Power Process Simulation

Period V Project

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1. Introduction

The presented work deals with the simulation of a Combined Heat and Power (CHP) power plant in the process simulation software AspenPlus ® [1]. A CHP produces not only electricity like an ordinary power plant but also district heat. This leads to the greatest benefit of a CHP plant, which is its high total efficiency: up to 90% or more of the fuel input is converted to useful energy. The plant in question works by exploiting the combustion of biomass, in particular wood fuel, whose composition is known. Alternatively, the system presented by us can be powered by Municipal Solid Waste (MSW), an alternative that will involve changes in terms of consumption, emissions, and production in the plant that will be analyzed in this project. After creating a digital twin of the process, a sensitivity analysis is made on two parameters by changing either the fuel input or the air mass flow rate. These changes are leading to different efficiencies and emissions, conditions that will be discussed in this document. Additionally, improvements to the process will be proposed such as using a reheater for the livesteam after the high-pressure turbine or the increase of the pressure in the feed water tank. Finally, the use of an alternative fuel, which is municipal solid waste, is discussed.

2. Methods

This section describes the model used on AspenPlus ® to simulate the plant under consideration. Initially, information regarding biomass and ashes were entered and modeled as non-conventional compounds. In addition, PR-BM and IAPWS-95 were selected as the Base property methods and the Free-water method, whose information can be found on the program itself, and the values used in the PROXANAL and ULTANAL sections were considered on a dry basis when required. The model main flowsheet can be seen in Appendix A. The DECOMP, RGIBBS and FLASH blocks, that can be seen in Appendix B in the combustion unit, simulate the biomass and air combustion process that takes place in the boiler. In particular,the separation of the solid part obtained as a result of this first process and the hot gases by means of an adiabatic flash separator is simulated. The hot gases therefore are the ones analyzed and the ones that transmit heat to the steam used in the plant processes. It should be mentioned that while the amount of fuel input is known, the air flow rate required for combustion was calculated through the specification of an oxygen conten of 5 vol% in the flue gas. As for the water/steam cycle, water enters the economizer (ECO), changes phase in the evaporator (EVA), and is superheated in the superheater (SUPERH) reaching a temperature of 350 °C. In these 3 heat exchangers, the hot fluid is the hot gas produced by the combustion of biomass and, knowing the temperature that this must reach after the boiler i.e. 650 °C, it is possible through this to determine the flow rate of water in the system.The outgoing hot gas stream (FlUE4) is used to preheat the incoming air in the system and is released into the environment at 165 °C. There are two high and low-pressure turbines whose efficiencies are known: in the first (HP-TURB), the pressure change is 10%, followed by a separator (SPLIT) to obtain a bleed flow stream that, after reaching the correct pressure thanks to the BLEED-TU turbine, enters the feedwater tank. The remaining steam stream passes into the low pressure turbine (LP-TURBINE) and reaches the pressure of the condenser (CONDENS). Here the vapor becomes saturated liquid by using the evaporation enthalpy for district heating. By specifying the inlet and outlet temperature of the district heating stream it is possible to specify its flow rate. Finally, the feedwater tank at 1.15 bar is simulated by using a mixer: here, the steam flow (BLEEDFWP) and the saturated water flow (WATERFWP) bring the water to 1.15 bar at vapor fraction=0 and the flow rate of these two streams is defined by a design specification: by imposing 0 kW is the net heat duty needed to have x=0 after FWTMIX (perfect balances between the two masses, no additional heat needed), it is possible to choose how to split the flow in SPLIT.

3. Results and Discussion

3.1. Model results

In the basic model, wood with a lower heating value of 11.5 MW is used as fuel. The high-pressure turbine produces 57.5 kW of electricity, the low-pressure turbine generates 1956.1 kW and the bleed turbine 47.9 kW. The two pumps require a total of 9.625 kW of electricity. The total amount of electricity that can be used is therefore 2051.875 kW, resulting in an electrical efficiency of the system of 17.84 %. In addition to the electrical output, in a CHP power plant heat is also produced and utilized. The district heat is provided by the condenser amounting to 8154.75 kW. This results in an overall efficiency of the plant of 88.75 %. All the results can be seen under E.2. Both efficiencies are calculated through the following equation based on the formula in Khartcheko (2013) [2] :

$$\varepsilon_{electrical} = \frac{W_{net}}{Q_{in,CG}} \tag{3.1}$$

$$\varepsilon_{overall} = \frac{W_{net} + Q_U}{Q_{in,CG}} \tag{3.2}$$

where:

$\varepsilon_{overall}$ = Overall Efficiency
W_{net} = Rates of net work
Q_U = Rate of useful heat output
$Q_{in,CG}$ = Rate of fuel energy input

This means for the analyzed process:

$$\varepsilon_{electrical} = \frac{W_{HP} + W_{BT} + W_{LP} - W_{PumpMain} - W_{PumpFWT}}{Q_{InBoiler}} \tag{3.3}$$

$$\varepsilon_{overall} = \frac{Q_{Condenser} + W_{HP} + W_{BT} + W_{LP} - W_{PumpMain} - W_{PumpFWT}}{Q_{InBoiler}} \tag{3.4}$$

where:

$Q_{Condenser}$ = Rate of useful heat output
W_{HP} = Electricity output of high-pressure turbine
W_{BT} = Electricity output of bleed turbine
W_{LP} = Electricity output of the low-pressure turbine
$W_{PumpMain}$ = Electricity input at main pump
$W_{PumpFWT}$ = Electricity input at pump at the feedwater tank

The EU Directive on the limitation of emissions of certain pollutants into the air from medium combustion plants [3] applies to medium-sized power plants with a rated thermal power of between 1 and 50 MW. In order to be able to apply these to the exhaust gas values of the base model, they must first be converted to the standard conditions specified in the directive (dry base, 0°C, 6% standardised oxygen content). For this purpose, the exhaust gas is first cooled down to 0°C by an additional cooler and then divided into liquid and volatile components in a flash separator. The stream parameters are then converted into a dry basis and then converted to the values of the standardised oxygen content using the conversion specification [4]. The results of this conversion can be found in E.3. Both the sulfur-dioxide values in the exhaust gas of 304 $\frac{mg}{Nm^3}$ and the nitrogen oxide values of 1646 $\frac{mg}{Nm^3}$ are clearly above the permitted limits of 200 and 300 $\frac{mg}{Nm^3}$ respectively. For this reason, further exhaust gas treatment would be necessary for the new approval of the plant. Only the dust values in the exhaust gas regulated by the directive could be complied with. However, this is due to the fact that in the digital twin of the plant, one hundred percent separation of all solid components in the flue gas was simulated by an ideal flash. In the real case, one hundred per cent separation cannot be assumed and further consideration of the issue would be necessary.

3.2. Sensitivity Analysis

The sensitivity analysis examines how the output changes when distinct variables are changed. This can be done with different methods. These can be classified into three categories, namely mathematical statistical or graphical[5]. In the scope of this report, the function built into Aspen Plus ® is used. Therefore, the methods can be classified as mathematical with an graphical assessment afterwards. The main goal of the analysis is the understand how the efficiency of the CHP plant can be increased. The efficiency is calculated through the equations 3.2. Thus, two different variables that are examined in the process are chosen. Firstly, the effect of varying mass flow of biomass is analyzed and a range for an optimal set up of the base model is defined. Secondly, the air intake is varied and thus the oxygen content is manipulated. For that reason the design spec to fix the air intake and with this the oxygen content is deactivated. With this analysis, a set up for low emissions can be found.

Biomass Mass Flow

In the base case the biomass mass flow is 1.4443 $\frac{kg}{s}$. To see how the process changes, the range is $+/-$ 1.5 $\frac{kg}{s}$, so from 1 to 3 $\frac{kg}{s}$. With an increasing biomass mass flow rate a linear increase of live steam

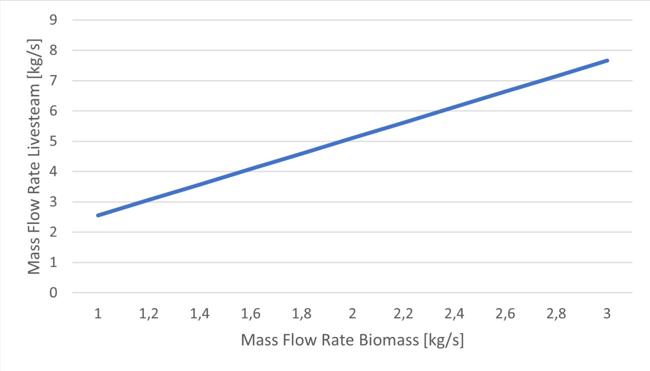

Figure 3.1.: Livesteam Mass Flow [$\frac{kg}{s}$]

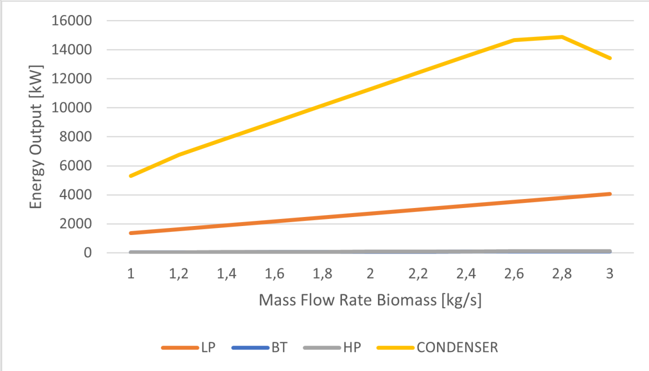

Figure 3.2.: Case 1 - Turbine and District Heating output

production can be observed as can be seen in figure 3.1. With that a linear increase of the output of the low pressure turbine can be seen in figure 3.2. The orange curve, that describes the low pressure turbine, more than doubles the output from 1 to 3 $\frac{kg}{s}$. The output of the bleed turbine (blue) and the high pressure turbine (grey) is not effected by the increase of livesteam production.The district heating output in the condenser (yellow) has an optimum at 2.8 $\frac{kg}{s}$ and it decreases afterwards.
The aim of the sensitivity analysis is to analyze the efficiency. This is calculated as described earlier according to Khartchenko (2013) [2]. In figure 3.3 it can be observed that from a mass flow rate of

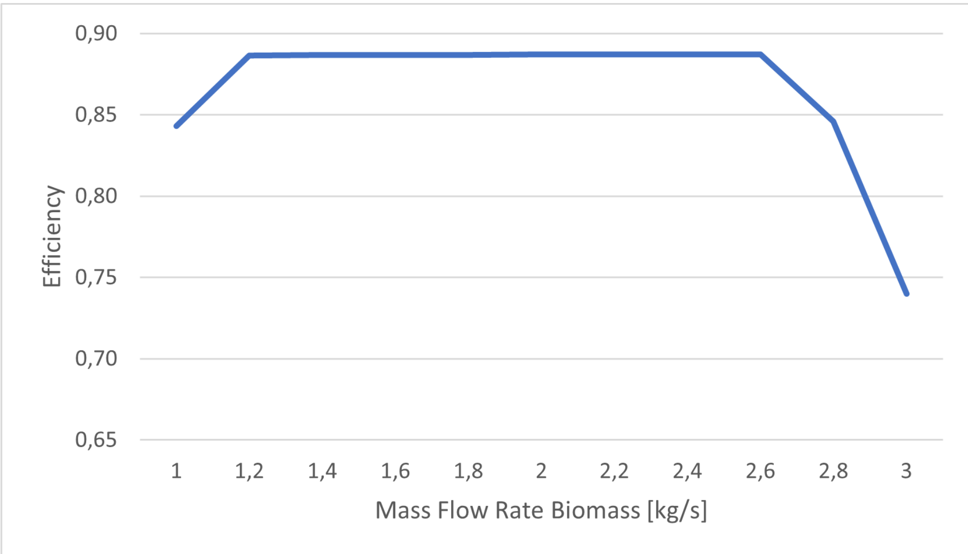

Figure 3.3.: Case 1 - Overall Efficiency

biomass from 1.2 to 2.6 $\frac{kg}{s}$ a stable efficiency of 88% can be achieved. Even though the optimum of the DH output is at 2.8 $\frac{kg}{s}$, the gradient decreases in figure 3.4. Therefore, the CHP should run in the range with the highest efficiency. This consideration could change if the aim changes to the highest DH output as possible at high DH prices. These considerations could be supported with a subsequent optimization.

Air Intake Mass Flow

In the base case the air intake is fixed by the oxygen content of the flue gas of 5 %. Through a varying air intake also the oxygen content of the flue gas content changes and with it the conditions for combustion. A air intake of 5.8 $\frac{kg}{s}$ is therefore determined by the simulation in the base case. To analyse the effects of an incomplete combustion the lower range of the sensitivity analysis is set at 3 $\frac{kg}{s}$ where as the upper boundary is fixed at 8 $\frac{kg}{s}$.

In figure 3.4 the output of the three turbines and the heat transferred to DH is visualized. As can be

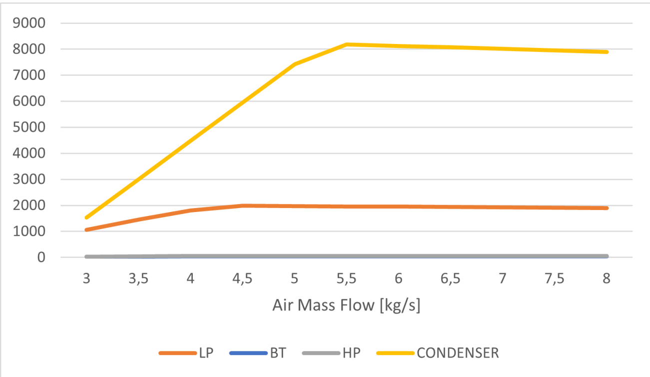

Figure 3.4.: Case 2 - Turbine and District Heating output

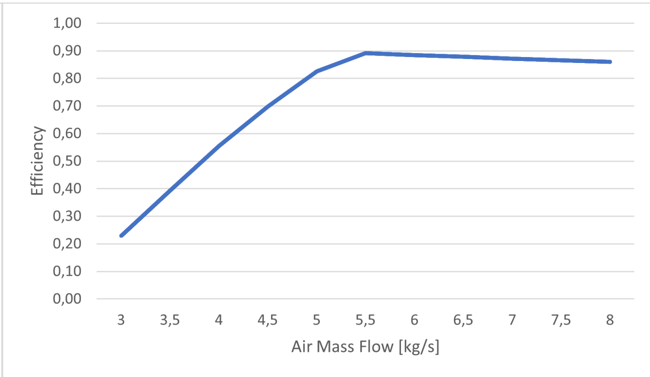

Figure 3.5.: Case 2 - Overall Efficiency

seen in figure 3.5 the biggest impact has the DH output. Its optimum is at 5.5 $\frac{kg}{s}$ which is close to the base case. This also means that not more heat can be transferred with the given values into the DH network than in the base case. Through the increase of the mass flow rate of the air, the useful output can not be increased. With the air intake also the stoichiometric combustion condition change.

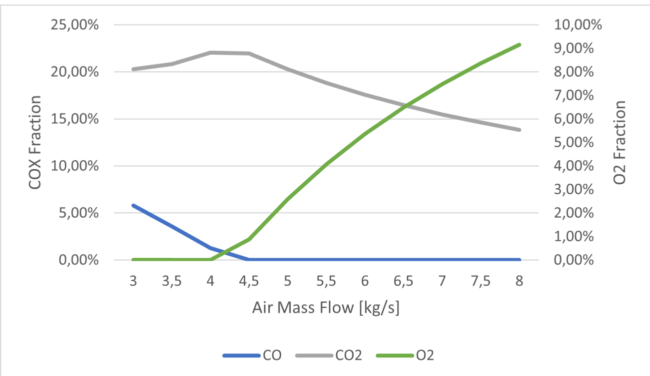

Figure 3.6.: Case 2 - CO & CO_2 emissions fractions

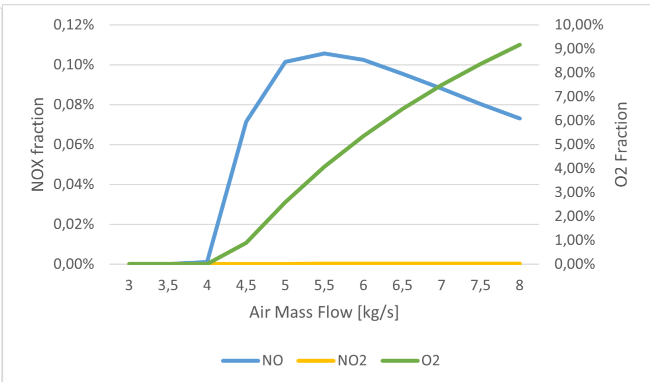

Figure 3.7.: Case 2 - NO & NO_2 emission fractions

From figure 3.6 it can be deducted that the minimum air mass flow rate for a complete combustion is 4.5 $\frac{kg}{s}$. With a smaller mass flow rate more CO is formed since not enough O_2 is present to form CO_2. Therefore after the point of complete combustion the CO emissions stay constant at a level of 0. The highest concentration of CO_2 in the fluegas can be observed. Afterwards the concentration of CO_2 declines but not the absolute values. The same can be observed in figure 3.7 where the highest fraction of NO_2 can be observed from 5.5 $\frac{kg}{s}$. After all carbon is oxidized to CO_2 the remain oxygen react with nitrogen. As the mass flow increases, more O_2 molecules enter and less O^- Ion which are more reactive. Thus less nitrogen reacts.

3.3. Model Improvement

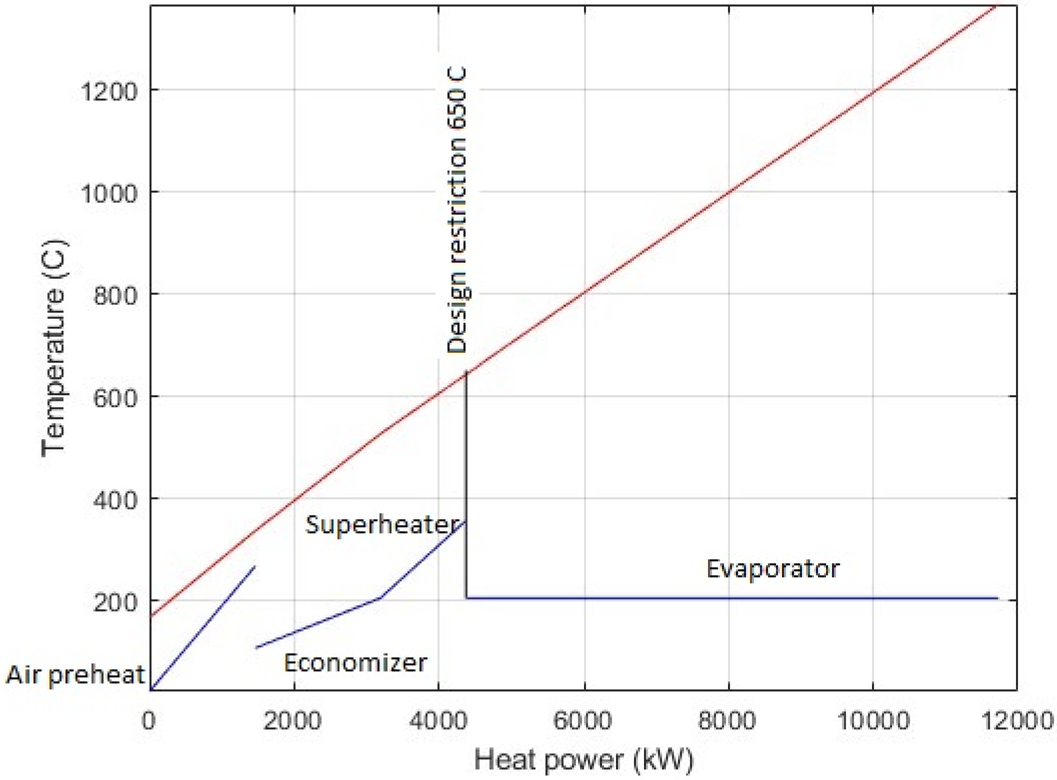

Figure 3.8.: Pinch analysis of base case

Figure 3.8 shows the pinch analysis of the only heat source of our boiler, the flue gas. The figure shows also the design restriction, that flue gas needs to be at 650 °C after the evaporator. It can be seen from the figure that all heat is already used in a sensible manner. Because of this, the model can be improved by exchanging district heat for more electricity. DH produced in the base case was 150 kW more than required, which gives opportunity to improve the electric efficiency.

The theoretical limit for the efficiency of any heat engine is given by the Carnot process efficiency:

$$\eta = \frac{Th - Tc}{Th} \tag{3.5}$$

By considering this equation, it makes sense that the Rankine process can be improved with either: 1.Increasing the average temperature of heat put into the process

2.Decreasing the average temperature of heat exiting the process.

The electric efficiency has been increased with two improvements, that increase the average input temperature: by adding a reheat cycle and by increasing the feedwater tank (FWT) pressure. Decreasing average output temperature is unpractical in this case, because DH return (cold) water enters at some temperature, which the power plant cannot dictate. The results of these improvements can be seen in appendix tables F.4 and F.5.

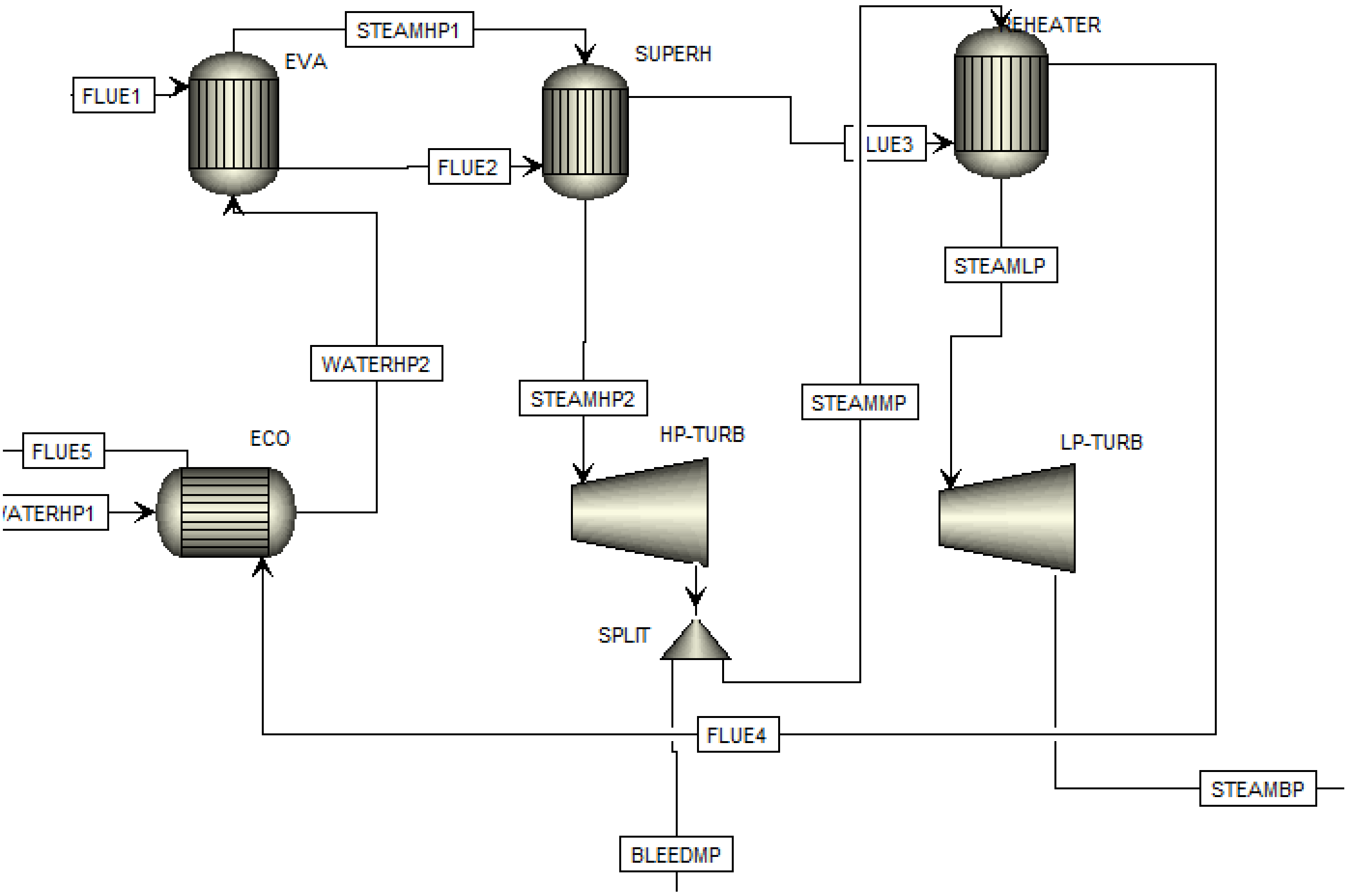

Figure 3.9.: Changes in process streams for the reheater

Adding the reheater consumes some heat, which results in smaller mass flow of water in the boiler. Smaller condensate flow and smaller DH output follow, as desired.

Figure 3.10 shows the Rankine process, which has been improved with a reheater. 1=Live steam, 2=LP steam, 3=Reheated steam, 4=Bleed for regeneration, 5=BP steam, 6=condensate, 7=condensate entering FWT, 8=FWT, 9=HP water, 10=saturated liquid, 11=saturated vapor. The process has 'grown' to the right because of the reheating process, which creates a larger area inside the red lines.

Even though the mass flow of water in the boiler is now smaller, the amount of work done per kilogram of water per cycle is larger. As a result, there is more electric output. Electric output increased and DH output decreased by 11 kW.

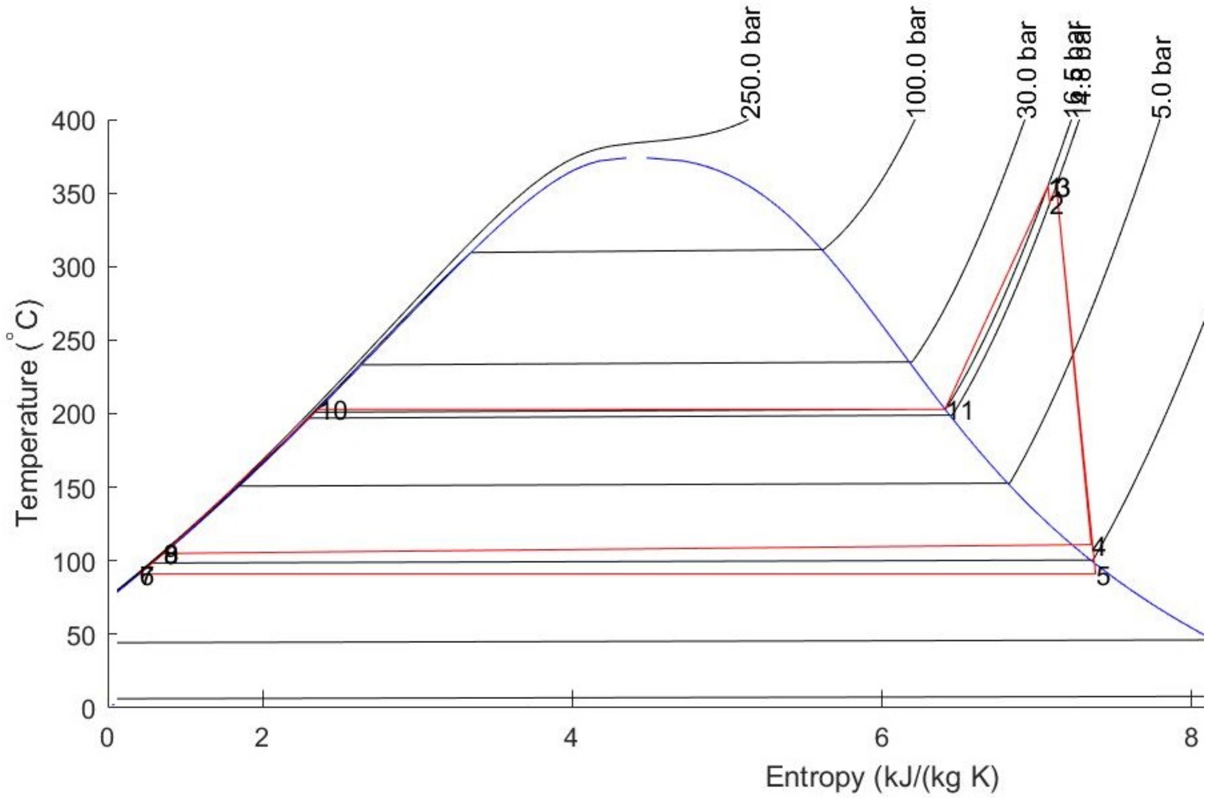

Figure 3.10.: Entropy Temperature diagram with reheater. XSteam by Magnus Holmgren was used to calculate Entropy values.

By increasing the FWT pressure the mass fraction of regeneration increases, which decreases the mass flow in the condensator. DH output decreases as intended.

Also FWT temperature increases, which decreases heat demand at the economizer. This enables a larger mass flow of water through the boiler, therefore increasing the electric output of the turbines. Electric output increased and DH output decreased by 57 kW.

3.4. Alternative Fuel Case

For the alternative fuel case, Municipal solid waste (2920) based on the ECN Phyllis classification is studied [6]. The same lower heating value of 11.5 MW is used for the fuel. Since MSW has higher LHV, it required lesser mass flow rate than that required in the base case. So, the MSW mass flow rate is 0.54937 $\frac{kg}{s}$. To change the input mass flow values, the Calculator block (CALCULTR) is used.This higher LHV of MSW can be attributed to the lower moisture content of the fuel which is 6.16%w, about 88% lower than that of the base case fuel. Fuel analysis of both fuels can be seen in the Appendix in E.1 and E.6.

The high-pressure turbine produces 57.36 kW of electricity, the low pressure turbine generates 1950.89 kW of electricity and the bleed turbine 47.75 kW. The two pumps require a total of 9.597 kW of electricity.

The total amount of electricity that can be produced is therefore 2046.393 kW, resulting in an an electrical efficiency of 17.79%. The district heat production in the condenser is 8132.98 kW, giving an overall efficiency of 88.52%. In comparison, for the same input fuel LHV at the boiler, the electrical and heating outputs and the efficiencies are only a little lower than that of the wood fuel case (less than 0.3%).All the results can be seen under E.7. All the calculations are done in the same way as the base case.

Additionally, there is reduction in the CO_2 %w in the exhaust flue gas, about 7% lower. However, there is growth in the wt-% of CO, NOx and SOx fractions due to higher N and S content in the input. All values in the exit flue gas for both the fuels can be seen in E.8.

Overall, it is seen that for a reduced input mass flow by more than 60%, MSW in the given composition produced nearly the same electrical and heating output and the same efficiency as that of wood for the power plant design. The products of the exhaust gas is dependent on the composition of the feedstock. Low-moisture MSW gives more energy for smaller fuel input as it saves the energy needed for evaporating water. However, high ash content in MSW is not ideal for the plant due to slagging issues. On the other hand, MSW gives higher H_2 yield which can be desirable for fuel production from syngas. A socio-economic analysis would provide more insights into the comparative study of the two fuels.

4. Conclusion

This study on a CHP power plant design using an Aspen plus® digital twin provides significant information about the role of the each component of the plant and the variations in the yield products and outputs with the change in input mass and other distinct variables. First, the starting plant was simulated whose outputs, flows and emissions were calculated. Results were verified by comparing with literature values. Regarding the emissions, further exhaust gas treatment would be necessary for the new approval of the plant as well as other considerations regarding the realistic properties of the model. Sensitivity analysis was then performed, which showed the differences recorded in the model as two parameters changed, which are fuel and air mass flow rate, regarding output calculated, overall efficiency and emissions.In the model improvement, with the aim of improving the base model, a flue gas reheater was added to the initial scheme as well as a higher pressure was imposed in the feedwater tank since it is not possible to increase the efficiency besides taking advantages of the different efficiencies of the components. By doing this, the district heat supplied is decreased and the electricity produced as well as its efficiency is increased. Finally, we evaluated the operation of the plant and the values obtained in the various components by varying the type of fuel and using municipal solid waste, also analyzing the composition of the exhaust gas.

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Appendices

A. Main Flowsheet

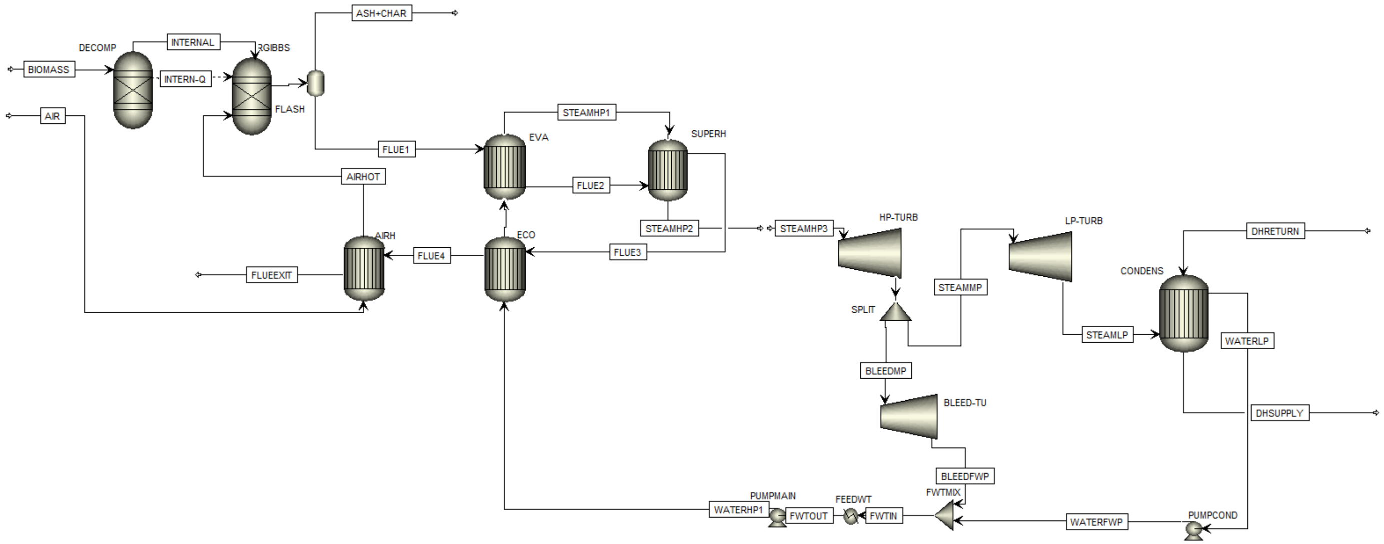

Figure A.1.: Aspen Simulation Flowsheet of CHP Plant

B. Combsution Unit

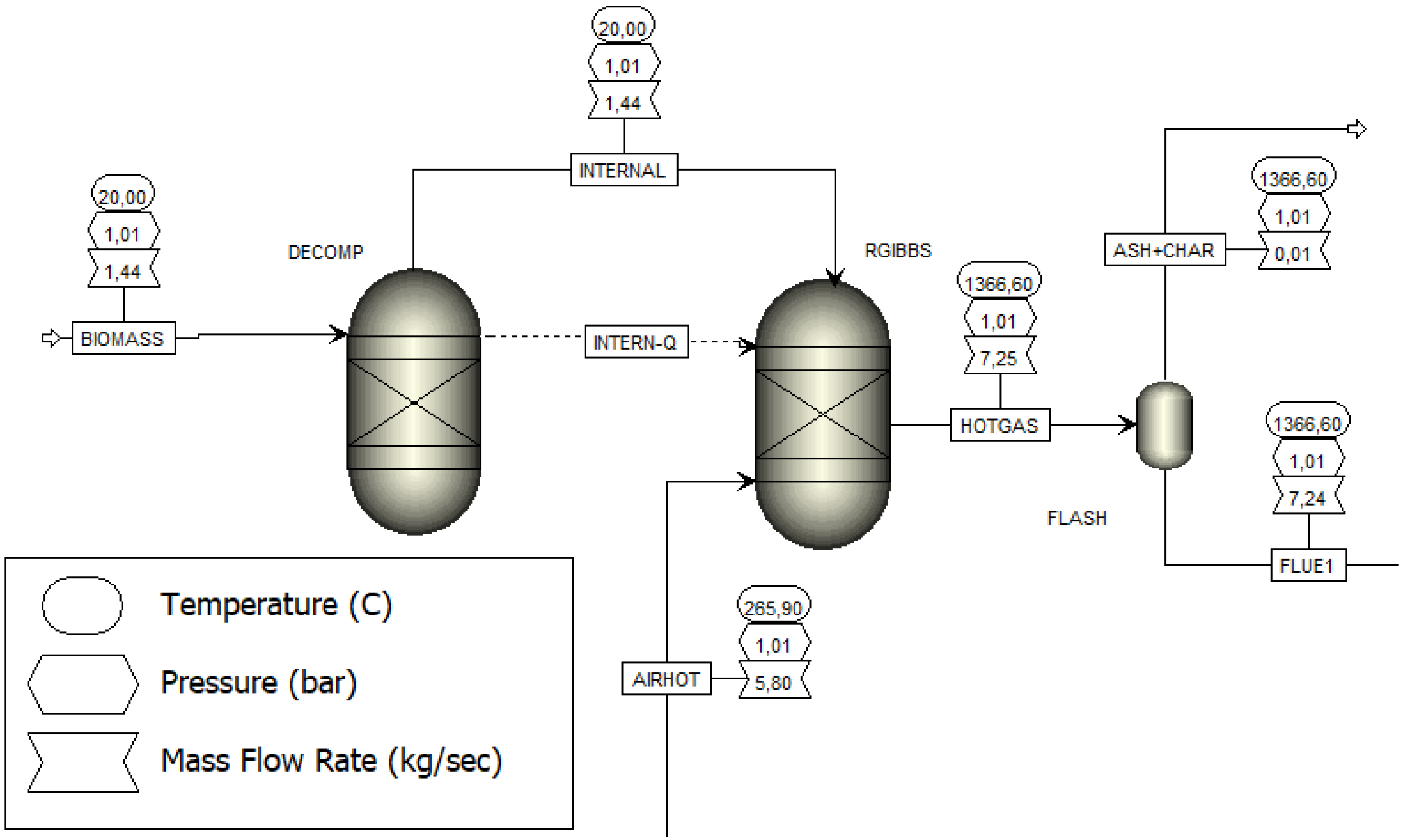

Figure B.1.: Aspen Simulation Flowsheet of Combustion Unit of CHP plant

C. Heating Unit

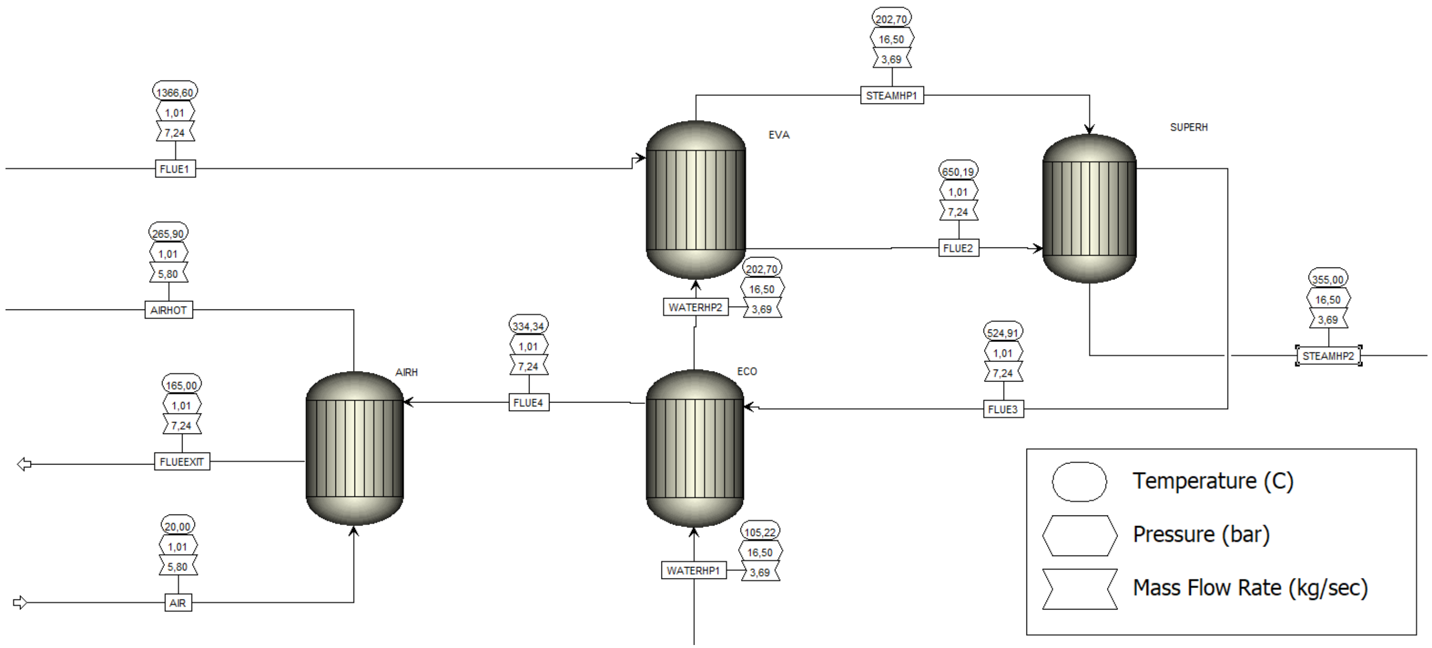

Figure C.1.: Aspen Simulation Flowsheet of Heating Unit of CHP plant

D. Power and District Heating Unit

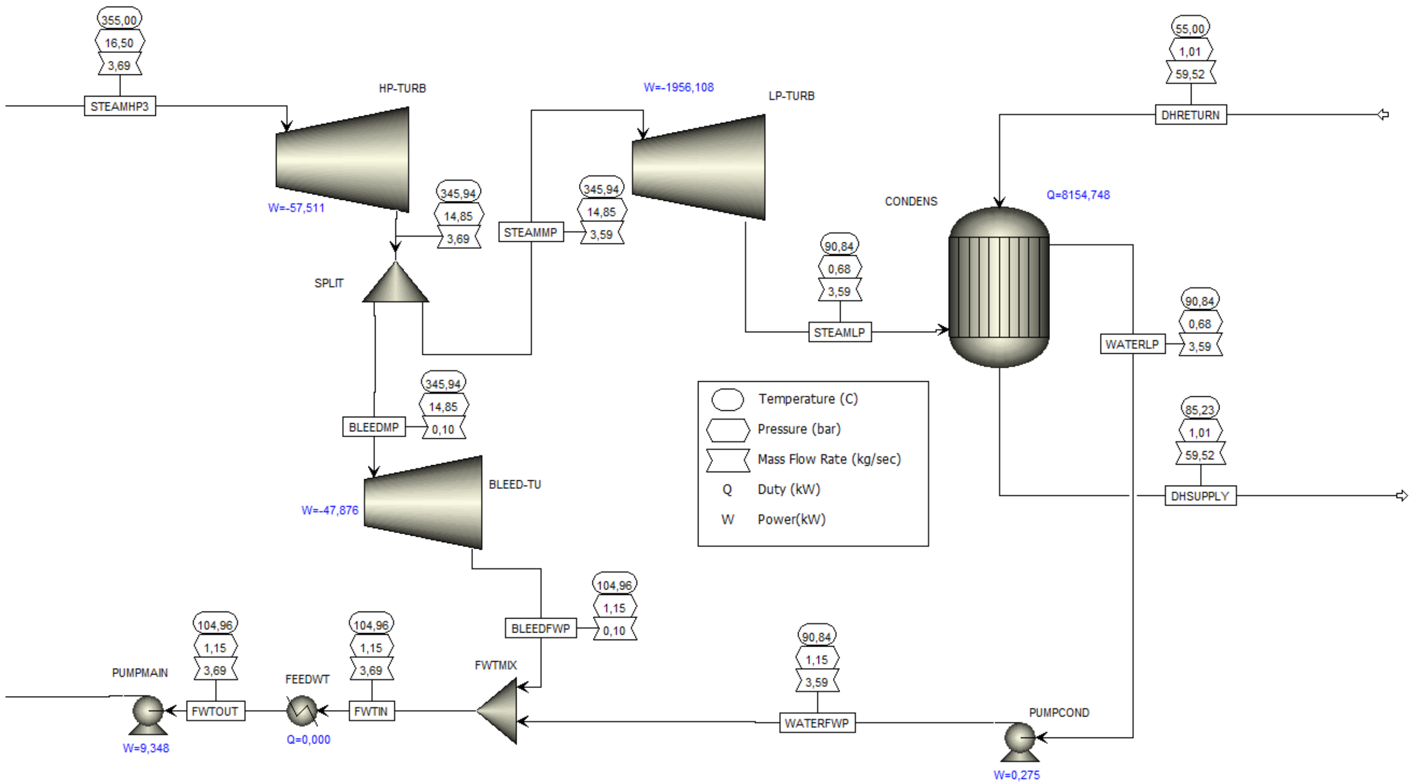

Figure D.1.: Aspen Simulation Flowsheet of Power and District Heating Unit of CHP plant

E. Block Diagram

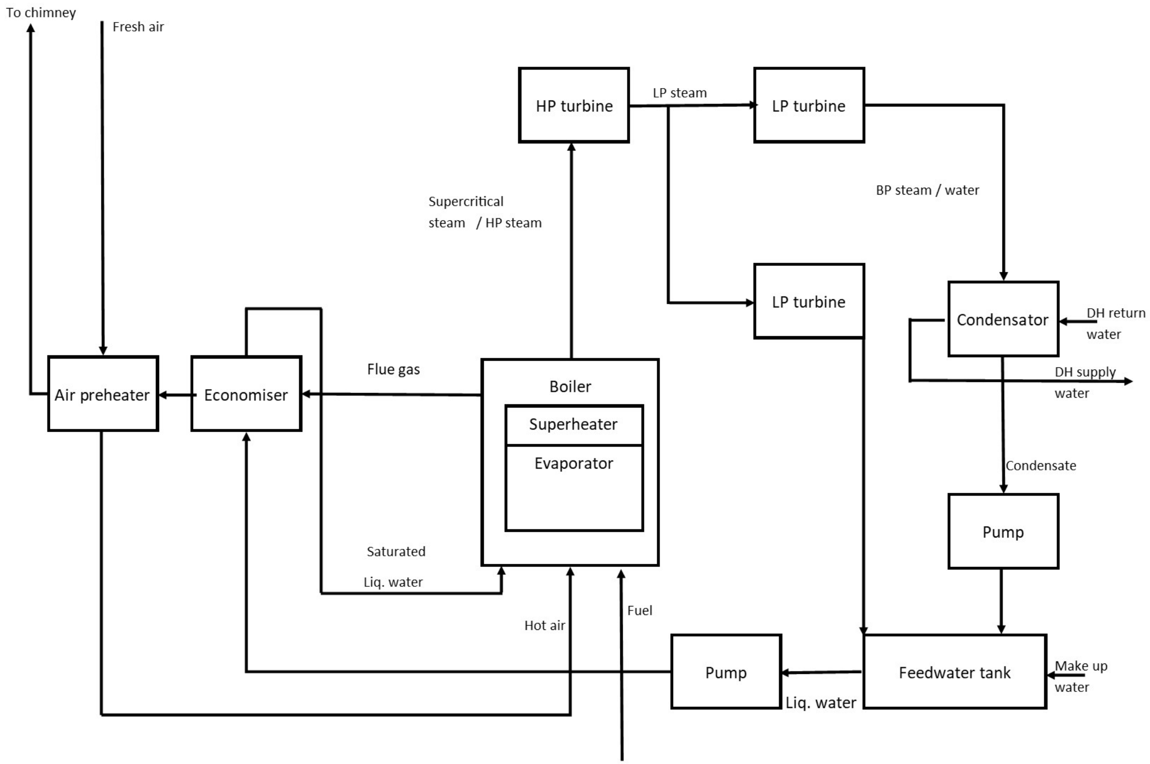

Figure E.1.: Block Diagram of CHP plant

Model Results

Ultimate analysis	**(wt-% dry ash-free)**
C	50,8
H	6,15
O	42,55
N	0,4
S	0,1
Proximate analysis	**(wt-%)**
FC (dry ash-free)	21
VM (dry ash-free)	79
Ash (dry)	0,8
Moisture (wet)	51

Table E.1.: Fuel analysis of wood

component	**energy output [kW]**	**energy loss [kW]**	**electricity need [kW]**
LHV_{wood}	11500	-	-
HP turbine	57,51	1,78	-
LP turbine	1956,11	60,50	-
Bleed turbine	47,88	1,48	-
Condenser	8154,75	-	-
feedwater pump	0,26	0,02	0,28
main pump	8,88	0,47	9,35

Table E.2.: Energy input and output

component	**mass in norm volume** [$\frac{mg}{Nm^3}$
C	0
0_2	85737
H_2	1,39
H_20	0
CO_2	283237,45
CO	28,81
NO	1642,54
NO_2	3,45
N_2	965134,93
S	0
SO_2	303,77

Table E.3.: Composition of the dry exhaust gas at 273,15K with a standardised oxygen content of 6 %

component	energy output [kW]
HP turbine	57,10
LP turbine	1966,90
Bleed turbine	47,5
Relative change in total electric power from base case	11,2
Condenser	8139,00
Total efficiency	88,8%
Electrical efficiency	18%

Table E.4.: Energy output with reheating

component	energy output [kW]
HP turbine	62,4
LP turbine	1941,80
Bleed turbine	103,00
Relative change in total electric power from base case	46,9
Condenser	8095,20
Total efficiency	88,7%
Electrical efficiency	18,3%

Table E.5.: Energy output with increased FWT pressure

Ultimate analysis	**(wt-% dry ash-free)**
C	59,19
H	9,80
O	28,53
N	2,19
S	0,29
Proximate analysis	**(wt-%)**
FC (dry ash-free)	12,72
VM (dry ash-free)	87,28
Ash (dry)	16,82
Moisture (wet)	6,16

Table E.6.: Fuel analysis of MSW

component	energy output [kW]	energy loss [kW]	electricity need [kW]
LHV_{wood}	11500	-	-
HP turbine	57,36	1,77	-
LP turbine	1950,89	60,34	-
Bleed turbine	47,75	1,48	-
Condenser	8132,98	-	-
feedwater pump	0,26	0,02	0,27
main pump	8,86	0,47	9,33

Table E.7.: Energy input and output of alternative fuel (MSW)

Wood	**-**	**MSW**	**-**
component	**wt-%**	**component**	**wt-%**
O_2	0,4878	O_2	0,05128
H_2	8,79 x 10^{-7}	H_2	58,17 x 10^{-7}
H_2O	0,15495	H_2O	0,07401
CO_2	0,18038	CO_2	0,16775
CO	1,82 x 10^{-5}	CO	31,61 x 10^{-5}
NO	0,001044	NO	0,0030059
NO_2	2,47 x 10^{-6}	NO_2	4,03 x 10^{-6}
N_2	0,61463	N_2	0,70317
SO_2	0,000194	SO_2	0,000449

Table E.8.: Exit flue gas composition (wood and MSW) for the same fuel input of 11.5 MW