

## ANALYSIS OF BIOMASS ORC PLANT CONNECTED TO DISTRICT HEATING NETWORK

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**ABSTRACT:** Today, biomass is most efficiently used in decentralized cogeneration plants. Through the use of the ORC (Organic Rankine Cycle) technology, power plants below 10 MWth thermal output can be operated at lower temperature and pressure than conventional steam plants, thus requiring less operation and maintenance effort. Due to high efficiency of part load operation such plants are an interesting alternative for municipal and commercial heat supply. However, the technology is rather new and practical experience is required to access the real performance and operational reliability.

The energy supply system of the urban area Scharnhäuser Park is a practical example for the utilization of the ORC technology. An urban quarter with a living space of 130000 m<sup>2</sup> and 48000 m<sup>2</sup> office space is heated by a cogeneration plant connected to a district heating network with a length of 13.5 km. The plant is fired mainly by park waste wood and forest residues are burned additionally. The cogeneration system is equipped with a 6.3 MWth biomass furnace and covers the main part of the heat demands of the quarter. The installation has a pilot project character and can be used for investigations of wood-fired cogeneration systems.

The paper contains a review about the practical experience and investigation results that have been gathered since begin of the plant operation. A wood chip boiler with a cogeneration module, connected to a district heating network is being completely monitored from the fuel delivery to heat distribution. More than 60 process parameters have been continuously archived by a data acquisition system. The analysis aims to estimate the efficiency and the ecological parameters of the combination of the ORC module and biomass furnace by consideration of the requirements of a district heating network.

**Keywords:** biomass combustion, combustion efficiency, cogeneration

### 1 INTRODUCTION

Biomass is widely used for energy purposes and it is believed that energetic utilization of solid biomass will become a major contributor to the global energy balance among renewable energy sources. Within the conversion technologies biomass combustion is the most mature and market-proven technology, which provides over 90% of the total energy generated from biomass [1]. The main advantage of biomass combustion is the relatively high efficiency of modern furnaces and the economical feasibility of bioenergy projects. However, problems still occur due to changing fuel properties and unstable operation of biomass combustion systems [2]. To meet the growing requirements for conversion efficiency, ease of operation and stability of the combustion process it is necessary to continuously develop the biomass combustion systems. This development should be based on practical experience from existing biomass combustion plants.

Due to the limitation of potentials the utilization of biomass has to be characterized by high efficiency. Therefore, the combustion of biomass is only feasible in decentralized cogeneration plants where the energy transport losses are relatively low and reasonable fuel transport distances can be guaranteed. In recent years a great development in research and employment of decentralized cogeneration systems based on biomass combustion could be observed. The technologies for decentralized biomass cogeneration have a unique advantage of combining high efficiency of biomass utilization and reducing the environmental impact of power generation. Among the technologies for decentralized cogeneration the ORC (Organic Rankine Cycle) plays the most important role due to its higher

availability and commercial maturity.

Over 140 biomass cogeneration plants based on ORC technology have been installed all over Europe. However, the data availability from existing plants is generally limited. Data on practical experience from existing plants and relevant conversion efficiencies is still lacking. Through analysis of data material gathered during the operation of the biomass cogeneration plant in Scharnhäuser Park a greater access to information on bioenergy plant technology and its application can be created.

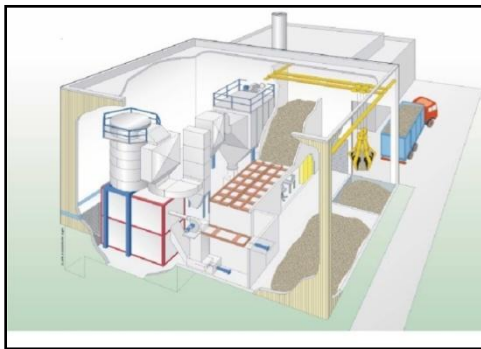
The aim of the paper is to analyze the efficiency of biomass combustion in a grate furnace which serves as the energy source for a biomass cogeneration plant connected to a district heating network. The biomass furnace is the core of the conversion system and its thermal efficiency influence substantially the overall system efficiency. The thermal efficiency of the biomass boiler should be accordingly high in order to maximize the useful energy produced from the chemical energy of the fuel. Efficient plant operation necessitates also the consideration of proper process controlling related to emission reduction and preventing problems of fouling and slagging, which can be produced by biofuels.

### 2 ENERGY SYSTEM DESCRIPTION

Scharnhäuser Park is a modern urban settlement located in Stuttgart-Ostfildern, Germany. The 140 ha area consists mainly of residential buildings and has 130000 m<sup>2</sup> of living space and 48000 m<sup>2</sup> of mixed commercial area. The main portion of energy supply of the area is provided by a biomass cogeneration plant with 6.3 MWth nominal capacity. The plant is fired mainly by natural wood scraps and forested wood is burned additionally.

The plant works in heat driven mode and provides more than 80% of the heating energy for the area. Additional two gas boilers (5 and 10 MW) have been installed on the plant to cover the heat demand during peak load periods.

Cogeneration of electricity and heat takes place in an ORC module, where silicone oil is used as the working medium. The use of silicone oil as working fluid has the advantage that electricity can be produced at lower levels of pressure and temperature, which enables a considerable reduction of the equipment costs. Additional advantage of the ORC technology is the excellent part load behavior [3]. The ORC module can operate efficiently in the range between 30 and 100 per cent of full load and can be treated as a suitable solution for a heat driven cogeneration within a heating network. The waste heat from the electricity generation process in Scharnhäuser Park is transferred to a district heating network, which spreads over a length of more than 13 km. The feed temperature of the district heating network is controlled by the ambient temperature, which allows an effective operation through a reduction of the heat losses. The good partial load performance of the ORC module enables flexible adaptation of the plant output capacity to the heating needs of inhabitants with an almost constant degree of efficiency.



**Figure 1:** Schematic illustration of the biomass cogeneration plant [4]

The core of the plant is a thermal oil boiler with a nominal capacity of 63 MW<sub>th</sub>. The state of the art biomass grate furnace serves as the thermal energy source for the cogeneration process. Thermal oil is utilized as a transport agent between the furnace and the ORC module, where electricity is produced.

## 2 DETERMINATION OF THE BIOMASS COMBUSTION EFFICIENCY

In recent years a great development of biomass combustion technology, which is still ongoing, could be observed. The primary aim of this development is to maximize the conversion efficiency and thus the profitability of bioenergy projects. The conversion efficiency of a biomass combustion plants depends mainly on two factors: the amount of unburned fuel components in exhaust fumes and ash as well as the excess oxygen in exhaust fumes. The energy losses due to incomplete combustion in modern furnaces are negligible. The amount of unburned carbon in the ash is usually lower than 5% of the dry fuel mass and the CO content of exhaust fumes is in most cases lower than 250 mg/Nm<sup>3</sup>. In modern biomass grate furnaces relevant energy losses are caused by relatively high oxygen

content of exhaust fumes (about 8%). This means that it is necessary to have an excess air ratio of above one in order to ensure complete combustion of the fuel. For high excess air ratios the combustion temperature will be significantly lower in comparison to the stoichiometrical combustion. This is caused by additional energy losses related mainly to the heating of inert nitrogen in the air. Therefore optimal mixing conditions in the combustion chamber are of high importance, enabling operation at lower overall excess air ratios and thus increased combustion efficiency.

### 2.1 Methodology and calculation

The combustion efficiency can be defined using the direct and indirect method. In the direct determination the efficiency is defined on the basis of the ratio between the generated energy and the fuel energy. The determination of burned fuel mass is in many plants not possible due to cost reasons. The evaluation of the fuel energy is therefore often based on fuel volume. However, the estimation of fuel energy content on the basis of fuel volume is related to significant uncertainties, since the bulk density of the combustible can vary in a wide range.

In the case of indirect method the combustion efficiency is defined on the basis of estimation of energy losses related to incomplete combustion and thermal losses of the hot flue gases. For an easier application a simplified method presented in [5] has been used in order to analyze the conversion efficiency.

In the range of CO < 0.5 Vol.-%, CO<sub>2</sub> > 5 Vol.-% and flue gas temperature < 400°C the conversion efficiency can be calculated by using following equation:

$$\eta_c = 100 - L_{chemical} - L_{thermal} \quad (1)$$

where:

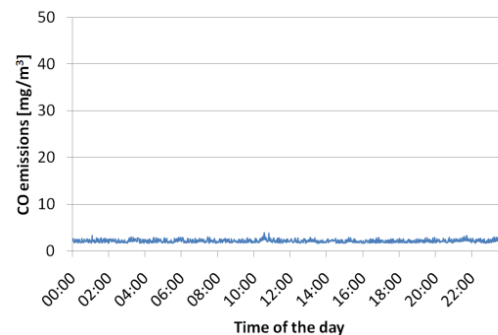
- $\eta_c$  - combustion efficiency [%]
- $L_{chemical}$  - chemical losses by incomplete combustion [%]
- $L_{thermal}$  - thermal losses by sensible heat of the flue gas [%].

The measured CO emissions presented in Figure 2 are close to zero and therefore following assumption can be accepted:

$$CO \approx 0 \rightarrow L_{chemical} = 0 \quad (2)$$

Where:

CO – Carbon monoxide concentration in dry flue gas [Vol.-%]



**Figure 2:** Measured CO emissions

The thermal losses are calculated with following equation:

$$L_{thermal} = \frac{(T_{Fg} - T_A) - \left\{ 1.39 + \frac{122}{CO_2 + CO} + 0.02u \right\}}{\frac{NCV_{Dry Fuel}}{100} - 0.2442u} \quad (3)$$

where:

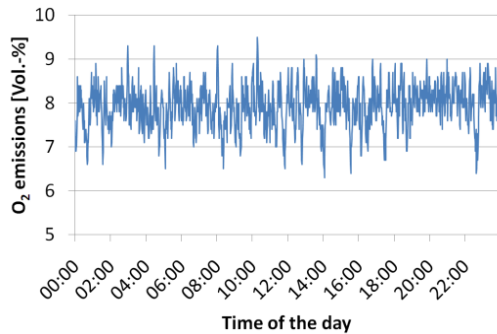
- $T_{Fg}$  - flue gas temperature [°C]
- $T_A$  - ambient temperature [°C]
- $CO_2$  - carbon dioxide concentration in dry flue gas [Vol.-%]
- $NCV_{Dry Fuel}$  - net calorific value of absolute dry fuel [kJ/kg (d.b.)]
- $u$  - humidity of the fuel [wt% (d.b.)] [7].

The  $CO_2$  emissions are calculated on the basis of  $O_2$  measurement results (Figure 2), on the basis of following equation:

$$CO_2 = 0.98(21 - O_2) - 0.61CO \quad (4)$$

where:

- $O_2$  - measured oxygen concentration in dry flue gas [Vol.-%].

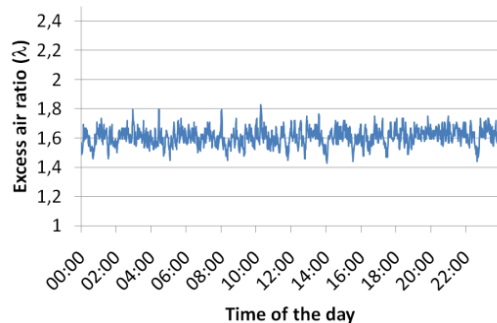


**Figure 3:** Excess oxygen measurement results

The excess air ratio ( $\lambda$ ) which is one of the most important process parameters can be determined by following equation:

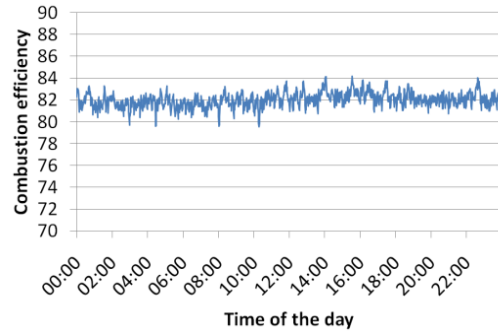
$$\lambda = \frac{21}{21 - O_2 + 0.4CO} \quad (5)$$

The calculated excess air ratio values are presented in Figure 3.



**Figure 4:** Excess air ratio

The conversion efficiency calculated with equation 1 is presented in Figure 4.



**Figure 5:** Combustion efficiency

## 2.2 Discussion

On the basis of the presented results it can be said that there are almost no emissions from incomplete combustion. This reduction can be achieved by high temperature in the combustion chamber, sufficient residence time of the combustible gases in the combustion zone and adequate mixing of combustion air and fuel [6]. However, in order to improve the mixing conditions more combustion air has to be fed to the combustion chamber, which has a negative influence on the combustion efficiency. Higher values of excess air ratio cause an increase of the oxygen content of exhaust fumes. The oxygen content of exhaust fumes measured in Scharnhäuser Park has an average value of about 8%, which is a relatively high value for modern biomass grate furnaces. Reduction of the excess oxygen in the flue gas can be therefore an effective measure to increase the efficiency of the energy generation of the plant Scharnhäuser Park. However, this optimization should be based on detailed analysis of combustion stoichiometry for each step of the combustion process in order to define optimal values for the excess air ratio.

The optimal excess air ratio for modern biomass furnaces should have a value between 1.4 and 1.8 [7]. The measured excess air ratio has an average value of about 1.6 and seems to be still relatively high causing a significant decrease in the conversion efficiency. The calculated combustion efficiency has a value of about 82%. This value is relatively low in comparison to values presented in [5]. The combustion efficiency for a 550 kW biomass grate furnace calculated by indirect method for a boiler load between 30 and 100% of the nominal load resulted in a range between 84.2 and 86.2%.

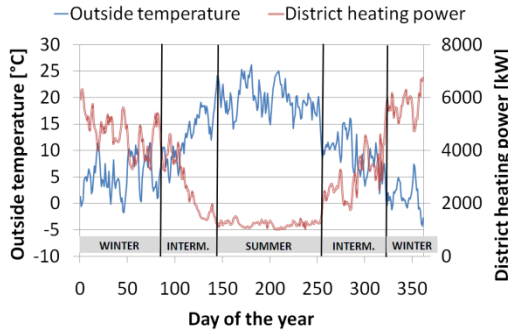
## 3 PLANT OPERATION

The plant works in heat driven mode and therefore it is especially important to estimate the expected heat demands and heat load profiles for the district heating area. The load profiles are of great importance for investigation of plant operation in respect to amounts of generated energy and combusted fuel. According to VDI 4655 [8] reference load profiles can be created on the basis of measurement results gathered during calendar year. The estimated reference load profiles can serve as a basis for the simulation of performance and operation characteristics of a biomass cogeneration plant connected to district heating network. The definition of the heat demand load profiles is based on detailed measurements of the heat demand of the area Scharnhäuser Park. The

heat demand is measured every minute and average hourly values are created using the gathered results.

### 3.1 Heating period

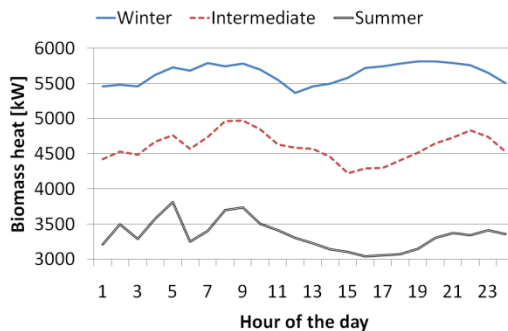
The heating demand of residential houses is directly determined by the outside temperature and there is a linear relation between the outside temperature and the heating demand. The calendar year was separated into seasons according to the measured outside temperature. According to measurement results, the year will be divided into seasons: winter, summer and intermediate (spring and autumn). The definition of the individual seasons was carried out on the basis of the 7 day average values for the outside temperature and the heat demand was not taken into account. For winter period the average 7 day temperature values have to be lower than 5°C and the summer period starts when the average temperatures are higher than 15°C. As it can be seen in the figure 6 there are significant changes of the heat demand at the limits of each period. The outside temperature is therefore a reasonable parameter for the definition of the individual seasons within a calendar year.



**Figure 6:** Outside temperature and district heating power

### 3.2 Load profiles

In order to plan the operation of a CHP plant connected to a district heating network it is especially important to estimate the heat load profiles and the expected maximum load. The load profile estimation is based on the measured amounts of produced heat for each season of the heating period. The heat load profiles presented in figure 7 have a typical shape for residential buildings with two peaks: in the morning and in the evening. This is most likely due to user behavior when more energy is demanded before the start of the working hours and after coming back home in the evening. During working time the heating demand of residential buildings decreases due to the low activity level and reduced use of heating appliances.



**Figure 7:** Load profiles

### 3.3 Biomass heat generation

According to the load profiles, the daily heat demand for each season can be estimated. Additionally the expected heat production in each season as well as for the whole calendar year can be calculated. The heat demand in winter season is almost twice time higher in comparison to the heat demand in summertime, when the heat demand for space heating is very low or almost non-existent. The analysis results showed that 39696 MWh biomass heat can be generated each year which means that the biomass furnace would achieve about 6600 full load hours per heating period.

**Table I:** Biomass heat generation

Biomass heat generation [MWh]			
	Winter	Intermediate	Summer
Daily	135	110	80
Seasonally	17 065	13 469	9 161
TOTAL YEARLY AMOUNT			39 696

### 3.4 Fuel demand

The main part of the combusted wood chips stem from park waste wood of relatively low quality. The combustible is often contaminated with impurities and has therefore a relatively high ash content and consequently also lower calorific value. According to information given in the online data basis of fuel properties [9] the estimated calorific value of dry park waste wood has an average value of 4.46 kWh/kg. The calorific value of wet fuel was calculated on the basis of water content measurements with following equation:

$$NCV = \frac{NCV_{Dry\ Fuel} * (100 - w) - 2.44 * w}{100} \quad (6)$$

where:

- NCV - lower calorific value of wet fuel [MJ/kg]
- w - fuel water content [%].

The expected fuel demand which was estimated during the planning phase of the project had a value of 63000 m<sup>3</sup>/year. The calculated fuel demand has a value 86601 m<sup>3</sup>/year (Table II) and is significantly higher in comparison to expected fuel demand. This is most likely due to the lower quality and consequently lower calorific value of the fuel. On the other hand the utilization of park waste wood as a fuel has the advantage of generating energy from materials that would otherwise be wasted. The relatively high amount of demanded fuel indicates the significant importance of developing a reliable fuel supply chain in course of planning of bioenergy projects.

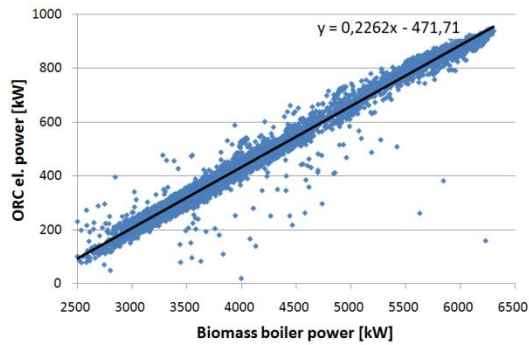
**Table II:** Fuel demand

Fuel demand [m <sup>3</sup> ]			
	Winter	Intermediate	Summer
Daily	295	241	175
Seasonally	37 229	29 385	19 986
TOTAL YEARLY AMOUNT			86 601

### 3.5 Electricity generation potential

The electric output of the ORC module is proportional to the heat output of the biomass furnace. On the basis of measurement results for energy produced at the CHP Scharnhauser Park, the relation between the

electric capacity of the co-generation plant and the biomass boiler power was established.



**Figure 8:** Power output in function of biomass boiler heat output [10].

The electricity generation potential was calculated on the basis of biomass heat output performance and the relation between biomass boiler power and ORC electrical power. Although the ORC module is characterized by good part load behavior, the amount of generated electricity in the summer period is relatively low. This is due to the relatively low heat demand during summer and lower electrical efficiency of the ORC module during part load operation.

One of the main goals of the project was to produce 4500 MWh electricity each year. According to the calculation results, 4878 MWh electricity can be generated each year if the plant works reliable for the whole year.

**Table III:** Electricity generation potential

	Electricity generation [MWh]		
	Winter	Intermediate	Summer
Daily	19	14	7
Seasonally	2434	1666	779
	TOTAL YEARLY AMOUNT		4878

#### 4 CONCLUSIONS

- The energy losses related to the emission of unburned fuel components in the flue gas are close to zero.
- The amount of excess oxygen measured in exhaust fumes is relatively high. Consequently, the thermal losses due to emission of hot flue gases have a negative influence on the combustion efficiency.
- According to the estimated load profiles 39696 MWh of biomass heat can be generated each year.
- The expected fuel demand is relatively high and has a value of 86601 m<sup>3</sup> per year. This is due to the utilization of fuel with relatively low quality and therefore lower calorific value.
- The expected yearly amount of produced electricity has a value of 4878 MWh. The targeted value of 4500 MWh electricity produced per year can therefore be achieved if the plant works reliable for the whole year.

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