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Integration Opportunities for Substitute Natural Gas (SNG) Production in an Industrial Process Plant

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This paper investigates opportunities for integration of a Substitute Natural Gas (SNG) process based on thermal gasification of lignocellulosic biomass in an industrial process plant currently importing natural gas (NG) for further processing to speciality chemicals. The assumed SNG process configuration is similar to that selected for the ongoing Gothenburg Biomass Gasification demonstration project (GoBiGas) and is modelled in Aspen Plus. The heat and power integration potentials are investigated using Pinch Analysis tools. Three cases have been investigated: the steam production potential from the SNG process excess heat, the electricity production potential by maximizing the heat recovery in the SNG process without additional fuel firing, and the electricity production potential with increased steam cycle efficiency and additional fuel firing.
The results show that 217 MW_{LHV} of woody biomass are required to substitute the site's natural gas demand with SNG (162 MW_{LHV}). The results indicate that excess heat from the SNG process has the potential to completely cover the site's net steam demand (19 MW) or to produce enough electricity to cover the demand of the SNG process (21 MW_{el}). The study also shows that it is possible to fully exploit the heat pockets in the SNG process Grand Composite Curve (GCC) resulting in an increase of the steam cycle electricity output. In this case, there is a potential to cover the site's net steam demand and to produce 30 MW_{el} with an efficiency of 1 $MW_{el}/MW_{added\ heat}$. However, this configuration requires combustion of 36 MW_{LHV} of additional fuel, resulting in a marginal generation efficiency of 0.80 MW_{el}/MW_{fuel} (i.e. comparing the obtained electricity production potentials with and without additional fuel firing).

1. Introduction

The biorefinery concept (i.e. the conversion of biomass into value-added products such as motor fuels, energy, and chemicals) is an interesting option for the refining and chemical industry to reduce their fossil feedstock dependence and to decrease greenhouse gas emissions. Since biomass is a limited resource, its high utilisation efficiency is of utter importance. The largest chemical process cluster in Sweden (consisting of six process sites producing a variety of different chemical products) is located in Stenungsund, on the West Coast of Sweden. The cluster has recently adopted a vision to increase its energy efficiency and to reduce its fossil feedstock dependence. One specific goal is to increasingly switch to biogenic feedstock, which implies substituting traditionally fossil-derived material flows by the introduction of the biorefinery concept. The cluster currently features high material integration between the different production sites, and the core process is a steam cracker plant producing ethylene and propylene from fossil feedstock, mainly naphtha (Hackl and Harvey, 2010). Investigation of the material flows exchanged within the cluster (e.g. ethylene, propylene, and natural gas) indicates that there are

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several opportunities to substitute traditionally fossil-derived feedstock/intermediate chemicals/final products by introducing biorefinery concepts. Integration of a biorefinery in an existing industrial cluster offers process integration opportunities with clear economic benefits. For example, efficient material and heat exchange possibilities appear, as well as the possibility to make use of existing infrastructure.
The cluster considered in this paper currently purchases grid natural gas for use in boilers and as feedstock for speciality chemicals production. This paper investigates integration opportunities (i.e. potentials for heat recovery in the SNG process for heat and power generation) for substitute natural gas (SNG) production based on thermal gasification of lignocellulosic biomass in one of the production plants processing 95 kt/y of natural gas (Hackl and Harvey, 2010) into speciality chemicals (via synthesis gas production in a Methane-Steam Reformer (MSR)). The SNG process is sized to exactly meet the methane gas requirements of the site, i.e. to fully substitute the current natural gas feed to the MSR. This approach implies only minimum changes to the existing core process. Furthermore, the natural gas grid can serve as a back-up/buffer in case of problems with the SNG process. The site has an electricity demand of approximately 10 MW_{el}. Furthermore the site has a steam demand currently supplied partially by excess heat from the chemical process and partially by a boiler firing process off-gases and extra fuel. The site's average net steam demand (LP steam at 3 bar level), currently produced using fuel gas imported from a neighbouring steam cracker plant, is 19 MW.

2. Methodology

This work is conducted as a case study, investigating opportunities of integrating a SNG process into an existing industrial process plant. The methodology is similar to that used in previous studies dealing with conceptual design of an SNG process (Gassner and Maréchal, 2009). Similar work investigating integration opportunities of biorefinery concepts into existing sites, e.g. between a similar SNG process and a biomass-fired Combined Heat and Power (CHP) plant (Heyne et al., 2012) or between a gas turbine, methanol, and Fischer-Tropsch (FT) synthesis and a mechanical pulp and paper mill have also been published (Isaksson et al., 2011).

2.1 Mass and energy balances of the substitute natural gas (SNG) process

In order to solve energy and material balances the SNG process is modelled in Aspen Plus based on the design concept of the Gothenburg Biomass Gasification project (GoBiGas) phase 1, currently under construction and aiming at a production of 20 MW_{LHV} of SNG by 2013 (Gunnarsson, 2011). The process is basically a combination of the Güssing gasification concept (i.e. indirect steam gasification) (Hofbauer and Rauch, 2000) and the Haldor Topsøe gas cleaning and upgrading concept (Haldor Topsøe, 2009). In addition to the GoBiGas phase 1 design a low-temperature air dryer (based on a model developed by Holmberg and Ahtila (2005)) is assumed in this study. Figure 1 shows the SNG process configuration together with the main assumptions used in this paper. It is worth noticing that in this representation heat sources and sinks are indicated separately, i.e. the figure does not include any assumptions about the possible lay-out of the heat exchanger network. The gasification of the dried biomass is modelled using a Gibbs equilibrium reactor with a steam-to-biomass ratio set to 0.5. The carbon conversion is set to match the energy requirements of the endothermic gasification reactions. In order to consider equilibrium deviations and to obtain a realistic product gas composition the formation of tars (3.5 g/Nm^3) and methane (10 vol%) are fixed (Hofbauer and Rauch, 2000). The biomass nitrogen, chlorine and sulphur are additionally assumed to be fully converted into ammonia, HCl, and H_2S respectively. After the gasification section the product gas is cooled and solid particles are separated in a fabric filter. After further cooling the tars are assumed to be removed in a bio-oil scrubber (0.025 $MW_{bio\text{-}oil}/MW_{SNG}$) (Gunnarsson, 2011). The gas is then compressed and sent through an amine wash to remove H_2S with 96 % removal efficiency using MDEA as solvent (Fiaschi and Lombardi, 2002). The specific energy demand for the H_2S separation is set to 3.33 MJ/kg absorbed (Götz et al, 2012). To maximize conversion of syngas into methane, the H_2/CO-ratio is first adjusted to 3 in a partial shift reactor which is modelled based on assumptions from Hamelinck et al. (2002). To provide the chemical production site with high quality SNG that meets natural gas grid specifications, CO_2 removal through another similar amine wash is assumed. The methanation is modelled as three adiabatic reactors in series with intercooling and a recycle on the first reactor which has the purpose of controlling the gas outlet temperature. Steam is added (to reach a mole fraction of 0.2) to the first

reactor in order to prevent carbon formation. The remaining water is removed by gas cooling with knock-out of the condensed water followed by a temperature swing adsorption process removing 98 % of the water. Aluminium oxide is used as adsorbing medium, with a regeneration heat demand of 11 MJ/kg H_2O separated (Bart and von Gemmingen, 2000). Finally the SNG is compressed to natural gas grid pressure.
The model results show that 217 MW_{LHV} of woody biomass (50 % moisture) are required to substitute the site's natural gas demand (12 t/h,162 MW_{LHV}) with SNG, corresponding to a wood-to-SNG efficiency of 66 %. The electricity demand for the SNG process is estimated at 21 MW_{el} (accounting for power requirements for compressors and blowers and other auxiliaries estimated at 2 % of the gasifier thermal load (Steinwall et al., 2002)).

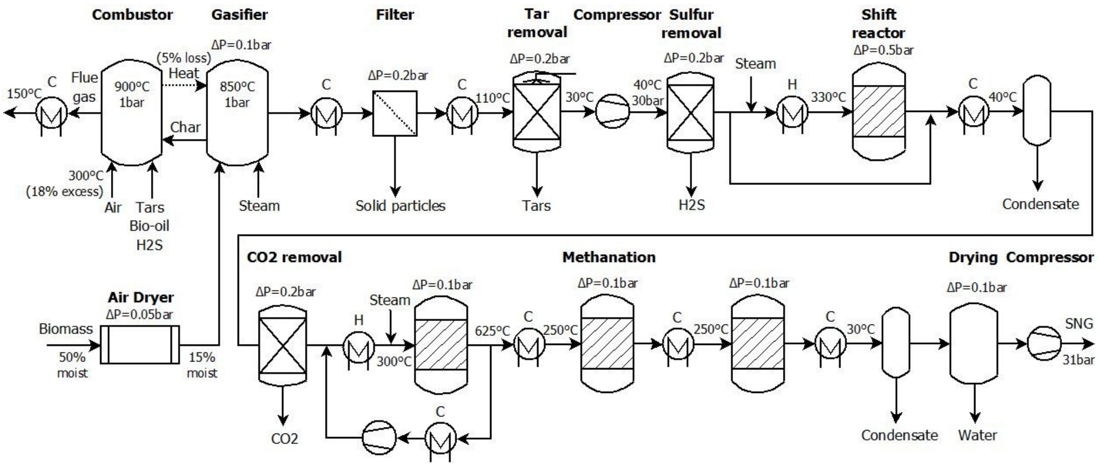

Figure 1: The SNG process configuration. Stream cooling requirements (heat sources) are noted with C, and streams requiring heating (heat sinks) are noted with H. The pressure drop for heating and cooling is assumed to be $\Delta P/P$ = 2 %.

2.2 Heat integration

The SNG process consists of several process steps requiring heating or cooling at various temperature levels. Pinch analysis tools are used in order to estimate targets for maximum heat recovery between process heat sources and sinks (Smith, 2005). In this work a global minimum temperature difference (ΔT_{min}) of 10 °C is used.
To illustrate the aggregated energy availability/deficit versus the process temperature level for the cases investigated, the Grand Composite Curves (GCCs) are constructed. In order to investigate the possibility of steam production and the integration of an additional heat recovery steam cycle the background/foreground (BGFG) graphical analysis concept is used. The heat integration potential (and the maximum steam cycle net power production) between the SNG process and the steam cycle are identified by activating at least one pinch point between the two process GCCs (Maréchal and Kalitventzeff, 1996). In other words, by applying the BGFG concept the potential of recovering heat in the SNG process for steam and electricity production are identified and consequently the extra fuel- and net electricity demand of the site integrated with the SNG process are estimated. The steam turbine inlet data assumed for the steam cycle are 80 bar, 530 °C. Assumed values for turbine and pump isentropic efficiencies are 0.85 and 0.80. The steam extraction and turbine outlet pressures are chosen to match the corresponding levels of the background process steam demands.

3. Results

3.1 Case 1 – Investigation of the steam production potential from SNG process excess heat

Pinch analysis results indicate that the SNG process has a minimum cooling demand ($Q_{C,min}$) of 21 MW available at a high temperature level, see Figure 2. This high temperature excess heat can be used to produce steam and/or electricity. These potentials are highlighted in a background/foreground (BGFG) analysis shown in Figure 2. The left side figure shows how excess heat from the SNG process (solid line) can be used to cover the site's LP steam demand (19 MW at 3 bar level, see dashed line in the figure). This arrangement could eliminate the site's current purchased fuel usage for LP steam production. The total electricity demand is 31 MW_{el} (21 MW_{el} for the SNG process + 10 MW_{el} for the background process).

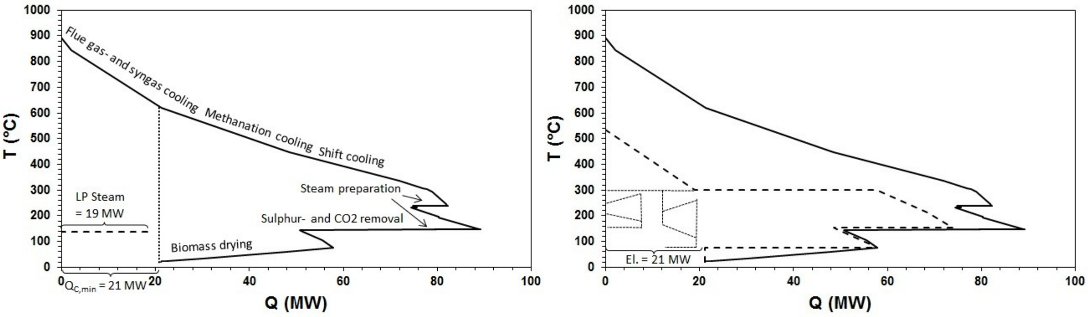

Figure 2: Background/foreground analysis - Integration between the SNG process sized to substitute the site's natural gas usage and the site's net steam demand (Case 1) (left), or a back-pressure steam cycle sized for maximum power generation from the available excess heat (Case 2) (right).

3.2 Case 2 – Investigation of the electricity production potential without additional fuel firing

The electricity production potential that can be achieved by maximizing the recovery of heat from the SNG process without additional fuel firing, is investigated by matching the GCC of a back-pressure steam cycle (dashed line) against the SNG background process (solid line), see Figure 2 (right). The steam cycle is sized to maximize the expansion to LLP steam, i.e. reaching full exploitation of the bottom pocket, and the LP steam extraction is a result of maximum heat recovery from the SNG process without adding extra fuel (i.e. $Q_{H,min}$ = 0 MW). The BGFG analysis indicates that it is theoretically possible to generate 21 MW_{el} by integrating a steam cycle with the SNG process with maximum heat recovery and without additional fuel firing. The SNG process can accordingly be considered self-sufficient concerning its electricity demand (21 MW_{el}). However, according to the results no net surplus electricity production can be obtained without firing extra fuel. Comparing Case 1 and Case 2, the results indicate that there is a potential for the SNG process to either reduce the site's current extra fuel demand (by producing LP steam) or to produce enough electricity to cover its own electricity demand.

3.3 Case 3 – Investigation of the electricity production potential with increased steam cycle efficiency and additional fuel firing

In order to take maximum advantage of the heat pockets in the SNG process GCC, the integration of a larger steam cycle allowing additional fuel firing is investigated. The site's net steam demand (19 MW at the temperature level of the heat receiving process, i.e. the minimum temperature difference is taken into account) is additionally included in the background process data. Accordingly the steam cycle is sized to maximize the exploitation of the background process heat pockets (at 4 pressure levels). Figure 3 illustrates the BGFG analysis of the SNG process and the site's net steam demand (solid line) and the steam cycle (dashed line). The results indicate that Case 3 has a minimum heating demand ($Q_{H,min}$) of 28 MW and an electricity production of 30 MW_{el}. This means that by fully exploiting of the electricity generation potential of the background process heat pockets an additional 2 MW_{el} compared to added heat can be produced, resulting in a potential to produce just over 1 $MW_{el}/MW_{added\ heat}$. Therefore, Case 3 results in a net electricity demand of the site integrated with the SNG process of approximately 0 MW_{el} (10+21-30). The configuration used in Case 3 has the potential to eliminate the site's current extra fuel demand for LP steam production, however an extra fuel demand of 36 MW_{LHV} (assuming a boiler efficiency of 0.8) is required to cover the arising heat demand of the steam cycle. Comparing Case 2 and Case 3 a marginal generation efficiency of 0.80 MW_{el}/MW_{fuel} is obtained.

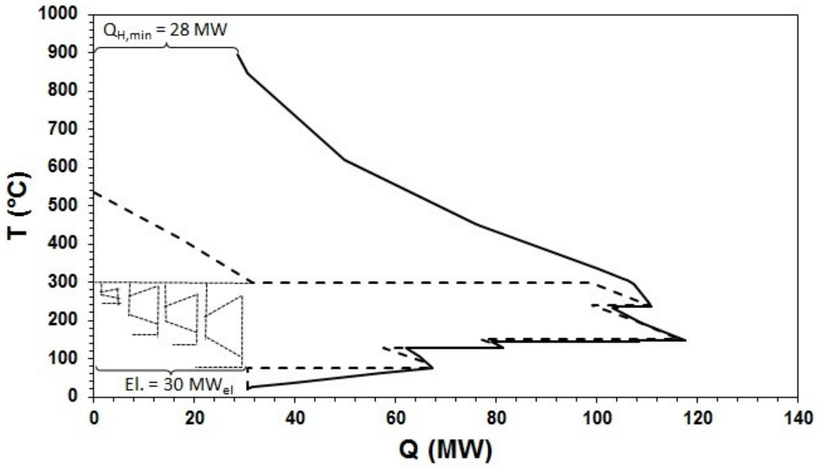

Figure 3: Background/foreground analysis – Integration between the SNG process sized to substitute the site's natural gas usage and a back-pressure steam cycle sized to cover the SNG and host site steam requirements and achieve maximum cogeneration (Case 3)

3.4 Summary of results

The results are summarized in Table 1.

Table 1: Results for the investigated cases. The current situation at the site is also presented. a) feed to the MSR unit, b) net electricity demand after covering the electricity consumption of the site and the SNG process , c) extra fuel demand for LP steam production and/or firing for steam cycle heat requirement assuming a boiler efficiency of 0.80.

		Current	Case 1 (Steam)	Case 2 (Electricity)	Case 3 (Steam & Electricity)
Biomass input (50 % moisture)	MW_{LHV}	-	217	217	217
Gasifier load (15 % moisture)	MW_{LHV}	-	244	244	244
SNG production	MW_{LHV}	-	162	162	162
SNG process electricity demand	MW_{el}	-	21	21	21
Site electricity demand	MW_{el}	10	10	10	10
NG demand[a]/SNG production	t/h	12	0/12	0/12	0/12
LP steam demand/production	MW	19	0/19	19/0	0/19
Net electricity demand[b]/el. production	MW_{el}	10	31/0	10/21	0/30
Extra fuel[e] demand	MW_{LHV}	24	0	24	36

4. Concluding discussion

In order to substitute the site's natural gas usage (12 t/h) with SNG (162 MW_{LHV}), 217 MW_{LHV} of woody biomass (50% moisture content) are required. If an SNG process with this output is implemented at the site, there are a number of different options for harnessing the excess heat flows from the SNG process. One option is to use SNG process excess heat to produce enough steam (19 MW) to eliminate the site's current purchased fuel demand (24 MW_{LHV}). However, given that the SNG process has a high electricity requirement (21 MW_{el}) this will increase the site's net electricity demand from 10 MW_{el} to 31 MW_{el}. Another opportunity is to harness the excess heat to drive a back-pressure steam cycle sized to produce enough electricity to cover the SNG process electricity demand (21 MW_{el})

leading to an unchanged net site electricity demand and purchased fuel demand compared to the current situation at the site.
The electric power generation output can be further increased by fully exploiting the integration opportunities offered by the heat pockets in the SNG process GCC expanded to include the steam demand of the remainder of the host site. In this case the power output of the steam cycle is increased but additional fuel must be fired in the boilers to meet the heat demand of the steam cycle. The results show that there is a potential to cover the site's net steam demand and to produce enough electricity to reduce the net electricity demand to approximately 0 MW_{el}. This indicates that there is a potential to produce just above 1 $MW_{el}/MW_{added\ heat}$. However, to achieve this 36 MW_{LHV} of extra fuel are required. The results show that by comparing the electricity production potential (i.e. maximum heat recovery of the background process) with and without additional fuel firing a marginal generation efficiency of 0.80 MW_{el}/MW_{fuel} is obtained.

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