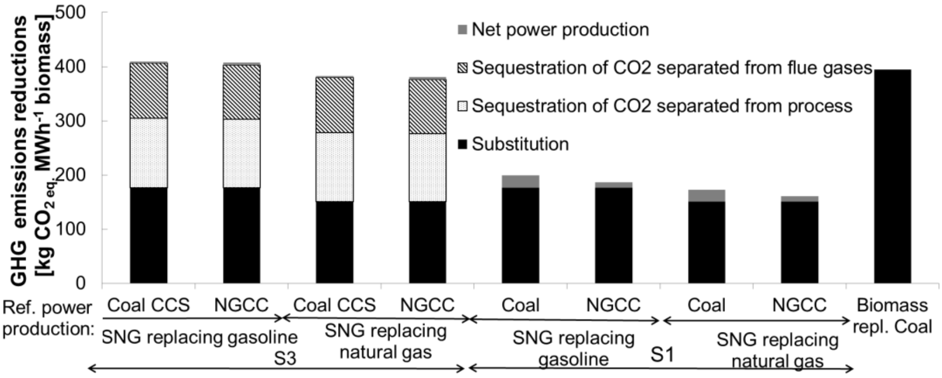

Figure 4: The GHG emission reductions with and without storage of separated CO_2 and for different reference power production technologies and fuels substituted by the SNG. The rightmost staple displays the reduction potential for using the biomass to replace coal in a condensing power plant

structure for CO_2 storage but locating the bio-SNG plant in an industrial cluster together with other large sources of CO_2 emissions increases the potential for future investments in such infrastructure.
Future studies should evaluate the GHG emission impact and economy of all the investigated configurations to reveal the importance of the surrounding system in terms of heat sinks, infrastructure for biomass transportation and drying, CO_2 transportation and storage etc. Such analysis will improve the knowledge of conditions for appropriate localisation of large scale biomass gasification systems.

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References

Axelsson E., Pettersson K., 2014, Energy price and Carbon Balances Scenarios tool (ENPAC) – a summary of recent updates, Chalmers University of Technology, Göteborg, Sweden.

Carbo M.C., Smit T.R., Van der Drift B., Jansen D., 2011, Bio energy with CCS (BECCS): Large potential for BioSNG at low CO_2 avoidance cost, Energy Procedia, 4, 2950-2954.

Gassner M., Marechal F., 2012, Thermo-economic optimisation of the polygeneration of synthetic natural gas (SNG), power and heat from lignocellulosic biomass by gasification and methanation, Energy & Environmental Science, 5, 5768-5789.

Gerber L., Gassner M., Maréchal F., 2011, Systematic integration of LCA in process systems design: Application to combined fuel and electricity production from lignocellulosic biomass, Computers & Chemical Engineering, 35, 1265-1280.

Gode J., Martinsson F., Hagberg L., Öman A., Höglund J., Palm D., 2011, Miljöfaktaboken 2011 - Estimated emission factors for fuels, electricity, heat and transport in Sweden (in Swedish), Report no 1183, Värmeforsk, Stockholm, Sweden.

Heyne S., Harvey S., 2014, Impact of choice of CO_2 separation technology on thermo-economic performance of Bio-SNG production processes, Int. J. Energy Res., 38, 299-318.

Heyne S., Seemann M., Harvey, S, 2010, Integration study for alternative methanation technologies for the production of synthetic natural gas from gasified biomass, Chemical Engineering Transactions, 21, 409-414.

Heyne S., Thunman H., Harvey S., 2011, Extending existing CHP plants for SNG production - a process integration study, International Journal of Energy Research, 36, 670-681.

Holmgren K.M., Andersson E., Berntsson T., Rydberg T., 2014, Gasification-based methanol production from biomass in industrial clusters: characterisation of energy balances and greenhouse gas emissions, Energy, 69, 622-637.

IPCC, 2007, Climate Change. The physical science basis, Contribution of working group 1 to the 4th assessment report of the International Panel on Climate Change, Cambridge University Press. Cambridge, UK.

Lindholm E.-L., Berg S., Hansson P.-A., 2010a, Energy efficiency and the environmental impact of harvesting stumps and logging residues, European Journal of Forest Research, 129, 1223-1235.

Lindholm E.-L., Berg S., Hansson P.-A., 2010b, Harvest of biofuels from a life cycle perspective (in Swedish), Dep. Energy and Technology, Swedish University of Agricultural Sciences, Report no 023, Uppsala, Sweden.

Martelli E., Nord L.O., Bolland O., 2012, Design criteria and optimization of heat recovery steam cycles for integrated reforming combined cycles with CO_2 capture, Applied Energy, 92, 255-268.

Smith R. 2005. Chemical process design and integration, John Wiley & Sons, Chichester, UK.

Steubing B., Ballmer I., Gassner M., Gerber L., Pampuri L., Bischof S., Thees O., Zah R., 2014, Identifying environmentally and economically optimal bioenergy plant sizes and locations: A spatial model of wood-based SNG value chains, Renewable Energy, 61, 57-68.

Steubing B., Zah R., Ludwig C., 2011, Life cycle assessment of SNG from wood for heating, electricity, and transportation, Biomass & Bioenergy, 35, 2950-2960.