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Extending existing CHP plants for SNG production – a process integration study

Stefan Heyne, Henrik Thunman, Simon Harvey

Abstract

In this work, integration of a synthetic natural gas (SNG) production process with an existing biomass CHP steam power cycle is investigated. The paper assesses two different biomass feedstock drying technologies – steam drying and low-temperature air drying – for the SNG process. Using pinch technology, different levels of thermal integration between the steam power cycle and the SNG process are evaluated. The base case cold gas efficiency for the SNG process is 69.4% based on the lower heating value of wet fuel. The isolated SNG-related electricity production is increased by a factor of 2.5 for the steam dryer alternative, and tenfold for the low-temperature air dryer when increasing the thermal integration. The cold gas efficiency is not affected by the changes. Based on an analysis of changes to turbine steam flow, the integration of SNG production with an existing steam power cycle is deemed technically feasible.

Keywords: Synthetic natural gas, process integration, biofuels, energy systems, modelling

Nomenclature

Abbreviations

CFB	circulating fluidized bed
CHP	combined heat and power
DH	district heating
FICFB	Fast internally circulating fluidized bed
LHV	lower heating value
SNG	synthetic natural gas
WGS	Water-gas-shift reaction
ΔT_{min}	minimum temperature difference

Indices

boil	boiler
el	electricity
is	isentropic
mech	mechanical
T	turbine
q	heat

Symbols

h	enthalpy
η	efficiency
$\dot{m}$	mass flow
P	pressure / power
$\dot{Q}$	thermal duty
s	entropy
v	average volume flow

1. *Introduction*

Biofuels are considered as an important tool for achieving reduction of anthropogenic greenhouse gas emissions on an intermediate time scale, in particular within the transport sector. A recent study within the Swedish context (Lindfeldt et al., 2010) on the opportunities for an import-independent transport system showed that biofuels can constitute between one quarter and half of all transport energy supply in 2025, with renewable electricity being even more important on the supply side. One of the alternatives among biofuels for transportation is synthetic natural gas (SNG) from thermal gasification of biomass. Even though transportation is considered a niche application for fossil natural gas, it is a very interesting application for SNG from renewable sources, with future gas engines estimated to be as efficient as – or even outperforming – Diesel engines in a hybrid setup according to a European well-to-wheel study (Edwards et al., 2007). Potential advantages of SNG compared with other biofuels are the synergy effect with biogas produced via digestion from a marketing perspective, and its large versatility considering potential applications in many sectors. In addition, SNG can be distributed using the existing infrastructure for fossil natural gas, thereby enabling a smooth transition from fossil to renewable fuels.

Several research projects are investigating the SNG production process on both an experimental and a modelling level [3-12]. In Güssing/Austria the most prominent indirect biomass gasification demonstration plant – the fast internally circulating fluidised bed (FICFB) gasifier – has been developed (Hofbauer, 2005; Hofbauer et al., 2002). The plant was designed for combined heat and power (CHP) production, converting the clean product gas to electricity and heat in internal combustion engines. Based on a slip-stream from the product gas, methanation to SNG was demonstrated on a pilot scale (Seemann et al., 2004), and recently scaled up to a 1 MW demonstration plant for SNG production (Rauch, 2009). However, very few data on the technical design of the plant are available in the open literature.

Gassner and Maréchal (2009) developed a thermo-economic model for production of SNG based on a superstructure combining various candidate technologies for the different steps in the production process. The model can be used in connection with multi-objective optimization using genetic algorithms for the determination of the most promising process chains. For the different process alternatives, energy efficiencies in the range of 69-76% were obtained, while exergetic efficiencies were estimated to 63-69%. These efficiencies are based on the lower heating value (LHV) and a wet fuel basis. Unless otherwise stated, the same basis of evaluation will be used throughout this paper.

Another consortium working with SNG production is the Energy Research Centre (ECN) in the Netherlands. ECN scaled up its allothermal (or indirect) MILENA gasification technology to a pilot scale of 800 kW_{th} and is investigating the complete gas cleaning and treatment chain for production of SNG (van der Drift et al., 2005; van der Meijden et al., 2009). Van der Meijden et al. (2010) modelled three different gasification technologies and compared their net overall efficiency on an input/output basis. The fuel input was assumed to be at 15 wt-% moisture content, the drying step not being considered in the systems studied.

Allothermal steam gasification was identified as the best technology, with an overall efficiency of 67% based on the LHV of the dry fuel (15 wt-% moisture).

An exergetic analysis of allothermal gasification for SNG production (Jurascik et al., 2010) identifies the gasifier, methanation step and CO_2 separation unit as the largest sources of losses. The overall exergetic efficiency of the process on a dry fuel basis (13.8 wt-%) – comparing the exergetic value of produced SNG, steam and additional excess heat to all exergetic input (fuel & electricity) – is shown to vary from 69.5 to 71.8% for different gasification conditions (650-800ºC and 1-15 bar).

Concerning industrial scale production of SNG, a plant producing 20 MW_{LHV} of SNG from biomass is planned to be in operation in 2012 in Gothenburg/Sweden (Gunnarsson, 2009). The plant is based on the Güssing demonstration plant to a large extent. Based on the experience from this plant, improvements are to be implemented in the second plant extending the capacity to 100 MW_{LHV} by 2016. The first-stage plant will only produce heat as a by-product, but for the large-scale plant combined heat and power production making use of the available process excess heat is envisaged.

To accomplish profitable operation of an SNG production plant, an efficient use of the available process excess heat is indispensable. A number of published modelling studies assume a steam turbine power cycle connected to the SNG process for production of electricity (Gassner and Maréchal, 2009; van der Meijden et al., 2010). Recently, a concept for extending existing fluidised bed biomass boilers with a gasification unit for indirect gasification has been proposed and demonstrated in pilot scale at Chalmers University of Technology in Gothenburg, Sweden (Thunman and Seemann, 2009). This concept makes it possible to use existing infrastructure in the form of CHP steam power plants for integrating SNG production using the existing steam power cycle for converting the process excess heat into electricity at high efficiency.

This study investigates such an integration of the SNG process with an existing biomass CHP steam power plant delivering heat to a district heating network. The CHP plant is assumed to be equipped with a flue gas condensation unit. The study focuses on the influence of the level of thermal integration on electricity and heat production. The SNG production will not be influenced by changes in thermal integration, as the process itself remains unchanged. The two processes are analysed and thermally integrated to varying degrees using pinch technology. Possible integration of two different biomass feedstock drying technologies – steam and low-temperature air drying – within the SNG process is assessed. The two alternative drying technologies result in different amounts and temperature levels of heat demand/excess, and thereby in different opportunities for integration with the steam power cycle. The main objective of this study is to evaluate the change in process performance due to varying levels of integration, with particular focus on the electricity production related to the SNG process. The energy conversion performance for electricity and district heat production related to the SNG process is measured by introducing appropriate performance indicators. Practical integration issues concerning the integration of the two processes, such as changes in steam flow through the turbines within the steam cycle, are analysed and discussed.

2. Methodology

2.1 Process integration study

The integration of the SNG production process with the biomass CHP power plant is investigated using pinch technology. Pinch technology is based on the first and second laws of thermodynamics and refers to the combination of pinch analysis and process design based on pinch rules. It is widely used for determining the minimum heating and cooling demand of various industrial processes and for identifying potential process improvements. The basics of pinch analysis have been developed by Linnhoff et al. (1994). Significant improvements of process efficiency can be achieved using this methodology, as demonstrated by earlier studies within the biomass processing industry (Andersson and Harvey, 2007; Andersson et al., 2006). To get an estimation of the process heat streams, models for the two processes have been built using the flowsheeting software ASPEN Plus®. The property methods used for the thermodynamic calculations are the Peng-Robinson cubic equation of state (Peng and Robinson, 1976) with the Boston-Mathias alpha function extension (Mathias et al., 1991) (PR-BM) for all processes involving gaseous streams, and 1984 NBS/NRC steam table correlations for thermodynamic properties (Haar et al., 1984) (STMNBS) for the water/steam streams.

In pinch analysis (Kemp, 2007) an individual contribution to the minimum temperature difference is assigned to each heat stream, accounting for the necessary temperature driving force between streams to enable heat transfer with reasonable heat exchanger surface areas. This individual contribution $\Delta T_{min}/2$ is the basis for the construction of the composite curves representing the overall process heat balance, and can be subject to economic optimisation, but is kept at fixed values for each type of stream in this study. $\Delta T_{min}/2$ is set to 20, 10, 5 and 2.5 K for reactor heating, gaseous, liquid and condensing/boiling streams, respectively. Applying this $\Delta T_{min}/2$ for all streams, it is possible to obtain a heat stream representation of the process showing the process minimum external heating and cooling demand, as well as the potential for internal heat recovery. This representation has been used for analyzing the thermal integration between the two processes in this study.

Different cases with varying level of thermal integration are analysed for the overall production of SNG, power and district heat. The overall efficiency η_{tot} of the different alternatives is calculated on a LHV basis:

$$\eta_{tot} = \frac{\dot{Q}_{DH} + P_{el} + \dot{Q}_{SNG}}{\dot{Q}_{fuel,CHP} + \dot{Q}_{fuel,SNG}} \quad (1)$$

where $\dot{Q}_{DH}$ is the district heating duty delivered, P_{el} the net electrical power and $\dot{Q}_{SNG}$ the SNG production. $\dot{Q}_{fuel,CHP}$ and $\dot{Q}_{fuel,SNG}$ denote the fuel input to the CHP plant and SNG process, respectively. All efficiencies are calculated on a wet fuel basis that is assumed to be at 50 wt-% moisture.

To isolate the effect of thermal integration on the performance of the SNG process, the electricity and district heat production amounts that can be allocated to the SNG process – $P_{el,SNG}$ and $\dot{Q}_{DH,SNG}$ – are defined as

$$P_{el,SNG} = P_{el} - \dot{Q}_{fuel,CHP} \cdot \eta_{el,CHP} \quad (2)$$

$$\dot{Q}_{DH,SNG} = \dot{Q}_{DH} - \dot{Q}_{fuel,CHP} \cdot \eta_{q,CHP} \quad (3)$$

where $\eta_{el,CHP}$ is the electrical efficiency of the stand-alone CHP plant, and $\eta_{q,CHP}$ its heat efficiency. The heat efficiency relates the useful heat provided by the process – district heat in this case – to the thermal energy input. These definitions, Eqs. (2) and (3), imply the assumption that the efficiency of the CHP steam power plant remains constant for all cases studied.

2.2 Biomass CHP plant

The combined heat and power plant model used for the integration study is based on data for biomass CHP plants reported in Steinwall et al. (2002). The schematic flow sheet layout of the plant is shown in Figure 1. Two steam extractions are used for feed water preheating in the high-pressure section of the turbine. In the low-pressure turbine section, one steam extraction is used for condensate preheating, while a second one heats up the district heating water to its final supply temperature. The steam pressure and temperature at the turbine inlet were set to 140 bar and 540 ºC, respectively, representing standard data for modern biomass CHP plants of the size of 100 MW_{th} fuel input (Wahlund et al., 2000). The turbine isentropic efficiencies for both turbine sections (HP and LP turbine) were determined using an empirical equation based on turbine specifications of the late 1990s according to Savola and Keppo (2005):

$$\eta_{T,is} = 0.023521 \cdot \ln(v) + 0.749538 \quad (4)$$

The average volume flow *v* used in Eq. (4) is defined as

$$v = \frac{\dot{m} \cdot \Delta h_{is}}{P_{in} - P_{out}} \quad (5)$$

where $\dot{m}$ is the mass flow, Δh_{is} the isentropic enthalpy change, and P_{in} and P_{out} the inlet and outlet pressure, respectively.

The value for $\eta_{T,is}$ for each turbine section stage (LP1-3 and HP1-3) was then determined by assuming a constant ratio *dh/ds* along all stages to obtain the final section outlet conditions according to Eq. (4). All modelling assumptions used for representing the CHP cycle are presented in Table 1. The pressure drops in pipes, heat exchangers, and the boiler are not taken into account in the model. Instead, a fraction of 2 % of the boiler load is assumed to be consumed by pumps, fans and other electrical control devices, in addition to the calculated power consumption of the feedwater pumps. The feedstock for both the CHP steam power plant and the SNG process is taken as forest residues with a composition according to Table 2. The resulting performance indicators for the simulated CHP plant are given in Table 3, and a heat flow representation obtained using pinch analysis tools is illustrated in Figure 2. In addition to the heat flows, the power output of the turbine sections is indicated by the dotted line in Figure 2. The solid curve represents the flue gas heat from the boiler, the district heating water heat load, and the air preheating. The steam cycle heat streams are represented by the dashed curve, the upper part being the evaporation and superheating in the boiler. The ridged part of the dashed curve represents the internal preheating steps within the steam cycle, while the two lowest horizontal lines represent the load in the steam condensers for district heat productions (units 7 and 8 in Figure 1). The dotted line is an illustration of the power production in the different turbine segments (HP1-3 and LP1-3). The temperature level of each turbine section represents the corresponding outlet pressure. As illustrated in Figure 2, the heat streams of the air preheating and district heat production by flue gas condensation (units 9 and 10 in Figure 1) have not been considered for integration with the SNG production process, but are considered to be a process internal to the CHP plant.

2.3 SNG production process

The SNG production process suggested in this investigation is a development of former work (Heyne et al., 2008), taking into account the pressure drop in the different process units as well as a feedstock drying step prior to gasification. The main modelling assumptions are given in Table 4. The process consists of an indirect gasification unit followed by tar reforming, two stages of amine-based CO_2 separation and isothermal methanation, and finally compression, H_2-purification by membrane separation and gas drying. A flowsheet of the process is illustrated in Figure 3. The fuel input into the gasifier is matched with the size of the CHP plant power boiler and set to 100 $MW_{th,LHV}$ (20 wt-% moisture content), corresponding to 90.33 $MW_{th,LHV}$ wet fuel input (50 wt-% moisture content) prior to drying. The cold gas efficiency – comparing wet fuel thermal input and SNG energy output on a LHV basis – for the resulting process is 69.4 %.

Two different processes for feedstock drying with interesting potential for thermal integration within the SNG production process have been assessed in this study: steam drying with a heat demand at around 200ºC and a heat recovery condenser resulting in a low net energy demand; and low-temperature air drying, using heat at around 60-70ºC with internal heat recovery. For more details on the drying technology models the reader is referred to Heyne et al. (2009).

2.4 Integration options investigated

Figure 4 illustrates the integration between the SNG process and the steam power cycle. For the thermal integration of the gasification reactor with the existing boiler, the boiler load is assumed to remain constant, resulting in a decreased steam production as the boiler now provides heat to both the steam cycle and the gasification process within the SNG process. At the same time, the biomass fuel input to the boiler is reduced, as additional fuel is supplied in the form of non-gasified char from the gasifier. The reduction of biomass fuel input to the boiler is adjusted to keep the exhaust temperature of the flue gases at the same value as in stand-alone operation. The change in fuel supply to the boiler also influences the flue gas composition and dew point, thereby changing the amount of recoverable heat in the flue gas condenser.

The heat excess and demand within the gas conditioning part of the SNG process allow both for internal heat recovery and for thermal integration with the steam cycle. The thermal integration with the steam cycle is done based on the concept of heat-cascading (Kemp, 2007): process excess heat at high temperature level is used to generate high-pressure steam for the steam power cycle, while lower-pressure steam extractions from the turbine are used to cover heat demands at lower temperature level in the SNG process. The pressure levels of the different steam extraction points in the CHP plant's steam turbine are kept at the same values as for stand-alone operation for all integration cases presented in this study.

3. *Results & Discussion*

In Figs. 5 and 6 the resulting grand composite curves from the pinch analysis for the two different SNG processes are represented with indication of the major heat sources and sinks. Figs. 5 and 6 also illustrate the different degrees of thermal integration that have been assessed within this study. The four cases defined are represented in Table 5. A low level of thermal integration (balancing integration) with the biomass CHP plant implies that the SNG process is making use of internal heat recovery to a very large extent, the integration with the steam cycle only serving to balance the heat demand/excess of the SNG process. For the case of steam drying (case 1A) this implies that only the high-temperature excess heat of the SNG process (light grey shaded area in Figure 5) is used for steam generation, while the remaining process excess heat is used for internal heat recovery. For the air dryer, the low level of integration (case 2A) implies that steam extraction from the turbine is used to cover the low-temperature heat demand (light grey shaded area in Figure 6), and all process excess heat is recovered internally within the SNG process. The high level of integration (cases 1B and 2B) refers to the case where the SNG process heat is used for steam generation as much as possible, using the concept of heat-cascading (dark grey shaded area in Figs. 5 and 6). This means that process excess heat at high temperature from the SNG process is used for high-quality steam generation to a maximum degree. This results in a heat deficit within the SNG process at lower temperature levels, as the internal heat recovery is not possible any more. Therefore, lower-quality steam from the steam cycle is used to cover the SNG process heat demand. By using the concept of heat-cascading, the amount of steam generated will be increased, resulting in higher electricity generation.

As can be seen from the results given in Table 6, the integration of the SNG production process with an existing CHP plant leads to an absolute reduction of both electricity and district heat production for all studied cases. Table 6 also shows that the overall efficiency η_{tot} decreases for all cases. Figure 7 illustrates the fuel input and the resulting products and services for the stand-alone CHP plant and the four cases of integrated SNG production, net electrical power and district heat production for all cases. For an increased thermal integration, the net electricity production increases by 11.8% for the SNG process with steam drying (case 1) and by 21.9% for the low-temperature air drying alternative (case 2). The

SNG production is not influenced by the degree of thermal integration and the drying technology applied, but remains constant at 62.7 MW_{LHV}. It is interesting to observe that the increase in electricity production due to maximum thermal integration is nearly double for the SNG process with air drying compared to the alternative process using steam drying. This increase is obtained at the cost of district heat production that decreases by 6.4 and 8.7% for the two cases. The heat stream representations for both cases with maximum thermal integration (cases 1B and 2B) are illustrated in Figs. 8 and 9. Table 6 also shows that the electrical power production associated with the SNG process $P_{el,SNG}$ increases substantially when increasing the level of thermal integration. In the case of feedstock drying by a steam dryer, the electricity production increases by a factor of 2.5 between the two cases (1A and 1B), while it increases by a factor of more than 10 in case of low-temperature air drying (2A and 2B). The decrease in overall efficiency η_{tot} with increasing thermal integration for both drying alternatives – comparing cases 1A to 1B and 2A to 2B –is therefore not considered as a suitable process performance indicator. Conclusions from former work (Heyne et al., 2009) pointed out steam drying as particularly interesting for internal heat recovery within the SNG process. Based on the results from this study, steam drying results in a higher overall efficiency, but low-temperature air drying can achieve a higher electricity production at maximum thermal integration.

When aiming at further maximising the overall process efficiency, the drying units used in the SNG production processes could be extended and used for drying of the power boiler biomass feedstock that is currently fed at a moisture content of 50 wt-%. Amos [20] estimated the increase in the boiler thermal efficiency to be about 5-15% for a biomass-based power generation system when implementing drying prior to combustion/gasification that would lead to an increased steam production in the power boiler in the current study.

The relative change of volumetric inlet steam flow to the different turbine stages, for the four integration cases studied compared to the conditions for the stand-alone CHP plant, is illustrated in Figure 10. It can be observed that the inlet steam flow variations are around or above 10 % for cases 1A and 2A in the high-pressure turbine and the first stage of the LP turbine, while they are below 10% for the increased thermal integration cases 1B and 2B. The inlet flow into the two last LP turbine stages – their outlet streams supplying heat for the district heating system – is changed to a larger extent, probably making some modifications to the turbine control necessary. It is interesting to infer that for the SNG process with low-temperature air drying, it would be possible to keep the flow through the HP turbine and the first stage of the LP turbine at the same level as for the stand-alone CHP plant. This could be achieved by an intermediate level of integration in between the two extreme cases 2A and 2B. Based on these results, the integration of the SNG process with an existing CHP plant is deemed technically feasible.

An increased thermal integration between the SNG process and the steam power cycle is, of course, associated not only with higher electricity production, but also with increased complexity of the overall process. Greater control complexity is to be expected, and the different sub-systems will be interdependent to a larger degree, making the process more vulnerable to failures. The design of the steam cycle for the thermal integration should aim at recovering a maximum of available process heat from the SNG process, but at the same time needs to have a robust design to still be able to operate in case of shutdown of the SNG process. This could be done, for example, by having a steam generation line parallel to the existing one that is making use of the SNG process heat only, with both lines feeding the existing steam turbine.

4. Conclusions

In this work, the integration of an SNG production process using two alternative drying technologies with an existing CHP steam power cycle has been assessed. For the SNG production alternative using steam drying for feedstock drying, an increased thermal integration leads to an increase in electricity production associated with the SNG process by a factor of 2.5. For low-temperature air drying, the increase in electricity production is more than tenfold. The SNG production of 62.4 MW_{LHV} is not influenced by the changes in thermal integration. The overall efficiency of the integrated processes decreases with increasing thermal integration, and therefore does not well represent the gains in electricity production. Based on a steam flow analysis, the integration of the SNG process with an existing CHP steam power plant showed variations of steam volume flow in the turbine below 10%, and therefore was deemed technically feasible. Using existing energy production infrastructure for the introduction of biofuel production processes – such as SNG – via indirect gasification, therefore, represents an interesting opportunity for energy-efficient production making maximum use of excess heat from the biofuel process.

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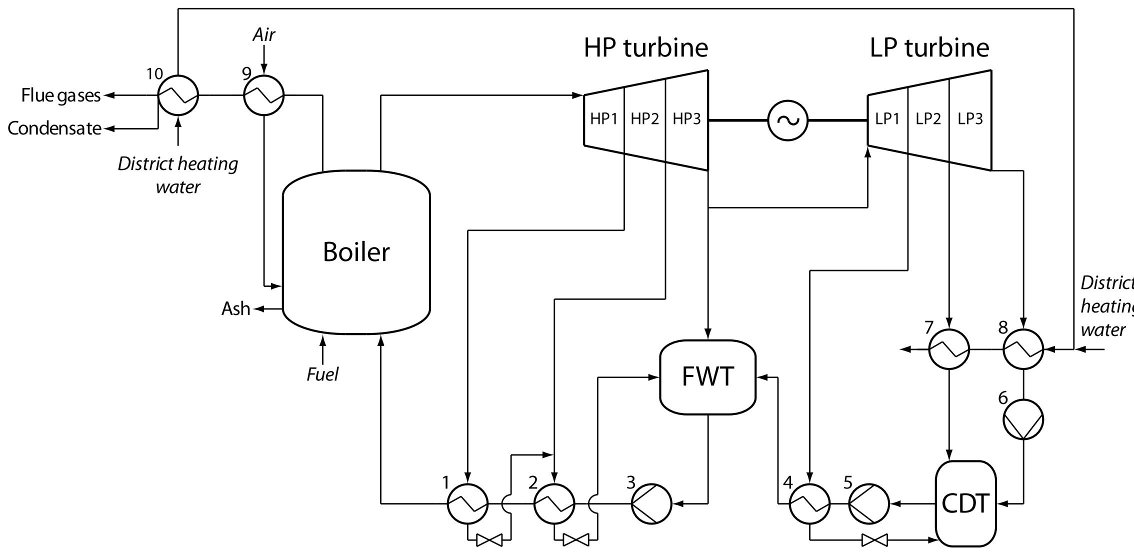

Figure 1: Schematic flowsheet of the biomass combined heat and power plant design used in this study. 1 - high temperature feedwater preheater, 2 - low temperature feedwater preheater, 3 - feedwater pump. 4 - condensate preheater, 5&6 - feedwater pump, 7 - high temperature DH condenser, 8 - low temperature DH condenser, 9 - air preheater, 10 - flue gas condenser, FWT - feedwater tank, CDT - condensate tank

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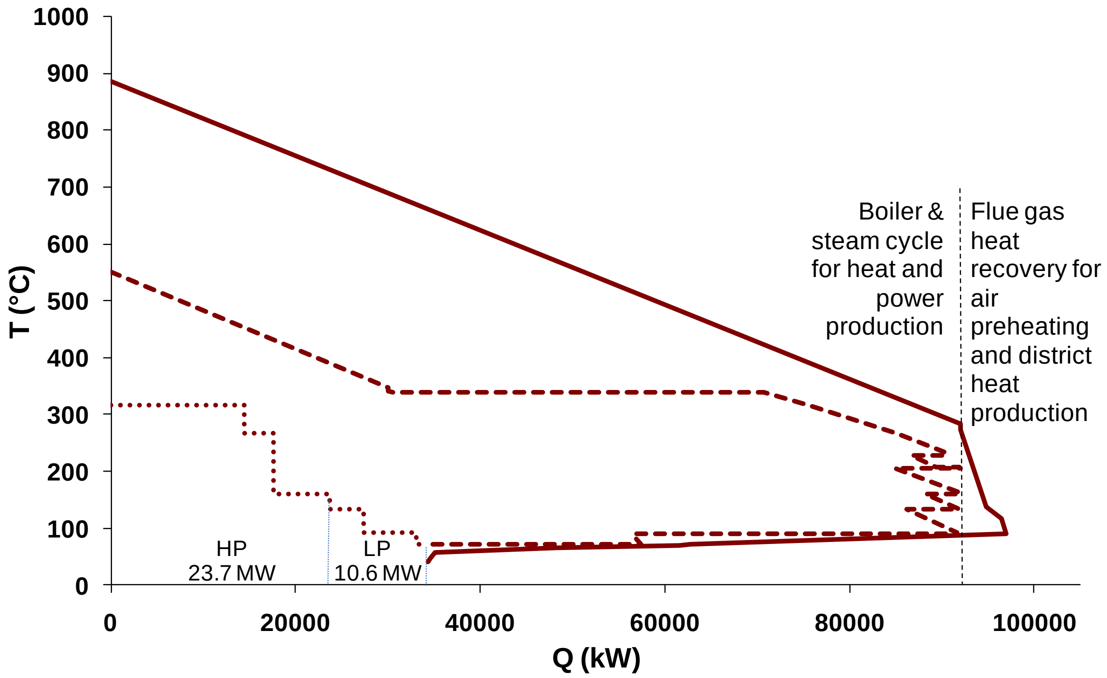

Figure 2: Pinch representation of CHP plant with the steam cycle as foreground process. Solid curve: heat streams for boiler flue gases, air preheat and DH system, dashed curve: steam cycle, dotted curve: turbine power. The temperature on the y-axis represents the interval temperatures taking into account the individual $\Delta T_{min}/2$ of each stream.

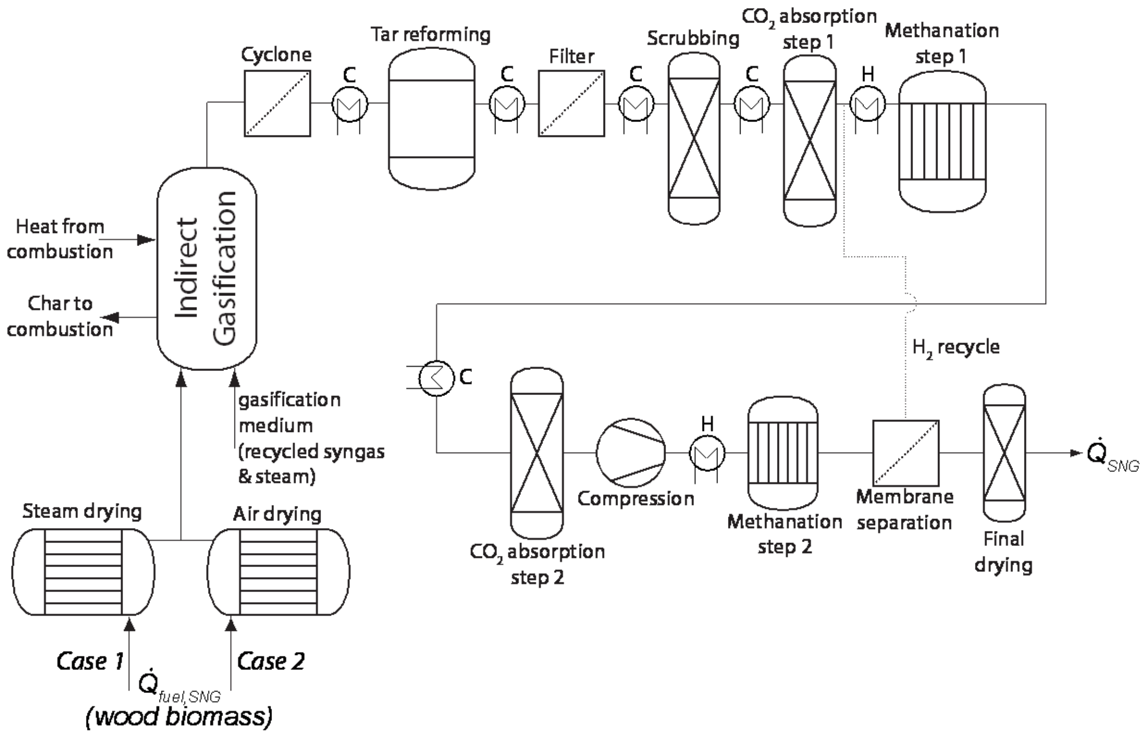

Figure 3: Flowsheet of the SNG production process indicating the two drying alternatives investigated. Case 1 A&B: steam drying, Case 2 A&B: air drying.

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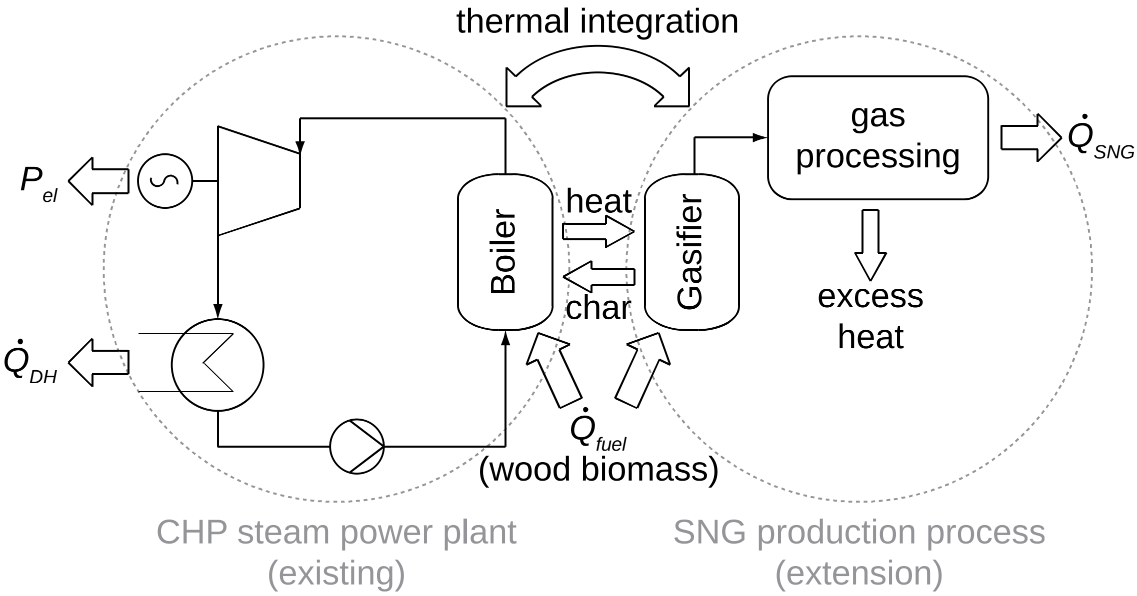

Figure 4: Schematic representation of the integration of the SNG production process with the existing CHP steam power plant.

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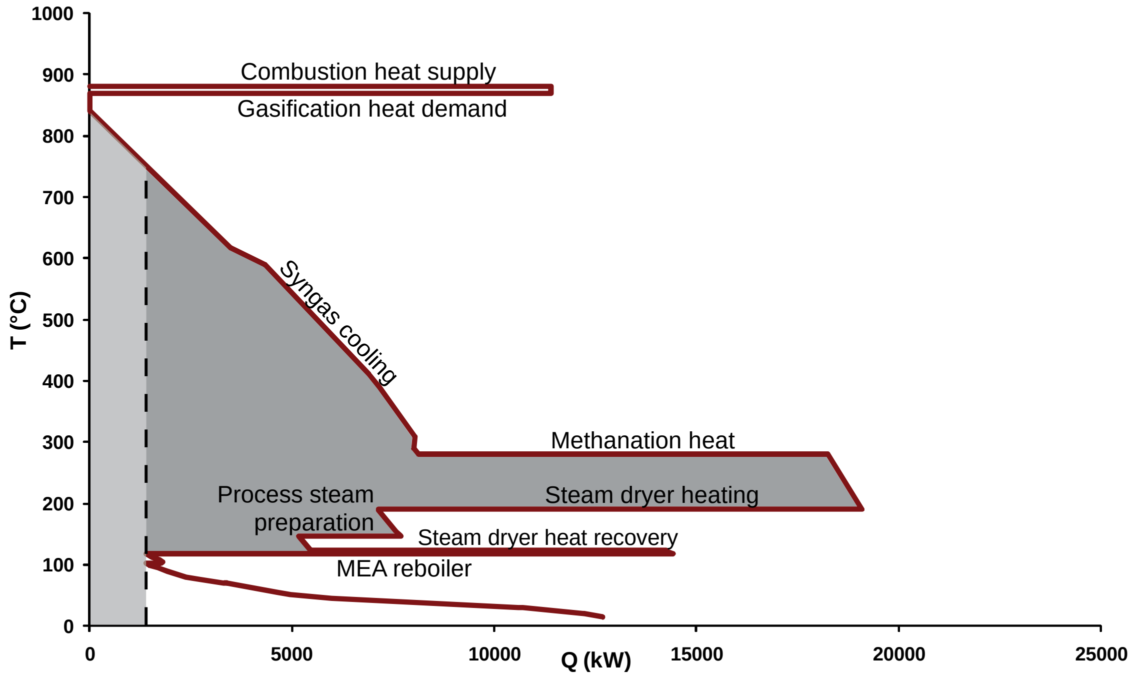

Figure 5: Integration alternatives studied based on the Grand Composite Curve representation for the SNG process with steam drying (with indication of the main process heat sources & sinks). Light grey shaded area: balancing integration (case 1A), dark grey shaded area: increased integration (case 1B). The temperature on the y-axis represents the interval temperatures taking into account the individual $\Delta T_{min}/2$ of each stream.

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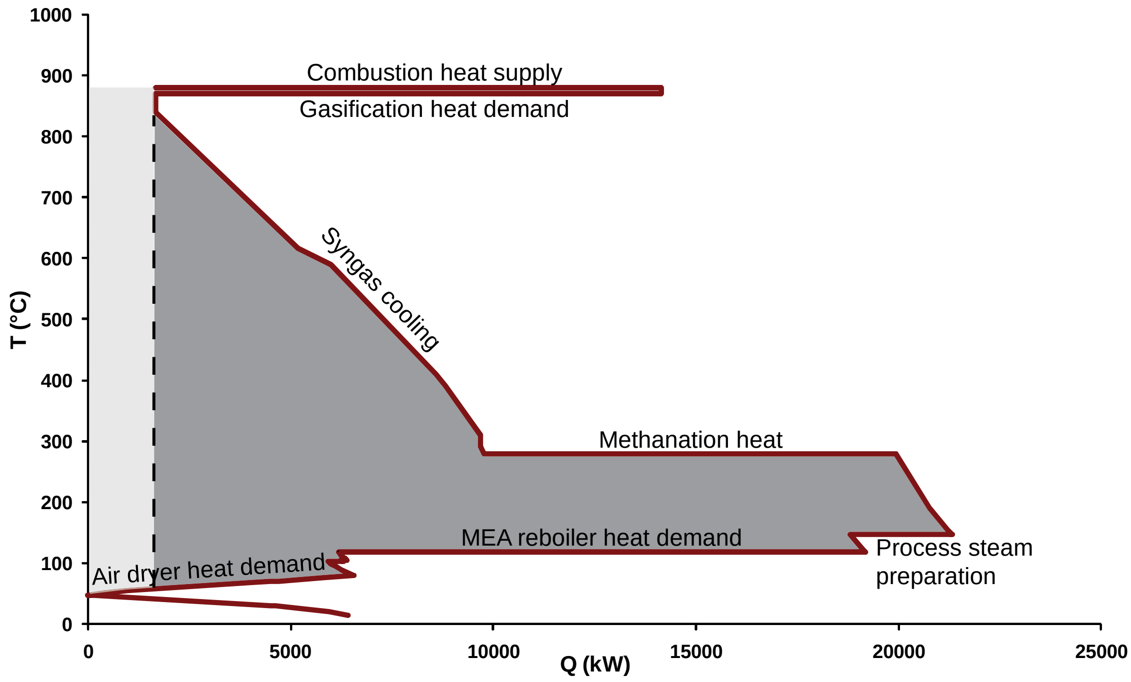

Figure 6: Integration alternatives studied based on the Grand Composite Curve representation for the SNG process with air drying (with indication of the main process heat sources & sinks). Light grey shaded area: balancing integration (case 1A), dark grey shaded area: increased integration (case 1B). The temperature on the y-axis represents the interval temperatures taking into account the individual $\Delta T_{min}/2$ of each stream.

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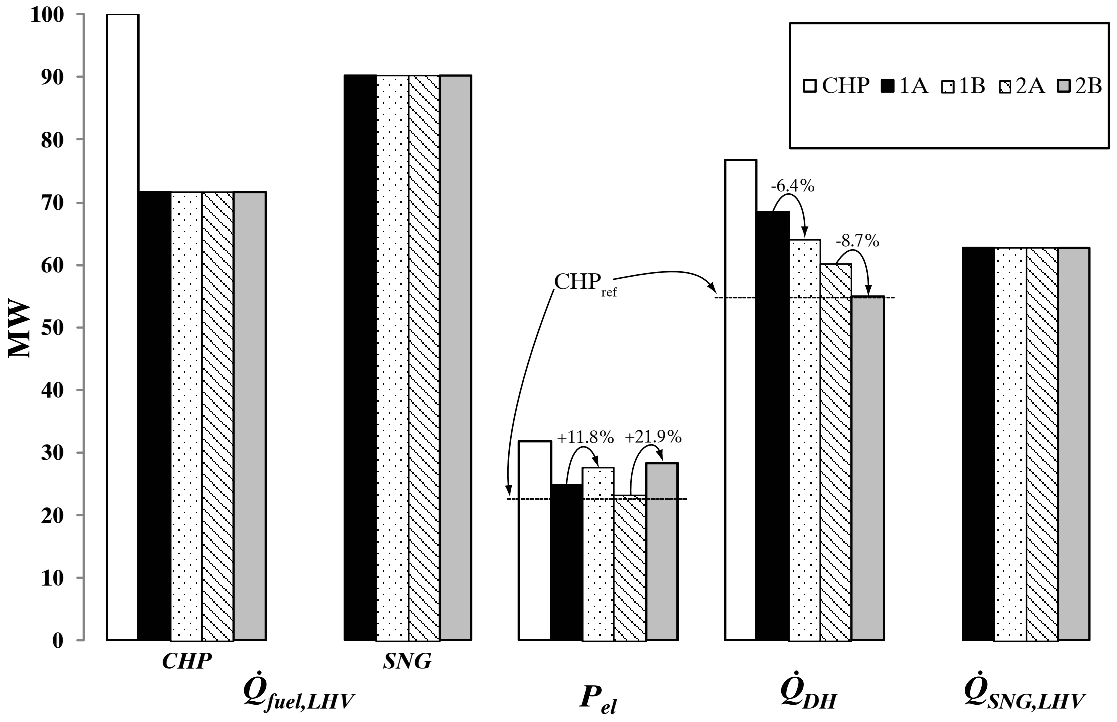

Figure 7: Fuel input ($\dot{Q}_{fuel,LHV}$), electricity (P_{el}), heat ($\dot{Q}_{DH}$) and SNG ($\dot{Q}_{SNG,LHV}$) production for the integration cases studied (Case 1A & B and 2A & B) and the stand-alone CHP steam power plant. *CHP_{ref}* indicates the theoretical amount of electricity and district heat produced from the biomass input to the CHP boiler alone for the four cases of integrated SNG production.

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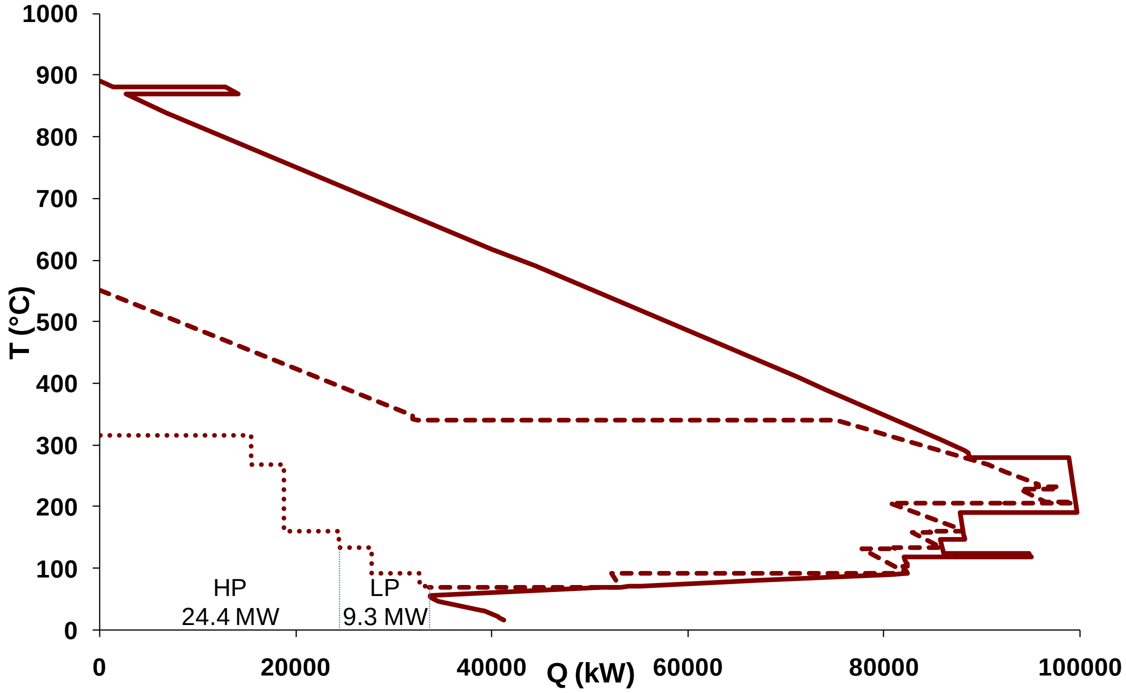

Figure 8: Pinch representation for Case 1B. solid curve: heat streams for boiler flue gases, SNG process heat & DH system, dashed curve: steam cycle, dotted curve: turbine power. The temperature on the y-axis represents the interval temperatures taking into account the individual $\Delta T_{min}/2$ of each stream.

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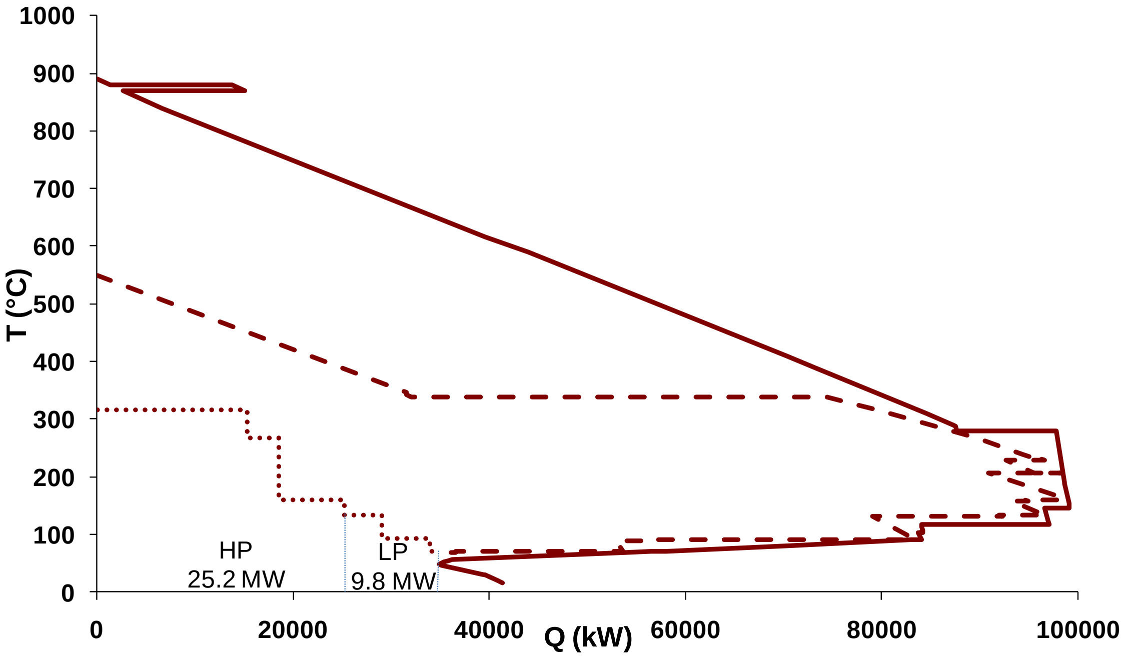

Figure 9: Pinch representation for Case 2B. Solid curve: heat streams for boiler flue gases, SNG process heat & DH system, dashed curve: steam cycle, dotted curve: turbine power. The temperature on the y-axis represents the interval temperatures taking into account the individual $\Delta T_{min}/2$ of each stream.

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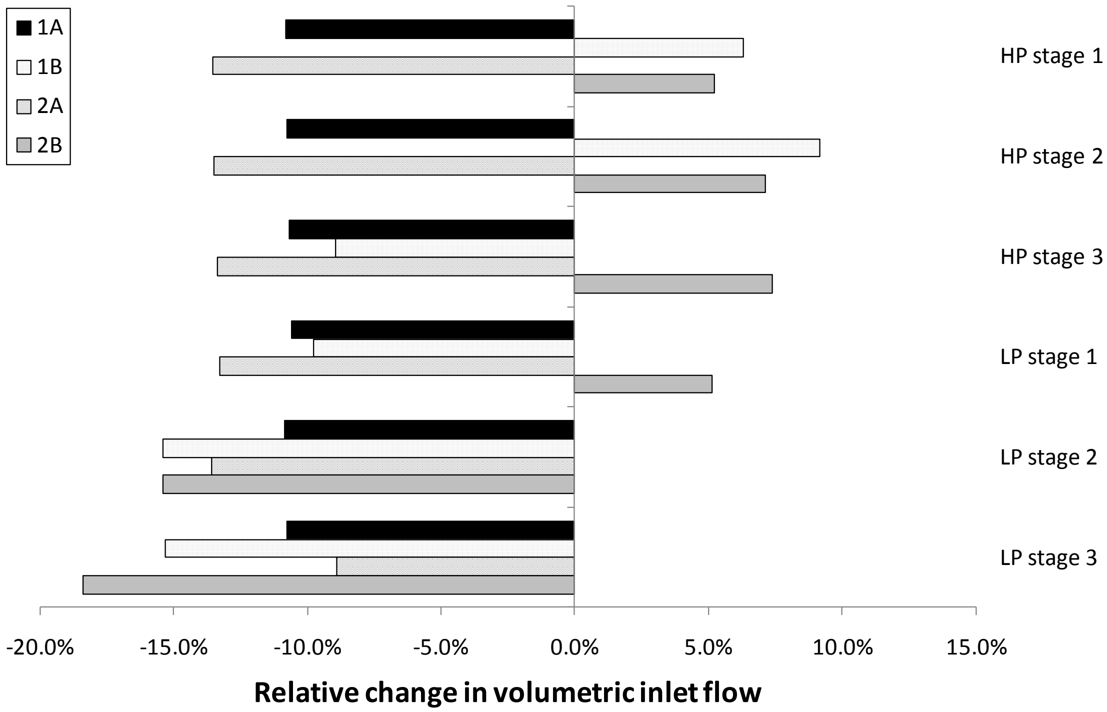

Figure 10: Change in volumetric inlet flow in the steam turbine stages for the four integration cases (1A, 1B, 2A & 2B) relative to the initial CHP standalone operation.

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Table 1: Modelling assumptions and input for biomass CHP plant (based on Steinwall et al. (2002)).

Parameter	Value
High pressure steam level [bar]	140
High pressure temperature level [ºC]	540
Feedwater temperature [ºC]	230
Feedwater tank pressure [bar]	6.2
ΔT_{min} for feedwater preheaters [ºC]	2
ΔT_{min} for DH condensers [ºC]	2
ΔT_{min} for flue gas condenser [ºC]	5
Pump isentropic efficiency [-]	0.8
Pump mechanical efficiency [-]	0.95
Turbine generator efficiency [-]	0.98
Internal electric power consumption (in addition to feed water pumps' power consumption) as percentage of boiler thermal load [%]	2
DH water return temperature [ºC]	45
DH water supply temperature [ºC]	90
DH network pressure [bar]	6
Heat load distribution high temperature / low temperature DH condenser [%]	60 / 40
Wood fuel energy input [MW_{LHV}]	100
Boiler efficieny	0.92
Wood fuel LHV [MJ/kg dry mass]	19.54
Wood fuel moisture content [wt-% ar]	50

Table 2: Biomass composition and heating value (forest residues) used for both SNG process and CHP steam power cycle.

Ultimate analysis	
C [wt-% df] [1)]	50.30
H [wt-% df]	5.43
O [wt-% df]	41.57
N [wt-% df]	0.47
S [wt-% df]	0.04
Cl [wt-% df]	0.01
Ash [wt-% df]	2.18
Proximate analysis	
Moisture content [wt-% ar]	50
Volatile matter [wt-% df]	77.82
Fixed carbon [wt-% df]	20
Ash [wt-%df]	2.18
Heating value	
LHV [MJ/kg df]	19.54
LHV [MJ/kg ar][2)]	8.55
HHV [MJ/kg df]	20.72

[1)] df: dry fuel (15 wt-% moisture)

[2)] ar: as received (50 wt-% moisture

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Table 3: Performance indicators for the base case biomass CHP plant based on the LHV of the wet fuel.

Parameter	Value
Boiler thermal load [MW]	92
Pressure levels HP turbine [bar]	140 / 27.53 / 18 / 6.2
Pressure levels LP turbine [bar]	6.2 / 3 / 0.76 / 0.34
Vapour fraction LP turbine final outlet [-]	0.868
HP turbine power production [MW]	23.71
LP turbine power production [MW]	10.63
Feedwater pumps power consumption [MW]	0.75
Additional electric power consumption [MW]	1.84
Net power production P_{el} [MW]	31.74
Flue gas condenser heat load [MW]	19.14
High temperature steam condenser heat load [MW]	34.64
Low temperature steam condenser heat load [MW]	23.03
Total district heat supply $\dot{\boldsymbol{Q}}_{\boldsymbol{DH}}$ [MW]	76.82
Flue gas dew point [ºC]	67.3
Flue gas outlet temperature [ºC]	50
Electric efficiency η_{el} [-]	0.317
Thermal efficiency η_q [-]	0.768
Overall efficiency η_{tot} [-]	1.086
Power-to-heat ratio α [-]	0.413

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Table 4: Modelling assumptions for SNG production process.

Air dryer		**Steam dryer**	
Pressure drop [bar]	0.05	Steam superheating temperature [ºC]	180
Recycle ratio [-]	0.7	Operating pressure [bar]	2.5
Heat loss [fraction of drying heat]	0.02	Heat loss [fraction of drying heat]	0.05
Heat supply level [ºC]	90	Pressure drop [bar]	0.05
Indirect gasification unit			
Operating temperature [ºC]	850		
Pressure drop [bar]	0.1		
Heat loss [fraction of thermal input]	0.02		
Steam-to-biomass ratio [kg H_2O/kg dry fuel]	0.6		
Pyrolysis modelling	Yield reactor based on (Thunman et al., 2001)		
Gasification modelling	• Gibbs equilibrium reactor at operating temperature • reactive species: C, CO, CO_2, H_2 & H_2O • WGS at equilibrium • 70% carbon conversion		
Tar reforming unit (Chemical looping reformer)		**Scrubbing unit (water scrubber)**	
		NH_3 removal efficiency [-]	0.99
Pressure drop [bar]	0.05	Pressure drop [bar]	0.02
Operating temperature [ºC]	625	Water recycle cooling temperature [ºC]	20
Reactions	complete reforming of tars to CO & H_2	Waste water stripper	operating a 1 bar, off-gases to be burnt in combustion boiler
CO_2 absorption (MEA unit)		**Methanation**	
CO_2 separation efficiency	0.95	Operating temperature [ºC]	300
Pressure drop [bar]	0.05	Pressure drop [bar]	0.05
Energy demand [MJ/kg CO_2 separated]	3.7 (@115 ºC)	Reaction modelling	Gibbs equilibrium reactor ($T_{approach}$ = 320ºC)
Recoverable energy [fraction of energy demand]	20% (@90 → 40 ºC)	Steam addition	adjusted to obtain H_2/CO = 3 taking into account simultaneous WGS reaction
Membrane separation		**Compressors & Fans**	
Inlet pressure [bar]	10	isentropic efficieny	0.72
Pressure drop [bar]	Permeate: 8 bar Retentate: 0.5 bar	mechanical efficiency	0.98
Split ratio [permeate/feed flow]	H_2:0.999 CH_4: 0.005	intercooling temperature[1] [ºC]	80 - 120
Pumps		**SNG delivery conditions**	
pump efficiency	based on efficiency curve for water[2]	Pressure [bar]	10
mechanical efficiency	0.98	Temperature [ºC]	30

[1] in case of multi-stage compression
[2] default in ASPEN Plus

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Table 5: Process integration alternatives studied.

Case	SNG process feedstock drying technology	Level of thermal integration
1A	**steam dryer**	**low** (balancing the SNG process high temperature excess heat)
1B		**high** (maximum heat-cascading)
2A	**low temperature air dryer**	**low** (balancing the SNG process low temperature heat demand)
2B		**high** (maximum heat-cascading)

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Table 6: Overall energy balances and efficiencies for CHP steam power plant and SNG integration cases.

	CHP	Case 1A	Case 1B	Case 2A	Case 2B
$\dot{Q}_{fuel,CHP}$ [MW_{LHV}]	100	71.55 (for all four cases)			
$\dot{Q}_{fuel,SNG}$ [MW]	-	90.33 (for all four cases)			
P_{el} [MW]	31.74	24.72	27.63	23.19	28.28
$\dot{Q}_{DH}$ [MW]	76.81	68.42	64.06	60.11	54.91
$\dot{Q}_{SNG}$ [MW_{LHV}]	-	62.7 (for all four cases)			
η_{tot} [%]	108.6	96.3	95.4	90.2	90.1
$P_{el,SNG}$ [MW]	-	2.0	4.9	0.5	5.6
$\dot{Q}_{DH,SNG}$ [MW]	-	13.5	9.1	5.2	0.0