

Lappeenranta University of Technology

Faculty of Technology

LUT Energy

LUT Scientific and Expertise Publications Tutkimusraportit – Research Reports 8

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## Integration of Torrefaction with Steam Power Plant



Lappeenranta University of Technology

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PL 20

53851 LAPPEENRANTA, Finland

ISBN 978-952-265-395-6

ISBN 978-952-265-396-3 (PDF)

ISSN-L 2243-3376

ISSN 2243-3376

Lappeenranta 2013



# **Abstract**

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Lappeenranta 2013

65 pages

Lappeenranta University of Technology, Department of Energy Technology

Torrefaction is one of the pretreatment technologies to enhance the fuel characteristics of biomass. The efficient and continuous operation of a torrefaction reactor, in the commercial scale, demands a secure biomass supply, in addition to adequate source of heat. Biorefinery plants or biomass-fuelled steam power plants have the potential to integrate with the torrefaction reactor to exchange heat and mass, using available infrastructure and energy sources. The technical feasibility of this integration is examined in this study. A new model for the torrefaction process is introduced and verified by the available experimental data. The torrefaction model is then integrated in different steam power plants to simulate possible mass and energy exchange between the reactor and the plants. The performance of the integrated plant is investigated for different configurations and the results are compared.

Keywords: biomass, bioenergy, steam power plant, torrefaction, integration, simulation



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## NOMENCLATURE

### Roman letters

$a_E, a_M$	experimental constants for energy and mass yield correlations [-]
$b_E, b_M$	experimental constants for energy and mass yield correlations [-]
$c_E, c_M$	experimental constants for energy and mass yield correlations [-]
$c_p$	specific heat at constant pressure [kJ / kgK]
$E$	energy yield [-]
$h$	specific enthalpy [kJ / kg]
$LHV$	lower heating value [MJ / kg]
$M$	mass yield [-]
$MC$	moisture content [kg <sub>H2O</sub> / kg <sub>total</sub> ]
$\dot{m}$	mass flow rate [kg / s]
$p$	pressure [bar]
$P$	power [W]
$t$	time [various]
$T$	temperature [°C]
$T_{ini}$	temperature where torrefaction reactions begin [°C]
$T_{torr}$	temperature maintained during torrefaction [°C]

### Greek letters

$\eta$	efficiency
$\eta_{drier}$	drier efficiency: ratio of heat usage to heat of evaporation $\times$ mass evaporated
$\eta_e$	electrical efficiency of a power plant
$\eta_{torr}$	torrefaction efficiency: ratio of heat usage to sensible enthalpy increase in solid biomass
$\Phi$	thermal power [W]

### Subscripts

d	condition at drier exit
daf	dry, ash-free
fuel	untreated CHP fuel
g	gas and vapour products
gen	generator
in	entry to component
L	liquid phase
out	exit from component
TB	torrefied biomass
torr	torrefaction
w	water
V	vapour phase

**Acronyms**

CHP	combined heat and power
daf	dry, ash-free
HP	high pressure
IP	intermediate pressure
LHV	lower heating value
LP	low pressure
MC	moisture content



# 1 Introduction

In order to increase the share of biomass for sustainable energy production, advanced pretreatment processes and technologies are one of the important focus areas. Torrefaction is a thermo-chemical conversion process that improves the energy density, grindability and hydrophobic properties of the biomass, among other advantages. Biomass can be torrefied in an inert environment at temperatures between 200 and 300°C resulting in torrefied solid fuel and combustible gases. The produced gas can be burnt as a fuel, for instance, to supply a share of required heat for the torrefaction process (Bergman, et al., 2005a). However, the required heat for torrefaction process might be supplied by other sources of heat, depending on the process design and available resources.

The first possible alternative is to provide the process heat by combusting a CHP fuel to provide heat for the torrefaction reactor, such as biomass or natural gas. There are different studies that have investigated different configurations and models for the combustion of torrefaction gas and other additional fuels, including possible process integration and energy optimization (Bergman and Kiel, 2005). Most of these studies are just focused on a torrefaction reactor as a separated unit or, in some cases, connected with a parallel furnace or boiler. However, torrefaction may also be utilized in more complicated units. For instance, torrefaction process can be combined with a bio-power plant or, in a broader concept, in a biorefinery plant with various integration possibilities in terms of process, energy and mass. Therefore, more detailed study of possible models, process integrations and energy optimization is crucial to promote the use of torrefaction in more innovative and efficient methods.

In this study, the combination of a torrefaction process with a steam power plant is examined. Since biomass logistics is already established for biomass-fueled steam power plants, they can be good choices for integrating a parallel torrefaction plant, if other requirements are met. In this study, the integration of a new torrefaction reactor into an existing biomass power plant is studied by simulating the models in IPSEpro environment. Different alternative sources for supplying the heat demand of torrefaction process and the relevant interactions are modeled, examined and compared. Mass and energy balance of these integrated plants is examined in different torrefaction temperatures and residence times for each case. These different sources of heat, including water from boiler drum, furnace hot gases and steam are extracted from different parts of the steam power plant. Therefore, the influence of each alternate on the bio power plant is also tracked and compared. In each case, the required configuration is built and modeled in the IPSEpro environment, which is a flexible tool for energy engineering (SimTech, 2012).

It is assumed that in all the cases the heat demand of torrefaction is indirectly supplied. In other words, there is no chemical reaction between heat agents and torrefaction feedstock or byproducts. Moreover, it is assumed that the torrefied biomass is completely exported from the plant. It means that the torrefied biomass is not used as

CHP fuel for the steam boiler, though there are still doubts about the economy of such a usage (Schorr, Muinonen and Nurminen, 2012).

## 2 Torrefaction

Torrefaction of biomass is a pre-treatment method that occurs at 200-300 °C in an inert oxygen-free environment. Using this thermo-chemical process, the decomposition reactions make the biomass feedstock dried and energy-dense with partially different physical properties resulted by the destruction of the fibrous structure of biomass (Bergman and Kiel, 2005). The grindability and energy content of biomass are improved, and the fuel becomes more hydrophobic. Torrefied biomass has darker color, brown to dark-brown, with the properties between wood and coal. This conversion of properties in torrefied biomass makes it more applicable for different combustion and gasification technologies. Moreover, torrefaction improves the logistic features besides the thermal conversion of biomass, in particular, when torrefaction is followed by densification, e.g. torrefied pellets (Bergman and Kiel, 2005).

Torrefaction products are not limited to the torrefied solid biomass. As the biomass becomes partly decomposed through the process, different types of volatiles are also produced. As a result, there is a loss of mass and energy from solid biomass released in produced gas called torrefaction gas in this report. The yield of mass and energy, from the normal biomass to the torrefied biomass is significantly related to biomass type in addition to torrefaction temperature and reaction time. According to Bergman and et al., these values are typically a mass yield of 80% and energy yield of 90%, based on dry ash free matter (2005a). It should be noted that the results vary greatly between different materials and experiments. Since there is more mass loss than energy, torrefied biomass maintains higher energy content. The mass and energy yields can be even 45% and 90% respectively, on the basis of “as received” for biomass with 35% moisture content (Bergman and Kiel, 2005).

In general, biomass consists of three main polymeric components, including cellulose, hemicellulose and lignin. Hemicellulose is most reactive part among these three so that it is highly devolatilized and carbonized in temperatures above 250°C. The degradation in the tenacious nature of biomass is mostly due to the destruction of hemicellulose matrix, which binds the cellulose fibers (Bergman, et al., 2005a). Since the polymeric composition of the different types of biomass is not similar, the mass and energy yield can also be different. However, in this research, the focus is in heat and mass balances between torrefaction reactor and steam cycle rather than the torrefaction process itself. The torrefaction model used is a simple mass and energy balance model based on the mass and energy yields obtained by Sarvilahti master’s thesis (2010) and the assumption of production of all LHV of untreated biomass in torrefaction products (solid and gaseous)

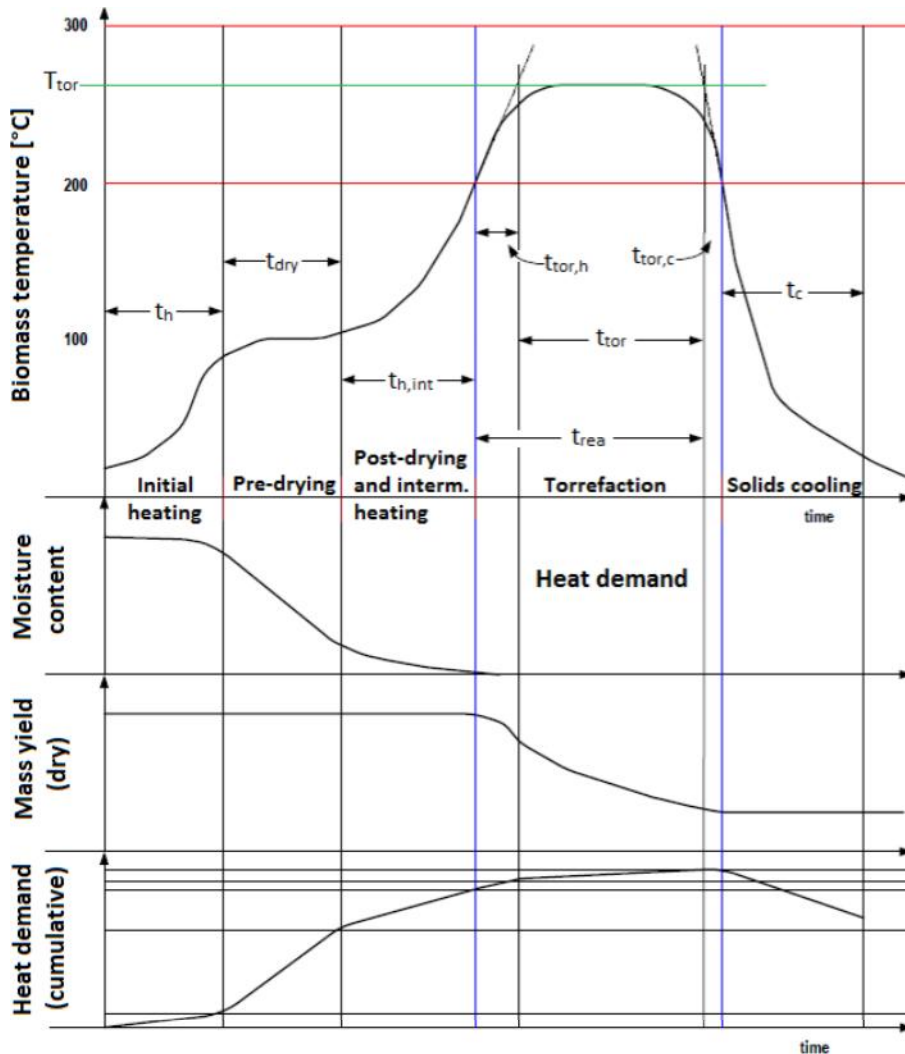
### 2.1 Torrefaction Process

Since there is a vast use of the terms “residence time” and “torrefaction temperature” in this research, they are now briefly introduced through the torrefaction process. To

understand the process better, Bergman and et al. divided the torrefaction process to five phases (2005a). In the “initial heating” phase, the heat is merely used to raise the temperature of biomass. This stage ends when moisture starts to evaporate. During the second phase called “pre-drying”, the temperature is constant and the free water constantly evaporates from the biomass. This stage ends when the adhesive moisture is evaporated and the amount of moisture in pores is critical as it is shown in picture 2.1.

When all adhesive water is evaporated, the temperature starts to increase and all the physically bound moisture is released so that the biomass is completely free of moisture. At this stage, called post-drying, also the first solid components undergo a phase transition to the produced gases, declining the mass yield. The temperature at the end of this stage is approximately 200 °C that is suitable for the beginning of the torrefaction phase.

Torrefaction phase, as the core of the whole process, consists a heating and a cooling phase in addition to a period in which the temperature remains constant. This temperature represents torrefaction temperature which is the highest level of the entire process. However, it should be considered that if temperature increases up to 300 °C, the pyrolysis occurs and the biomass undergo another process that is not literally torrefaction anymore. The torrefaction phase ends when the temperature decreases to 200 °C again. However, the reaction time or residence time consists of the time when the material is heated from 200 °C to the required temperature level of torrefaction process (torrefaction temperature), in addition to the time that temperature is kept constant for torrefaction. Hence, the period that occurs afterwards from the torrefaction temperature down to 200 °C is not accounted in the reaction time, though it happens in torrefaction phase (Bergman and et al., 2005a). These phases are illustrated in figure 2.1.



**Figure 2.1:** Biomass temperature, moisture content, mass yield and heat demand through the entire process of torrefaction (Picture from Schorr, Muinonen and Nurminen, 2012).

## 2.2 Heat Demand

The method by which the required heat is supplied for the entire process of torrefaction is one of the important aspects in torrefaction design and performance. As mentioned before, to reach the torrefaction temperature up to 300°C, a suitable heat source is required to meet both temperature and energy requirements. The entire process can be divided into two separable sections, including drying and torrefaction, which occur in a row. The biggest share of supplied energy is used in drying section to evaporate the moisture content of the biomass. However, the temperature requirement for this section is not as high as torrefaction section. Therefore, heat supply system should be designed

in a way that supports the smaller part but with higher temperature for the torrefaction section, while maintaining the more energy share with lower temperature for the drying section.

Torrefaction heat can be provided both directly or indirectly, depending on the process design and available technology. In direct heat supply, the heating media is in direct connection with the biomass to transfer heat for drying and torrefaction processes. Using this method, a hot heat-carrying medium can be passed through the biomass supply stream, in an opposite direction. It first maintains the high temperature demand of torrefaction section by providing the required energy, and then passes through the drying section. Controlling the required conditions to evade unwanted reactions, auto-combustion and oxidation is very important in this method. The separation, refining or recycling of the torrefaction gases from the media is another challenging question. The formation of acidic compounds in use of agents like steam should also be carefully considered to avoid tar formation, corrosion and other environmental hazards.

In indirect heat supply, the heat demand of the torrefaction process is supplied through the heating walls of a heat exchanging reactor. In this method, there is no contact between the heating agent and torrefaction biomass or produced gases. This can decrease the risk of auto-combustion, but imposes further efforts in reactor design and operation (Schorr, Muinonen and Nurminen, 2012). The heat loss in the heat exchanger is another fact that should be taken into account. The medium can provide high temperature heat for the torrefaction section first, and be used for the drying section afterwards. Since different torrefaction technologies are highly based on the available practices for drying, gasification or combustion, both direct and indirect methods are currently utilized in running torrefaction reactors. The use of each method highly depends on available technology and the process requirements..

Since torrefaction gases are combustible, they are potentially the initial heat source in both methods. However, as the produced gases are likely insufficient for an auto-thermal process in all settings, use of other sources of heat should also be provided for torrefaction. Torrefaction gases can be refined and recycled for direct heating, supported by other media if needed. For indirect heating, torrefaction gases can be burnt with a CHP fuel in the same burner providing adequate heat for the process. Since the torrefied biomass yield is different for different biomass types and process conditions, the amount of harvested gas is also case-sensitive.

### 2.3 Integration with a Steam Power Plant

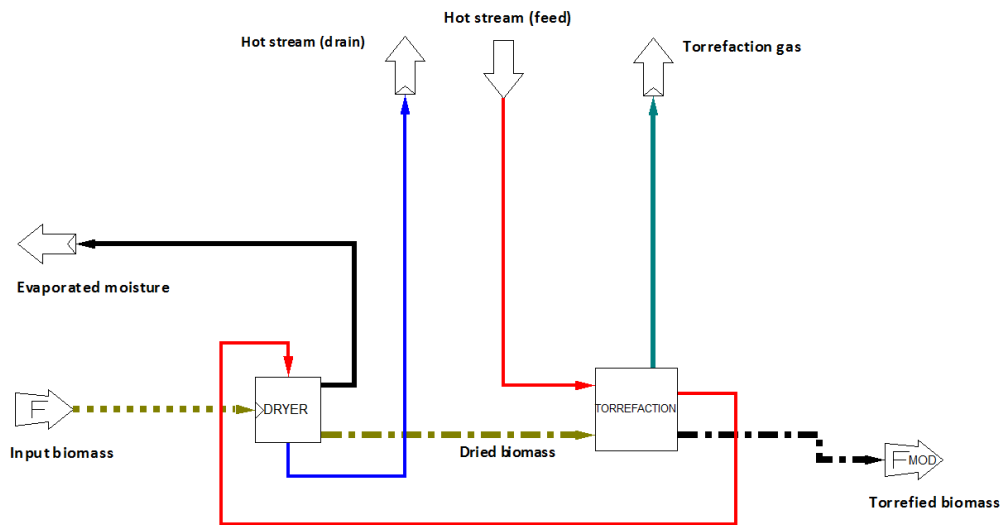
In a steam power plant based on Rankine steam cycle, superheated steam is provided by the combustion of fuel in a boiler. Then, by expanding the steam through the blades of turbine, it rotates the connected shaft generating power. Then, steam is condensed and circulated in regenerative stage(s) to form a closed cycle. In order to combine a torrefaction reactor with a steam power plant, the input requirements of the reactor and output streams should be carefully considered, in addition to the working conditions of

the steam cycle. The possible variations in steam power output and other operational constraints should also be taken into account. The type and amount of biomass and output requirements are important factors to define the torrefaction temperature, residence time, and consequently, the amount of required heat. In general, as mentioned before, if the two sections of drying and torrefaction can be studied separately, the analysis can be simplified for monitoring the possible mass and energy exchange with the steam cycle.

The integration may be designed in terms of process, mass and energy. The type of torrefaction process - direct or indirect heated - is the most important criterion to define the possible integrations. In direct heating, the heating medium may react with the solid biomass and volatiles, producing some gaseous streams that may be subject to further treatment for burning or recycling. The direct heating media can be flue gases from the furnace or superheated steam, if it is provided from the steam cycle. Controlling the operation conditions is very important since the environment should remain inert for an efficient torrefaction. If flue gases are used for direct heating, they should be controlled in terms of oxygen content and condensed materials. The problem in the use of superheated steam medium is that it should not be condensed in the whole process, which demands the larger mass flow of steam. Moreover, complicated processing would be needed before the steam could be re-introduced to the steam cycle.

However, the integration between an indirect-heated torrefaction reactor and steam cycle is more feasible solution. The limited capacity of the plant, like the boiler capacity or turbine requirements, should be carefully considered to make a practical and economical combination. Torrefaction reactor requires heat with mentioned requirements and produces some combustible volatiles that can be utilized as an additional fuel for the steam cycle. If the energy gained from the torrefaction gases exceed the heat demand of whole torrefaction process, it can stand alone in an auto-thermal cycle. The extra heat can be used in steam cycle, reducing the fuel requirement of the boiler improving efficiency.

However, if the energy balance of torrefaction process remains negative, this heat demand should be supplied from the steam cycle. There are different options for heat supply from the steam cycle to the torrefaction process, such as hot water from boiler, furnace hot gases, and steam extraction from turbine or even superheated steam after the boiler. Although all the sources can be theoretically used, the feasibility of such usage depends on possible interaction facilities between torrefaction reactor and steam cycle, considering the efficiency and economy of the combination. In this research, the feasibility of different integration options in indirect heating of the torrefaction process is examined from thermodynamic point of view. A typical block diagram of indirect-heated torrefaction is depicted in Fig 2.2. As discussed, the drying and torrefaction section may be merged in a same unit.



**Figure 2.2:** Block diagram of indirect-heated non-integrated torrefaction process and main streams

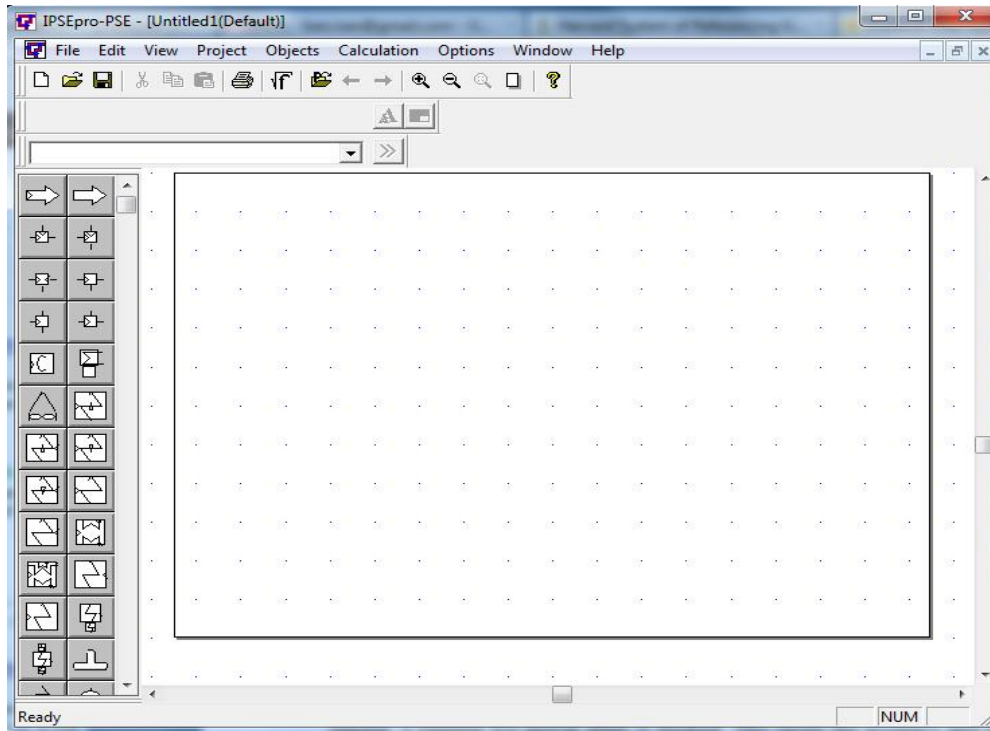
Furthermore, hot torrefied biomass that leaves the reactor in torrefaction temperature is another source of heat recovery for the steam cycle. The most convenient use of this low-value heat is for preheating the combustion air before the burner. All in all, the torrefaction reactor including two parts of drying and torrefaction requires heat that can be partly supplied by the produced gases from the process itself. The other part is supplied by the steam cycle in different means. The hot solid output of torrefaction reactor can be used for air preheating, meaning increasing the efficiency of the steam cycle.



## 3 Power plant and torrefaction IPSEpro models

### 3.1 IPSEpro modelling tool

For studying the integration of the steam power plant and torrefaction reactor in an accurate and reliable method, IPSEpro modeling tool is employed in this research. IPSEpro is a flexible tool for simulation, modeling, analysis and design of components and processes in energy and process engineering (SimTech, 2012). SimTech Simulation Technology is an Austrian firm providing IPSEpro tool for a wide range of power and process industries. IPSEpro is used for this research to create the required models where needed. In addition to a library of common components used in thermal power plants, IPSEpro provides a Model Development Kit (MDK) by which the designer can build new models or modify the existing models according to the project's requirements. IPSEpro can also be employed for the online control of a working plant (SimTech, 2005). All the simulation, modeling, calculations and unit design in this research is carried out by the use of this modeling environment. The main interface window of this application is shown in Fig 3.1. The standard library can be seen on the left side bar.



**Figure 3.1:** IPSEpro main interface window

### 3.2 CHP and District Heat Plant Models

Two types of bio-fired CHP plants heat-only plant are considered in this study. The smaller CHP plant is a condensing plant under conditions of minimal heat production ( $P_{\text{gen}}=9.8$  MW,  $\Phi_{\text{heat}} = 0.63$  MW) and is based largely on plant data obtained from (Komulainen, 2012). The larger plant is CHP plant with 0.38 power-to-heat ratio with 82 MW electricity and 218 MW process and district heat production with 16.5 bar(a), 10 bar(a) and 4.5 bar(a) steam extractions and 1.4 bar(a) back pressure turbine for district heat production.

The main operating characteristics are summarized in tables 3.1 and 3.2 and schematics illustrated in figures 3.2 and 3.3 respectively. The characteristics of the heat-only plant are given in Table 3.3.

**Table 3.1:** Working properties of the 10 MW  $P_{\text{gen}}$  CHP plant.

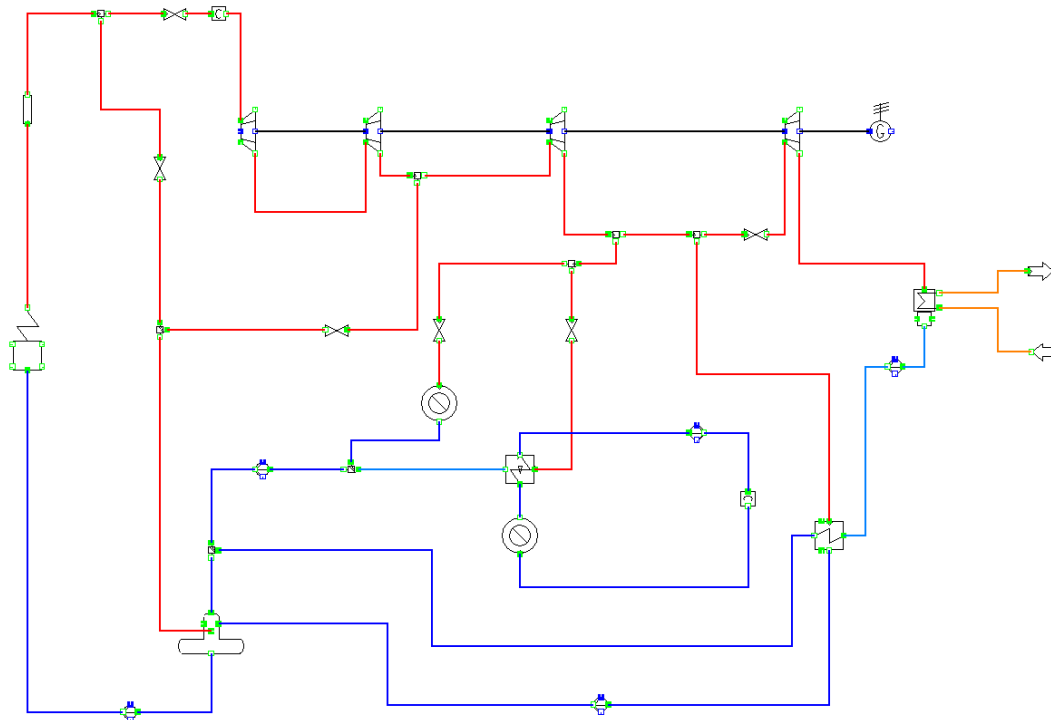
Component	Parameter	Quantity	Explanation	
Boiler	Fuel power	31.55 MW		
Live steam	Pressure	93 bar		
	Temperature	505°C		
Turbine	Inlet	Turbine inlet temp.	500°C	
		Pressure	90 bar	
		Steam flow rate	10.45 kg/s	
	Part 1	Isentropic efficiency	62 %	A governing stage, no extraction.
		End pressure	59 bar	
	Part 2	Isentropic efficiency	87.3 %	to deaerator (0.94 kg/s)
		MP bleed pressure	8.60 bar	
	Part 3	Isentropic efficiency	88.4 %	to process + preheater (0.28 + 1.03 kg/s)
		LP bleed pressure	1.97 bar	
	Part 4	Isentropic efficiency	77.7 %	to condenser (8.2 kg/s)
Outlet pressure		0.07 bar		
Condenser	Pressure	76 mbar		
Deaerator	Pressure	5.64 bar		
Process heat	Power	0.63 MW	(0.54 + 0.09 MW)	
Generator	Power	9.8 MW		

**Table 3.2:** Main characteristics of the 82 MW  $P_{\text{gen}}$  CHP plant.

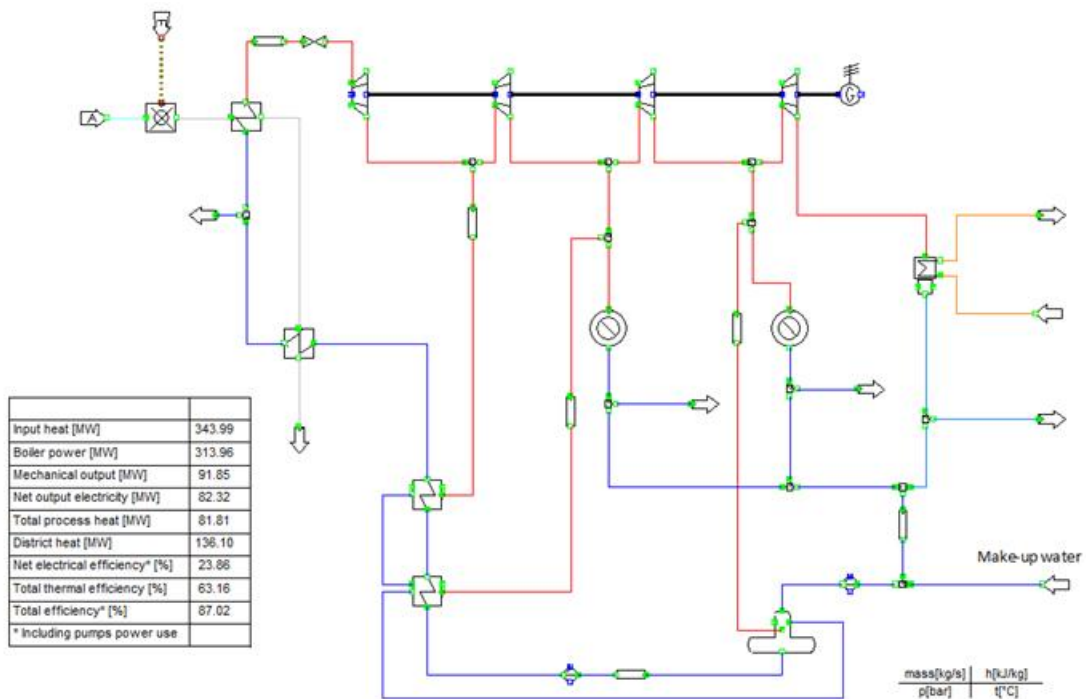
Component	Parameter	Quantity	Explanation	
Boiler	Thermal power	311 MW		
	Fuel input	344 MW		
Live steam	Pressure	115 bar		
	Temperature	550 °C		
HP turbine	Inlet $T$	545 °C		
	Inlet $p$	110 bar		
	Steam flow	120 kg/s		
	Isentr. efficiency	85 %		
HP turbine extractions and outlet	HP bleed	Pressure	16.5 bar	Process heat and HP preheater
	IP bleed	Pressure	10 bar	Process heat and HP preheater
	LP outlet	Pressure	4.5 bar	Process heat, deaerator and LP turbine
LP turbine	Isentr. efficiency	85 %	steam flow to district heat exchanger 63 kg/s	
	Back pressure	1.4 bar		
Deaerator	Pressure	4.2 bar		
Heat	Power	218 MW	(82 bleed steam + 136 MW distric heat)	
Generator	Power	82 MW		

**Table 3.3:** Main characteristics of the district heating plant.

Boiler power, MCR	20 MW
Boiler power (during torrefaction)	10 MW
Feedstock to torrefaction	10 MW
Flue gases exit temperature $T$	188 °C
District heating water exit $T$	90 °C
District heating water return $T$	50 °C



**Figure 3.2:** Schematic flow diagram of 9.8/0.63 MW generator power / heat bio-CHP plant in IPSEpro environment.



**Figure 3.3:** Schematic flow diagram of 82/218 MW generator power / heat bio-CHP plant in IPSEpro environment.

By utilizing the given data and making the required assumptions for other parameters needed for the model, the models were built in IPSEpro environment. In this stage, all the required units and components are used from the provided standard library of IPSEpro. Then, the model variables are calculated and the results for different streams are presented in appendix 1. Using the provided results, all the important properties of the main streams of working steam, condensed streams, and cooling water are available for further analysis.

The main features of the CHP and heat plants are summarized in the table 3.2. This helps to compare the performance of the plant when it is integrated with the torrefaction plant in the next step.

According to the calculated results in table 3.2, electrical efficiency of the plant before integration is 30.71%, calculated from equation (3.1a). When gaseous products from torrefaction are burned in the boiler, two separate definitions for electrical efficiency are used:  $\eta_{e,a}$  (eq. 3.1a) considers only the solid CHP fuel, while  $\eta_{e,b}$  (eq. 3.1b) includes also the heating value of the gaseous torrefaction product.

$$\eta_{e,a} = \frac{P_{\text{gen}} - \sum P_{\text{pump}}}{\dot{m}_{\text{fuel}}(LHV_{\text{fuel}} + h_{\text{fuel}})}, \quad (3.1a)$$

$$\eta_{e,b} = \frac{P_{\text{gen}} - \sum P_{\text{pump}}}{\dot{m}_{\text{fuel}}(LHV_{\text{fuel}} + h_{\text{fuel}}) + \dot{m}_g(LHV_g + h_g)}, \quad (3.1b)$$

in which  $P_{\text{gen}}$  is the power at generator terminals, and  $P_{\text{pump}}$  the electric power used by the pumps in the steam cycle (boiler feed water pump and condenser pump).

**Table 3.4:** Performance data of the CHP and heat plants. All data for maximum load without torrefaction integration unless otherwise noted.

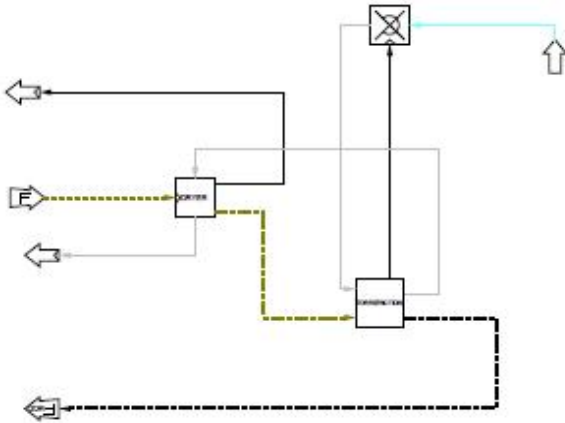
	Small CHP	Large CHP	District Heat
<b>Power at generator terminals [MW]</b>	9.8	82	N/A
<b>Heat output [MW]</b>	0.6*	218	20/10**
<b>Electrical efficiency [%]</b>	31	24	N/A
<b>Total efficiency [%]</b>	33	88	88

\* During summertime

\*\* Maximum/during torrefaction

### 3.3 Torrefaction Reactor Model

Since there is no available torrefaction reactor in the standard Advanced Power Plant (APP) library of IPSEpro, a new model is built to simulate the torrefaction process. In order to clarify the analysis and make the requirements more visible, the torrefaction reactor is modeled in two sections. As mentioned in the part 2.1 of this report, the entire torrefaction process can be divided into two parts: drying and torrefaction. From now on, the term “torrefaction section” addresses the second part of the whole process. It means biomass is dried first, before it is delivered to the torrefaction section. Then, dried biomass is led to torrefaction section at the output temperature of the dryer. After torrefaction section, torrefied biomass, that is hot as torrefaction temperature, may be cooled in another unit by preheating the combustion air of the steam boiler. The block diagram of torrefaction reactor is illustrated in Fig 3.3.



**Figure 3.4:** Block diagram of torrefaction process in a full auto-thermal mode.

#### 3.3.1 Drying section

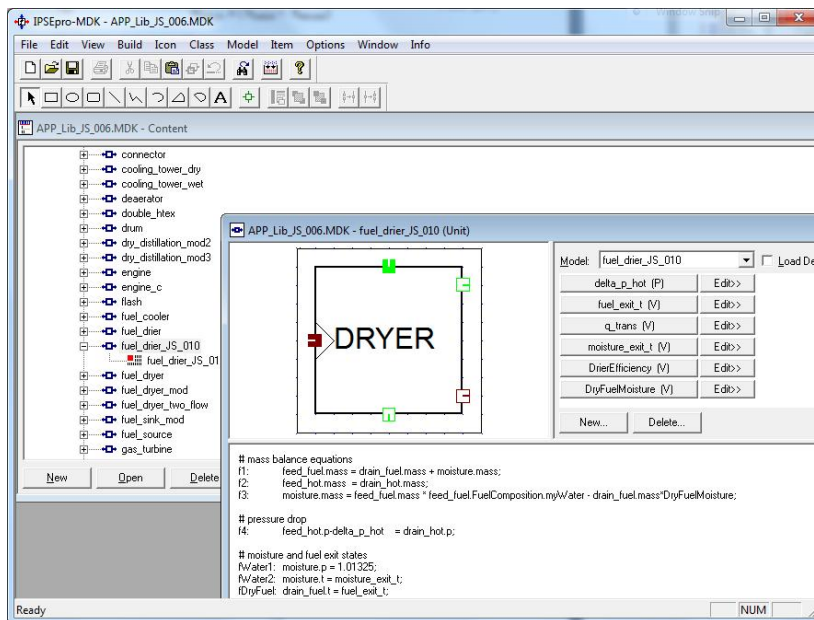
Before torrefaction, the biomass must be dried to reduce its moisture content. In an ideal case the moisture content of dried biomass  $MC_d$  would be zero and the heat load  $\Phi_{dryer}$  would be the product of wet biomass mass flow rate, its moisture content, and latent heat of vapourization.

In a practical drier perfectly bone-dry product is unachievable, however, and due to the long residence times and large sizes of drying equipment, significant heat losses are usually unavoidable. Representing the heat loss in terms of a drier efficiency  $\eta_{dryer}$ , a following expression for  $\Phi_{dryer}$  can be obtained from the dryer energy balance:

$$\Phi_{dryer} = \frac{1}{\eta_{dryer}} \dot{m}_{wet} \left\{ \begin{aligned} & (MC_{wet} - MC_d)(h_{wL,in} - h_{wV,out}) + \\ & [(1 - MC_{wet})c_{p,dry} + MC_d c_{p,wL}](T_{out} - T_{in}) \end{aligned} \right\} \quad (3.2)$$

where  $h$  is enthalpy [kJ/kg],  $c_p$  the specific heat [kJ/kgK], and  $MC$  the moisture content [kg<sub>H2O</sub>/kg<sub>total</sub>]. The subscripts  $wet$  and  $d$  refer to untreated and dried biomass and  $wL$  and  $wV$  to liquid and vapour-phase water, respectively. A value of  $c_{p,dry} = 1.6$  kJ/kg was assumed for the biomass, with water enthalpies estimated according to temperature. The moisture content is reduced from  $MC_{wet} = 40\%$  to  $MC_d = 10\%$  and an efficiency  $\eta_{dryer} = 60\%$  is assumed in this study. The exhaust moist air exits at 70 °C and atmospheric pressure, resulting in a dryer heat requirement of approximately 1.2 kWh/kg of evaporated water.

By transferring the balance equations into the Model Development Kit (MDK) of IPSEpro, a new Drying model was designed and built. This newly-built unit is added to IPSEpro library for the future usage. The main interface page of MDK and the built drying model including defined parameter and variables are shown in figure 6.



**Figure 3.5.** New Dryer model and associated parameter and variables in MDK environment

### 3.3.2 Torrefaction section

In torrefaction section, the dried biomass is torrefied producing torrefaction gas as well as torrefied biomass (TB). The mass and energy yields of the process are highly dependent on residence time and torrefaction temperature: The longer the residence time and higher the temperature, the more volatiles are evaporated, resulting in lower mass and energy yields, but a higher energy content for the solid product.

The type, particle size and moisture content of the biomass also affect the torrefaction performance. These are not considered as variables in this study, however.

Accurately measuring the average temperature of the biomass and maintaining a constant, flat temperature profile in the reactor is challenging. The heating and cooling rates as well as presence of any air in the reactor will also affect the performance. Possibly due to these issues, the mass and energy yields obtained in different experimental studies even with different laboratory-scale equipment sometimes vary noticeably for similar feedstocks. The results should therefore also be considered subject to significant uncertainties and more predictions of general trends rather than exact results.

The torrefaction model is based the results published by Sarvelainen 2011 for whole-wood chips.

### 3.3.2.1 Correlations for mass and energy yields

The experiments of Sarvelainen were made with wood chips dried for 24 hour in 105 °C. This results in a completely dry biomass according to the definition of CEN/TS 14774-2 standard (Suomen standardisoimisliitto SFS, 2004). The ash content of whole-tree chips is typically only in the order of 0.5 %, increasing to >1% only for logging residues or bark (Alakangas 2000), which was considered negligible for the purposes of this study. The mass and energy yields obtained in the experiments by Sarvelainen were thus considered to represent the mass yield  $M$  and energy yield  $E$  on a dry, ash-free basis, calculated from the results from

$$M = \frac{m_{TB}}{m_d}, \text{ and} \quad (3.3)$$

$$E = \frac{LHV_{TB}m_{TB}}{LHV_d m_d}, \quad (3.4)$$

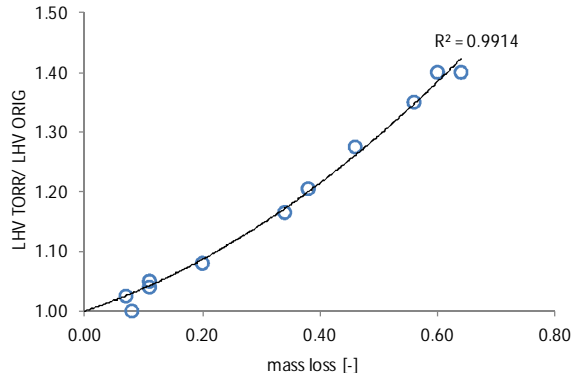
where  $LHV$  and  $m$  are the lower heating value and mass of the sample, with subscript  $d$  referring to the state after drying, and  $TB$  after the torrefaction.

The experimental data included mass and energy yields at 200 °C to 300 °C temperature at 0.5 hour residence time, and mass yields for residence times from 0 to one hour at 250 °C at 15 minute intervals. Energy yields at different residence times were not available. Lower heating value change of torrefied biomass was found to have a strong correlation with mass loss with the 0.5 hour, 200...300 °C temperature cases, however, demonstrated in Fig 3.5 below. A simple 2<sup>nd</sup> order polynomial for the relative LHV increase as a function of mass loss due in torrefaction,

$$\frac{LHV_{TB}}{LHV_d} = 1 + 0.5218(\dot{m}_d - \dot{m}_{TB})^2 - 3.217(\dot{m}_d - \dot{m}_{TB}), \quad (3.5)$$

was found to describe the correlation well within the range of mass losses considered.





**Figure 3.6.** LHV change as a function of mass loss at 200...300 °C and 0.5 h residence time.

This polynomial fit was used to estimate LHV of torrefied biomass at 0...1 hour residence time and 250 °C temperature, and from there the energy yields were obtained from mass and energy balances.

From this data the curve fits of the form

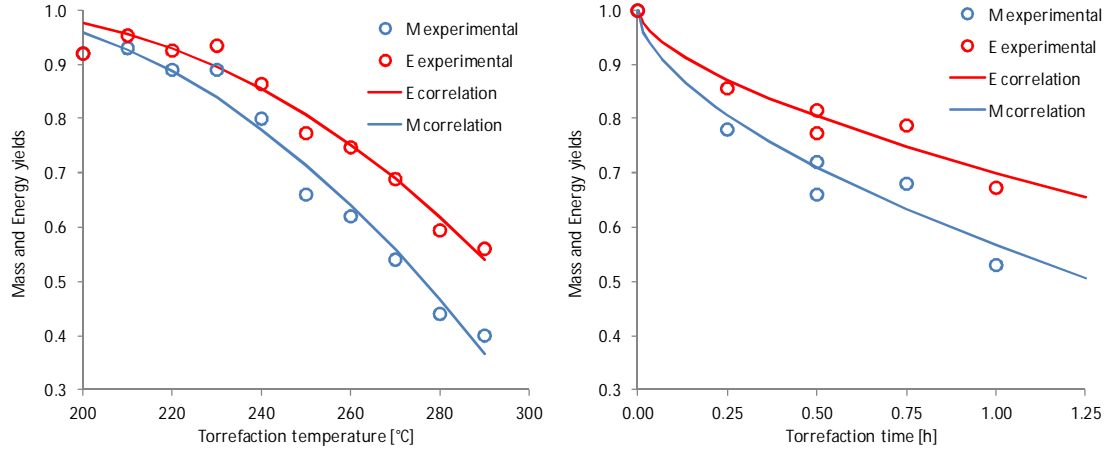
$$M = 1 - a_M (T_{\text{torr}} - T_{\text{ini}})^{b_M} \cdot t_{\text{torr}}^{c_M} \quad (3.6)$$

$$E = 1 - a_E (T_{\text{torr}} - T_{\text{ini}})^{b_E} \cdot t_{\text{torr}}^{c_E} \quad (3.7)$$

were then generated for both mass and energy yields.  $T_{\text{torr}}$  [°C] represents the torrefaction temperature,  $T_{\text{ini}}$  [°C] the temperature at which torrefaction begins and  $t_{\text{torr}}$  [h] the residence time, with constants  $a$ ,  $b$  and  $c$  for both mass and energy yields (subscripts M and E) found by minimizing the residual sums of squares (RSS). Values of  $T_{\text{ini}}$  from 160 °C to 200 °C were tested:  $T_{\text{ini}} = 170$  °C produced the smallest RSS for both  $M$  and  $E$  and was therefore used. The constants obtained are listed in table 3.3. below. The mass and energy yields obtained from experiments versus by the correlations are plotted in Figure 3.5.

**Table 3.3:** Coefficients for the mass and energy yield experimental correlations

	<b>a</b>	<b>b</b>	<b>c</b>
<b>Mass</b>	$9,3 \cdot 10^{-5}$	1,93	0,58
<b>Energy</b>	$2,6 \cdot 10^{-5}$	2,14	0,66



**Figure 3.7.** Mass and energy yields as a function of a) different torrefaction temperatures at 0.5 h residence time, and b) different residence times at 250 °C temperature. The “E experimental” data is based on torrefied biomass LHV calculated from equation 3.x, not measured.

### 3.3.2.2 Torrefaction module

The torrefaction model developed for IPSEpro was based on the assumptions of negligible energy need in the devolatilization reactions, negligible loss of heating value through partial combustion of the biomass, and perfectly bone-dry torrefied biomass as the solid product. Mass and energy yields  $M$  and  $E$  for the torrefied solid biomass product are defined on a dry ash-free basis (daf), with values obtained from the empirical correlations described above.

Mass balance yields the following expression for mass flow rate of torrefied biomass  $\dot{m}_{TB}$ :

$$\dot{m}_{TB} = M[1 - (MC_d + AC_d)]\dot{m}_d + AC_d\dot{m}_d, \quad (3.8)$$

where  $AC$  is the ash content of the fuel. Heat losses to environment were accounted for with an efficiency  $\eta_{\text{torr}}$ , and energy requirement for the torrefaction is obtained from

$$\Phi_{\text{torr}} = \frac{1}{\eta_{\text{torr}}} \dot{m}_d \{ MC_d (h_{wL,\text{in}} - h_{wV,\text{out}}) + (1 - MC_d) c_{p,\text{dry}} (T_{\text{out}} - T_{\text{in}}) \}. \quad (3.9)$$

With the net loss of heating value negligible, the lower heating value LHV of gas phase then becomes

$$LHV_g = \frac{(\dot{m}_d LHV_d - \dot{m}_{TB} LHV_{TB})_{\text{daf}}}{\dot{m}_g}, \quad (3.10)$$

where subscript  $g$  refers to the gas and vapour products, and solids mass flow rates and LHVs are given on a dry ash-free basis (daf).

Actual torrefaction gas would typically be a mixture of carbon dioxide and monoxide, water vapour, organic acids, and a number of other organic compounds mostly of low heating value. As the IPSEpro gas property library includes only a handful of gaseous compounds and lacks the majority of combustible fractions present in the actual gas, the gas is modelled as such a mixture of carbon dioxide and methane ( $LHV = 50.1 \text{ MJ/kg}$ ), that would correspond to the correct  $LHV_g$ .

### 3.3.2.3 Results of Torrefaction Simulation

The mass and energy yield of the torrefaction model created on the basis of Sarvelainen 2011 data is depicted in table 3.4.

The data of this table can be visually compared in figures 3.7 and 3.8. The growth in torrefaction gas power in higher temperatures is a result of the significant influence of temperature in torrefaction process which results in more devolatilization of solid biomass (Fig 3.7). The small share of torrefaction heat demand compared to drying is another obvious result in this figure. In other words, the majority of the energy consumed by the reactor is used to dry the feed biomass before the actual torrefaction itself.

**Table 3.4:** Mass and energy yield of torrefaction and drying of 1kg/s biomass (40% moisture). Dry biomass flow is 0.67 kg/s (10% moisture content).

Torr temp.	Time	Mass yield <sup>1</sup>	Energy yield	$LHV^1$ torrefied biomass	Torr gas power <sup>2</sup>	Torr heat use <sup>3</sup>	Total Heat use <sup>4</sup>	Net energy to steam <sup>5</sup>	Heat of torrefied biomass <sup>6</sup>	Total balance <sup>7</sup>
°C	min	%	%	MJ/kg	MW	MW	MW	MW	MW	MW
230	20	0.87	0.92	19.08	0.892	-0.281	-1.846	-0.954	0.084	-0.870
	40	0.80	0.87	19.61	1.414	-0.281	-1.846	-0.432	0.078	-0.354
	60	0.75	0.83	20.05	1.838	-0.281	-1.846	-0.008	0.073	0.065
250	20	0.77	0.85	19.93	1.644	-0.298	-1.864	-0.220	0.083	-0.137
	40	0.65	0.76	21.07	2.612	-0.298	-1.864	0.748	0.071	0.819
	60	0.56	0.69	22.18	3.395	-0.298	-1.864	1.531	0.061	1.592
270	20	0.65	0.76	21.23	2.646	-0.316	-1.881	0.765	0.077	0.842
	40	0.47	0.62	23.94	4.206	-0.316	-1.881	2.325	0.056	2.381
	60	0.33	0.5	27.84	5.465	-0.316	-1.881	3.584	0.039	3.623
290	20	0.50	0.65	23.49	3.907	-0.334	-1.899	2.008	0.065	2.073
	40	0.24	0.44	32.77	6.202	-0.334	-1.899	4.303	0.032	4.335
	60	0.04	0.27	114.54	7.881	-0.334	-1.899	5.982	0.006	5.988

1) Based on bone dry biomass

2) Torrefaction gas power = produced gas mass  $\times$  ( $h_g + LHV_g$ )

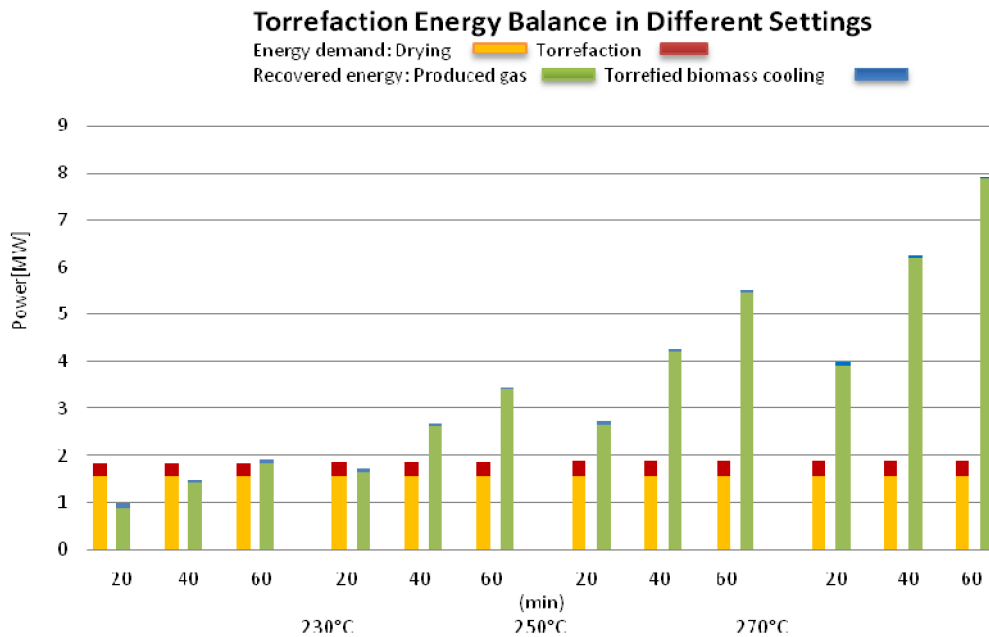
3) The amount of required heat for torrefaction section (after drying)

4) Drying section requires 1.57 MW heat for 1 kg/s feedstock at efficiency of 60%

5) Net useful energy gained from torrefaction = useful heat of produced gas to steam cycle – heat demand of torrefaction reactor

6) Recovered heat from torrefied biomass for air preheating in steam boiler

7) The sum of 5 and 6

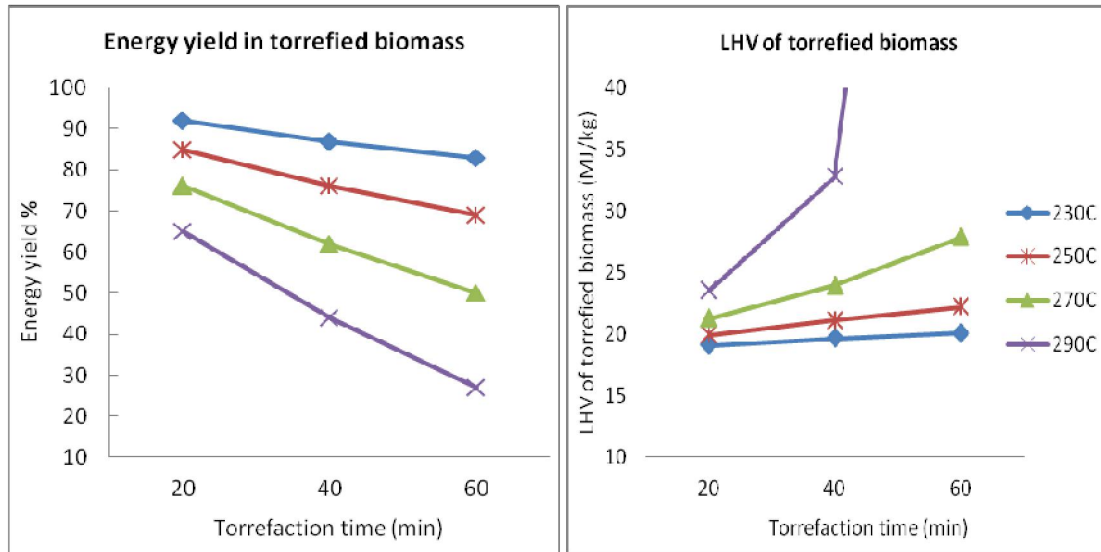


**Figure 3.8.** Torrefaction heat demand and extractable energy of produced gas

Increasing torrefaction temperature yields a higher LHV in solid product while a bigger mass fraction is simultaneously devolatilized. Hence, similar to mass yield, the final energy yield declines dramatically when torrefaction temperature rises (figure 3.8).

The very high LHV yet low energy yield figures for the combinations of longest residence times and highest temperatures are clearly more indicative of the limited applicability range of the model than actual torrefaction reactor performance. Energy yields are predicted at unrealistically low levels, but mass yield even more so, resulting in extreme LHV values. The further the case is from the 30 min, 200...300 °C and 0...60 min, 250 °C cases on which the model is based, the less accurate the results must be considered.

For practical purposes this was considered a minor deficiency, as combinations of high temperature and long residence time would appear unlikely to be desirable in torrefaction: the solid product energy yield would suffer even if not as much as the correlations predict, the solid product would become very brittle, and unnecessarily high temperature levels and equipment size would be required.



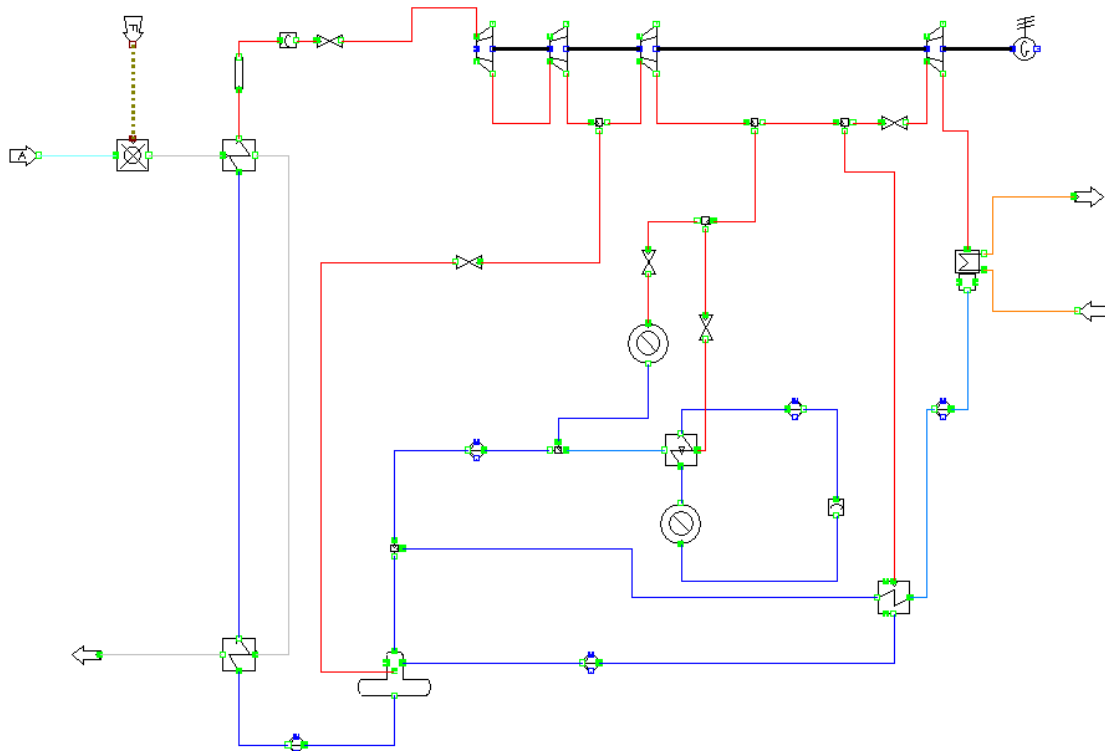
**Figure 3.9.** Energy yield (left) and LHV (right) of the torrefied biomass in different torrefaction conditions. Results for 40 to 60 minute residence times at 290 °C torrefaction temperature are not realistic, but reflect the limited applicability range of the correlations.

## 4 Integration options for torrefaction and CHP and district heating plants

The following chapter presents the different cases studied for heat integration of torrefaction process and CHP and district heating plants. Chapter 4.1 describes the integration with the smaller of the two CHP plants; the cases available for the larger plant are essentially the same, and not separately discussed. Chapter 4.2 describes the integration possibilities with the district heating plant.

### 4.1 Integration of torrefaction with a CHP plant

For supplying the heat required by the torrefaction reactor, different combinations of processes and heating media are examined. In order to model the steam cycle in a way that can be integrated with torrefaction reactor, the boiler is modeled as a combustion chamber and two heat exchangers. One represents the economizer, the other the steam generator and superheater. The fuel stream and combustion air can be regulated to maintain either thermal power or steam flow rate after the integration with the torrefaction reactor. This basic model is illustrated in Fig 4.1. In some configurations where it is possible, these two heat exchangers are unified, however.



**Figure 4.1.** Steam power plant schematic flow diagram with new boiler model (by IPSEpro)

For having a base for the future comparisons an initial configuration called case 0 is built. This is a case of two plants working in the same model side by side, but having no interaction. It is assumed that the torrefaction reactor can operate in an entirely standalone mode. The block diagram of case 0 is simply the same as the initial configuration of both plants, shown in figures 3.3 and 3.9. The calculated results of this case, containing useful data of both plants and related characteristics, are presented in appendix 2. All other cases are built based on the same assumptions and models.

All the models are based on indirect heating of the torrefaction reactor. The produced gas is assumed to be completely burnt with boiler fuel. Due to the limitations of IPSEpro software, this is modeled separate combustors for each fuel, with the hot gases mixed to represent the net flue gas flow from the combustion of the two fuels.

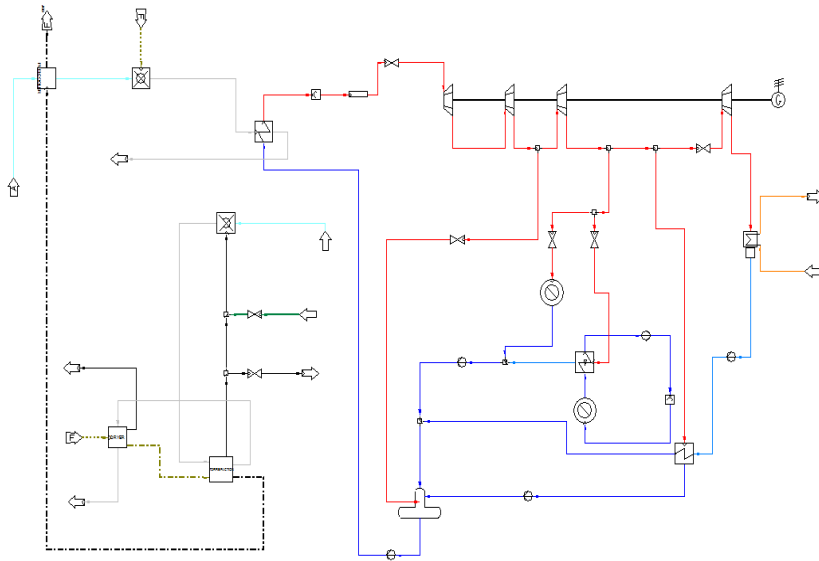
If the boiler has extra capacity to burn this additional fuel, it can supply more steam and/or heat demand of torrefaction process. Otherwise, the heat demand of the torrefaction process reduces the output superheated steam, and thereby also the electricity generation. However, there is additional fuel in some cases compensating the reduction in electrical efficiency. The complexity and difficulty of inferring the performance impacts of such combinations necessitates the careful investigation of each case using a computer-aided modeling tool. Then, possible models can be examined in terms of possible process configurations, heat recovery from torrefied biomass, and steam extraction considerations.

The following assumptions are applied in all five cases introduced in the chapters below:

- Hot torrefied biomass from the torrefaction reactor is cooled by using this heat to preheat the boiler combustion air
- Live steam temperature and pressure are fixed at the CHP plants design values
- Deaerator pressure remains unchanged from design value
- Condenser and back pressure remain unchanged from design values.

#### **4.1.1 Case 1: Stand-alone Torrefaction Reactor with air preheating**

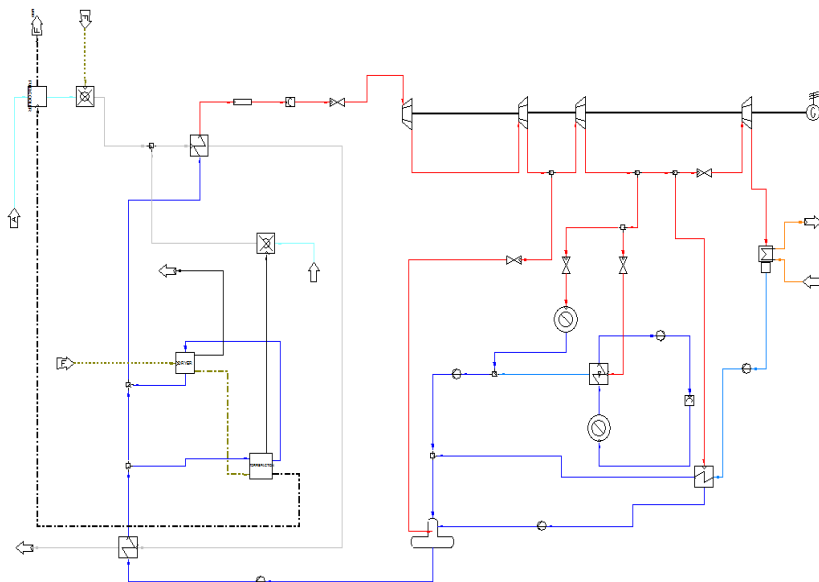
In this case, it is assumed that the torrefaction reactor is otherwise separated from the power plant, but the waste heat from the torrefied biomass cooling is used for steam boiler combustion air preheating. The schematic flow diagram of this case is illustrated in Fig 4.2. The deficiency of heat is supplied by burning additional methane in those cases where the heat from combustion of the torrefaction gases is less than the heat demand of the reactor.



**Figure 4.2.** Case 1: Stand-alone torrefaction plant at the same site as CHP-plant

#### 4.1.2 Case 2: Hot Water from Boiler

The heat demand of torrefaction is supplied from hot water directly supplied from the boiler drum, and is returned to the boiler after supplying the heat demand of the torrefaction reactor. The schematic flow diagram of the interaction between boiler and torrefaction reactor is shown in Fig 4.3.



**Figure 4.3.** Case 2: Hot water from boiler to torrefaction reactor (with torrefied biomass cooling)

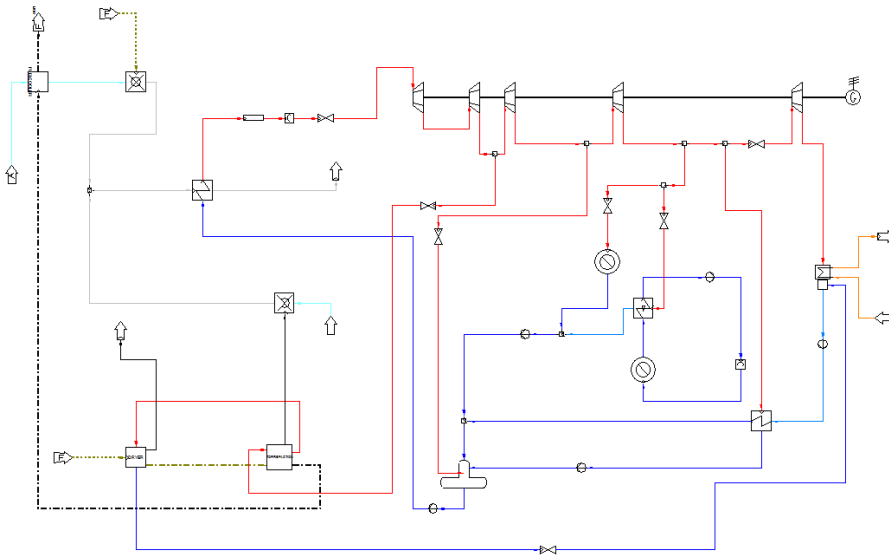
The flexibility of temperature and mass flow are advantages of this case: if the boiler has extra capacity, heat could be supplied for torrefaction while maintaining the steam



flow to turbine at 10.45 kg/s. Otherwise, the steam flow declines. Considering a fixed boiler capacity, the results of this integration model as well as output properties of the integrated plant are depicted in appendix 3.

#### 4.1.3 Case 3: Steam Extraction from Turbine

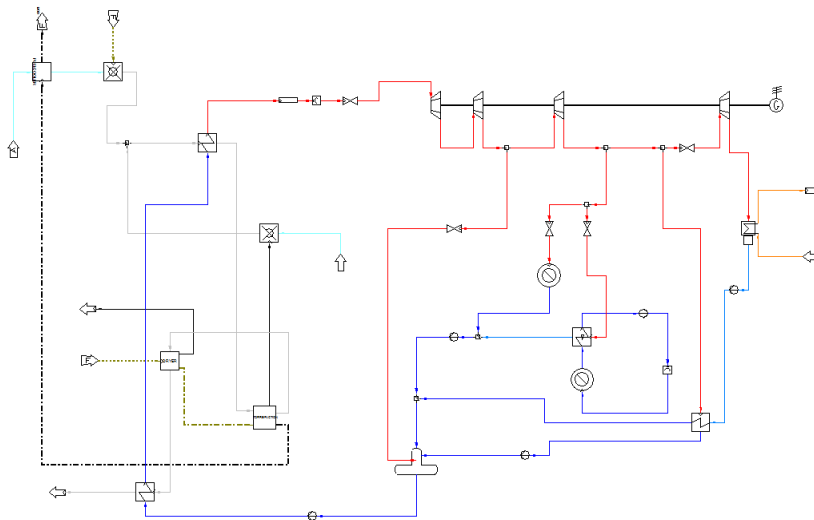
Having heat supply of the torrefaction from turbine steam bleed is examined in this case. The heat demand must be fulfilled by a new steam extraction from the turbine as the existing bleeds are not hot enough for torrefaction section. Since the torrefaction temperature reaches up to 300°C, the minimum possible extraction pressure is 18 bar for this plant. It is also depended on torrefaction thermal efficiency and reactor design. The exact steam temperature (and relevant pressure) is depended on the turbine design and configuration. The condensed water of this steam bleed is returned to the hotwell of the condenser. It is assumed that the Torrefaction reactor (including dryer) is designed so that the temperature of the output water can be reduced to 90°C for both cases 3 and 5. This integration model is shown in figure 4.4.



**Figure 4.4.** Case 3: steam extraction from turbine to supply torrefaction heat

#### 4.1.4 Case 4: Boiler Flue Gases

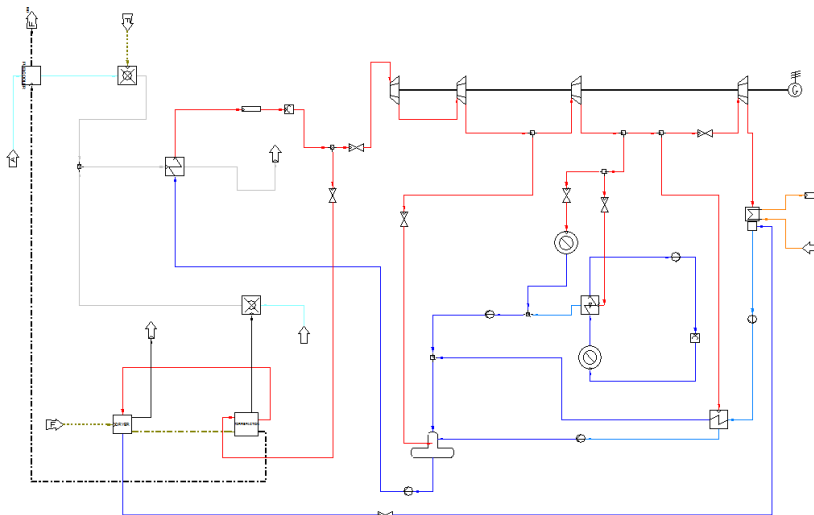
The heat demand of torrefaction reactor is provided by using hot gases from boiler section in this case. Having the flexibility for different temperatures is an asset, but the high temperature of the flue gases can be used for hot steam production. It is assumed the heat can be harvested so that the flue gases can cool down to about 188°C after economizer. This model is illustrated in figure 4.5.



**Figure 4.5.** Case 4: Using boiler flue gases for torrefaction

#### 4.1.5 Case 5: Live Steam before Expansion in Turbine

In this case heat is supplied by using live steam from the boiler. The condensed water is returned back to the condenser. The flexibility in temperature and no requirement of suitable extractions from the turbine are advantages compared to case 3. This configuration and related results are shown in Appendix 7 for the fixed boiler capacity. If the boiler capacity remains fixed, providing hot steam for torrefaction reactor will result in less superheated steam passing the turbine. As a result, the loss in output electricity and efficiency is more considerable in this case. The schematic flow diagram of the integrated plant in this case is presented in figure 4.6.



**Figure4.6.** Case 5: Live steam for torrefaction

## 4.2 Integration of torrefaction with a district heating plant

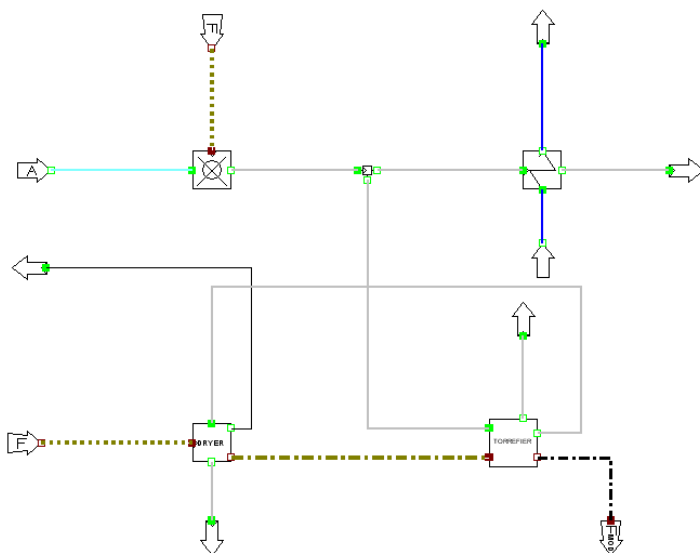
Integration of torrefaction process with a district heating plant represents another possible solution. District heating plants cover heat demand for various applications, such as space heating and technological processes. Heat energy (in the form of water or steam) is provided to consumers from hot water boiler through the network of pipes. After that cooled water or condensate is returned back to the cycle.

In the current report possibility of combined operation of small-scale district heating plant and torrefaction unit is investigated. Boiler is modeled as a combustion chamber and one heat exchanger.

It was assumed that boiler capacity is 20 MW. Full load is required just during the winter, and it is assumed there would be no torrefaction performed in this period. The simulation is performed under an assumed 50% load for autumn and spring periods with water return and exit temperatures to and from the plant of 50 °C and 90 °C. Input fuel power for torrefaction section is constant at 0.556 kg / s untreated biomass and temperature of solid product after cooling 50 °C in both cases. Initial data for heating plant and torrefaction performance is as presented in the Table 3.4.

### 4.2.1 Case 1: Boiler flue gases for torrefaction reactor

The only feasible heat source for torrefaction that is at a high enough temperature level in a district heating plant are the boiler flue gases. The schematic flow diagram of a simple combined district heating and torrefaction plant is shown in Figure 4.7. In this case energy of torrefaction products is not utilized in the main cycle.

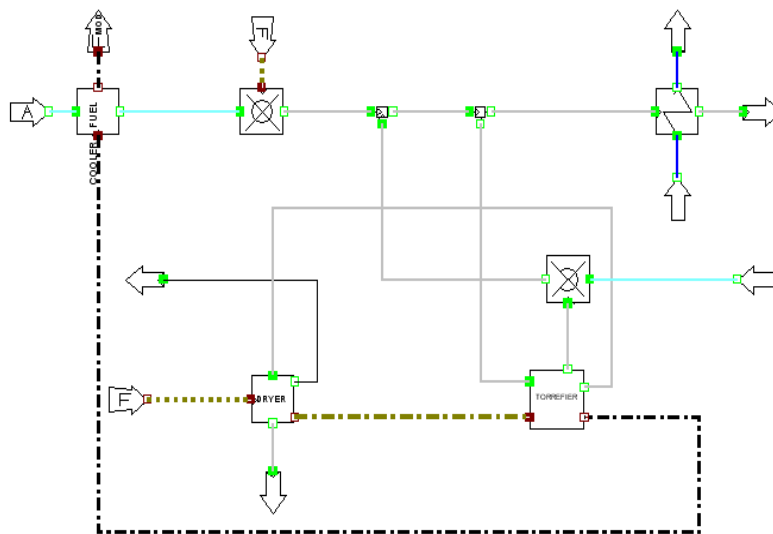


**Figure 4.7:** Case 1. Boiler flue gases for torrefaction reactor

#### 4.2.2 Case 2: Integration of torrefaction process into district heating plant

The heat demand of torrefaction process is covered by hot flue gases. It is assumed that the produced gas is completely burned with boiler fuel, and the heat from cooling the torrefied fuel is used for combustion air preheating. As it was mentioned previously, due to limitations of IPSEpro combustion of gas is presented in a separate chamber.

The schematic flow diagram of the interaction between district heating plant and torrefaction reactor is shown in Figure 4.8.



**Figure 4.8:** Case 2. Integration of torrefaction process into district heating plant

## 5 Simulation results

In the following chapter the results for simulation experiments with all three plants are presented. Similar trends were clear with both the small, high power-to-heat ratio plant and the larger low power-to-heat ratio plant were evident from the experiments. The full range of experiments was thus performed only with the smaller CHP plant. Same biomass characteristics and torrefaction equipment characteristics, summarized in Table 5.1 below, were used in all experiments.

**Table 5.1:** General settings and assumptions for all models

Biomass LHV <sub>d</sub> (MC=10%)	18 MJ/kg
Moisture content (untreated)	40 %
Moisture content (from drier)	10 %
Moisture content (torrefied)	0.0 %
Torrefaction reactor efficiency	90 %
Drier efficiency	60 %
Water vapour exit $T$ from drier	70 °C
Biomass exit $T$ from drier	70 °C
Torrefied biomass exit $T$ from cooler	50 °C

When biomass flow rate was not the studied parameter, a rate of 1 kg/s untreated biomass was used in the case of the small CHP plant, 10 kg/s for the large CHP plant, and 0.56 kg/s for the district heating plant.

### 5.1 Small CHP plant, 1 kg/s untreated biomass

In order to establish a comparison base between different configurations, Case 1 is used as a reference. Except for air preheating by cooling of the torrefied biomass, present in all cases except the Case 0 with no integration, there is no other interaction in this case.

It is also possible to extract excess heat from torrefaction process, in terms of produced gas for co-firing, under specific conditions. In other words, having torrefaction in higher temperatures with long residence time may result in excess heat from torrefaction reactor. This excess heat can be captured by steam cycle to reduce the amount of CHP fuel.

In other words, it is assumed that boiler performance does not vary due to the mixture in feed fuel. In addition, efficiency of torrefaction reactor is assumed to remain unchanged with different heating agents. The heat provided by the combustion of torrefaction gas is considered as a fuel source along with the main boiler fuel for efficiency calculation (eq. 3.1b).

### 5.1.1 Fixed Steam Flow at Turbine Inlet

First, it is assumed that the capacity of boiler can be increased for supplying the extra heat demand of torrefaction reactor in cases 2, 4 and 5, without declining the initial rate of hot steam to the turbine. The results of this assumption are collected in table 5.2. The first and visible result is higher electrical efficiency of the steam power plant in case 3 compared to all cases but the stand-alone case 1, while at the same time the generator power from this option is the lowest. This is unsurprising, as the amount of steam flow rate into turbine is the same in all cases, and case 3 is the only one reducing the amount of steam from full expansion into condenser pressure.

**Table 5.2:** Comparison of generator power and electrical efficiency of the steam power plant in different cases. In all cases 1 kg/s untreated biomass is torrefied at 270 °C for 30 minutes while maintaining a 10.45 kg/s steam flow at the turbine inlet)

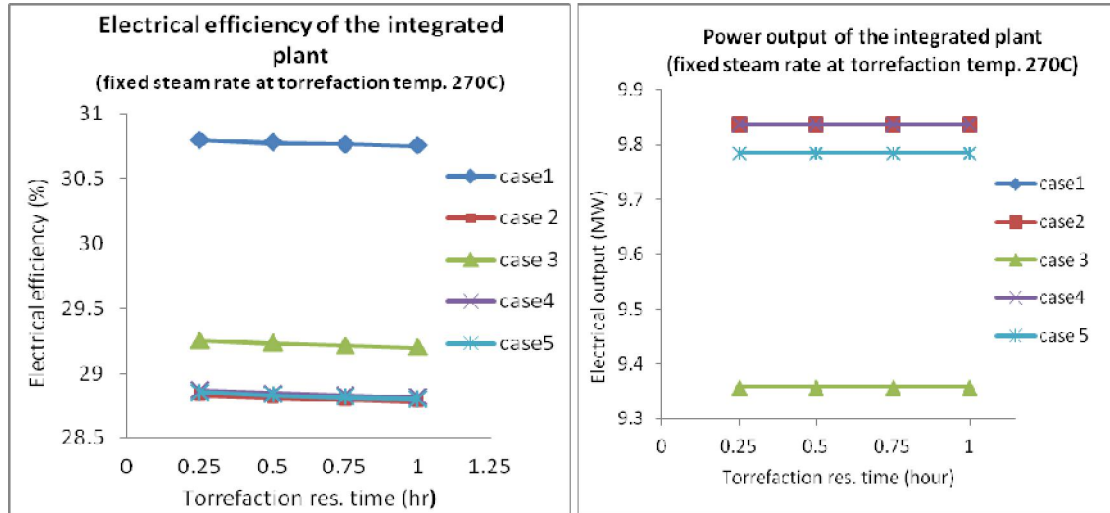
Case description	CHP fuel input <sup>1</sup> [kg/s]	Boiler power [MW]	Generator power [MW]	Electrical efficiency <sup>2</sup> [%]		Modifications
				$\eta_{e,a}$	$\eta_{e,b}$	
<b>0: no interaction</b>	2.72	28.5	9.84	30.7	30.7	Basic power plant
<b>1: stand-alone</b>	2.72	28.5	9.84	30.8	30.8	Air preheating by torrefied biomass
<b>2: hot water</b>	2.60	30.3	9.84	32.1	28.8	Boiler power increased to maintain steam rate
<b>3: extraction</b>	2.42	28.5	9.36	32.8	29.2	Steam extraction at 25bar
<b>4: boiler flue gas</b>	2.60	30.3	9.84	32.1	28.8	Increasing boiler capacity to maintain steam rate
<b>5: live steam</b>	2.58	30.2	9.79	32.2	28.8	Steam to turbine 10.3kg/s

1. Solid biomass only, torrefaction gas output not considered.

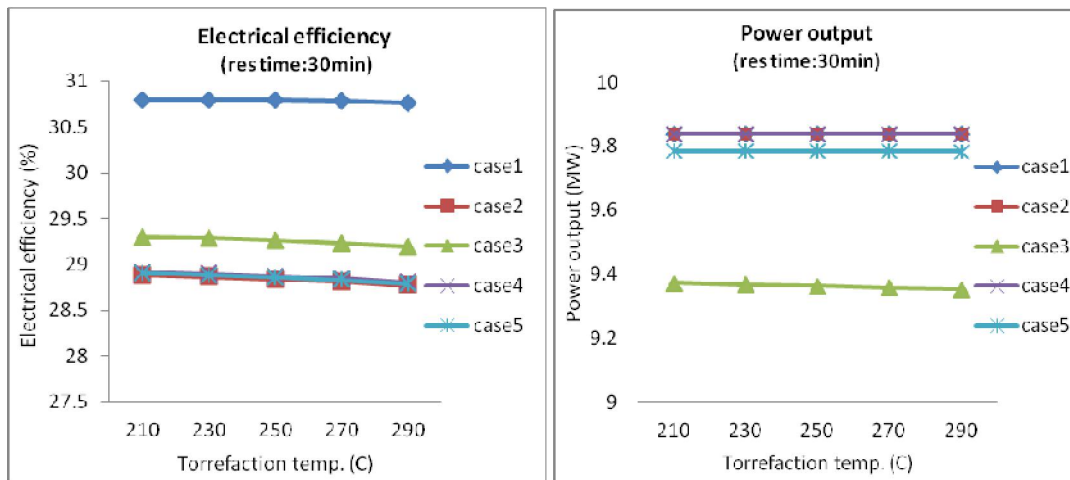
2.  $\eta_{e,a}$  considers only solid CHP fuel as fuel input,  $\eta_{e,b}$  includes torrefaction gas; see eq. (3.1a) and (3.1b).

The results of varying residence time at 270 °C are seen in Figure 5.1, while Fig 5.2 shows the results at 30 minute residence time with varying temperatures. The trend of smallest efficiency reduction but highest power output loss with using extraction steam for heat source remains unchanged. Temperature and residence time appear to have only very slight effect on the efficiency. Efficiency reduces with the increased heat demand of longer residence times and higher temperatures, but the effect is small. Power output remains unaffected with all cases except the steam extraction (case 3) where a slight reducing trend with increasing time is visible; again, this is unsurprising, since power output with all other cases is kept unaffected by maintaining unchanged steam flow through the turbine, only extraction showing the effect of increasing heat demand from more severe torrefaction.

The results also show similar trends for cases 2, 4 and 5. This is due to the fact that torrefaction heat is supplied from boiler side in these cases, without considering detailed differences and heat losses in each configuration.



**Figure 5.1.** Effect of residence time in electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and power output of the steam plant. Torrefaction of 1kg/s untreated biomass at 270 °C with additional methane if needed)



**Figure 5.2.** Effect of torrefaction temperature in electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and power output of the steam plant for different cases with fixed steam rate at turbine inlet (torrefaction of 1kg/s wet biomass in 30min residence time)

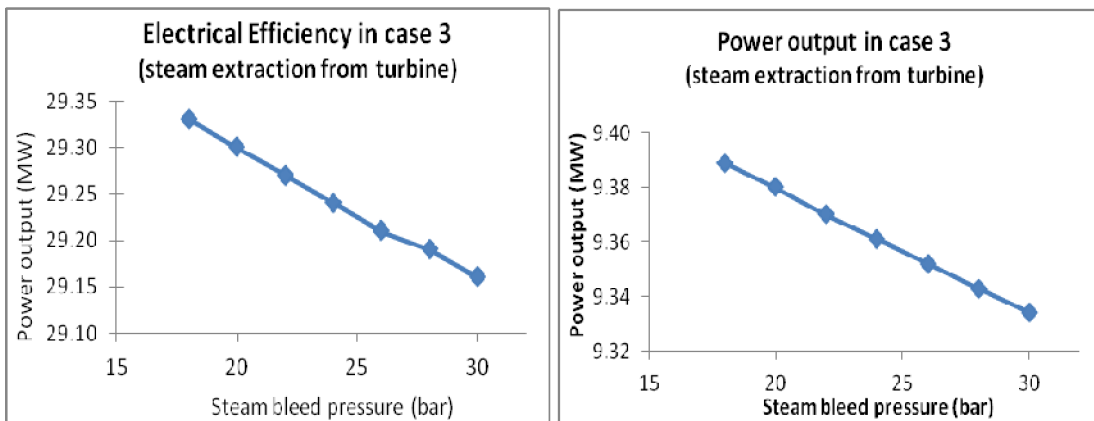
### 5.1.1.1 Varying turbine extraction pressure in Case 3

Since there is no exact data about possible extractions from turbine, a limited range of pressures were examined under Case 3. The power output and electric efficiency in each case is collected in table 5.2. If the steam flow rate could be reduced by subcooling the

condensate return from the torrefaction section, the efficiency could be also further improved by almost 0.1%.

**Table 5.2:** Case 3: Different steam pressures extracted from turbine for heating torrefaction reactor (Torrefaction of 1kg/s biomass, residence time 30 min at 270°C)

Steam $p$ (bar)	Steam $T$ (°C)	Extraction flow (kg/s)	Generator power (MW)	Electrical Efficiency (%)
18	294	0.712	9.39	29.33
20	307	0.706	9.38	29.30
22	318	0.701	9.37	29.27
24	328	0.696	9.36	29.24
26	338	0.691	9.35	29.21
28	347	0.687	9.34	29.19
30	356	0.683	9.34	29.16



**Figure 5.3.** Electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and generator power in different steam pressures when torrefying of 1 kg/s biomass (wet) with a residence time of 30 min at 270 °C.

The result are summarized in figure5.3.. It should be noted that steam bleed temperature depends on turbine configuration and possible extractions. In Appendix 5, the steam extraction at 25 bar pressure is modelled including the results and output features of the integrated plant.

### 5.1.2 Fixed Boiler Capacity

In the second set of simulations, the capacity of the boiler is assumed to be fixed. As the boiler thermal power is kept constant, the mass flow rate of steam will change depending on the heat demand of the torrefaction process, reducing the amount of steam available for turbine and thus also generator power output. The results for torrefaction conditions of 270 °C and 30 minutes are shown below in table 5.3. The generator power and electrical efficiency of all integration cases for fixed boiler capacity are illustrated



in figure 5.4 for 270 °C temperature at varying times, and in figure 5.5 for varying temperatures and 30 minute residence time.

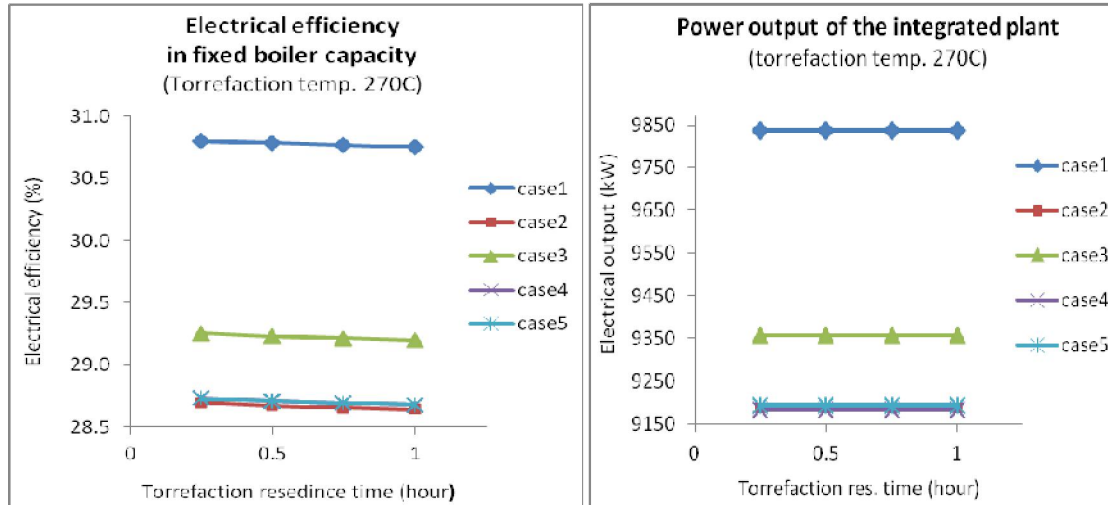
**Table 5.3.** Power output and electricity efficiency of the steam power plant in different cases for torrefaction of 1kg/s of untreated biomass at 270 °C for 30 minutes and assuming a maximum boiler capacity of 28.45 MW.

Case description	CHP fuel input [kg/s]	Steam to turbine [kg/s]	Generator power [MW]	Electrical efficiency <sup>1</sup> [%]		Modifications
				$\eta_{e,a}$	$\eta_{e,b}$	
<b>0: no interaction</b>	2.72	10.45	9.84	30.7	30.7	Basic power plant
<b>1: stand-alone</b>	2.71	10.45	9.84	30.8	30.8	Air preheating by torr. biomass
<b>2: hot water</b>	2.42	9.76	9.19	32.2	28.7	
<b>3: extraction</b>	2.42	10.45	9.36	32.8	29.2	Steam extraction at 25bar
<b>4: boiler flue gas</b>	2.42	9.76	9.18	32.2	28.7	
<b>5: live steam</b>	2.42	9.82	9.19	32.2	28.7	

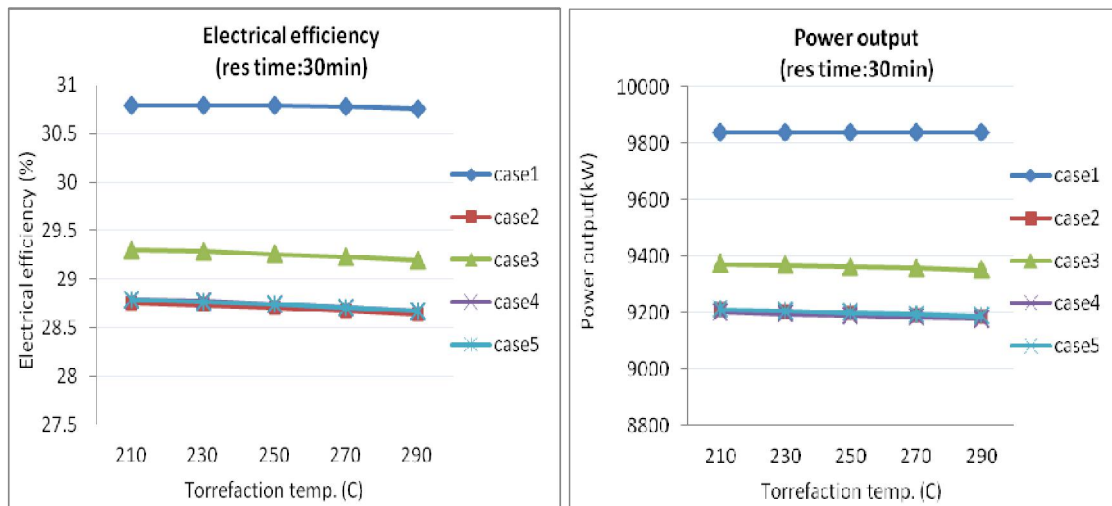
<sup>1</sup>  $\eta_{e,a}$  considers only solid CHP fuel as fuel input,  $\eta_{e,b}$  includes torrefaction gas; see eq. (3.1a) and (3.1b).

Similarly as with the fixed turbine inlet conditions experiments of previous chapter, case 3 has highest efficiency at all torrefaction temperatures and residence times among the integrated cases, and when the boiler power is not allowed to increase to maintain steam flow to the turbine, this obviously must translate to highest generator power output as well. The power plant achieves a better performance only with the stand-alone case 1, which benefits from waste heat of torrefied biomass cooling without any heat used for the torrefaction

The comparison of electrical efficiency and generator power with varying residence times (Fig 5.4) and temperatures (Fig 5.5) shows similar results to the fixed turbine inlet cases: an increasing severity of torrefaction within a specific integration case results in a performance drop ranging from very small to non-existent.



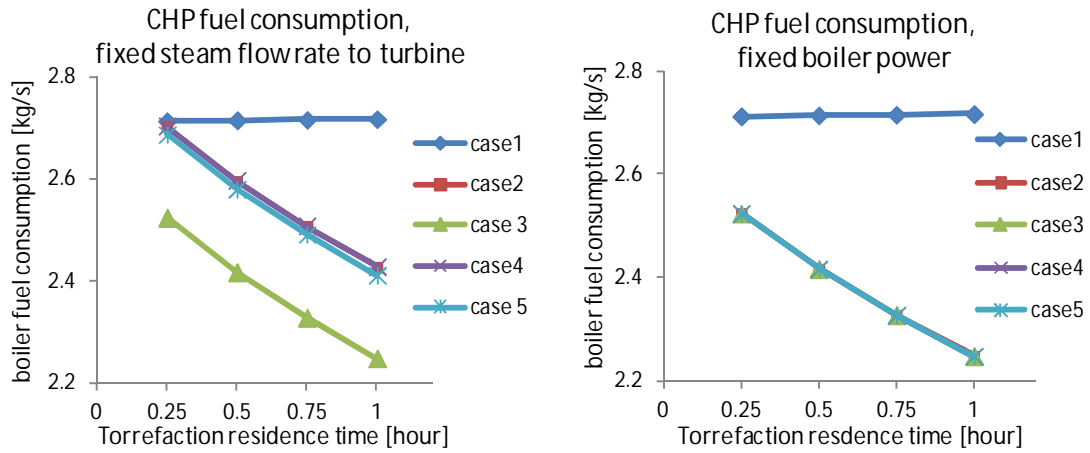
**Figure 5.4.** Effect of residence time in electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and power output of the integrated steam plant (torrefaction of 1kg/s wet biomass at 270C, in fixed boiler power)



**Figure 5.5.** Effect of torrefaction temperature in electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and power output (right) of the integrated steam plant

### 5.1.3 Effect of Torrefaction Process on CHP Fuel for the Steam Cycle

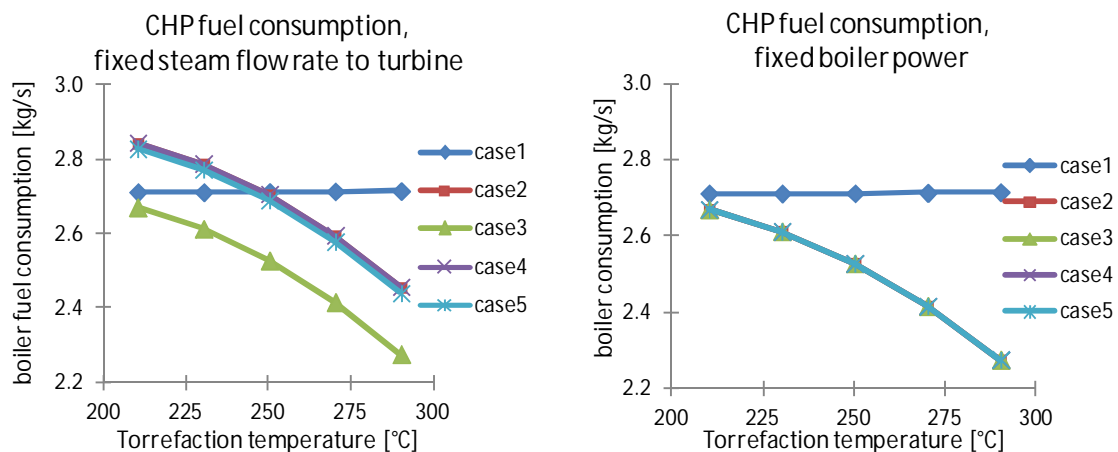
The produced gas from torrefaction is considered as an additional fuel in efficiency calculations (equation 3.1b). Therefore, it cannot be clearly seen from the efficiency figures how the heat from combustion of the gaseous torrefaction products affects the solid biomass usage of the boiler. Therefore, it is useful to compare the changes in different cases by monitoring the amount of primary CHP fuel for the steam boiler (figure 5.6 and 5.7). This comparison is done for the predried feed biomass which may cause reduction in required CHP fuel by increasing the residence time (figure 5.6) or torrefaction temperature (figure 5.7).



**Figure 5.6-** CHP fuel for integrated plant with fixed steam rate at turbine inlet (left) and fixed boiler capacity (right) in different torrefaction residence time. 1kg/s predried biomass torrefied at 270 °C.

Considering figures 5.5 and 5.6, it can be concluded that the case 3 which uses extraction steam from turbine for heat supply shows more reduction of CHP fuel consumption rate than the other integrated cases when the steam supply to turbine is kept constant. This is a result of the other integrated cases, taking the heat from the boiler or live steam, requiring an increase of boiler thermal power to maintain turbine steam supply which partly offsets the additional fuel from torrefaction gas. When the extraction steam is used, boiler operation is unaffected, however.

There is no difference in fuel solid consumption reduction between the different integration cases if the boiler thermal power is maintained constant: the same torrefaction conditions will yield the same torrefaction gas output and therefore same reduction of solid fuel requirement regardless of integration choice.



**Figure 5.7.** CHP fuel for integrated plant with fixed steam rate at turbine inlet and fixed boiler capacity in different torrefaction temperature. 1kg/s predried biomass torrefied for 30 min.

### 5.1.4 Increasing the Mass Flow of Torrefaction Feedstock

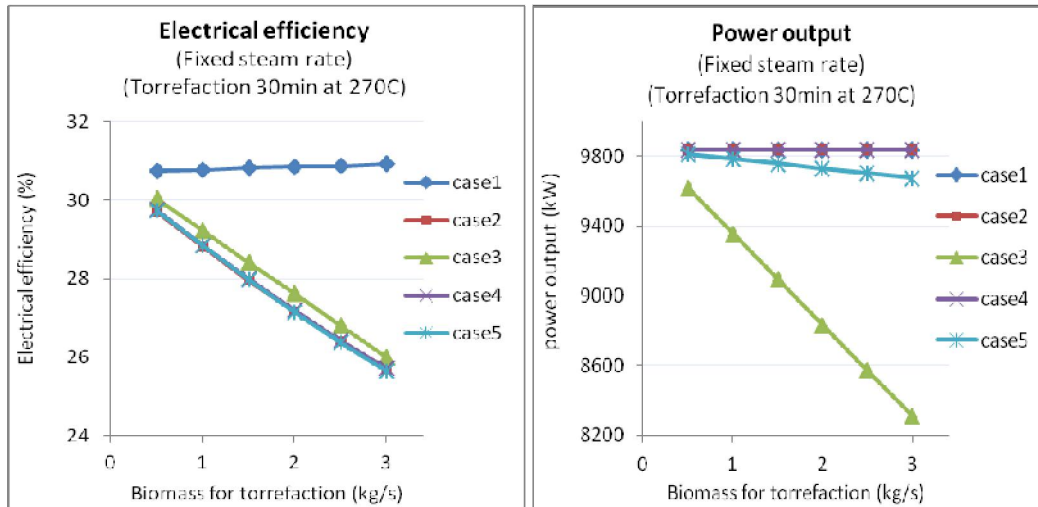
In this section, the effect of torrefaction mass flow rate is examined in different cases. First, steam flow rate at the turbine inlet is kept fixed at initial amount of 10.45 kg/s for all the cases. In the next stage, the boiler capacity is assigned to be fixed at initial power, 28.45 MW.

#### 5.1.4.1 Fixed steam rate at turbine inlet

In this setting, since the steam rate at turbine is fixed, the heat deficiency of torrefaction process must be compensated with extra fuel for steam power plant, or additional methane in case 1. The stand-alone case 1 produces the highest efficiency: in this option the power plant cycle benefits from combustion air preheating from cooling the torrefied biomass, without the penalty of heat loss to the torrefaction process. As the mass flow rate of biomass through torrefaction increases, so does the heat benefit to boiler from the torrefied biomass cooling, further improving the efficiency of the power plant cycle.

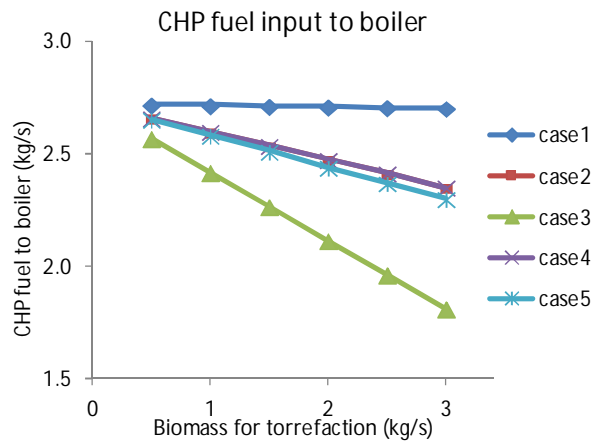
As the results show (figure 5.8), the electrical efficiency of the case 3 remains highest among the integrated cases for different mass flow rates for torrefaction feedstock. However, for all the integrated cases efficiency decreases if the mass flow rate for torrefaction increases. However, it is the matter of fact that the output electricity for the case 3 decreases dramatically compared to the other cases (figure 5.7-left). For instance, if the torrefaction mass flow increases from 0.5 to 3 kg/s, the electrical output for case 3 declines from 9.61 to 8.31 MW.

The faster power output reduction with increasing amount of biomass torrefied is a result of increasing amount of extraction steam required to match the heat requirement, thus reducing mass flow rate through the turbine after the extraction. The power output is slightly reduced also if live steam is used: this is because although the steam supply into turbine is maintained, the increasing steam supply to torrefaction reactor increases the condensate flow rate from condenser, increasing the amount of steam extracted from the turbine to the preheater and deaerator, thereby reducing the steam flow through the low-pressure parts of the turbine.



**Figure 5.8** Electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and power output for different amount of wet torrefaction feedstock. Temperature 270 °C, residence time 30 minutes.

The amount of CHP fuel conserved by the use of torrefaction gas is not the same for all cases. In figure 5.9, the reduction in CHP fuel consumption is illustrated for different amount of torrefaction feedstock. Case 3 shows more CHP fuel conservation compared to other cases.

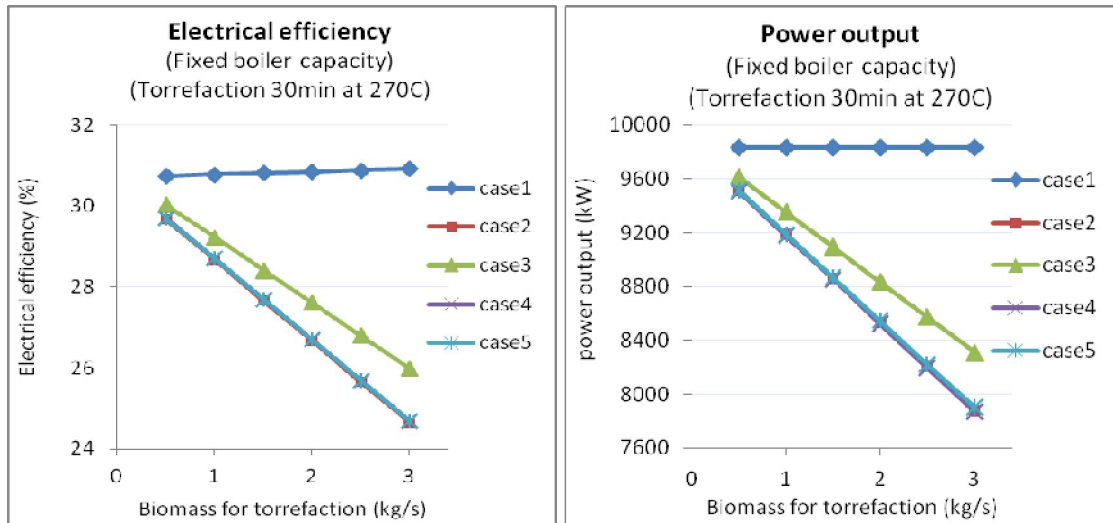


**Figure 5.9.** CHP fuel in different amount of torrefaction feedstock. Temperature 270 °C, residence time 30 minutes.

#### 5.1.4.2 Fixed boiler capacity

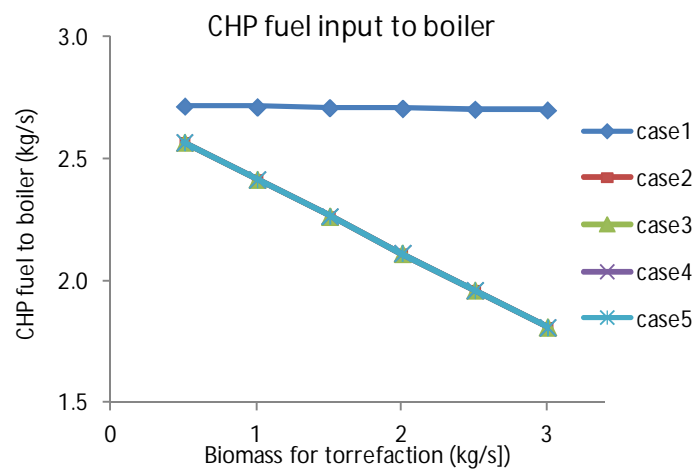
In the second series of calculations, the boiler capacity is fixed at 28.45 MW. Similarly to the previous approach, the amount of torrefaction feedstock is changed from 0.5 to 3 kg/s. Comparison of the results collected in figure 5.9 shows a general pattern in reduction of efficiency in all cases for wet biomass feedstock for torrefaction. Although the trend is partly identical to the previous step, the reduction of efficiency in cases 2, 4 and 5 is higher compared to the base case 1. A visible increase of efficiency can also be seen with case 1, resulting from the increased benefit from combustion air preheating

Another important and predictable fact is the higher amount of power output for case 3 in all different settings, except for the base case 1. In other words, having limited boiler capacity decreases the power output if a fraction of the boiler thermal output is used for drying and torrefaction. Power output is higher for case 3, compared to all the cases using heat directly from boiler side, since the steam can be first expanded to some extent in turbine, and then is directed to the torrefaction reactor with lower temperature, resulting in lower exergy loss. This is shown also in the higher efficiency of case 3.



**Figure 5.10** Electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and power output for different amount of wet torrefaction feedstock. Boiler capacity is limited to the initial value of 28.45 MW

Based on the results, case 3 again shows less loss in efficiency and power output, by increasing the amount of torrefaction feedstock. Similarly to the results in chapter 5.1.3, when boiler thermal power remains unchanged, the reduction in utility fuel consumption depends only on torrefaction conditions and mass flow rate through the reactor, and thus the combustible gas output, but not on the choice of integration case (Fig. 5.11).



**Figure 5.11.** CHP fuel consumption in different amount of torrefaction feedstock

### 5.1.5 Heat Recovery from Torrefied Biomass

So far, all the models and figures are calculated based on the possibility of air preheating before boiler, gained from cooling process of hot torrefied solid products. However, since the detailed information about the possible interactions between torrefaction reactor and boiler is not available, the other alternatives are examined in this section. Moreover, as air preheating is usually accomplished by using boiler flue gases, it is beneficial to find other solutions to utilize this waste heat. One possibility could be using condensate between the condenser and first feedwater preheater, or to preheat the air needed for combustion of torrefaction gases, if they are burnt in a separated combustor. There is a comparison between power output and electrical efficiency of all the cases in different utilization of waste heat obtained from cooling process of torrefied products (table 5.4).

Table 5.4 Electrical efficiency and power output of the integrated plant using different WHR options

Case <sup>1</sup>	Torrefaction heating medium	Power <sup>2</sup> (MW)	Efficiency <sup>3</sup> (%)	
			without WHR	WHR for air preheating
1	Stand-alone	9.837	30.71	30.78
2	Hot water	9.188	28.61	28.67
3	Steam bleed	9.357	29.162	29.23
4	Boiler flue gases	9.183	28.64	28.71
5	Live steam	9.193	28.64	28.71

1. With fixed boiler capacity in torrefaction of 1kg/s wet feedstock for 30min at 270°C
2. Output electrical power of the integrated plant
3. Electrical efficiency of the integrated plant (equation 3.1b)

Since there is no interaction between two plants in case 1, the use of this waste heat affects the efficiency when used for boiler air preheating. The general trend in all three alternatives remains the same, introducing the highest efficiency for case 3 among integrated cases. It should be mentioned that the possibility of such usage depends on the combustion technology, co-firing possibility, and other technical feasibility considerations.

## 5.2 Large CHP plant, 10 kg/s untreated biomass

The trends for larger plant with lower power-to-heat ratio were broadly similar to the smaller one, and thus only simulations with fixed boiler thermal power were performed.

Extraction heat from IP (10 bar) and LP (4.5 bar) extractions was also maintained constant at 25 MW and 60 MW respectively, while the district heating load from 1.4 bar(a) backpressure steam was allowed to fluctuate. In practise this meant a reduction of district heating power from 136 MW (case 0, CHP plant without torrefaction) to 120 MW in case of extraction steam and 123...124 MW in other integrated cases. These figures are summarized in Table 5.5 below.

**Table 5.5.** Boiler and heat output pressure levels and thermal powers

	Pressure [bar]	Thermal power [MW]
Boiler thermal power	114*	316
HP extraction steam	16.5	-
IP extraction steam	10.0	25
LP extraction steam	4.5	60
District heat	1.4	120...125**

\* live steam

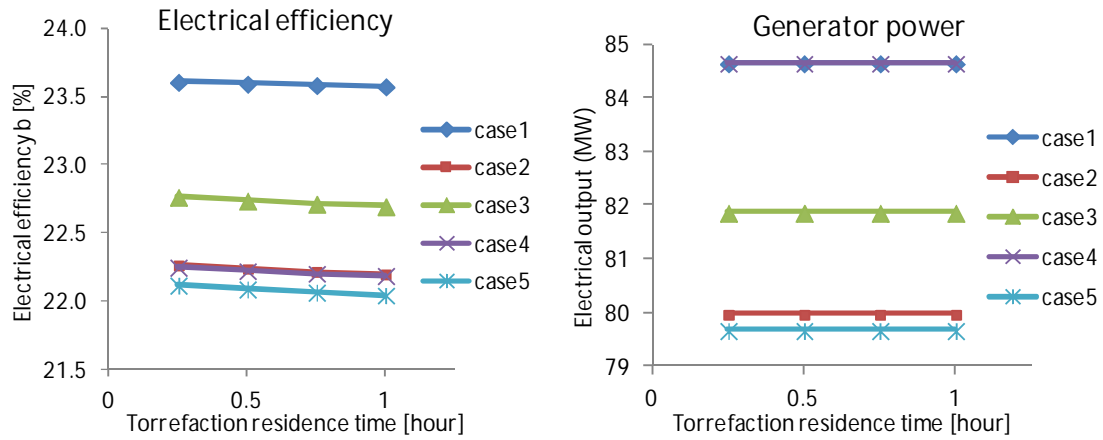
\*\* 136 MW without torrefaction integration

Electrical efficiency and electricity output figures for different residence times are shown in Figure 5.12 below. The curves for total efficiency of the CHP plant along with solid biomass fuel usage are given in Figure 5.13.

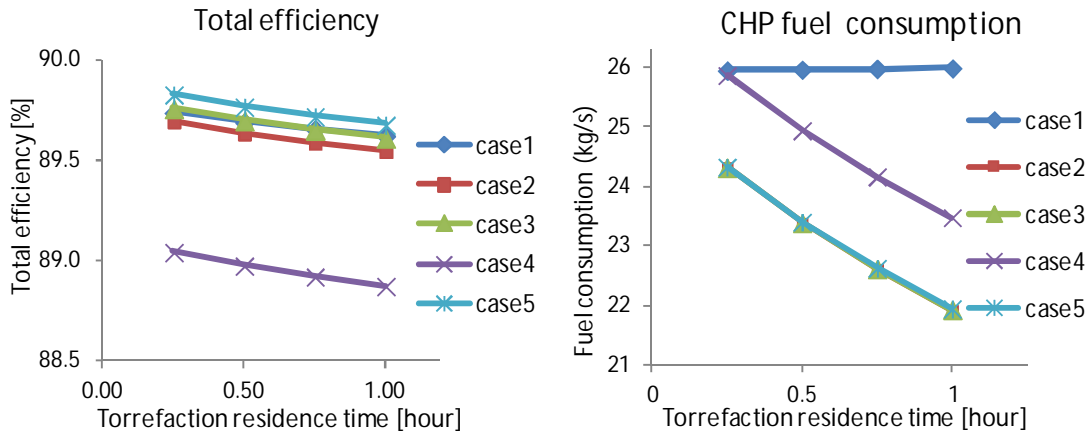
The general trends are similar to the small CHP plant at 1 kg/s torrefaction rate, but the advantage of extraction steam over the other integration options seems noticeably higher. This is largely explained by the use of 16.5 bar HP extraction steam at 290 °C in combination with higher live steam pressure and 1.4 bar(a) back pressure instead of 76 mbar condenser of the smaller plant: relatively less potential further expansion through the turbine is lost in this case.

The other notable difference is the behaviour of case 4 (flue gas). This is not an indication of different performance impact from same solution, however, but a different assumption applied. With the larger plant it was assumed that the boiler could continue producing unchanged thermal power into steam cycle while also supplying heat for torrefaction, while in the case of the smaller plant in chapter 5.1 the assumption was that it is the total thermal output of torrefaction + steam cycle that remains unchanged. As a result, the generator power is not reduced (Fig 5.12), but the efficiency is clearly reduced while the CHP fuel input reduces much less than with the other integrated cases 2, 3 and 5.



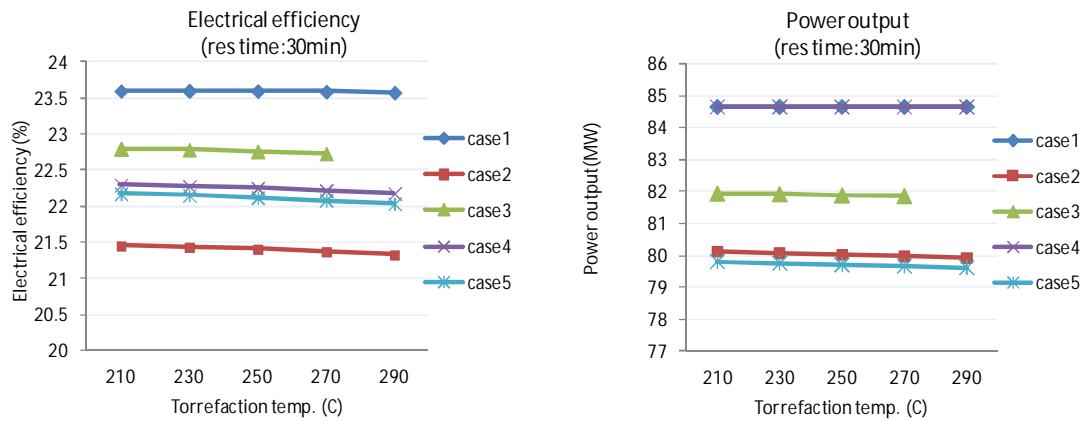


**Figure 5.12.** Electrical efficiency  $\eta_{e,b}$  (eq.3.1b) and generator power for with torrefaction of 10 kg/s feedstock at 270 °C.

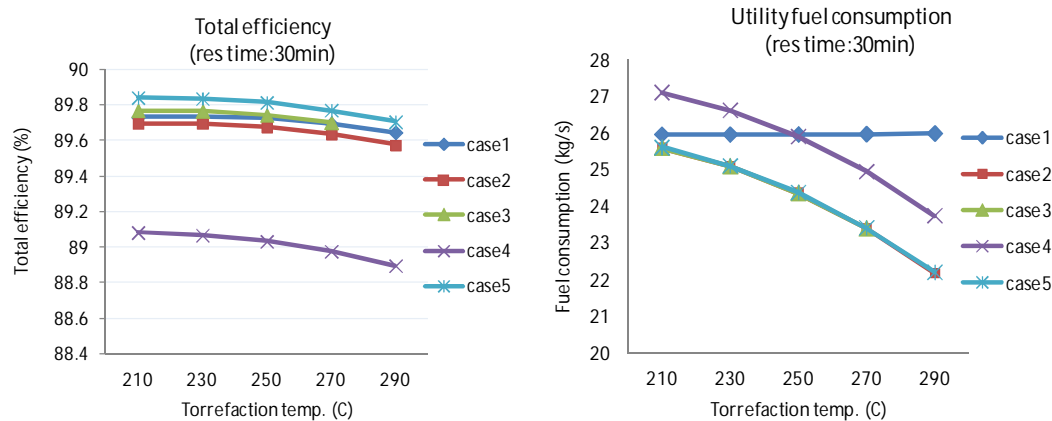


**Figure 5.13.** Total efficiency and fuel consumption for with torrefaction of 10 kg/s feedstock at 270 °C at varying residence times.

The results of varying torrefaction temperature at 30 minute residence time with different cases are shown in Figure 5.14 (electrical efficiency and power output) and 5.14 (total efficiency and fuel consumption). The trends are again largely similar to the smaller plant, with except for the flue gas case 4, where a different assumption on boiler performance limit was applied.



**Figure 5.14.** Electrical efficiency and generator power for with torrefaction of 10 kg/s feedstock at 30 minute residence time and varying temperatures.



**Figure 5.15.** Total efficiency and fuel consumption for with torrefaction of 10 kg/s feedstock at 30 minute residence time and varying temperatures.

### 5.3 District heating plant

Two cases of integration torrefaction into district heating plant have been studied. Hot water boiler produces heat energy with required parameters. The most beneficial way to cover heat demand of torrefaction process is the utilization of flue gases from boiler.

First case presents a minimal level of interaction between two cycles. Hot flue gases supply heat for torrefaction and drying stages. Torrefaction products are not applied to boiler cycle. But it is possible that they can be efficiently used in some other applications.

Second case offers more complete interplay between water heating and torrefaction processes. Similar to the first case, heat demand of torrefaction is covered by hot flue gases from boiler section. However, in this case torrefaction gases provide additional

source of energy. Gases are burned with the main fuel in the boiler. Moreover, waste heat from cooling of the torrefied solids is used for combustion air preheating.

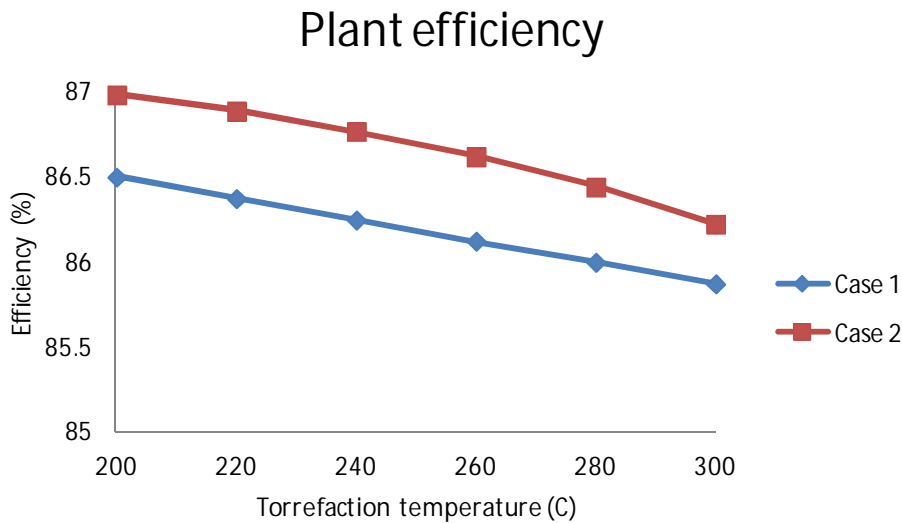
Boiler cycle performance depends on torrefaction section parameters. In first case, hot flue gases have been used for heat needs in torrefaction process. As a result, performance values and efficiency decrease with an increase of torrefaction section demands. In Case 2, interactions between two sections are more complicated. Higher torrefaction parameters require more flue gases from boiler. However, product gas quantity increases with the higher torrefaction temperatures. As a consequence, Case 2 presents higher values for thermal efficiency.

Plant efficiency is calculated with the following formula:

$$\eta_{total} = \frac{Q_{out}}{\dot{m}_{fuel}(LHV_{daf} + h_{fuel})} \quad (5.1)$$

where  $Q_{out}$  is a boiler output [MW].

The dependence of efficiency from torrefaction temperature for two considering cases is presented in Figure 5.12.

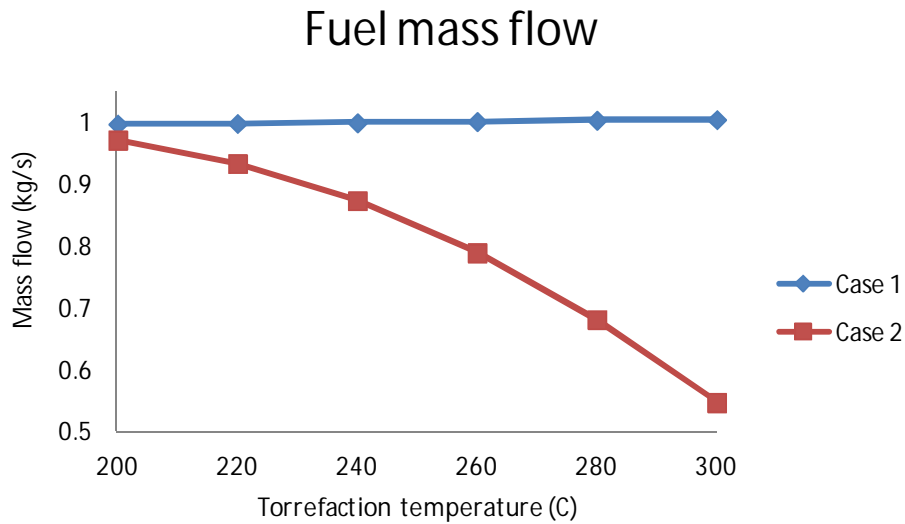


**Figure 5.16.** Effect of torrefaction temperature in total efficiency in the torrefaction of 0.86 kg/s wet biomass in 30 min residence time.

Amount of fuel that should be burned in a boiler furnace is affected by torrefaction process. In Case 1 growth of torrefaction temperature results in higher fuel consumption to cover it. As for the Case 2, higher torrefaction temperature leads to bigger share of produced gas and, as a result, decreases primary fuel consumption. Fuel power has been calculated with the following formula:

$$Q_{fuel} = \dot{m}_{fuel}(LHV_{daf} + h_{fuel}) \quad (5.2)$$

Dependence between torrefaction temperature and primary fuel input in the boiler is shown on the Figure 6.4.



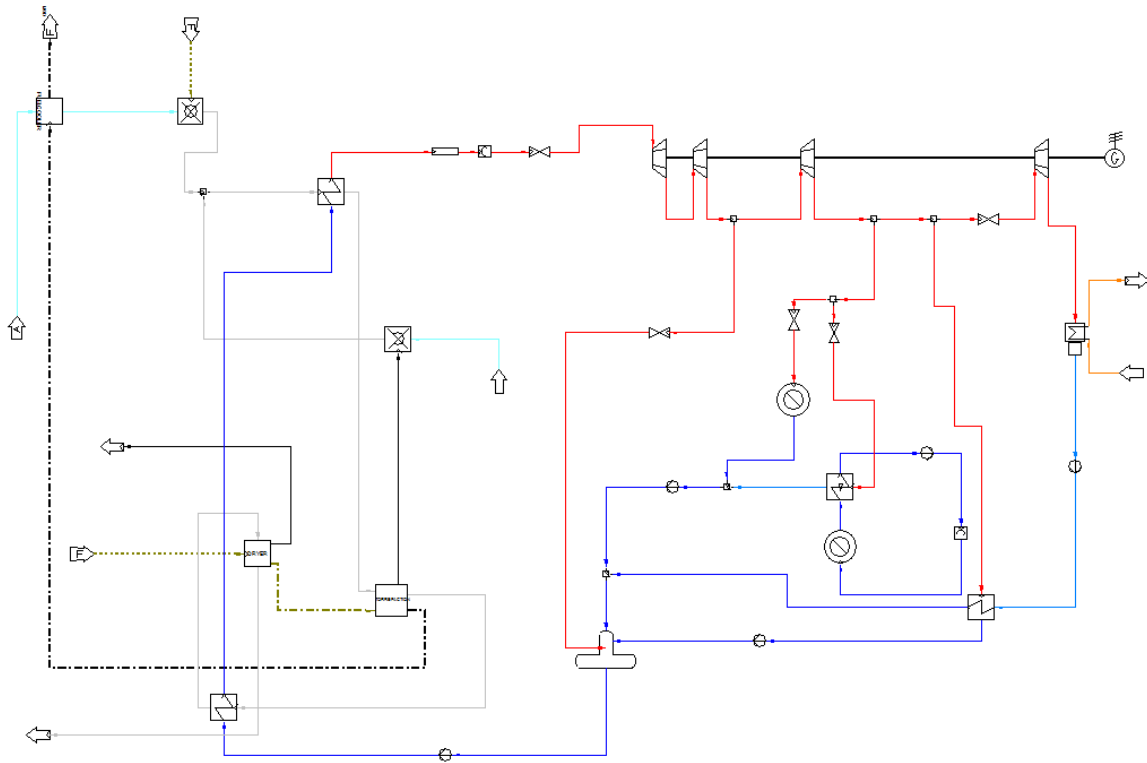
**Figure 6.4.** Effect of torrefaction temperature in fuel mass flow rate in the torrefaction of 0.86 kg/s or 10 MW of wet biomass in with 30 min residence time.

As it can be noted from this analysis, with higher torrefaction temperatures fuel consumption decreases but total efficiency decreases. So, in order to choose optimal operating parameters all factors should be taken into account.

## 6 Potential Areas for Further Research

### 6.1 Using Waste heat for Predrying

It is possible to increase the efficiency of the integrated plant by having a more careful consideration to the torrefaction process. The biggest heat demand of torrefaction process is allocated to the drying section while it requires low-temperature heat. It can lead to some innovative designs in waste heat recovery for pre-drying or even drying section itself. This process model is shown in figure 28. It can be observed that hot furnace gases are only used for torrefaction section, but not for drying. The calculated result and related data tables are shown in appendix 8 for case 4. The results offer 1.35% higher electrical efficiency for the integrated plant than normal case with the same settings. Considering the end temperature of flue gases after pre-drying, which is 122°C in this mode, it can be resulted that this model configuration is not overambitious. However, the feasibility of such improvement is highly depended on possible changes in flue gas cooling possibility, and the relevant costs and limitations.



**Figure 6.4.** Schematic flow diagram of case 4 in waste heat recovery mode with pre-drying

If this configuration can be modeled for other cases as well, the waste heat can be used efficiently in parallel to other heating media. The result shows that the case 3 has again the highest efficiency in this mode as well. However, the practical system design for this efficient harvest of energy has new challenges and complexities that can be subject to further research.

Flue gases supply the heat demand of drying agent, or in some cases pre-drying, while the heat of torrefaction process is maintained by another hot stream, such as steam bleed. The calculated results for this case are presented in appendix 9.

## 6.2 Integrated Torrefaction-Gasification Process (ITGP)

Gasification of biomass for synthesis of gaseous biofuels or power production is one of the focus areas in bioenergy production. There are significant researches and investment to discover more efficient and reliable solutions to promote the use of gasification technologies. Gasification as a thermochemical process has a variety of functional options for mass and heat integration, as well as process integration. Since gasification takes place in rather very high temperatures (800-1200°C), there is more possibility for waste heat recovery (Prins et al., 2006). Moreover, there is an established biomass logistics in gasification plants that can be simultaneously used for torrefaction feedstock supply.

In addition, based on a research by Prins et al. (2006), torrefaction of biomass is a state-of-the-art to reduce the cost of grinding in entrained-flow (EF) gasification application. In other words, not only energy can be recovered from gasification for supplying heat demand of torrefaction, the torrefied product is more suitable feedstock for gasification. Considering these alternatives in a biorefinery concept offers more new opportunities to increase the sustainable use of biomass, as a renewable energy source (RES). The simulation and modeling of integrated torrefaction-gasification processes (ITGP) in different applications can be a novel topic for future researches.

## 7 Conclusions

Increasing the share of bioenergy in final energy consumption is one of the priorities to meet the energy demand in sustainable development. Torrefaction of biomass, as a multi-purpose pretreatment process, can be employed not only to improve the biomass fuel properties but also to ease the use of biomass in a wider range of applications, such as gasification or cofiring. Any industry with established infrastructure in biomass logistics as well as sufficient heat availability, e.g. biomass-fueled power plants or biorefinery plants, has a great potential in integration of torrefaction process with existing processes.

Integration of torrefaction process with a steam power plant was examined in this research. First, a torrefaction reactor was modeled and simulated with a computer-aided tool (IPSEpro) to investigate different aspects of torrefaction process, as well as realizing the possible options for mass and heat exchange. The experimental data of two different sources was employed to formulate this model. Dividing the entire process into two sections, it was revealed that the bigger share of heat is used for drying section, almost 90%, while demanding low-temperature heat. The results of torrefaction modeling agree that the increase in torrefaction temperature, will decline the mass and energy yield in solid product, while having higher LHV. However, if the produced gases of torrefaction process can be efficiently burnt in a combustor, this devolatilized fraction of biomass can be efficiently used, e.g. to increase the efficiency of the steam plant by reduction of CHP fuel.

In order to draw a reliable comparison between different integration alternatives, a real steam power plant was modeled and investigated. The model was carefully built based on received data of the plant to increase the accuracy and applicability of the outcome results. Then, two plants were integrated considering that the whole process heat demanded by torrefaction reactor is supplied by different heating agents from steam cycle. It was also assumed that the whole produced gases from torrefaction process can be co-combusted with the CHP fuel of the steam plant. For making the possible integration models, two general conditions are possible for torrefaction reactor. The first condition, and more probable, is a torrefaction process that imposes extra load to the steam cycle. The second situation is a torrefaction reactor with sufficient produced gases that can contribute the steam cycle in terms of useful energy. This can occur if the feedstock for torrefaction would be dried enough before entering the integrated plant resulting in less heat demand, as well as, in high torrefaction temperature and residence times that produce higher amount of produced gases. It was discovered that the pattern of electricity efficiency and power output remains almost identical in these two torrefaction settings.

Then, different heating streams were extracted from steam cycle to indirectly supply the torrefaction heat. These hot streams were taken from boiler hot water after economizer (case 1), steam bleed from turbine (case 3), boiler hot flue gases (case 4), and live steam after superheater (case 5). Condensate were returned to the condenser hotwell where

steam was the heating medium. Having another torrefaction model based on self-sustaining process (case 2), these five models were modeled and compared in different torrefaction conditions. It should be reminded that the feasibility of these integration alternatives in terms of possible modifications in the steam plant, technical arrangements, and economical aspects were not examined in this study. Moreover, the characteristics of steam cycle, such as mass flow rates and equipment capacities, were assumed invariable in this study.

The first considerable result was that the electrical efficiency of case 3 (steam from turbine) was the highest in any torrefaction conditions. Depending on possible pressure of extraction this efficiency can be 0.55% higher than other cases in similar conditions. Moreover, this configuration (case 3) showed the highest power output as well, in invariable capacity for the boiler. However, if the boiler capacity can be improved for utilizing the additional torrefaction gas maintaining the same steam flow to turbine, power output of the case 3 will be lower than other cases. The other important outcome was the increases in electrical efficiency of the plant in case 3, even torrefaction with excess heat. This can be attributed to changes caused by condense return in arrangement of mass flow around condenser, feed water preheater and low-pressure turbine.

However, the technical possibility of extracting a new steam bleed from turbine is another important aspect that should be examined. Case 5 (live steam after boiler) showed almost the lowest efficiency, similar to other cases that use the heat from boiler side (case 1 and 4). Cases 1 and 4 showed a similar behavior in all settings with some slight differences. In another set of experiments, the amount of biomass feedstock for torrefaction was assigned to change for monitoring the reflection of the integrated plant. Case 3 (steam bleed) showed a non-linear growth in efficiency, compared to the other cases, with increasing the amount of predried biomass in torrefaction with extra heat. Other settings were also examined to track the power output and efficiency of the integrated plant in different cooling alternatives of torrefied biomass. The results agreed that case 3 has the higher efficiency than other cases, even without waste heat recovery from cooling process of hot torrefied biomass.

The characteristics of torrefaction products are highly depended on feedstock type, size, moisture content, fibrous structure, torrefaction time and temperature, and reactor thermal efficiency. Simulation and modeling of more influential parameters will increase the accuracy of the results. The study of possible integration of torrefaction process with other biomass conversion routes, like gasification, as well as integrated co-firing of torrefied biomass with other fuels, like coal, can be other subjects to future researches following this research.



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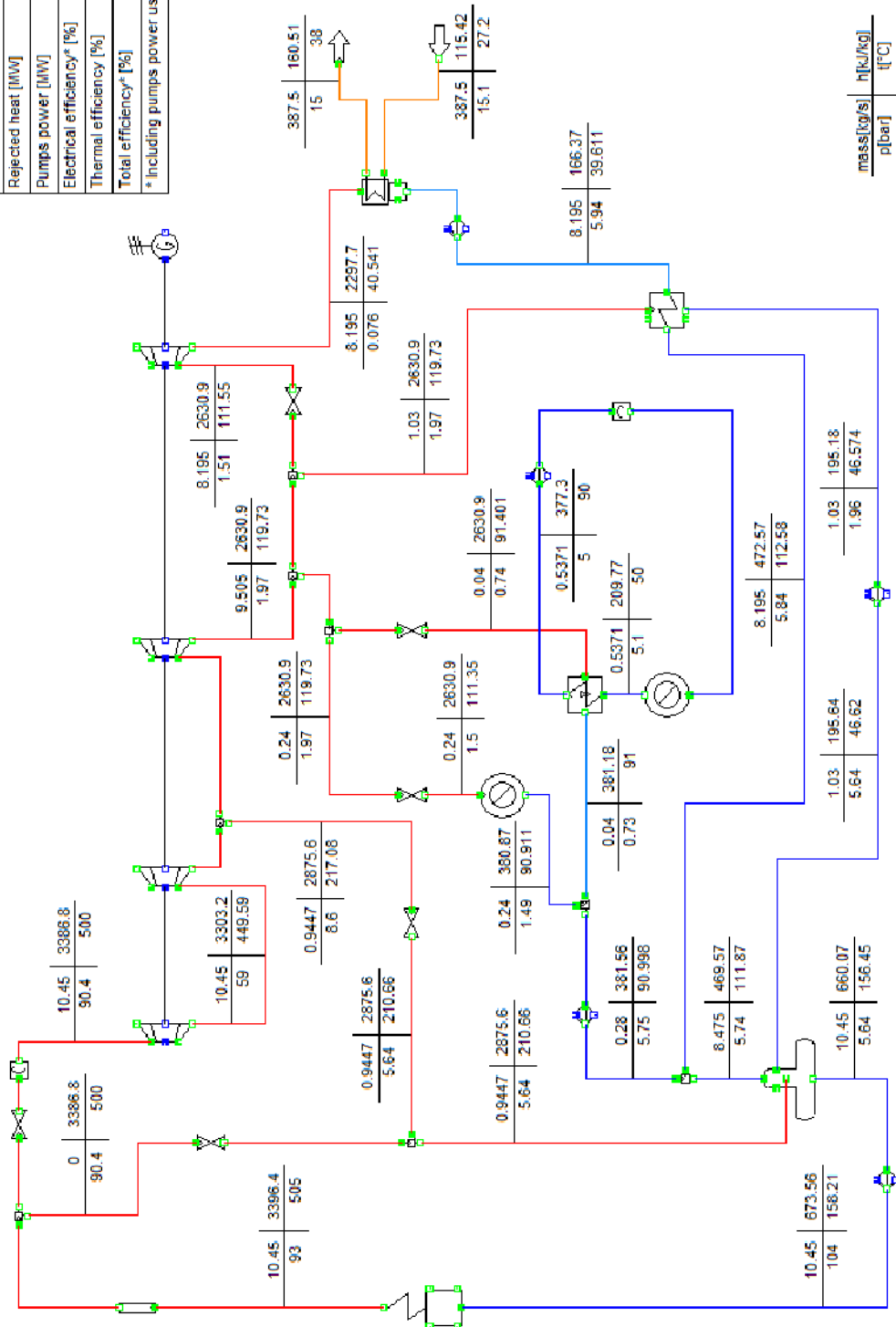
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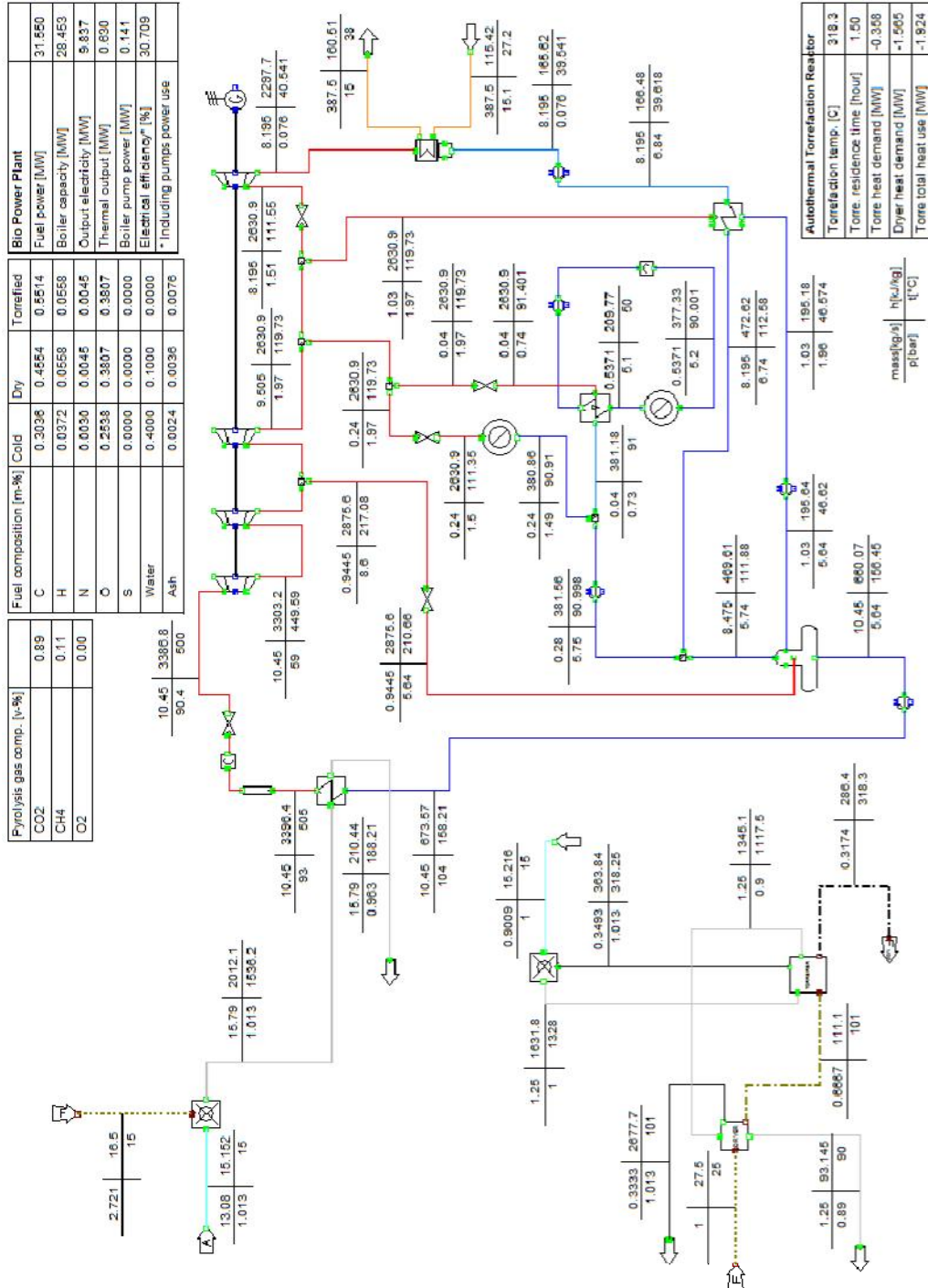
# Appendices

## Appendix 1: Bio power plant in basic condition

BIO Power Plant	
Input heat [MW]	31.550
Boiler capacity [MW]	28.453
Output electricity [MW]	9.837
Total process heat [MW]	0.630
Rejected heat [MW]	17.472
Pumps power [MW]	0.148
Electrical efficiency* [%]	31.179
Thermal efficiency* [%]	1.997
Total efficiency* [%]	30.712
* including pumps power use	

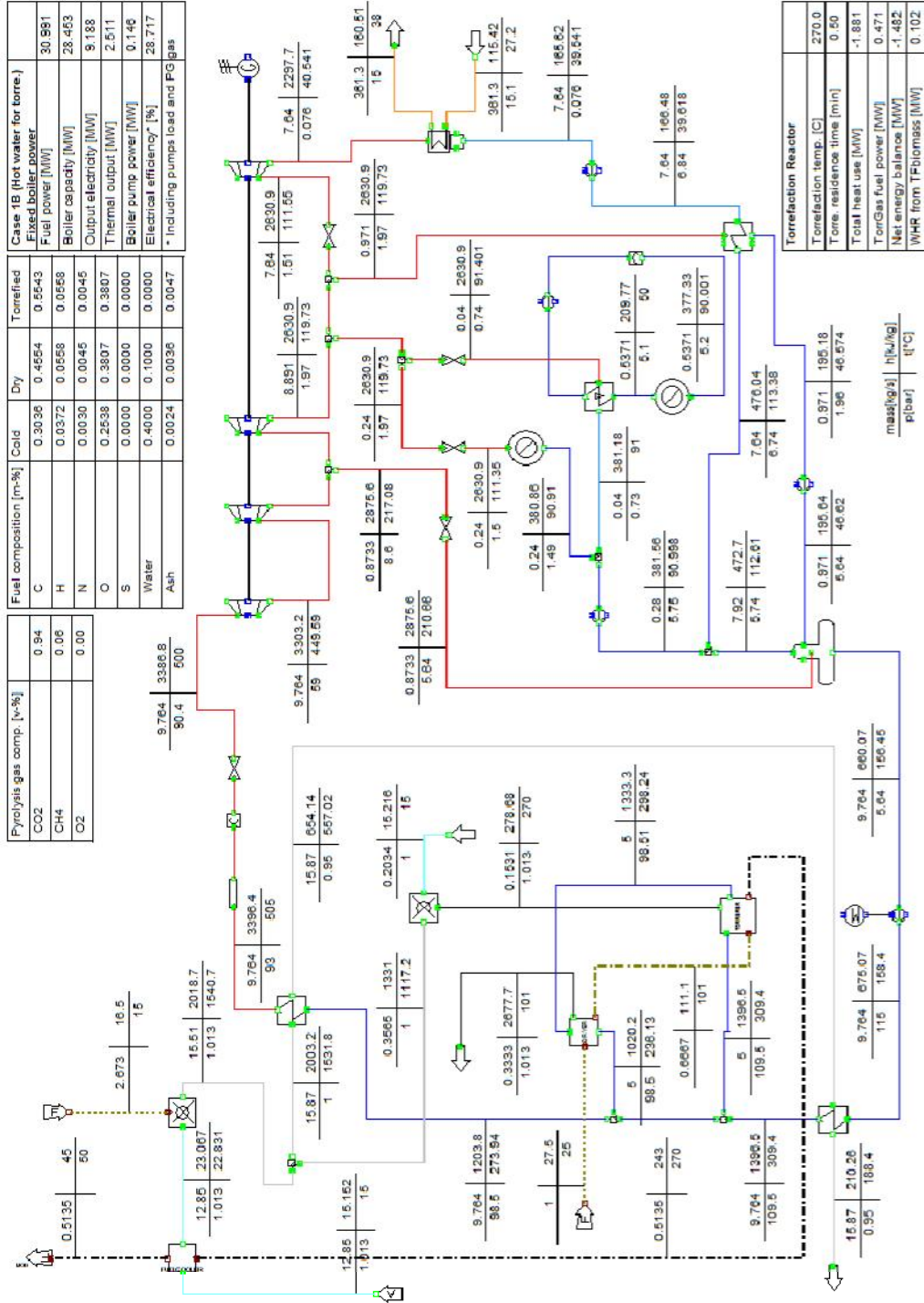


## Appendix 2: Case 0- Two plants before integration

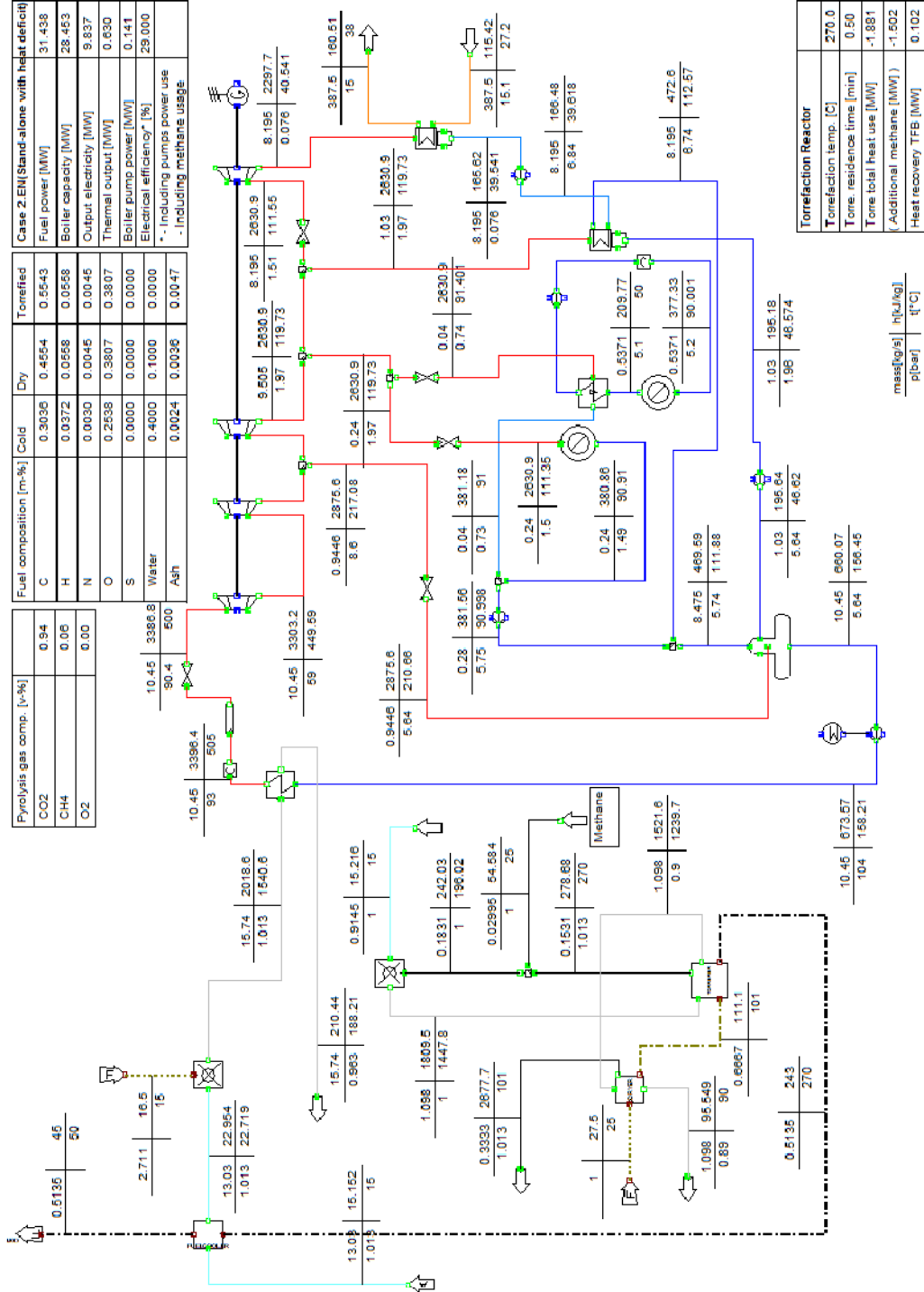


Left- Torrefaction plant: 1kg/s feed in residence time of 20 min at 270°C  
 Right- Steam plant modeled by a combustor and heat exchanger replaced the boiler

### Appendix 3: Case 1- Hot water from boiler to torrefaction plant



## Appendix 4: Case 2- Stand-alone torrefaction reactor

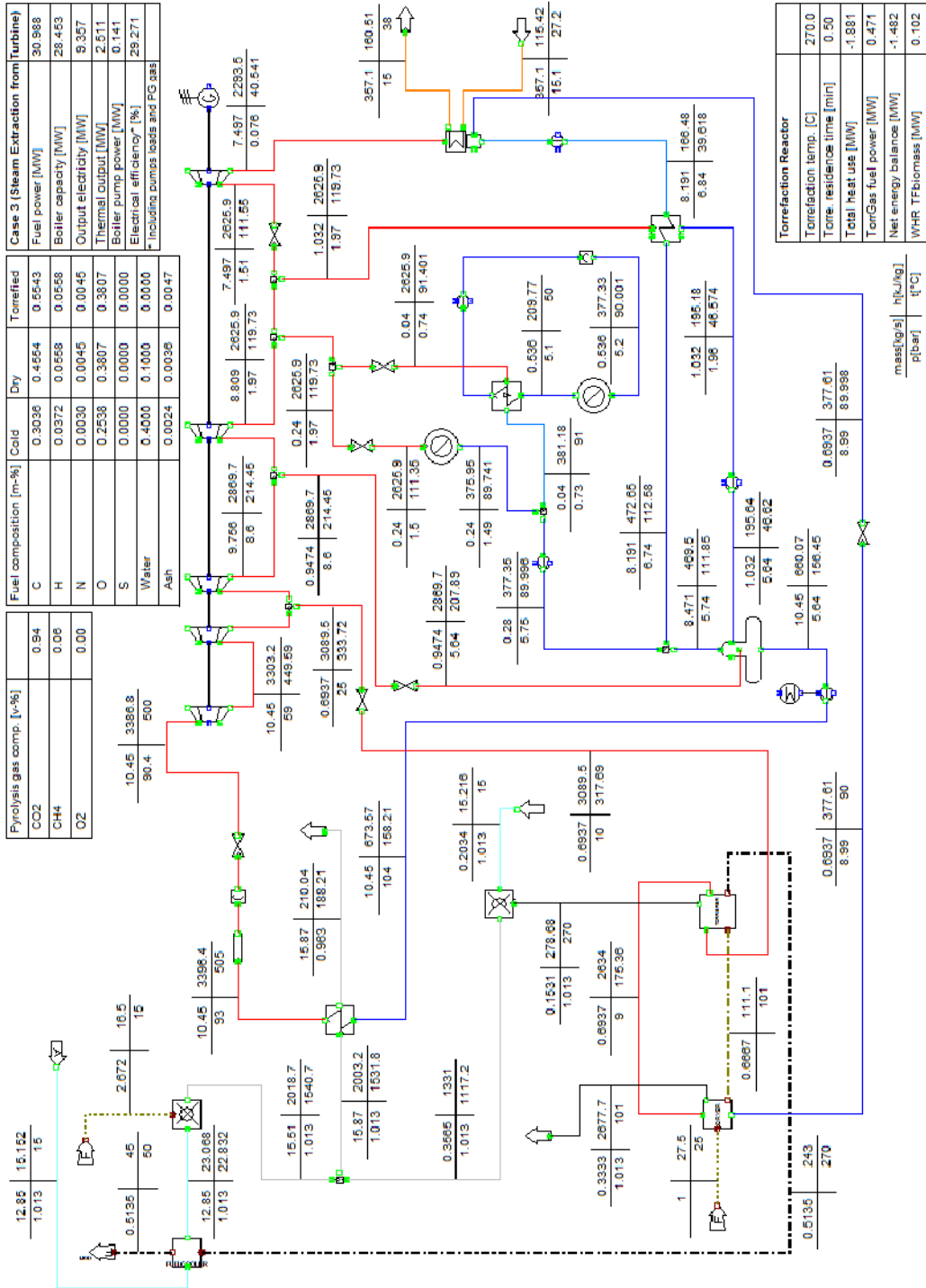


Pyrolysis gas comp. [v-%]		Fuel composition [m-%]		Dry		Torrefied	
CO2	0.94	C	0.3036	0.4554	0.5543	Fuel power [MW]	31.438
CH4	0.06	H	0.0372	0.0558	0.0558	Boiler capacity [MW]	28.453
O2	0.00	N	0.0030	0.0045	0.0045	Output electricity [MW]	9.837
		O	0.2538	0.3807	0.3807	Thermal output [MW]	0.830
		S	0.0000	0.0000	0.0000	Boiler pump power [MW]	0.141
		Water	0.4000	0.1000	0.0000	Electrical efficiency* [%]	29.000
		Ash	0.0024	0.0036	0.0047	* - Including pumes power use - including methane usage	

Torrefaction Reactor	
Torrefaction temp. [°C]	270.0
Torre. residence time [min]	0.50
Torre total heat use [MW]	-1.881
(Additional methane [MW])	-1.502
Heat recovery TFB [MW]	0.102

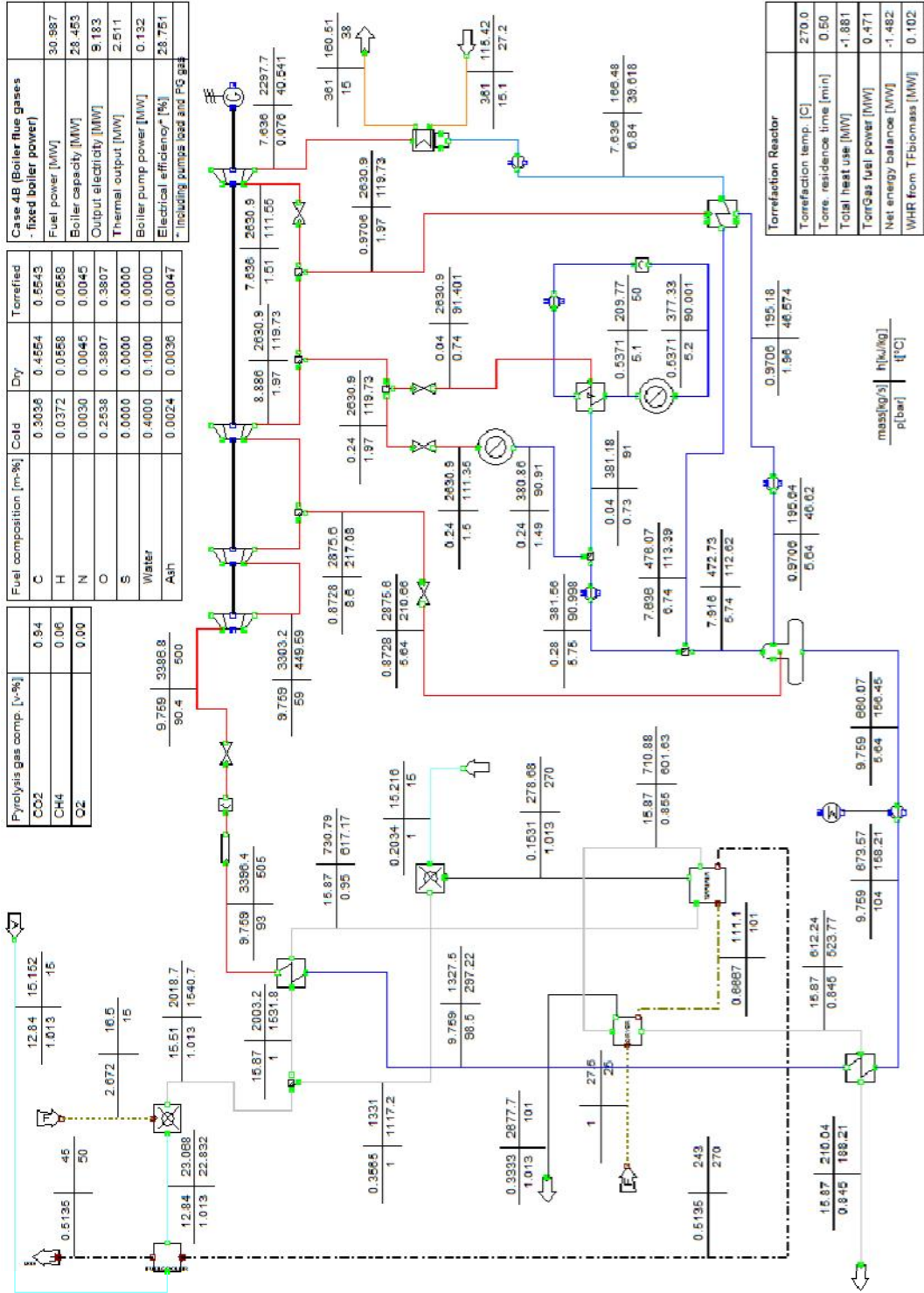
mass [kg/s] | h [kJ/kg]  
p [bar] | t [°C]

## Appendix 5: Case 3- Steam extraction from turbine at 25 bar



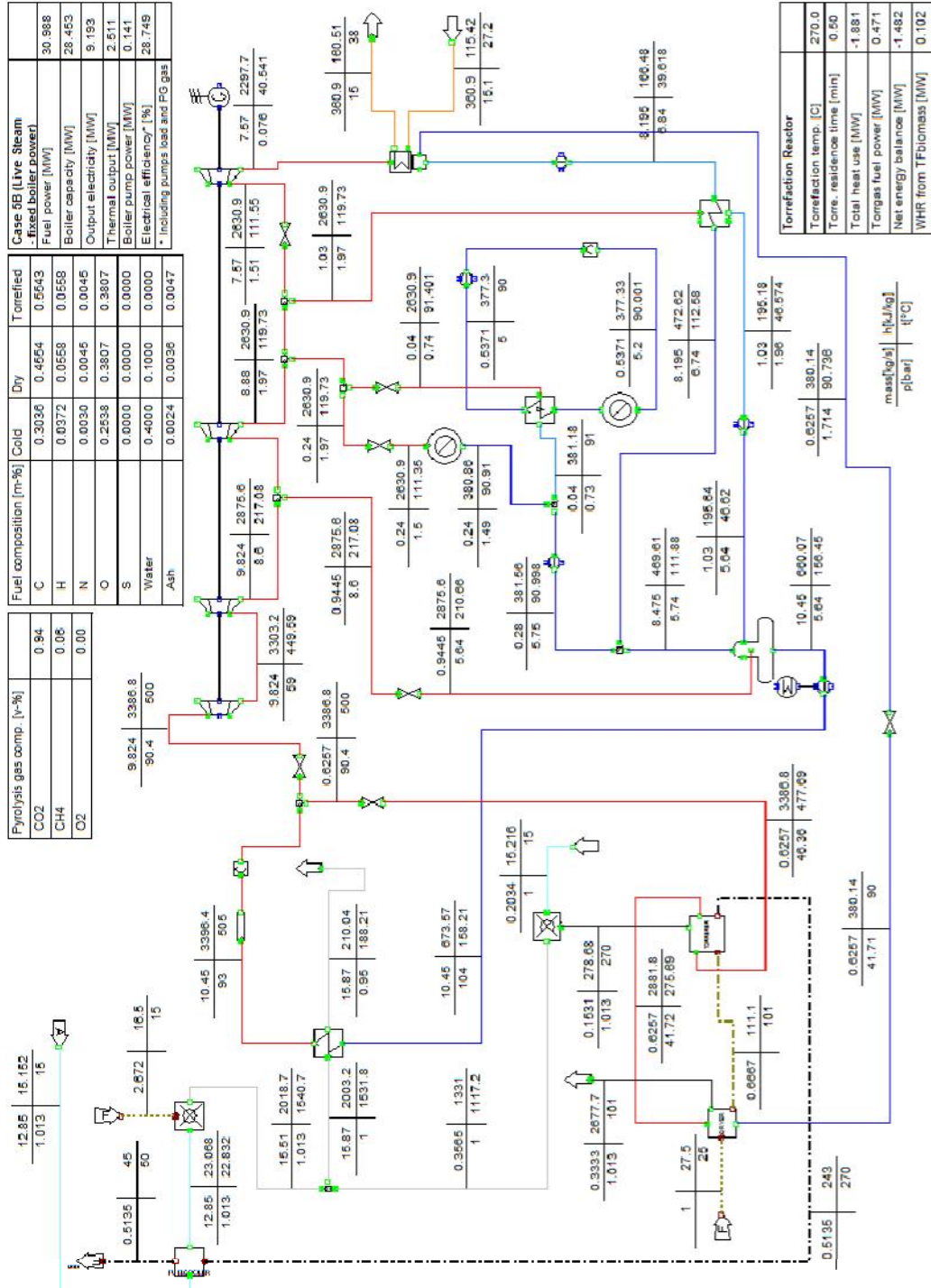


## Appendix 6: Case 4- Using boiler flue gases for heating torrefaction reactor

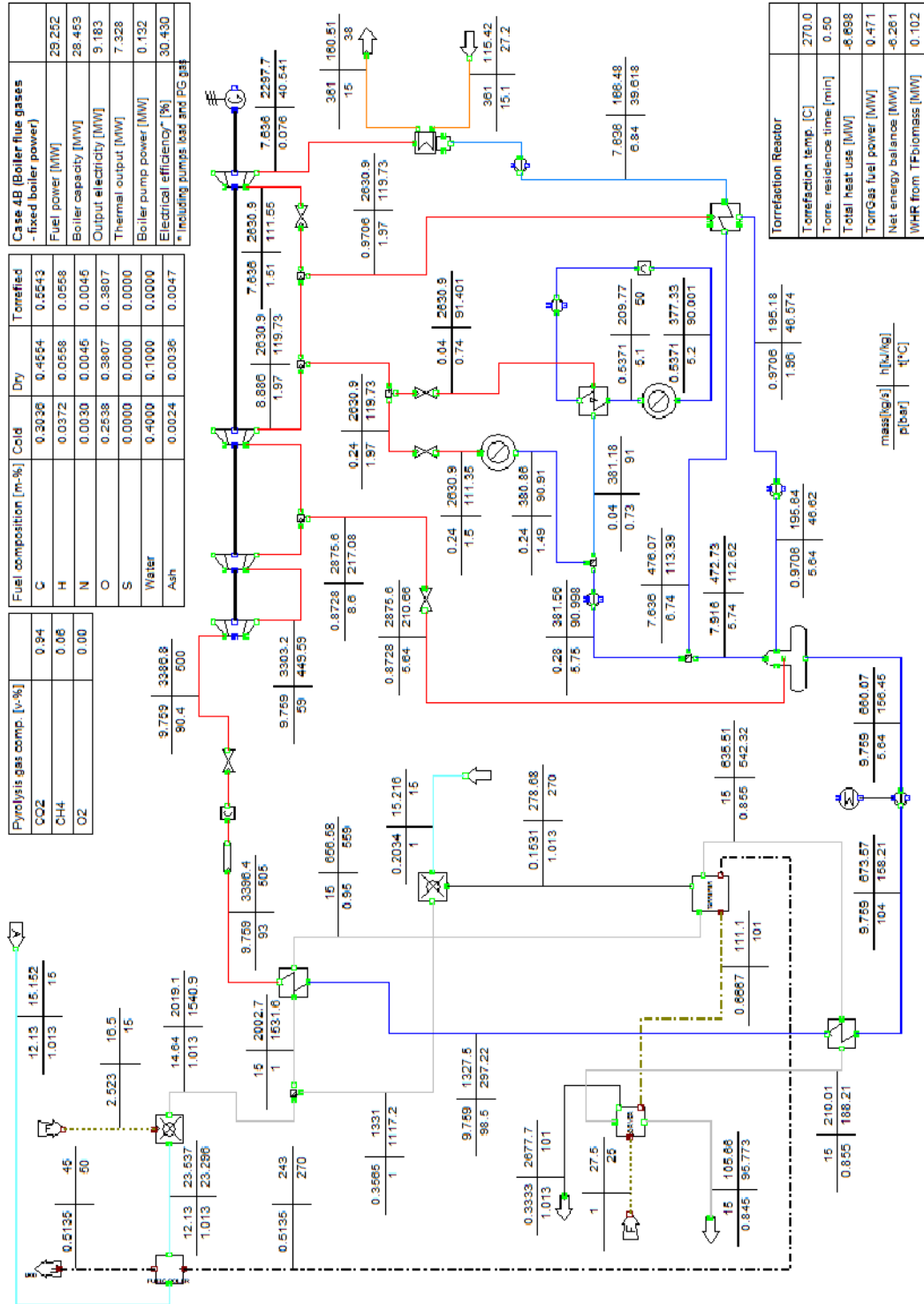




## Appendix 7: Case 5- Live steam from boiler to torrefaction reactor



## Appendix 8: Case 4 in waste heat recovery model with pre-drying



## Appendix 9: Case 3 in waste heat recovery model with pre-drying

