INTEGRATION OF BIOMASS TORREFACTION WITH A CHP PLANT

Recipients:

Fortum Power and Heat Oy
Andritz Oy

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1 INTRODUCTION

In this study the integration of wood chip torrefaction with an existing combined heat and power (CHP) plant is investigated. The CHP plant considered is an existing and operating CHP plant, while the torrefaction process is based on Andritz-designed belt drier and continuously operating torrefaction equipment using flue gas as heat source. The purpose of the study is to provide preliminary performance estimates for comparison with stand-alone torrefaction.

Full- and part-load operation of both boiler and torrefaction plant at different seasonal conditions are considered. For this purpose a heat balance model of CHP plant boiler and steam cycle were developed based on data supplied by Fortum. For integration in the plant model, simple drier and torrefaction components were created based on heat and mass balance data from Andritz. The primary aim was to find the effect of integration on plant electricity and district heat output, and boiler solid fuel use.

2 STUDIED CASES

The study is based on the assumption of 7000 hour annual operating time of the CHP-torrefaction integrate. An annual maximum production of 100 000 tons of solid torrefied product is assumed, corresponding to a 4.1 kg/s total torrefied solid product mass flow rate (3.9 kg/s dry) at full load. Torrefaction gases are combusted in the boiler. Three seasonal cases are considered, winter, autumn/spring, and summer, summarized in Table 1 below.

Table 1. *Seasonal conditions considered.*

	Autumn/Spring	**Winter**	**Summer**
Ambient temperature [°C]	+10	-20	+25
DH water supply/return temperature [°C]	75/45	100/60	75/45
Fuel moisture [%]	45	50	45

A full load boiler fuel input of 74 MW based on [1] is considered for all seasons. Simulations of autumn/spring and summer conditions were performed also at 59 % total boiler fuel power (solid fuel + torrefaction gas), winter case was calculated only at full boiler load. Full- and 50% torrefaction loads were simulated for all five boiler load and season combinations.

In all cases the biomass feedstock to torrefaction is assumed to be dried to 5% moisture content in a belt drier where heat is supplied from a combination of LP steam and district heating water. Torrefaction reactor heat is taken from boiler flue gas, extracted between the superheaters and economizer. The returning cooled flue gas is then returned back to the boiler before the economizer from the torrefaction reactor.

IPSEpro modeling tool was employed in this research. IPSEpro is a tool for simulation, modeling, analysis and design of components and processes in energy and process engineering. For modelling the boiler and steam cycle, standard library components are sufficient.

All the simulation and modeling were carried out in IPSEpro modeling environment. The complete IPSE model of the integrated plant is shown in Figure 1 below. Main modelling assumption and the data used is summarized in the following chapters.

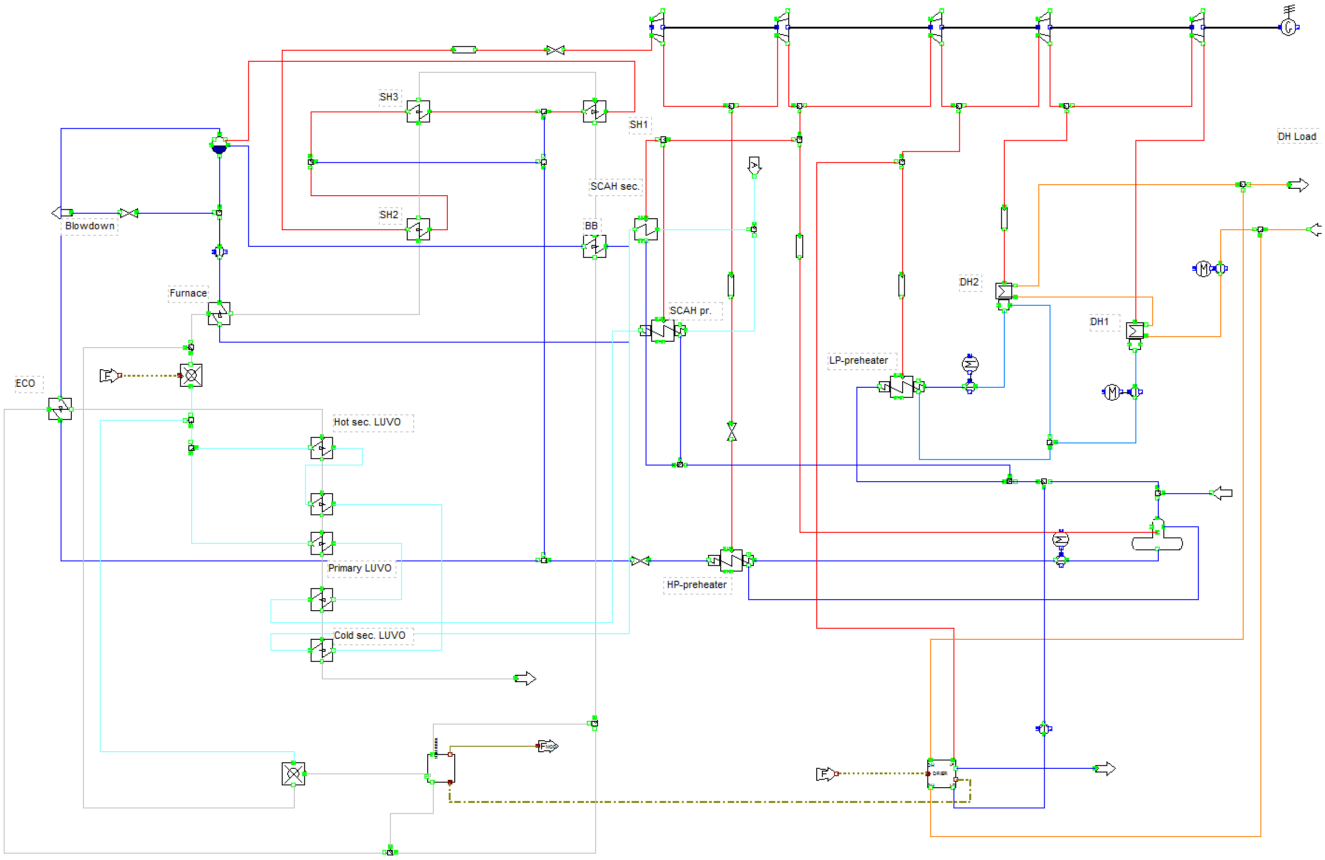


Figure 1. *IPSE model topography of the CHP-torrefaction integrate.*

3 CHP PLANT MODEL

3.1 Steam cycle model

The model was based on heat balance data supplied by Fortum. Three load points from reference [1] were chosen to serve as the basis of steam cycle models in IPSEpro.

The only load point in reference [1] that was reasonably close to 50% boiler load was with 59% boiler fuel input, was used for all boiler part load calculations.

3.2 Boiler model

The boiler model was based on actual heat transfer surface data and CHP plant process computer screen captures supplied by Fortum.

The overall heat transfer coefficients U [W/m^{2}K] for the superheaters, boiler bank, and economizer and were calculated by a Fortran code originally developed for doctoral dissertation of Esa Vakkilainen [2], while the U values for the air preheater surfaces were determined from the correlations from VDI Heat Atlas [3].

For superheaters SH1 and SH2, the process computer screen captures provided steam temperature values before and after the superheater surface. Due to the inherent inaccuracies of theoretical heat transfer correlations, this steam temperature data rather than calculated overall heat transfer coefficients was set fixed in the model. The resulting heat transfer coefficients varied generally within approximately 20 % of values calculated by the Fortran boiler code.

The combination of temperature measurement data when available, otherwise heat transfer coefficients calculated by the Fortran code or VDI Heat Atlas method was used as they appeared to provide reasonable results. The correlations of heat transfer coefficients as function of steam flow rates would have required the use of correction factors to provide results matching the heat balance and process computer screen capture data.

For combustion air, a primary/secondary air split of 32/68 per cent was assumed. Varying steam flow to the steam coil air preheaters was used to maintain a constant flue gas stack temperature of approximately 151 °C.

4 TORREFACTION MODEL

For the torrefaction process, two components were created in IPSEpro’s Module Development Kit (MDK) on the basis of Andritz-supplied heat and mass balance data.

Due to the limitations of IPSEpro software, a separate combustor had to be used to for torrefaction gases. The flue gases from gaseous fuel combustion are mixed with flue gas from the solid fuel combustor before the heat exchanger representing the furnace. Since most of the actual gaseous components forming the torrefaction gas are not available in IPSE fuel library, the gas is represented by a mixture of CH_4 and CO_2 yielding the same heating value as that obtained from the balance sheet provided by Andritz.

4.1 Drier

Biomass is dried to a moisture of 5% in a belt drier using a combination of district heating water and low-pressure steam as heat source. The drier balances for the models for different seasons are shown in Table 2 below.

The specific thermal powers of district heating water $P_{\mathrm{spec,DH}}$ and low pressure steam $P_{\mathrm{spec,LP}}$ consumed per kg of evaporated water are calculated separately for each seasonal case. With the specific thermal powers and the LP steam and DH water incoming and outgoing states determined, the required mass flow rates for 100% or 50% torrefaction output can then be determined in the model.

Due to the limitations of IPSEpro software, the winter case could not be simulated at -25 °C temperature, but only -20 °C ambient temperature. The drier performance data at -25 °C was assumed to be close enough to provide an adequate approximation for this condition.

Table 2. *Drier mass balances*

Feed		T_{amb} = 10 °C			T_{amb} = -25 °C			T_{amb} = 25 °C		
		feed in	**solid out**	**H_2O out**	**feed in**	**solid out**	**H_2O out**	**feed in**	**solid out**	**H_2O out**
MC	%	45.1 %	5.0 %		50.0 %	5.0 %		45.1 %	5.0 %	
q_m	kg/h	35589	20566	15023	39076	20566	18510	35589	20566	15023
q_m	kg_{dry}/h	19538	19538		19538	19538		19538	19538	
q_m	kg/s	9.886	5.713	4.173	9.886	5.713	4.173	9.886	5.713	4.173
q_m	kg_{dry}/s	5.427	5.427		5.427	5.427		5.427	5.427	

4.2 Torrefier

Torrefier heat and mass balances were determined from the drawing provided by Andritz. The dried biomass feed enters the torrefaction reactor having a moisture content of 5 %.

For the dry solid product the torrefaction process is assumed to have a mass yield of M = 0.716 and energy yield of E = 0.826, defined as

$$M = \frac{q_{\mathrm{m,out,db}}}{q_{\mathrm{m,in,db}}} \tag{1}$$

and

$$M = \frac{q_{\mathrm{m,out,db}} HHV_{\mathrm{out,db}}}{q_{\mathrm{m,in,db}} HHV_{\mathrm{in,db}}} \tag{2}$$

The lower heating value of the torrefaction gas varies somewhat depending on the type of feedstock, as well as the severity of torrefaction. At high mass yields of solid product, much of the gas output consists of carbon dioxide, water and acetic acid from hemicellulose decomposition [4]. As the torrefaction severity increases and more gas is produced, the fraction of combustible components also increases, and thus the heating value of the gas also increases.[4,5]

Published results cover only a limited number of woody biomass types, but would appear to indicate that the torrefaction gas compositions do not vary very much between different wood species [5]. Torrefaction of other types of biomass such as grasses or wastes sometimes result in very different gas compositions, however.

Depending on the composition of the gases, the ratio of carbon and hydrogen in the gas varies, and therefore so does the amount of water vapour in the combustion gases, and the difference between lower and higher heating values.

The composition of the torrefaction gas was estimated by taking an average composition of the combustible fraction of torrefaction gas from from four of the cases reported by Prins et al. in [5]: larch at 290 °C for 10min and 270 °C for 15 min, and willow at 280 °C for 10 min and at 250 °C for 30 min.

By assuming water and carbon dioxide fractions at 33 % and 9 % of the gas-phase products, a torrefaction gas composition presented in Table 3 below was obtained, resulting in a lower heating value of LHV = 7.95 MJ/kg (HHV = 8.82 MJ/kg). Water vapour was considered inert and its latent heat ignored for the higher heating value.

Table 3. *Approximation of torrefaction gas composition.*

		m-fraction %	LHV MJ/kg	HHV MJ/kg
Water	H_2O	33.0	0	0
Carbon dioxide	CO_2	9.0	0	0
Acetic acid	$C_2H_4O_2$	15.7	13.1	14.6
Formic acid	CH_2O_2	10.4	4.6	5.55
Methanol	CH_4O	11.6	20.0	22.7
Lactic acid	$C_3H_6O_3$	10.4	13.6	15.1
Furfural	$C_5H_4O_2$	2.3	23.5	24.4
Carbon monoxide	CO	4.1	10.1	10.1
Hydroxy acetone	$C_3H_6O_2$	3.5	20.1	21.9
		100.0	7.95	8.82

Table 3 is not an exhaustive list of gas-phase components: several other organic compounds would also be present in the gas. In addition to the genuinely gas-phase components, also some solids and heavier liquid-phase tars are likely to be carried from the torrefaction reactor suspended in the gas flow in small particles and droplets. The elemental compositions and amounts of these are not known, however.

The IPSEpro modelling software used in this study does not include the majority of the components listed in Table 3. To overcome this limitation, the torrefaction gas is modelled as a mixture of methane and carbon dioxide matching the heating value of the estimated torrefaction gas mixture of Table 3. Since the water vapour from hydrocarbon combustion remains in gas phase in the boiler and the latent heat of phase change is lost in stack losses, the lower heating value is used; matching the higher heating value would introduce an additional error if the amount of hydrogen in the fuel would not also match the actual.

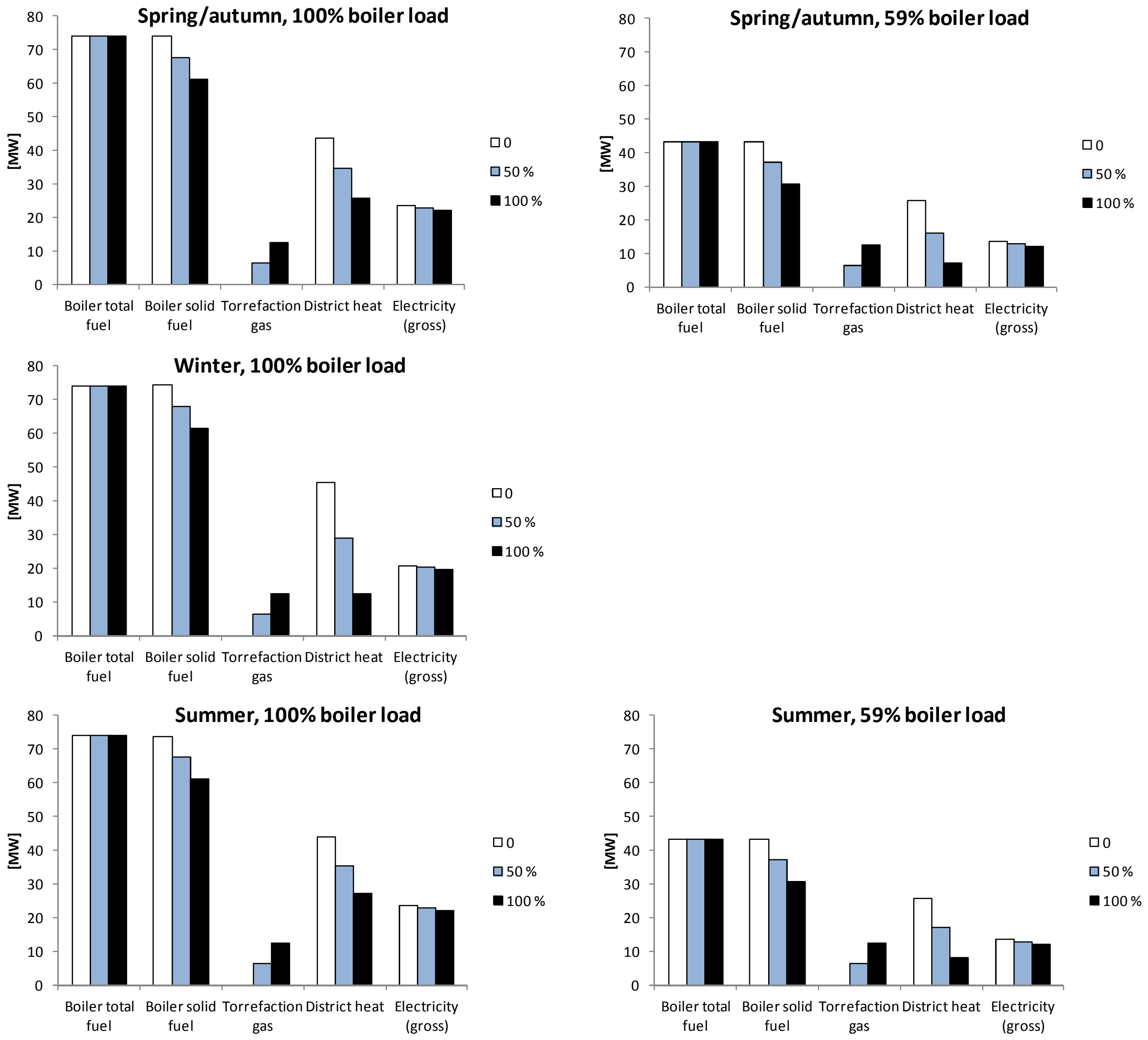
This approach of using matching the gas mixture to the lower heating value of the torrefaction gas results in the correct amount of heat input to the resulting flue gas. The uncertainty of the actual torrefaction gas composition and a flue gas mass flow rate and specific heat different from actual flue gas torrefaction combustion still causes some inaccuracies, but these errors were considered to be of small magnitude compared to other uncertainties and modelling simplifications.

5 RESULTS

The main simulation results for different boiler loads (100% or 59%), torrefaction rates (none, 50% or 100%) and seasonal conditions are presented in Figures 2 below. In each case 100% torrefaction load corresponds to a 4.14 kg/s of torrefied solid product output at 6% moisture content from the cooler (3.89 kg/s bone-dry before the cooling), yielding 100 000 tons per year with 7000 operating hours.

A slight fluctuation of approximately 2 °C in the flue gas stack temperature between different cases was considered to be of negligible importance.

The case of winter part-load boiler operation is omitted due to this being considered a relatively unlikely case, as well as the difficulty of accurate modelling due to lack of data for a load point with winter district heat temperature but part-load boiler operation in the heat balances of reference [1].



Spring/autumn, 100% boiler load

Spring/autumn, 59% boiler load

Winter, 100% boiler load

Summer, 100% boiler load

Summer, 59% boiler load

Figure 2. *Fuel, generator and district heat powers at winter at varying boiler and torrefaction loads.*

Table 4 summarizes the impact of torrefaction on plant solid fuel consumption, and electricity and district heat production in terms of absolute power inputs/outputs, and the change caused by the integration of torrefaction process. Torrefaction feedstock and solid product heat rates are based on the fuel data found in supplied energy balance sheet for torrefaction equipment for this case: LHV_{feed} = 9.3 MJ/kg at normal 45% moisture content (7.17 MJ/kg at 55% moisture content during winter), and 22.12 MJ/kg bone-dry solid product LHV. At 6% moisture content of solid product, $LHV_{MC=6\%}$ = 20.6 MJ/kg was assumed.

In the winter case feedstock has higher moisture content and torrefaction needs more of the higher-moisture feedstock for same solid product output. Due to the reduced lower heating value of the moist feedstock, the fuel heat rate out of the reactor is in fact greater than the input on an LHV basis, however, although the gross calorific rate would obviously be smaller in the output flow.

Table 4. *Impact of torrefaction on boiler solid fuel consumption, electricity production and district heat production at 100% and 59% boiler load and 50% and 100% torrefaction output*

	Boiler load [%]	**Torrefaction [kg/s]**		**Torrefaction [MW_{LHV}]**		**Boiler solid fuel [MW_{LHV}]**		**Electricity [MW]**		**District Heat [MW]**	
		feed	**product**	**feed**	**product**	**abs.**	**change**	**abs.**	**change**	**abs.**	**change**
Spring / Fall	**100**	0	0	0	0	73.8	0	22.6	0	43.6	0
	100	4.93	2.07	45.9	42.7	66.3	-7.5	21.8	-0.7	34.0	-9.7
	100	9.87	4.14	91.8	85.5	58.7	-15.1	21.2	-1.4	24.3	-19.4
	59	0	0	0	0	43.4	0	13.0	0	25.6	0
	59	4.93	2.07	45.9	42.7	35.8	-7.5	12.3	-0.7	15.9	-9.7
	59	9.87	4.14	91.8	85.5	28.3	-15.1	11.8	-1.2	6.1	-19.5
Winter	**100**	0	0	0	0	74.2	0	20.2	0	45.1	0
	100	5.43	2.07	38.9	42.7	66.7	-7.5	19.6	-0.6	27.8	-17.3
	100	10.85	4.14	77.8	85.5	59.1	-15.1	19.1	-1.1	10.4	-34.8
Summer	**100**	0	0	0	0	73.6	0	22.7	0	43.9	0
	100	4.93	2.07	45.9	42.7	66.1	-7.5	21.9	-0.8	34.8	-9.1
	100	9.87	4.14	91.8	85.5	58.6	-15.1	21.1	-1.6	25.6	-18.3
	59	0	0	0	0	43.2	0	13.0	0	25.8	0
	59	4.93	2.07	45.9	42.7	35.7	-7.5	12.4	-0.7	16.6	-9.2
	59	9.87	4.14	91.8	85.5	28.2	-15.1	11.8	-1.3	7.2	-18.6

Estimates of annual feedstock and boiler solid fuel usage by a torrefaction-CHP integrate, and total electricity and district heat productions, are shown in Table 5 and Table 6.

The figures of Table 5 are based on an assumption of constant 100% boiler load for 7000 hours. The basic reference case is CHP only without torrefaction integration. The impact of torrefaction integration was calculated at constant 50% and 100% torrefaction rates through the year. In all cases a 25-50-25 winter-autumn/spring-summer split of seasonal operating conditions was assumed.

Again the reduction of moisture in torrefied solid product is sufficient to produce a slight net increase of torrefied fuel LHV although some of the gross calorific value is lost.

Table 5. *Impact of torrefaction on boiler solid fuel consumption, electricity production and district heat production at 100% boiler load, 7000 h/a operating time, and 25-50-25 winter-autumn/fall-summer split of seasonal conditions.*

Case	Torrefaction [t]		Torrefaction [GWh$_{LHV}$]		Boiler solid fuel [GWh$_{LHV}$]		Electricity [GWh]		District Heat [GWh]	
	feed	product	feed	product	absolute	change	absolute	change	absolute	change
CHP only	0	0	0	0	517	0	154	0	309	0
50% torre	127 443	52 143	309	299	464	-53	149	-5	228	-80
100% torre	254 841	104 285	618	598	412	-106	144	-10	148	-161

Constant full-load operation is unlikely to represent well a typical annual operating cycle of a CHP plant, however. In the figures of Table 6, the reference case splits the 7000 hour annual operating time in 4 equally long periods: winter, 100% boiler load; spring/autumn, 100% boiler load; spring/autumn, 59% boiler load; and summer, 59% boiler load.

The impact of torrefaction integration is calculated for two operating strategies. In case “Const-DH” the district heat production is maintained at an approximately constant value. This is achieved fairly closely by running 100% boiler load and 100% torrefaction when the boiler load in pure CHP operation would be 59%. At 100% pure CHP load no heat is available for feedstock drying and torrefaction, and torrefaction is not operated.

The resulting torrefaction production rate matches the 50% constant annual production of Table 5, but consumes slightly less feedstock mass (but more if measured in LHV) because the high-moisture, low-LHV winter feedstock is not being used. The resulting annual DH production rate closely matches the base case of CHP-only operation.

The case “Max-torre” represents a maximum torrefaction production, where torrefaction is operated at 100% rate at all periods except for the winter, for which a 50% torrefaction rate was assumed.

Table 6. *Impact of torrefaction on boiler solid fuel consumption and production of electricity and district heat compared to CHP-only base case of 100% winter, 100% spring/fall, 59% spring/fall and 59% summer load, split in equal-length fractions of the 7000h annual operating time.*

Case	Torrefaction [t]		Torrefaction [GWh$_{LHV}$]		Boiler solid fuel [GWh$_{LHV}$]		Electricity [GWh]		District Heat [GWh]	
	feed	product	feed	product	absolute	change	absolute	change	absolute	change
Base	0	0	0	0	411	0	120	0	245	0
Const-DH	124 324	52 143	321	299	464	54	149	28	243	-3
Max-torre	220 676	91 249	550	523	425	14	145	25	178	-67

It is evident that when the base case of CHP-only operation attempts to account for the reduced DH demands of significant parts of the plant annual operating time, the impact of torrefaction integration becomes very different from the constant full-load operation. Rather than being reduced, the annual electricity production is increased by almost 20%, and district heat production is also much less affected.

With the extremely simple approximation of changing annual operating conditions, a torrefaction production representing 50% of maximum theoretical rate is achievable without reducing the district heat production.

6 CONCLUSIONS

Due to the limited time available for the project, a number of simplifications had to be made in the model, and a thorough validation of the models could not be performed with the time and data available. There appeared to be some discrepancies particularly between reported boiler heat transfer surface performance correlations, calculation results from traditional heat transfer correlations, and process computer measurement data.

Consequently the results presented in chapter 5 should be considered as rough estimates and indications of general trends, rather than exact predictions.

Despite the significant simplifications, limited validation and assumptions inevitable present in the model and simulations, some conclusions can be drawn from the results:

1) Electricity production is affected very little by the introduction of torrefaction if the boiler thermal power is maintained constant. The heat demand of the torrefaction reactor is comparatively small, and the drier operating with low-pressure steam and DH water allows most of the steam to expand almost through the entire pressure range of the turbine.

2) District heat production is more severely curtailed by the introduction of torrefaction at any given boiler thermal power, because much of the low pressure steam as well as the hot district heating water itself is consumed by the drier.

3) Conversely, at low district heating load the torrefaction process could serve as additional heat load to facilitate increased electricity production. If the plant is run based on district heat load, significant increase of electricity production can be achieved at low district heat loads.

   Based on the results it can be seen that the DH output at 59 % boiler load and no torrefaction is very close a case of 100% boiler load and 100 % torrefaction rate, torrefaction increasing the electricity ouput by 8 to 9 MW, or over 60 %.

   For whole-year production, assuming the relatively simple approximation of the annual CHP-only operating case represented in Table 6, torrefaction production of half the theoretical maximum could be achieved without reducing the district heating output at all. At the same time the annual electricity production would increase by 25 %, and boiler solid fuel consumption by 15 %.

4) At part-load boiler operation, maximum torrefaction operation comes close to the theoretical maximum possible both in terms of available LP steam and DH water for drying, and flue gas available for torrefaction. At 275 °C exit temperature from the reactor the flue gas still has enough energy available for 100 % torrefaction at 59 % boiler load, and torrefaction rate becomes limited by LP steam first; however, this may be a result of the boiler model which appears to somewhat overestimate the actual flue gas temperature before economizer.

The profitability of the torrefaction-CHP investment would depend on energy costs, investment costs and annual operating demands, as well as availability and cost-effectiveness of alternative means of district heat production. Since such cost and operating data was not available in this research, even rough estimates of attractiveness of the torrefaction-CHP integrate could not be made here.

Although the annual energy balance estimates are by necessity somewhat crude, they show that without curtailing heat production, a significant amount of torrefied solid product could be produced during the year, with the added benefit of noticeably increased electricity production. On the basis of this, it appears that further study on the operation and cost-effectiveness of a torrefaction-CHP is probably warranted.

NOMENCLATURE

Roman letters

c_p	specific heat, kJ/kgK
h	enthalpy, kJ/kg
HHV	higher heating value, MJ/kg
LHV	lower heating value, MJ/kg
MC	moisture content, %
p	pressure, bar
P	power, MW
q_m	mass flow rate, kg/s; t/h
T	temperature, °C
U	overall heat transfer coefficient, W / m^2K

Greek letters

ϕ_{spec}	1. drier specific energy requirement, kWh / kg_{H2O}
	2. torrefier specific energy requirement, kWh / kg_{feed}
Φ	thermal power, MW
λ	air-fuel ratio, -

Abbreviations

CHP	combined heat and power
DH	district heat
FW	feedwater
LP	low pressure (steam)
MC	moisture content
SCAH	steam coil air heater
SH	superheater

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