

# Recovery of excess heat from methanation into WoodRoll® gasification and modelling of an integrated heat and mass balance

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July 2015

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## Abstract

This objective of this master thesis work is to explore which are the possible fuels that can be converted starting from the clean syngas produced by WoodRoll® technology. Syngas can be raw material for hydrogen, diesel, methanol, DME and SNG production. For each of these fuels, state-of-the-art technology is presented, showing thermodynamic parameters, configurations and catalytic materials that are commonly adopted in the industry. In the framework of Cortus' collaboration with KIC InnoEnergy with the aim of synthesizing CH<sub>4</sub> from 100% renewable waste biomass feedstock, the focus in the literature review is mainly on methane conversion from hydrogen-rich syngas; Cortus and KIC Innoenergy have tested the joint operation of methane from biomass gasification in Köping pilot plant. Further objective of the thesis is to model integrated systems, which are able to maximize the thermodynamic efficiency of the SNG production process from raw biomass. Firstly, the simplest case with standard WoodRoll® technology connected to methanation unit, with no waste heat recovery, is shown. Here, results are compared to the results of a VBA model developed by Cortus, yielding a small deviation. Secondly, an integrated case has waste heat from methanation supplied to a steam cycle with the aim of combined production of electricity and methane. Thirdly, the option of processing fibre sludge from paper mills with 70% moisture content is analysed: the waste heat is here supplied to the drier. These models are compared to each other in efficiency and impact on the environment.

**Keywords:** Gasification, methane, syngas, biomass, optimization.

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## 1. Introduction

Bioenergy is supplying 10% of the world total primary energy supply. In the industrialized world, biomass residues are used in thermal plants to yield electricity and heat; while anaerobic digesters and fuel conversion units are used to achieve combustible gaseous or liquid fuels, easing storage, consumption and distribution.

Energy conversion from biomass resources might not yet always be competitive with power generation from fossil fuels. However, new bioenergy policies are in the EU target for Horizon 2020, as it is of primary importance to move towards a cleaner, more decentralized and more sustainable energy-supply chain.

On a global level, bioenergy production is expected to experience a robust annual increase about +7%. The International Energy Agency foresees a world biomass power production ten-fold increase up to 2050 to 3000 TWh, while biomass use for heat supply will ramp up to 24 EJ by 2050 (IEA - Bioenergy, 2015).

### 1.1. Research focus and Process description

In Sweden, with abundant forest resources and a thriving settled forest industry, bioenergy plays an important role in reaching the EU targets for renewable energy incorporation in the country's energy consumption mix.

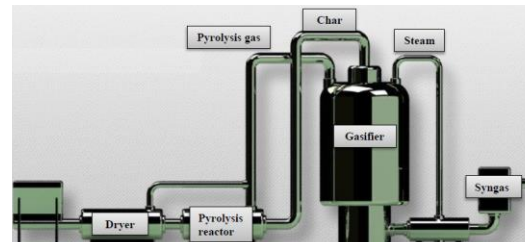
Patented by Cortus Energy AB, the WoodRoll® is a gasification technology which produces clean syngas with high-energy content. The company is running a 500 kW pilot test plant in Köping in order to gain knowledge about the process and build the first commercial version of the system. The WoodRoll® process is divided in three steps - drying, pyrolysis and gasification. The principle behind is to separate the solid material flow from the pyrolysis gas in the pyrolysis reactor and burn the latter gas to heat the gasification process indirectly. The separation of solid and gases enables the process to become cleaner and more efficient than state-of-the-art. In Figure 1, a scheme of the process is presented. The incoming biomass is grinded, dried and then fed to a slow pyrolysis reactor. The resulting char is gasified at high temperature with steam into an externally-heated reactor. Consequently, the syngas is clean from condensable tars and nitrogen and, therefore, is very suitable for combustion in power production units or cost-effective bio-

methane production. The total thermal efficiency of the system can reach up to 80%.

The process has been tested with more than 100 types of feedstock, ranging from wood, to microalgae and sludge. The syngas typically presents the following composition:

- H<sub>2</sub>: 55-60%
- CO: 25-30%
- CH<sub>4</sub>: 1-2%
- CO<sub>2</sub>: Remainder

Cortus Energy actively works on cost efficient green energy for power, process and transport industries. Hydrogen from a completely green



source and in industrial scale is becoming necessary to realize the vision of the non-pollution cars driven by fuel cells.

Figure 1 - Representation of WoodRoll® system

Cortus has got a new patent granted in the USA for a process solution where the WoodRoll® biomass gasification technology can integrate a water gas shift process in order to generate a clean renewable hydrogen. The hydrogen level from the WoodRoll® process is normally 55 - 60% but the newly patented process increases the hydrogen level to almost 100% of the energy from gasification of biomass. Cortus Energy AB has established a partnership with KIC InnoEnergy in order to test out its syngas in the DemoSNG methane synthesis unit developed by Karlsruhe Institute of Technology. Under the umbrella of the DemoSNG project, there is also an attempt of including the Power-to-Gas technology and make use of the surplus electricity injected into the grid from the increasingly popular Intermittent Renewable Energy sources; however, this branch of the system is not considered in the present work, as no data is available yet.

## 2. Literature Review

### 2.1. Background information

The declining petroleum resources, combined with increased demand for petroleum by emerging economies, and political and environmental concerns about fossil fuels, are imperative to develop economical and energy-

efficient processes for the sustainable production of fuels and chemicals. In this respect, biomass allows, through a variety of mechanisms, the synthesis of biofuels. Biofuels are the only current sustainable source of liquid and gaseous fuels and they can retrofit more traditional fossil fuels used in the transportation and power production sector. They generate significantly less greenhouse gas emissions than fossil fuels do and can even be greenhouse-gas-neutral if efficient methods for biomass collection and conversion are developed (Klass, 2004).

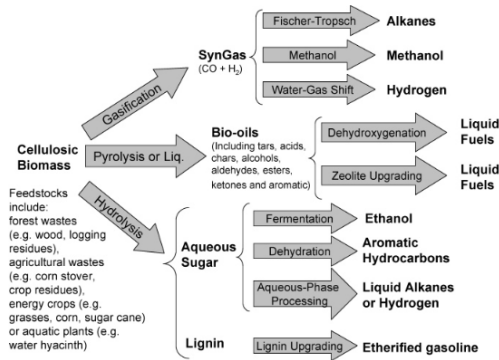


Figure 2- Strategies for production of fuels from lignocellulosic biomass (Huber & Dumestic, 2006).

Lignocellulosic material can be converted into liquid fuels by three primary routes, as shown in Figure 2, including syngas production by gasification, bio-oil production by pyrolysis or liquefaction or hydrolysis of biomass to produce sugar monomer units. Synthesis gas can be used to produce hydrocarbons (diesel or gasoline), methanol, and other fuels (Huber & Dumestic, 2006).

	H <sub>2</sub> /CO	Temperature range	Pressure range
<b>Hydrogen</b>	Any	21 – 38 °C	4-30 bar
<b>Diesel</b>	>1	220 – 350 °C	<27 bar
<b>Methanol</b>	2	275 – 350 °C	50 – 100 bar
<b>DME</b>	1-2	250 °C	70 bar
<b>Methane</b>	3	250 – 700 °C	10 – 50 bar

Chart 1- Summary of operating parameters industrially adopted in the conversion of syngas to hydrogen, diesel, methanol, DME and methane

In Chart 1 there is a summary of the operative conditions to adopt for fuel conversion in each case.

### 3. Analysis of the WoodRoll® gasification and methanation units

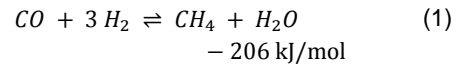
#### 3.1. Description of the InnoEnergy system

Cortus Energy AB has a partnership with KIC InnoEnergy to provide clean high-hydrogen-yield syngas to the DemoSNG pilot plant built by the

Karlsruhe Institute of Technology (KIT), installed in Köping next to the gasification pilot plant. The joint operation of WoodRoll® 500 kW and Demo SNG is currently being tested for a fraction of the total syngas flow. A gas cleaning system

#### 3.2. DemoSNG - Estimation of heat availability

With the purpose of estimating the waste heat availability from the methanation, only the global reaction will be considered:



(Rostrup-Nielsen J. , 2011)

By introducing the gas volume composition that is experimentally obtained adopting a ratio Steam/Biomass equal to 1.2 and by using the LHV of the pure gases (see Chart 2), follows that:

$$LHV_{syngas} = \sum_i x_i \cdot LHV_i \quad (2)$$

$$= 10,45 \text{ MJ/Nm}^3$$

Steam/Char = 1.2		
	%	LHV [MJ/Nm3]
H2	60%	10,26
CO	30%	12,05
CO2	8%	0,00
CH4	2%	33,94
		<b>10,45</b>

Chart 2- Syngas composition and LHV, for Steam/Char ratio equal to 1.2 and gasification temperature equal to 1100°C

The waste heat available from methanation can be found as:

$$\dot{Q} = \dot{V}_{tot} \cdot x_{CO} \cdot \Delta h = \left( \frac{\dot{E} [MW] \text{ Nm}^3}{10,45 \text{ s}} \right) \cdot 0,30 \cdot \quad (3)$$

$$\left( -0,206 \frac{\text{MJ}}{\text{mol}} \right) \cdot \left( \frac{1}{0,022414 \text{ Nm}^3} \right) = 0,2638 \cdot$$

$$\dot{E} [MW] \text{ MW}$$

Given a certain syngas flow, equation (3) says how much of the heating value contained in the syngas is lost in the methanation conversion step. In other words, how much less energy it is possible to extract from complete combustion of methane, compared to complete combustion of syngas before the conversion step.

#### 3.3. Calculation model tool

A heat and mass balance is implemented in order to obtain thermodynamic values (temperatures, pressures, mass flows, heat flows) and assess if the proposed design for the system is feasible or not, at least in theory. The

simulation is carried out in Matlab, making use of Simulink Thermolib toolbox.

### 3.4. Case I: WoodRoll®

#### 3.4.1. Description Case I

##### Drier

The drier is a rotating drum that acquires heat from a flow of flue gases. This flow is circulating counter-wise on the external jacket of the drier, where a shell & tube configuration improves the heat exchange with the biomass. The amount of heat to be supplied equals to:

$$\dot{Q}_{Drier}^{in} = \dot{m}_{BM\ in} \cdot c_{p_{BM\ in}} \cdot (T_{evap} - T_{BM\ in}) + \dot{m}_{BM} \cdot \left( \frac{(1-w_{BM\ in})}{(1-w_{BM\ out})} \cdot w_{BM\ out} \right) \cdot \Delta h_{H_2O}^{evap} \quad (4)$$

The TGA data regarding the biomass water content before and after the drying process are validated by a humidity scale device, measuring the weight loss of the sample over a period of time at 105°C, then yielding the moisture content of the sample. The humidity is removed due to a warm airflow that circulates through the drier. Afterwards, the stream is cooled down and the condensate is separated from the air to avoid spilling possible contaminants present in the biomass to the environment.

$$\dot{Q}_{Drier\ cond} = \dot{m}_{humidity} \cdot (\Delta h_{water}^{evap} + c_{p\ water} \cdot (T_{evap} - T_{out})) \quad (5)$$

Where,  $\dot{m}_{humidity}$  is the evaporated mass of water,  $T_{evap}$  equals to 100°C and  $T_{out}$  is the outlet temperature of the condensate.

$$\dot{Q}_{Drier\ cond} = \dot{m}_{Cooling\ water} \cdot c_{p\ water} \cdot (T_{Water\ in} - T_{Water\ out}) \quad (6)$$

The cooling medium is water extracted from a natural source. The assumption is to take it out at 5°C and return it at 25°C. However, the environmental regulation on the return temperature of cooling water flows is region dependent and should be seen case by case.

The ventilation airflow is modelled on the software as *Wet air*, which allows simulating the psychometric behaviour of air.

##### Pyrolysis

The pyrolysis step is the milestone of the whole WoodRoll® process, as it produces the gaseous fuel that feeds every endothermic process in the

system. The reactor is a rotary drum that receives heat from the flue gases stream. The flow takes place counter-wise on the external jacket surrounding the reactor. As the first dry biomass enters the reactor, the temperature increases up to about 400°C, at which thermal decomposition begins.

The heat supplied to the pyrolysis reactor has the main purpose of warming up the biomass to the desired temperature, while the thermal decomposition has proved to be nearly adiabatic. However, this heat is calculated as:

$$\dot{Q}_{pyro}^{in} = \dot{m}_{dry\ BM} \cdot \left[ \Delta h_{BM}^{pyro} + c_{p_{BM\ in}} \cdot (T_{pyro} - T_{dry\ BM\ in}) \right] \quad (7)$$

The thermal decomposition of biomass is considered to be adiabatic, hence  $\Delta h_{BM}^{pyro} = 0$ . Basically, there is no additional heat to be supplied to the reactor apart from the sensible heat that is necessary to increase the temperature of dry biomass. Given the complexity of the phenomenon of the biomass thermal decomposition, chemical reactions are not computed in this model, as biomass is always a very heterogeneous fuel. It is instead preferable to take a sample of the fuel, run a TGA analysis under the same operative condition of the real process and use the Gas Chromatography to obtain concentrations of all species. The bomb calorimeter test determines the LHV of the fuel. Here is the behaviour of LHV of pyrolysis gas with variations on the pyrolysis operative temperature:

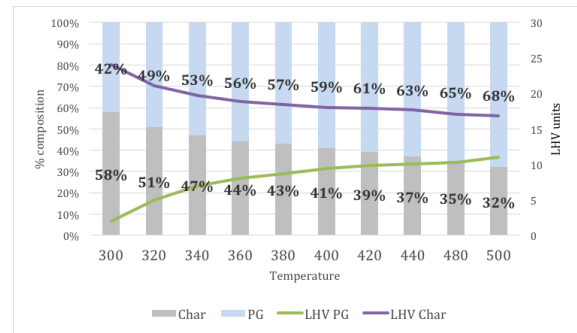


Figure 3- Curve describing the pyrolysis process. Lower pyrolysis temperature yields more char, with higher heating value and less PG with lower heating value.

Figure 3 shows how the pyrolysis process occurs in a wide range of temperature. Depending on the reaction temperature, a certain amount of volatile matter is evaporated as PG, leaving the remaining mass in the form of char. Assuming that the residence time in the

reactor is the same in every case, the trend for the pyrolysis process is that of increasing the yield of char as the pyrolysis temperature decreases. The energy content of char is higher at lower temperature, while PG formed at low temperature is less energetic than PG produced in high-temperature pyrolysis. PG contains a high percentage of condensable tars, which are modelled as benzene molecules. Hence,

$$LHV_{PG} = \sum x \cdot LHV_i \quad (8)$$

The LHV of the char is calculated from the elemental analysis, through the formula (Coalspot.com, 2015):

$$LHV_{Char} = 337 \cdot C + 1442 \cdot \left( H - \frac{O}{8} \right) + 93 \cdot S \quad (9)$$

Where C, H, O and S are percentages from the dry ash free char and [MJ/kg] are dimensional units of  $LHV_{Char}$ .

Afterwards, the validation of the calculations carried out above is done through the energy balance:

$$\frac{LHV_{Char}}{m_{Char}} = \frac{m_{test\ BM} \cdot LHV_{BM} - m_{PG} \cdot LHV_{PG}}{m_{Char}} \quad (10)$$

The heat capacity of char is assumed to be 1.24 kJ/kgK, independent of temperature.

#### Char handling

The char flow is conveyed to a grinder that reduces its size to ease the reaction rates in the gasifier.

Parameters: Grinding specific energy consumption - 260 kJ/kg<sub>Char</sub>

#### Gasifier

In the gasifier, finely grinded char and steam are injected together in the gasifier of Cortus' own design. The temperature in the reactor is kept at 1100°C through combustion of the pyrolysis gas formerly produced in irradiative burners. The operation is always over-stoichiometric to avoid the deposition of unreacted char, which represents an unnecessary energy loss. The mass and energy balance for this block is:

$$\dot{m}_{Char} + \dot{m}_{Steam} = \dot{m}_{Syngas} \quad (11)$$

$$\begin{aligned} \dot{Q}_{PG} = & \dot{m}_{Char} \cdot c_p(T) \cdot (T_{React} - T_{in}) + \\ & \dot{m}_{Steam} \cdot (h_{React}^{1\ bar} - h_{165^\circ C}^{7\ bar}) - \dot{m}_{Syngas} \cdot \\ & c_p(T) \cdot (T_{React} - T_{out}) + \dot{m}_{Char} \cdot \\ & \Delta h_{Gasif\ React} \end{aligned} \quad (12)$$

Where  $\dot{m}_{Syngas} = \sum_i \dot{m}_i \cdot y_i$ , with  $i$  being gas in the syngas and  $y_i$  mass percentage for each gas;  $\Delta h_{Gasif\ React}^{T_{React}}$  is the enthalpy of reaction of carbon gasification with water at the reaction temperature, 1100°C.

#### Steam production

Syngas comes out of the cyclone at around 700°C. The flow is cooled down to 30°C in a shell&tube boiler, where saturated steam at 7 barg is continuously produced to feed the gasifier, from water pumped from atmospheric to 7 bar pressure. Hence, the condensate is removed from the flow. The water consumed in the process is taken from the municipal pipes: therefore, it needs to be purified from all the minerals. The heat exchanger has a counter-flow arrangement, modelled on Thermolib by a predefined component. The model does not account for pressure losses in the tubes.

UA global between two fluids	1000 W/K
External temperature	5°C
UA to environment	200 W/K

#### Electrical power consumption

The plant consumes electrical power mainly in the grinder, gas fans for recirculation of flue gases and heating cables for temperature control of areas where condensation of hydrocarbons needs to be avoided. The fans in the system are connected to variable speed engines, accounting for a total power consumption of 221 Power units (PU).

#### 3.4.2. Result Case I

The flow chart below presents the solution to the optimized system. To better protect the internal knowledge of the company with regards to the heat and mass balance, power and mass flow data have been multiplied by two different constants.

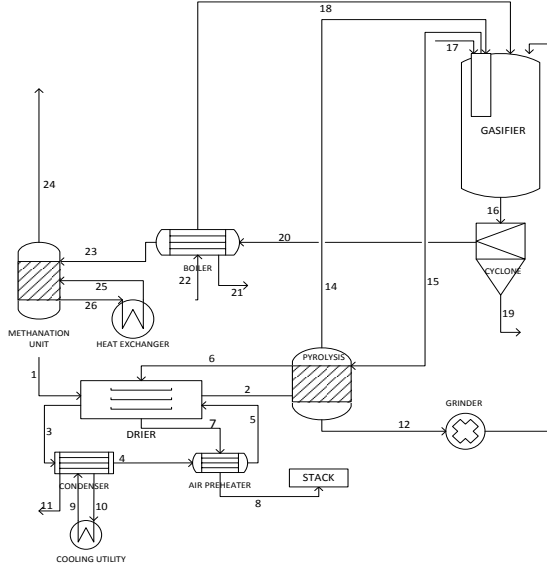


Figure 4- Standard WoodRoll® scheme connected to methanation unit, without recovery of the waste heat

The temperature in the pyrolysis reactor is 400°C. Of the dry biomass, 40,93% is converted into char and 59,06% in pyrolysis gas, accounting for, respectively, 63.51% and 36.49% of the energy yield. The fuel conversion efficiency is calculated as:

$$\eta_{BM \text{ to } Syn} = \frac{\dot{E}_{Output \text{ fuel}}}{\sum \dot{E}_{Inputs}} \quad (13)$$

$$= \frac{\dot{m}_{Syn \text{ gas}} \cdot LHV_{Syn \text{ gas}}}{\dot{m}_{Dry \text{ BM}} \cdot LHV_{Dry \text{ BM}} + P_{El \text{ engines}}}$$

$$= \frac{14542}{18434 + 365} = 77,4\%$$

The simulation converged to the solution, which means that the energy from biomass is sufficient to the self-sustainment of the system with no need for further input of fossil fuels.

$$\eta_{BM \text{ to } CH_4} = \frac{\dot{E}_{Output \text{ fuel}}}{\sum \dot{E}_{Inputs}} = \quad (14)$$

$$\frac{\dot{m}_{Methane} \cdot LHV_{Methane}}{\dot{m}_{Dry \text{ BM}} \cdot LHV_{Dry \text{ BM}} + P_{El \text{ engines}} + \dot{E}_{Steam \text{ WGS}}} =$$

$$\frac{10907}{18434 + 365 + 1257} = 54,4\%$$

Results concerning the energy flows in the system are reported in Chart 5. The power values associated to a flow of combustible material such as BM, char or PG, are always meant as chemical energy (referred to as  $\dot{E}$ ), that is the energy that could be released after complete combustion and cooling of product gases to 150°C.  $\dot{Q}$  values are, instead, heat loads transferred between two different flows; while electrical power is referred to as  $P$ . The water consumption of the process is 97 Mass Units, while 70 Mass Units are collected as

condensate, which needs to be disposed of in a regulated fashion. With regards to the cooling, the plant has to take in 537 Mass Units of water, which is returned to the natural water source at 25°C. Alternatively, there can be a cooling evaporating tower or an air fan cooler, which can however decrease the total efficiency of the plant to 36,17%: the electrically driven air fan cooler is clearly not an option for such large heat loads. For a large commercial system it is preferable to adopt water-cooling from a natural stream or an evaporative cooling tower.

The result of the simulation is in good agreement with the calculation model carried out inside the company on Microsoft Excel Visual Basic. The values have been compared and deviations have been calculated between the outcomes as:

$$\varepsilon_{Rel} = \left| \frac{x_{Simulink} - x_{VBA}}{x_{VBA}} \right| \quad (15)$$

Where  $\varepsilon_{Rel}$  is the relative mismatch between the Simulink model and the Visual Basic model, and  $x_{Simulink}$  and  $x_{VBA}$  are the values of a certain parameter resulting from, respectively, the Simulink and the VBA model. From the comparison,  $\varepsilon_{Rel \text{ Max}} = 6,24\%$  relatively to the heat released to condensate the water in the ventilation air. The reason for this gap should be found in Simulink's ability to compute  $c_p$  heat capacity coefficients for all the gases as a function of temperatures; while in the VBA simulation, they are averaged over the temperature gap of interest for a certain heat exchanger. This fact only proves that the Simulink Model is in very good agreement with the VBA model, but it does not say that the results of any of them are valid. In fact, the confirmation of the validity of these models can only come from the measurements of thermodynamic values of the real plant.

#### 4. Process integration alternatives: Results and discussion

##### 4.1 Case II: Electricity and methane

###### 4.1.1 Description Case II

One integrated solution could aim at the production of both electricity and methane. A heat exchanger where the waste heat conveyed from the methanation process at 250°C, together with a boiler fed on PG could bring a water flow to superheated steam conditions at 350°C and 40 bar. Then, a steam flow can be stripped at 7 bar and be introduced into the gasifier to produce new syngas. The rest of the flow is expanded through a steam turbine to produce

electricity. The choice of the pressure in the steam cycle is aimed at establishing an efficient heat exchange between the methanation reactors and the steam cycle. In fact, the heat exchange takes place at constant  $\Delta T = 10^\circ\text{C}$ , between  $260^\circ\text{C}$  at which the heat is available, and  $250^\circ\text{C}$ , saturation temperature of the steam at 40 bar. The superheating phase of the cycle receives heat from a burner fed on pyrolysis gas. Then, the steam expands into a steam turbine with 60% isentropic efficiency. A flow of superheated steam at 7 bar is extracted and fed to the gasifier. The remaining steam expands to 7385 Pa (saturation pressure for  $40^\circ\text{C}$ ) and is cooled in a heat exchanger with cool water from a natural source. A feedwater stream is added to the condensed steam and the flow is pumped to 40 bar. Then, it enters another heat exchanger, where it is warmed up from  $40^\circ\text{C}$  to  $250^\circ\text{C}$  through the heat released by the flue gases. The remaining part of the pyrolysis gas is burnt into the irradiative burners of the gasifier. The flue gases coming from the burner on the gasifier are added to the superheating steam boiler. Part of the flue gases collected after pyrolysis gas combustion in the boiler are conveyed to a mixing chamber, regulating the inlet temperature of the flue gases entering the external jacket of the pyrolysis reactor and warming up biomass to the optimal pyrolysis temperature. This parameter is target of the optimization, as it will determine in which proportion the heating value of the biomass will be divided between the char flow and the pyrolysis gas flow. The syngas produced in the gasifier, leaving the cyclone, undergoes separation of smaller ashes and particulate in the filter and cools down into the drier passing through the tubes inside the rotary drum, where the steam that has condensed is separated.

#### 4.1.2. Results Case II

This arrangement aims at converting biomass into both methane and electricity. The flow sheet is displayed below, together with the thermodynamic values resulting from the Simulink model.

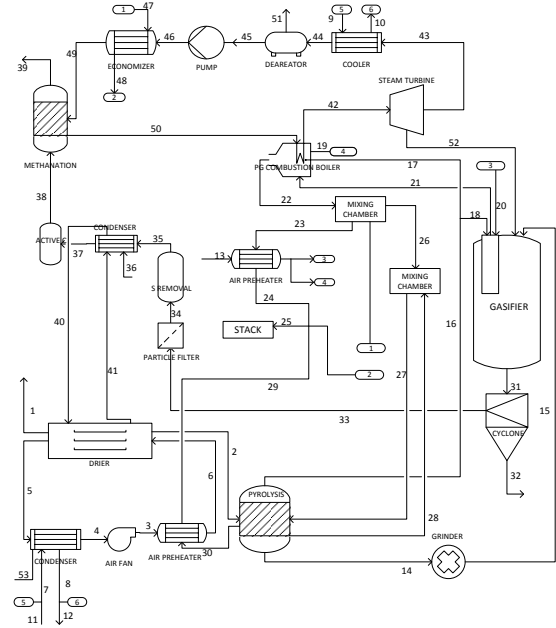


Figure 5- Flow diagram for the integration of WoodRoll® with methanation unit and steam cycle

The performance of this setting is evaluated as:

$$\eta_{BM \text{ to Syn}} = \frac{\dot{E}_{Output \text{ fuel}}}{\sum \dot{E}_{Inputs}} \quad (16)$$

$$= \frac{\dot{m}_{Syngas} \cdot LHV_{Syngas}}{\dot{m}_{Dry \text{ BM}} \cdot LHV_{Dry \text{ BM}} + P_{El \text{ engines}}}$$

$$= 86,0\%$$

$$\eta_{BM \text{ to CH}_4} \quad (17)$$

$$= \frac{\dot{E}_{Methane}}{\dot{E}_{BM} + P_{El \text{ engines}} + \dot{E}_{Steam \text{ WGS}}}$$

$$= 65,2\%$$

Where  $\dot{E}_{Steam \text{ WGS}}$  is the electrical power supplied by the renewable sources connected to the integrated system, producing steam for WGS reactor. The steam cycle takes heat inputs from the methanation reactor, as for the evaporative phase, from the flue gases, as for the preheating of process water and from the combustion of part of pyrolysis gas for the superheating of steam. The electrical efficiency of the steam cycle can be calculated as:

$$\eta_{El} = \frac{P_{El}}{\dot{Q}_{Eco} + \dot{Q}_{Methanation} + \dot{Q}_{Superheating}} \quad (18)$$

$$= 23,3\%$$

Where,  $\dot{Q}_{Eco}$  is the heat supplied to the economizer,  $\dot{Q}_{Methanation}$  the waste heat from the methanation reactor supplied for the evaporation of water in the steam cycle and  $\dot{Q}_{Superheating}$  is the heat required by the steam to reach  $600^\circ\text{C}$  at 40 atm, which is supplied by the

PG burner. Then, the electrical efficiency considering the entire biomass energy input is:

$$\eta_{BM\ to\ El} = \frac{P_{El}}{\dot{E}_{BM}} = 12,8\% \quad (19)$$

As said above, this configuration is designed to be applied to isolated system that have no connection to gas and energy grid. Therefore, its value lies on the possibility of providing both electricity and methane in the same supply point, using the same feedstock. However, both electricity and methane are produced online, with no intermediate storage buffer. In the occurrence of a programmed stop of the plant for maintenance or technical failure, the supply is immediately interrupted. If this configuration were ever implemented, the storage question should be carefully addressed. A possible way to avoid power shortage would be installing a methane buffer and a backup diesel engine for methane combustion, connected to an electricity generator. This arrangement should only operate during occasional stops, hence it should be cheap and not necessarily very efficient.

#### 4.2. Case III: Syngas production with wet fuel

##### 4.2.1. Description Case III

One of the biggest limitations of the biomass conversion processes is the fuel quality. In Sweden there is abundance of fibre sludge coming from pulp mills, where it represents a waste to be disposed of. It is then possible to get paid for withdrawing this feedstock, drying it with the excess waste heat from methanation and then feeding it to the WoodRoll® system. This type of waste is not very appealing as a solid fuel since it can have up to 70% moisture content and it requires too much heat to dry up the whole biomass down to 5% moisture content. However, the negative cost of the fuel would compensate for the inefficiency introduced by a more moist fuel. In case the feedstock is even more wet for the process, it can be mixed with recycled wood residues in order to make it processable.

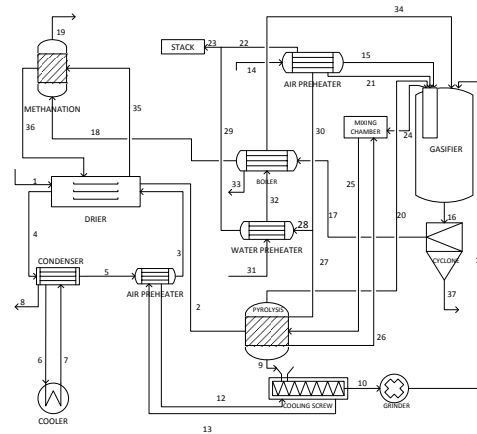


Figure 6- Flow diagram for integration of the WoodRoll® with methanation unit, with 70% moist feedstock

In the case of using 70% moist fibre sludge from paper mills, the heat from methanation can be recovered to the drier. The heat exchange is arranged with flue gases as heat carrier, because they ease the design of the drier. The pyrolysis gas produced is entirely burnt into the gasifier. Here the flow splits into a main stream, leading to a mixing chamber and a smaller flow, leading to a heat exchanger for preheating of combustion air. The purpose of the chamber is to provide a temperature control on the external jacket of the pyrolysis reactor. A recirculation flow is extracted by the outlet of the jacket and reintroduced to the mixing chamber to decrease the temperature of the incoming flow to the jacket, to 550°C. The target temperature for the outlet of the jacket is 400°C. After going through the jacket, this flow is flowing to a heat exchanger for preheating of water. The chimney temperature of the flue gases is set at 130°C to minimize the heat discharged to the atmosphere but also avoid condensation at the chimney. The wet syngas leaves the cyclone at 700°C and goes through the boiler to evaporate the steam for the gasification reactions. The gasification and pyrolysis reactor are modelled in the same way as in Case I. The only cooling utility in this setting is on the drier ventilation loop, where moisture is condensed. The cooling is arranged with a water flow from a natural source, assuming inlet temperature of water at 5°C and imposing an outlet temperature at 25°C.

As the water in the biomass increases, the system tends to produce less pyrolysis gas and more char. In fact, in order to supply as much heat as it is required at the drier, the syngas flow has to increase: the wet syngas mass flow is directly proportional to the char mass flow. The fuel conversion efficiency is calculated as:



$$\eta_{BM\ to\ Syn} = \frac{\dot{E}_{Syngas}}{\dot{E}_{BM} + P_{El}} = 93,2\% \quad (20)$$

$$\eta_{BM\ to\ CH_4} = \frac{\dot{E}_{Methane}}{\dot{E}_{BM} + P_{El} + \dot{E}_{Steam\ WGS}} = 66,0\% \quad (21)$$

## 5. Discussion

The three calculation models were run with equal dry biomass input, so that direct comparison of thermodynamic values is possible. Comparing Case I to Case II and III, BM-to-Syn efficiency of Case I is lower. The reason for this is because PG has to supply heat to gasifier, pyrolysis and drying steps, while in Case II and III the drying step takes heat from, respectively, syngas cooling and methanation. In Case II, air is preheated and steam is produced from cooling flue gases and burning part of pyrolysis gas, so the increase in efficiency is inferior to Case III. However, in Case III, the entire drying heat load is provided by the waste heat from methanation, so pyrolysis temperature can be lowered in order to reduce production of PG, maximizing char and syngas yields.

Parameter	Case I	Case II	Case III
Fuel conversion efficiency - BM to syngas	77,4%	86,0%	93,2%
Fuel conversion efficiency - BM to CH <sub>4</sub>	54,4%	65,2%	66,0%
Cooling utilities	5591	10052	14496
Char %	40,93%	43,53%	46,90%
Pyrolysis gas %	59,07%	56,47%	53,10%
Pyrolysis temperature	400°C	393°C	341°C
Electrical consumption	365	374	386
Electrical power output	-	2368	-
Electrical efficiency	-	12,9%	-

Chart 3- Comparison of key parameters for all cases. Power values are expressed in P.U.

Compared to the standard WoodRoll®, Case II and Case III present an advantage: the air for combustion of PG is preheated. This allows reducing the consumption of PG per unit volume of syngas produced. In Chart 12, the three cases are compared among themselves with key parameters of the process.

With regards to the cooling utilities, Case II presents nearly twice the load discharged by Case I because of the cooler positioned in the steam cycle; the cooling effect on the drier is the same. Looking at Case III, the cooling need is almost threefold the Case I need: this is due to a very large moisture content in the lower-grade fuel.

## Conclusions

The literature review presents the different alternatives for fuel synthesis, starting from syngas with high hydrogen content (H<sub>2</sub>/CO=2). Each fuel conversion process has been outlined with a description of the thermodynamic conditions to adopt in order to achieve the required output fuel. As for the modelling section, the main task is exploring how could Cortus integrate the WoodRoll® technology with the methanation unit developed by KIC InnoEnergy in Karlsruhe Institute of Technology, making good use of the waste heat available from the methanation process. In this section, the commercial version of the WoodRoll® gasification plant is modelled on Simulink in order to be able to verify the coherence of the model with the already-existing model produced by the company on VBA code. The analysis revealed a close match between the set of data. Consequently, two integration alternatives are modelled. The first configuration allows conversion of syngas to methane plus conversion of electricity through a steam cycle, using waste heat from flue gases and methanation as thermal input. This configuration can be suitable for isolated systems having both electricity and methane grid, with abundance of wood or agricultural residues. This setting can yield 65,2% BM-to-CH<sub>4</sub> conversion efficiency and 12,9% electrical efficiency. The last configuration targets the utilization of very wet biomass waste streams, such as paper mill sludge, characterised by moisture levels about 70%; paper mills have to get rid of this feedstock, so they pay to have it withdrawn. The configuration is designed to shift a large thermal load on the drier, so the efficiency of the process is obviously reduced, as the heat supplied to the biomass for water evaporation cannot be further recovered: BM-to-CH<sub>4</sub> efficiency is 66,0%. The lower conversion efficiency is compensated by a negative cost on the feedstock supply. To further implement one of these models, a preliminary economical assessment should be carried out, together with a Life Cycle Analysis, in order to assess global emissions, consumption of natural resources and waste streams.

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