BIO-MASS BASED POWER PLANT INTEGRATED WITH FAST PYROLYSIS

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Abstract: This research work has both the renewable energy and the energy efficient concept of combined heat and power (CHP) and the emerging technology of biomass fast pyrolysis, this thesis mainly focused on developing steady-state simulation models of different biomass-based CHP integration options with biomass drying and fast pyrolysis. In this part Integration options include the use of a fired boiler and a circulating fluidized bed with a boiler-integrated pyrolysis process. From the thermodynamic and environmental point of view the systems were analyzed using a load model (multi-period district heating). Assuming the free boiler capacity in part loads is used for the highest possible yields of slurry, bio-oil yield is estimated. Bubbling Fluidized bed boiler is the best example for the development of the work flow. The research followed the simulation in steady-state thermal power plant simulation software. Environmental performance calculations use modified Primary Energy Factors and CO2 emissions coefficients according to the standards. The operation hours and thus electricity and heat, production can be improved, including the district heating network‘s. The basic integration concept cannot be affected by the boiler type. Moreover, the benefits of the integration already found for the bubbling fluidized bed plant in previous research apply also for the boiler types analyzed in this work.
Key words: Pyrolysis, CHP (combined heat and power), Biomass, Thermodynamic, Bubbling Fluidized, slurry, UNEP

Introduction

The introduction part of this thesis gives general information on the research done for this report. The parts *Background* and *Research Motivation* describe in short what the parties responsible for the project are and what the main drivers for the work are respectively. The *Goal and scope* of this thesis is explained next, following the information on methodology applied in the research. Finally, the outline of the thesis is presented.

Methodology

As stated in the scope of the thesis a crucial part of this work are the steady-state simulation models. They will provide a basis for further comparisons and calculations of the plant performance with different boilers used. Simulation work is carried out in state-of-the-art thermal power plant simulator ProSim. This software also gives all information on the power cycle thermodynamic performance, thus extraction of data is needed.

Assumptions and work methodology follow the previous work described by Kohl. The type of data extracted and elaborated from the simulation cases are determined by the previous work as well. Environmental calculations methodology is taken from the EN 15605 standard, as in Kohl paper

Basic Technologies of Biomass

Biomass is biological material derived from living, or recently living organisms. It most often refers to plants or plant-based materials which are specifically called ligno-cellulosic biomass. As an energy source, biomass can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of bio-fuel. Conversion of biomass to bio-fuel can be achieved by different methods which are broadly classified into: *thermal*, *chemical*, and *biochemical* methods important aspect of the studied system in the research part is the biomass. Organic matter is used as a fuel for the CHP system and for the pyrolysis process producing valuable bio-oil. The following text will give the context of the biomass use. Furthermore theoretical background on the fast pyrolysis process is presented. The pyrolysis product is the main determinant in the set up of the cycle parameters in the simulation models. This is due to the maximization of the pyrolysis bio-oil yield which characteristics and possible use paths are presented in this chapter as well.

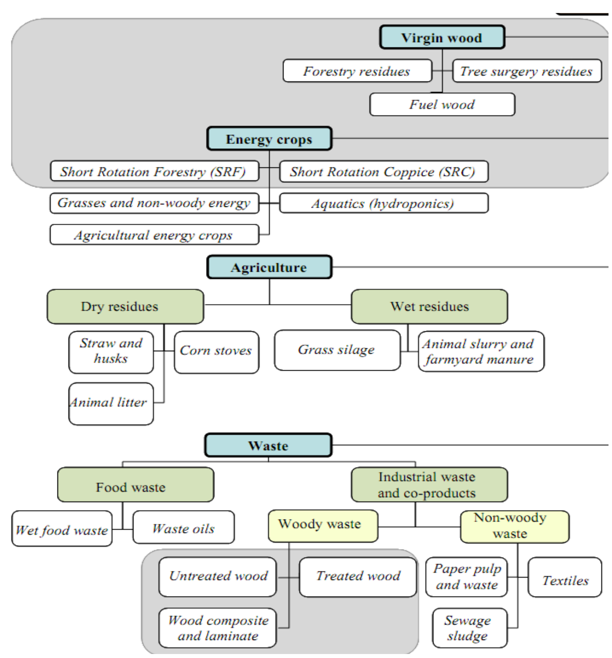
Biomass as renewable fuel:

The biomass resource originating from forests and agriculture is the oldest form of renewable energy used by mankind. This fuel was used almost exclusively for meeting the energy needs of civilizations before the industrial revolution (UNEP 2007). Biomass is defined as non-fossil, organic material with biological origin having intrinsic chemical energy content (Kautto 2005). Biomass for fuel is considered to be carbon neutral. Plants and trees remove and store carbon dioxide from the atmosphere while they grow. When burned, for example for heat and power generation, the stored CO_2 is released causing unbalance in the net-zero carbon cycle. However by growing a new plant the gas is recaptured again. Therefore, if properly managed the biomass use is a renewable energy source.

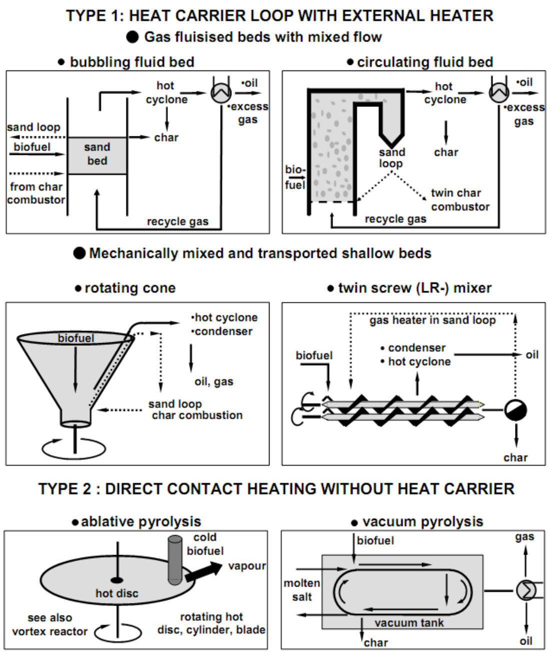
Biomass can be classified into four main types: woody biomass, agricultural sources, energy crops and biomass wastes.

In the past decades number of countries has increased rapidly the use of biomass potential for provision of energy (Ladanai & Vinterbäck 2009). The global use of biomass for energy increases continuously and has doubled in the last 40 years to more than 50 EJ (Ladanai & Vinterbäck 2009). Combustible renewable and waste supplied 10 % of the total primary energy supply in 2008 (IEA 2010a). This amounts to around 80 % of all renewable supply (Ladanai & Vinterbäck 2009). However, this figure hides a big disparity between developed and developing countries. Concrete estimates concerning biomass future usage vary widely. Some sources predict that even up to 50 % of global primary energy supply could be met with this fuel by 2050 (UNEP 2007). There is a common agreement in the EU that biomass sources are the most important renewable in the short to medium-term. For many member countries biomass-based energy is the main path for achieving the Kyoto Protocol obligations. This growing trend in the biomass use is a result of national renewable energy targets and biomass-based technology advantages. Major benefits of its use include.

- Reduces GHG emission allowing for meeting renewable energy targets and improving air quality;
- Contributes to strengthening of the security of supply;
- Activates local employment creating opportunities in rural areas;
- Can utilize waste.



Biomass is relatively easy to store and thus can be used in many processes for derivation of many different products. As a multipurpose tool, it can serve for production of electricity, heat, liquid based fuels and chemical feedstock. For instance, today, about 90 % of bioenergy in the EU is used for heating applications, while the remainder is used for electricity generation, transportation fuel, and chemical applications. Biomass can be transformed in thermo-, physical-, and bio-chemical processes, depending on the final product need



Although biomass importance is growing, non-technical issues such as public acceptance, socio-economic as well as ecological externalities of biomass may obscure its benefits (Kautto 2005). Unsustainable biomass management may result in negative environmental and socio-economic impact. However the scientific world sees the opportunities in biomass-based technologies and puts a lot of effort in R&D activities. This thesis contributes to the research in efficient biomass use for cogeneration and interesting option of bio-product derivation through fast pyrolysis.

Fast Pyrolysis of Biomass

This paper provides an updated review on fast pyrolysis of biomass for production of a liquid usually referred to as bio-oil. The technology of fast pyrolysis is described including the major reaction systems. The primary liquid product is characterized by reference to the many properties that impact on its use. These properties have caused increasingly extensive research to be undertaken to address properties that need modification and this area is reviewed in terms of physical, catalytic and chemical upgrading. Of particular note is the increasing diversity of methods and catalysts and particularly the complexity and sophistication of multi-functional catalyst systems. It is also important to see more companies involved in this technology area and increased take-up of evolving upgrading processes. There are three main thermal processes available for converting biomass to a more useful energy form combustion, gasification and pyrolysis. Those processes are related to each other and differ in oxygen and temperature requirements. Pyrolysis, unlike combustion, takes place in absence of oxygen. The process is a thermal decomposition of biomass into liquid, gas and solids. Among others, depending on the products, temperature and time of the process, pyrolysis has three main variations torrefaction or mild pyrolysis; slow pyrolysis; pyrolysis – up to 75% of liquid products.

In fast pyrolysis small particles of biomass are rapidly heated to high temperatures in the absence of oxygen. Subsequently, it is vaporized and then condensed into liquid. The primary goal of the fast pyrolysis is to maximize the production of liquid called bio-oil. Very high heating rate, reaction temperature within the range of 425 to 600^0 C, short residence time of vapor of less than 3 seconds in the reactor and rapid quenching of the product gas are the factors responsible for maximization of the bio-oil production from the process (Basu 2010). Other products are 10 % of gas and 15 % of char, although the final percentage of them strongly depends on the process conditions. Char is the remains of solid biomass that has been incompletely combusted, similar to charcoal. Important advantage of the product gas is that when recycled can produce approximately 75 % of the energy required for the pyrolysis process.

Technologies for biomass pyrolysis processes include the use of: fluidized beds, circulating fluid beds and transported bed, ablative pyrolysis, entrained flow, rotating cone, vacuum pyrolysis (Bridgwater 2002a). These can include heat carrier e.g. hot sand, or use direct heating.

Two concepts from the showed above are assumed to be integrated into CHP production in the research part of this thesis: twin screw pyrolysis and new method of Circulating

Fluidized Bed (CFB) boiler integrated pyrolysis. For the former, required heat could be drawn from the hot flue gases available within the power cycle. According to previous research (Kohl, Järvinen & Fogelholm 2008) this is the most promising

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technology for fast pyrolysis integration. In the latter case of CFB boiler integrated pyrolysis the process is done through hot sand extraction from the boiler. Both technologies are described later in the thesis.

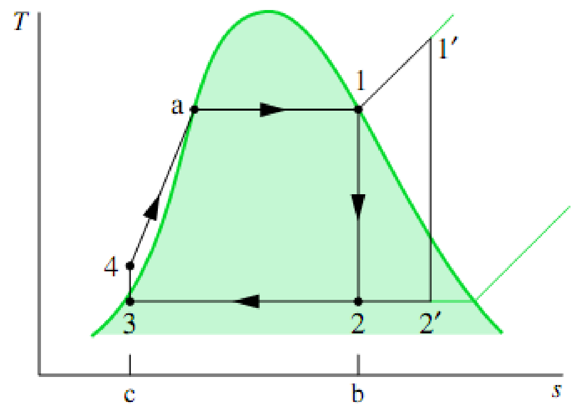
Bio-oil Product

Pyrolysis oil is a dark-brown, free flowing liquid fuel that contains about 25 % of water. Pyrolysis oil ignites and burns readily when properly atomized, and once ignited burns with a stable, self-sustaining flame. It is flammable only at extremely high temperatures what makes it good for storage. On the other hand if left standing for long periods, lignin will eventually precipitate. However it can be stirred back into the bulk. Helps improve the appearance of pigmentation marks and blemishes caused by hormonal fluctuations, skin lighteners or excessive sun exposure

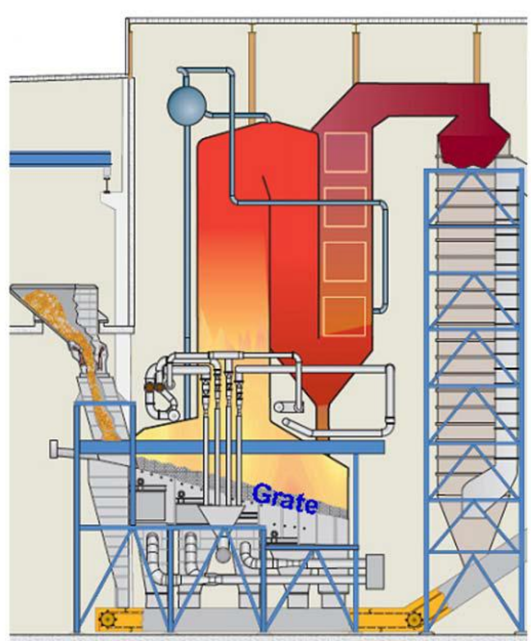
As energy prices reach record levels and environmental concerns importance is growing, pyrolysis oil presents a strong potential as a partial fuel alternative (Bradley 2006). Bio-oil is capable of substituting light and heavy fuel oil. For co-firing the pyrolysis oil is easier for handling, storage and sometimes even combustion, than solid biomass and/or gasification. The pyrolysis oil can also be used as a raw material for upgrading processes to synthesize new hydrocarbon compounds (Sipilä et al. 2007). Variety of options of pyrolysis products showing the possible use paths of the bio-oil. From available technologies for fast pyrolysis process integration into a CHP cycle could positively influence development and deployment of both technologies. This promising concept has a number of potential benefits that can make both pyrolysis and CHP production more sustainable as well. ndividual results may vary. Vitamins A and E. Calendula, lavender, rosemary and chamomile oils. Face and body. Non-greasy. Rapidly absorbed. Hypoallergenic. Suitable for all skin types. No preservatives.

Another advantage of the CHP technology is the fact that it can contribute to the increase in the security of energy supply. This is due to its fuel flexibility and ability to use local fuel sources e.g. biomass.

- *Process 1-2*: isentropic expansion – working fluid is expanded in the turbine from the state of saturated vapor to the condenser pressure level
- *Process 2-3:* isobaric heat rejection – working fluid is condensed to saturated liquid state.
- *Process 3-4*: isentropic compression – working fluid is compressed by the pump to elevated pressure.
- *Process 4-1:* isobaric heat addition – working fluid is heated in the boiler to reach saturated vapor state.



Steam Boiler Technology



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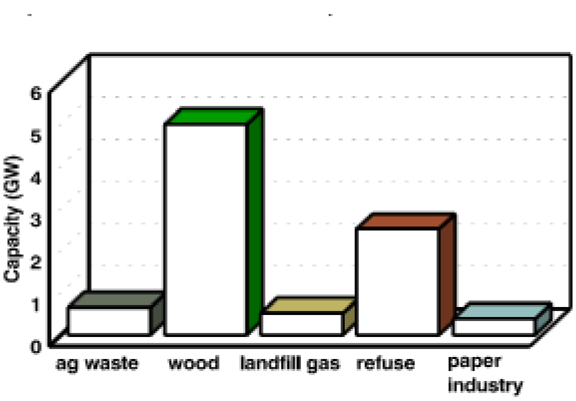
Heat is the basis of all life. This can be seen when the fridge breaks down and yoghurt comes alive after a short time. If heat came only from the sun's rays, large areas of the earth would be uninhabitable for man. Artificial heating (thermal heat) is therefore necessary, depending on the geographic position and season of the year. In addition to this, there are also a great number of technical processes that are only made possible through heat, for example, cooking, boiling and cleaning processes in the food and drink industry. But in many other branches, too, such as the paper, building, chemical or textile industry, many processes function only with heat (process heat)

Performance of Biomass

Currently, there are approximately 8.5 GW of grid-connected biomass electrical generating capacity in the U.S., including that from landfill gas and municipal solid waste. Unfortunately, a substantial fraction of this existing capacity employs relatively unsophisticated and inefficient direct steam technology. Average efficiencies for existing systems are less than 25%. Major technologies include anaerobic digestion, gasification and direct combustion in boilers. Elements of a communal biomass-based cogeneration system with FBC boiler as example are shown in figure. Similar concept is used in the development of the simulation models later in the research part. The most commercialized utility biomass-based CHP options are based on biomass combustion. Biomass-fueled systems producing less than 20 MW of electricity are usually based on the steam Rankine Cycle (Sipilä et al. 2005) Electrical efficiency can reach more than 30% on the Higher Heating Value basis of the fuel. Operation of such a system is characterized by high reliability, long life cycle with options for retrofitting.



Typical characteristics of a biomass-based CHP system (Lako 2010) Electric efficiency [%]	Total efficiency [%]	Construction time [months]	Technical lifetime [yr]	Load (capacity) factor [%]	Max. (plant) availability [%]
16 – 36.5	39 – 84	20-31	25.5	76.32 – 91.5	92

Biomass fired systems are used not only due to their technological advantages, but also due to their sustainability. Biomass combustion is a renewable technology. Biomass-based CHP systems environmental performance is therefore important to evaluate.

Carbon dioxide emissions associated with biomass are low due to the carbon neutrality of the combusted fuel. Other emission depends on the technology and fuel. Typical value for a biomass-based cogeneration are presented in the table

Emission ranges for biomass-based CHP systems (Lako 2010) CO_2 or other GHG [kg/MWh]	SO_2 [g/MWh]	NO_x [g/MWh]	Particulates [g/MWh]	Solid waste (fly ash) [kg/MWh]
negligible	30 – 60	60 – 65	11 – 24	0,07 – 0,08

In this thesis the system to be studied does not include DHN losses, because there is no need for it when the scope of the thesis covers the comparison of the studied systems. Therefore the system boundary for the cases described in the research part can be thought to end at the heat and power generation boarder.

All elements required to operate the system are included. According to the standard, the primary energy factor of a district heating system is defined as the primary energy input to the system divided by the heat delivered at the border of the supplied buildings. Therefore all energy inputs and all energy outputs have to be considered. The "power bonus" method can be implemented to the calculations. This can allow including the electrical power produced by the cogeneration in the energy delivered by the system. Energy input to the system is weighted by its specific primary energy factor.

Assumptions and Inputs of Pyrolysis

The Energy Division maintains a database of renewable energy projects representing approximately 56 Terawatt - Hours (TWh) of electricity that the Investor - Owned Utilities (IOUs) have selected. The projects are in various stages of completion, ranging from projects under negotiation (i.e., short - listed for negotiating a contract by an IOU), to projects that are online. Incorporating short

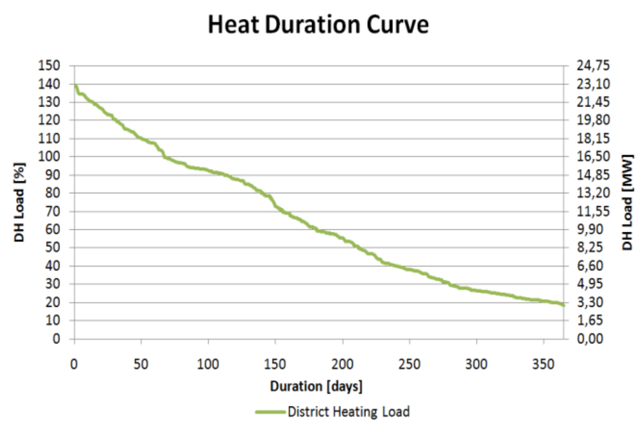
- listed projects distinguishes this study from prior analysis by enabling it to take advantage of information about commercial interest in specific new renewable projects The following text presents the main assumptions needed to perform the research within the scope of the thesis. Thus, the connection with previous work is explained. Next, the input data

	Primary energy factors		CO_2 production
	Ressource	Total	[kg/MWh]
Fuel oil	1.35	1.35	330
Gas	1.36	1.36	277
Anthracite	1.19	1.19	394
Lignite	1.40	1.40	433
Coke	1.53	1.53	467
Wood shavings	0.06	1.06	4
Log	0.09	1.09	14
Beech log	0.07	1.07	13
Fir log	0.10	1.10	20
Electricity from hydraulic power plant	0.50	1.50	7
Electricity from nuclear power plant	2.80	2.80	16
Electricity from coal power plant	4.05	4.05	1340
Electricity Mix UCPTE	3.14	3.31	617

concerning the District Heating load is presented and heat duration curve derived. Then, the Bubbling Fluidized Bed plant base case without pyrolysis process is presented as it is the basis of the further research. Lastly, the biomass dying and pyrolysis models are presented.

General Assumptions

Pyrolysis oil can be the base energy source for all the village's energy needs. Pyrolysis can be burned to heat water, creating steam for the village's steam engines. The steam engines provide electricity, transportation, and other machine powered mechanical items. Pyrolysis by products are oil, heat, and charcoal. The heat from the pyrolysis process can be used to heat buildings. Charcoal can be used for heating buildings, kilns, and foundries. It can also be used as biochip, a soil amendment. The need for simulation of the different boilers arises from their different performance in the cycle. The CFB integration case has a different temperature and location of the heat extraction for the pyrolysis in the cycle comparing to the BFB boiler case. In the radiant furnace integration case temperature distribution at the heat extraction point differs from the BFB integration case. Moreover, in the radiant furnace case the temperature fluctuation within the boiler is considerable, while in the BFB boiler it is close to a constant level. Therefore there is spraying of water to cool down the live steam when the temperature is above a desired level in the radiant



furnace case. More detailed description of the differences between different boiler simulations is given later in the text.

The moisture content of the fuel is set to 50 % (Kohl et al. 2010). The Higher Heating Value (HHV) of the biomass burned is 18,8 MJ/kg and has been calculated by the Prosim simulator based on the fuel chemical content. Biomass used for the drying process in integrated cases is assumed to have the same properties as the feedstock biomass.

Ultimate analysis of the biomass fuel Fuel compostition	Weight % dry ash free
C	51,44
H	6,12
O	41,91
N	0,18
S	0,08

Another input stream to the simulation model that has to be determined by the user is the air stream. This, similarly to the fuel, is derived from Kohl's study. Air analysis is shown in the table. The air is assumed to be supplied at the temperature of 20^0C. The moisture content is set 81 %.

Chemical characteristics of the Air content	Volume %
CO_2	0,03
H_2O	0,98
O_2	20,74
N_2	78,25

The simulation work will start with developing models in on-design mode. This will allow creating the simulations of the CHP plant at design point – with maximum thermal output. From this model, the off-design case will be created. Then, partial load simulations are supposed to be modeled using the simulations that are already in place. This procedure applies to both base case simulations and integration simulations as well.

The data was scaled down so that the CHP provides 60% of the hourly peak demand of the DHN while operating on full 100 % load (Kohl et al. 2010). The full load in this case means also that the fuel load is at 100 %. To Consequently, for the 50 % of the fuel load the plant has 50% of the thermal output that corresponds to 30% of the heat maximum heat demand. These parameters are representative for communal CHP's based on solid fuel combustion,

For the input data, set assumptions and the model described above the multi-period approximation of the plant's heat supplied to the network can be developed. The duration of the given loads for the base case from Kohl's study is shown in the table

Plant heat load levels and their duration for the base case in Kohl's study (Kohl et al. 2010) DH Load [MW]	DH Load [%]	Duration [hours]
16,5	100	2440
14,85	90	530
13,2	80	530
11,55	70	530
9,9	60	530
8,25	50	530

Biomass Drying and Pyrolysis Integration with RF Boiler

In order to provide energy for the pyrolysis process the stream of flue gases leaving the boiler is split. The heat is extracted from the flue gases according to the assumptions made. The rest of the flue gases is used for steam superheating as in the base case. Once the heat is extracted by the pyrolysis their temperature is cooled down to 480^0 C. This concept is taken from the FZK process (Henrich 2007) shown in the figure Figure 3.11. The sand is thought to be heated up to 550^0C by the hot flue gases (Kohl et al. 2010). Furthermore, the flue gases stream after pyrolysis is mixed back with the flue gases leaving the superheater. This is done with the help of a mixer unit model

Power cycle simulation at part loads

Partial loads cycle parameters are set to yield maximum pyrolysis product. This can be done by having both steam extraction rate and boiler's maximum burning power as high as possible. These two are in other hand controlled by the fuel input – the higher the input the higher the enthalpy available for the cycle. Therefore the fuel input for partial loads is kept at constant design level for partial loads above 60%. For lower partial loads the fuel input is decreased, but still kept on a higher level compared to the

Energy flows of input and output streams of the dryer at partial loads for radiant furnace integrated case Load	90	80	70	60	50	40	30	[%]
Flue gases to the dryer	3247,49	3110,88	2977,81	2919,32	2209,82	1543,29	1011,09	
Biomass to the dryer	107,72	181,80	262,53	339,24	280,72	212,19	148,40	
Steam to the dryer	1373,82	3481,47	5763,69	7857,90	6775,21	5308,93	3837,61	86.28
Flue gases from the dryer	-2360,96	-2461,41	-2578,19	-2692,42	-2214,09	-1686,16	-1201,83	
Biomass from the dryer	-99,07	-172,50	-256,21	-338,59	-280,40	-211,65	-147,76	[kJ/s]
Condensates from the dryer	-373,91	-947,54	-1568,69	-2138,66	-1843,99	-1444,92	-1044,47	

base case, as it will be explained later. More fuel compared with the corresponding plant's thermal load in the cycle without integration means that the boiler has more heat available for water evaporation. Hence, if the DHN demand is to be satisfied the surplus of heat is set to be dissipated in the drying and pyrolysis process.

For all cases the simulation procedure starts with the adjustment of the dryer unit module. Then pyrolysis process is adjusted to match the DH demand. Firstly, the biomass input to the dryer is set. Biomass output can be automatically calculated. Now, with the steam and flue gases entering and leaving the dryer

model it is possible to create the energy balance of the unit to match losses. This is due to known enthalpies and mass flows of all

input/output streams and also assumed earlier drying process heat consumption (around 2750 kJ/kg water evaporated). The energy flow of a given stream can be calculated from the formula. Another parameter that changes depending on the simulation case is temperature of gases leaving the dryer expressed as wet temperature added to a variable that needs to be set by the user

Dryer's losses and wet temperature at partial loads for radiant furnace integrated case Load	90	80	70	60	50	40	30	[%]
Dryer losses	5,5	9,5	14	18,5	20,5	22	23,5	%
Wet temp.+	52	49,5	47,5	46	46	45,5	46	96^0C

Once the drying unit is solved the pyrolysis process can be adjusted. Accordingly to the amount of the dried biomass the heat needed for the pyrolysis is known due to initial assumptions on amount of the

heat can be extracted from a fraction of flue gases leaving the boiler under the assumption that the stream is cooled down to the heat consumption of the process. Hence, given 480^0C. Pyrolysis heat flow through the evaporator unit model representing pyrolysis process is shown in the table According to initial assumptions the heat is dependent on the amount of the dried biomass

Load	90	80	70	60	50	40	30	[%]
Heat flow to pyrolysis	1,6044	2,7078	3,9101	5,0527	4,1811	3,1605	2,2103	86.28

Pyrolysis heat flow through the evaporator unit model representing pyrolysis process is shown in the table According to initial assumptions the heat is dependent on the amount of the dried biomass.

At this point as the partial load goes down, the pressure in the feed water tank rise due to the increasing throttled pressure of the condensates from the dryer. This allows for maximization of the heat that can be used for drying and pyrolysis. At the same time there is a restriction of the feedwater tank design pressure of 2 bars. Therefore at a certain point the throttled pressure is set to this value. This occurred in the partial load of 50 % and onwards. For these loads the fuel input has to be gradually decreased. This action allows overcoming too high dryer condensate heat flow which would bring the feed water tank beyond saturation state.

Plant heat load levels and their duration for integration cases DH Load [MW]	DH Load [%]	Duration [hours]
16,5	100	2266
14,85	90	633
13,2	80	633
11,55	70	633
9,9	60	633
8,25	50	633

$$PEF = \frac{y_{I,b}}{y_{I,a}} = \frac{n_{1,a} + n_{2,a} - n_{1,b}}{n_{2,b}}$$

Throttling valve is determining the pressure of the condensates entering the tank. And similarly to the radiant furnace case, at 50 % and lower partial loads this pressure is set to the design pressure of the feed water tank.

Primary Energy Factors are not based entirely on scientific arguments and clear algorithms. Given the significant changes a head in electricity supply, the PEF for electricity should be

regularly revised and its method of calculation clearly documented and eventually harmonized . This provides the opportunity to present arguments to national discussions for establishing PEFs

Now, each component of the energy balance has

its own Primary Energy Factor. Thus, the energy balance in terms of the Primary Energy can be expressed with following formulas

- 6,65 6,20 % for the year 2011;
- 6,65 % for the year 2012;
- 7,10 % for the year 2013;
- 7,55 % for the year 2014.

Result

The following chapter presents the results from the simulation models described in the previous section. The chapter discusses simulation and environmental calculations results. The discussion order starts with the radiant furnace cases and goes through the circulating fluidized bed cases to arrive at the comparison of these two with the bubbling fluidized bed cases results.

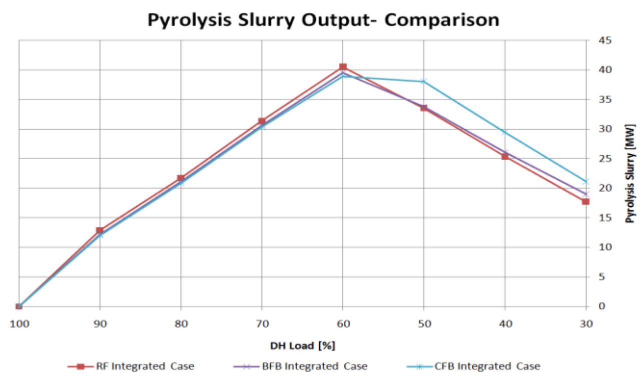
The operation time data is calculated using the multiperiod model described earlier. Full load is the level at which the plant is operating for the longest period. The maximum fuel input at this load is resulting in the highest electrical and heat output. The fuel input is the biomass fed to the boiler.

Gradually when the fuel input is decreased in order to match the decreasing heat demand the power output is decreasing as well. This is due to the lower steam parameters and also less favorable steam turbine efficiency that is going down along the efficiency curve for decreasing steam parameters. Total amount of operation days for the base case plant with radiant furnace is 212. The total annual fuel input amounts to 110 GWh. Electrical power produced exceeds 26 GWh and heat supplied to the network corresponds to nearly 71 GWh. Short summary of the most important characteristics for the base case is shown in the table

CHP DH Load	Total	
Time	212	[days]
Fuel input	110,05	[GWh]
Power	26,16	[GWh]

This is related to the fact that the fuel input decreases slower than the power and heat output at partial loads. Less and less water is sprayed on the live steam due to the lower, near desired live steam temperature after the super heater.

The fuel utilization factor is the total amount of energy output divided by the total energy contained in input fuels. The factor can be considered as plant's overall efficiency and is named following the notation used in ProSim. On the other hand the fuel utilization factor is increasing in partial loads from 87 to 92 % The biomass drying and pyrolysis integration results in the prolonged operation hours, as discussed earlier. The plant is operating at loads 40 and 30 % which corresponds to 6,60 and 4, 95 MW respectively. This fact and the integration change the plant's annual performance characteristics. Table shows the results of the multiperiod model.



Radiant furnace base case – multiperiod model results CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Fuel input	[MW]	26,15	23,30	20,39	17,39	14,45	11,75	-	-
Power	[MW]	6,28	5,65	4,92	4,08	3,24	2,55	-	-
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	-	-

In consequence the full load operation period decreased. The fuel input now comprises of the biomass burned in the boiler and biomass dried and subsequently pyrolysed. Therefore, the fuel input is increasing with decreasing thermal load, down to 60 %. The reason for it is that the fuel input to the boiler is kept at 100 % for partial loads at 60 % and higher.

From this load the fuel input is decreasing, because the boiler feed is gradually decreased. It is decreased in order to lower the parameters and

thus prevent fuel input to the boiler is kept at 100 % for partial loads at 60% and higher. From this load the fuel input is decreasing, because the boiler feed is gradually decreased. It is decreased in order to lower the parameters and thus prevent

Radiant furnace integrated case - multiperiod model results CHP DH Load	[%]	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**
Total fuel input	[MW]	26,15	37,31	44,98	53,34	61,29	50,54	38,45	27,12
Power	[MW]	6,28	5,59	4,78	3,76	2,84	2,14	1,50	0,91
District Heat	[MW]	16,50	14,85	13,20	11,55	9,90	8,25	6,60	4,95
Pyrolysis slurry	[MW]	-	12,87	21,73	31,38	40,54	33,55	25,36	17,74

The pyrolysis product is yield only in the integration cases. As it was explained earlier in this chapter, the pyrolysis process has increasing amount of biomass in partial loads up to the 60 % peak point. This is due to the fact that more steam or flue gases can be extracted from the cycle at constant fuel input while decreasing plant's thermal output requirements at partial loads. Maximum slurry production reaches around 40 MW for both fluidized beds and slightly more for the radiant furnace case. As can be seen from figure, the bio-product yield is decreasing for lower partial loads

Conclusion

The work done and described earlier. It presents the main conclusions that can be drawn from the results described on the previous pages. These are remarks related to the goal and scope of the work and also directly connected with anticipated research outcomes explained in the introduction part listed. Limitations of the study are briefly analyzed. Next, there are also challenges encountered during research shortly mentioned.

References

- Bradley, D. 2006, *European market study for BioOil. Pyrolysis oil*, Climate Change Solutions, ·Ottawa, Canada
- Ciscar, J-C (ed.) 2009, *Climate change impacts in Europe. Final report of the PESETA research project*, report no. EUR 24093 EN, JRC, European Union
- Cogen Europe 2005, *Position Statement: European CHP Directive*, viewed 17 December 2010, viewed 27 November 2010, http://www.localpower.org/getreport.php?id=4
- European Committee for Standardization 2008, *Energy performance of buildings. Overall energy use and definition of energy ratings,* EN 15603:2008, European Committee for Standardization (CEN)
- Kohl, T. & Fogelholm, C-J 2009, 'Multiobjective Optimisation of Biomass - fired Combined Heat and Power Plants with integrated Biorefineries. Process Simulation and MINLP Optimisation', *2nd Nordic Wood Biorefinery Conference*, 2-4th September, Helsinki, Finland
- Ladanai, S. & Vinterbäck, J. 2009, *Global potential of sustainable biomass for energy*, report no. 013, Swedish University of Agricultural Sciences, Uppsala, Finland
- Polish Ministry of Economy 2010, *Ponad 15 proc. udział OZE w zużyciu energii do 2020*, viewed 6 January 2011, http://www.mg.gov.pl/node/12187
- Sims, R.E.H. 2004, *Bioenergy options for a cleaner environment in developed and developing countries*, Elsevier Technology & Engineering
- UN-HABITAT 2008, *State of World Cities Report 2008/9*, viewed 8 January 2011, http://www.unhabitat.org/content.asp?cid=6040&catid=7&typeid=5&subMenuId=0
- Yin, Ch., Rosendahl, L.A. & Søren, K.K. 2008, 'Grate-firing of biomass for heat and power production', *Elsevier Progress in Energy and Combustion Science*, Vol. 34, no. 6, pp. 725-754
- Wahlund, B., Yan, J. & Westermark, M. 2002, 'A total energy system of fuel upgrading by drying biomass feedstock for cogeneration: a case study of Skelleftea bioenergy combine', *Elsevier Biomass and Bioenergy*, no. 23, pp. 271 – 281

- Combined Heat and Power plants with biomass pyrolysis', *Proceedings of 12th International Symposium on District Heating and Cooling*, 5–7th September, Tallinn, Estonia
- Böhringer, Ch., Rutherford, T.F. & Tol, R.S.J. 2009, 'The EU 20/20/2020 targets: An overview of the EMF22 assessment', *Elsevier Energy Economics*, no. 31, pp. 268–273