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Energy and environmental performance of a biomass cogeneration plant in an urban area

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ABSTRACT: High efficiency of the energy generation from biomass can be achieved in cogeneration plants which are based on the ORC technology. Due to the high efficiency of part load operation, such plants are an interesting alternative for municipal and commercial heat supply. The energy supply system of the Scharnhauser Park urban quarter near Stuttgart, Germany is a practical example of the utilization of the ORC Technology. The paper contains a review of the practical experiences and results that has been gathered during the first four years of plant operation. The results can be used for the estimation of the energetic, ecological and economic parameters of the plant operation. The main object of the work was the analysis of the wood combustion process in the biomass furnace. The efficiency of the energy generation process was evaluated on the basis of operating results and experience. The measurements of the emission values allowed the estimation of the environmental impact of the energy generation process. The emission values measured speak in favour of the possibility of integrating such installations in the energy management systems of urban areas. The research results show that biomass cogeneration plants can be effectively integrated into the energy supply systems of urban areas.

Keywords: Clean combustion of biomass; Combined heat and power plant (CHP)

1. INTRODUCTION

More than 80% of the worldwide energy supply is based on fossil fuels. The replacement of fossil energy by renewable energy sources has a high signigicance in respect to the disadvantages of the utilization of fossil energy sources. With more than 75% biomass has the highest share of the energy generation from renewables [1]. Wood is the largest contributor to the amount of energy produced from biomass. There is a high variety of technologies which can be used for energy generation from wood.

Considering the limited availability of wood, the efficiency of the utilization of its potentials should be as high as possible. The efficiency of several technologies for energy generation from wood can be compared on the basis of the relationship between the amounts of generated effective energy and invested primary energy. The highest efficiency for the utilization of wood potentials can be achieved by using wood-fired heating installations without a heating network [2]. However it should be considered that the environmental impact of small-scale wood combustion systems is high as a result of relatively high emission values. The highest efficiency for the substitution of fossil fuels can be achieved with the energy generation from wood in combined heat and power plants (CHP). In combination with relatively low emission values, the utilization of wood potentials in plants like the Scharnhauser Park cogenerated heat and power plant is the most reasonable alternative for energy generation from wood. New developments, such as energy generation on the basis of ORC technology in combination with a biomass furnace results in an increasing importance of wood fired CHP systems. However, problems occur in relation to changing fuel quality and ineffective combustion control systems. A deeper insight into the complex process of wood-fired systems for energy generation is needed to establish new strategies for the optimization and further development of wood combustion based CHP systems with regard to emission reduction and efficiency enhancement.

2. SCHARNHAUSER PARK ENERGY SUPPLY SYSTEM

Scharnhauser Park is a community in Stuttgart-Ostfildern. The 140 ha area mainly consists of new built terraced houses and apartment buildings, but also has individual commercial areas as well as public buildings. The energy demand of Scharnhauser Park and its daily distribution are determined primarily by the residential area.

A wood-fired cogeneration plant was built in order to ensure an environmentally-friendly heat supply for the area. The main goal of the project was the achievement of CO_2 neutral production of heat for the whole district with a rate of 80%. The plant is mainly fired by natural wood scraps and forested wood is burned additionally. The wood chips are stored in a silo with a holding capacity of 1000 m^3. The fuel is automatically transported in a daily storage, which is equipped with a hydraulic floor. The wood chips are then transported hydraulically to the burning chamber.

By a heat exchanger the heating emission is transferred to a heat carrier (thermo oil) which acts as a heat transport agent between the burner and the ORC module, where the electricity is produced. Use of thermo oil has the advantage that no steam boiler must be used to produce electricity. This makes the operation of the plant easier and above all more economical.

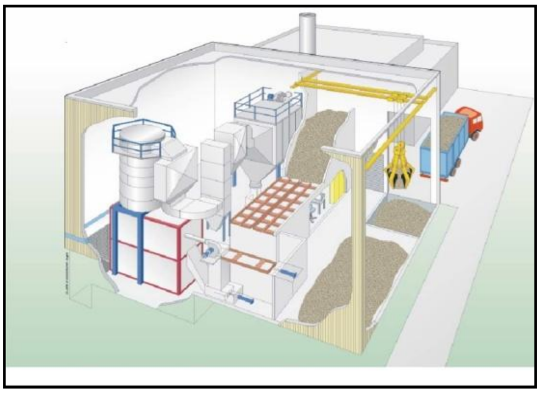

Figure 1: Wood-fired cogeneration power plant.

Table 1: Technical data.

Technical data biomass power plant	
Thermal power furnace	6000 kW_{th}
Electrical power ORC	1000 kW_{el}
Thermal power ORC	4650 kW_{th}
Capacity of wood storage	1400 m^3
Wood consumption full power	200 m^3/day
Annual wood consumption	63.000 m^3/year
Fossil fuel savings	~40mill. kWh/year
Reduction CO_2 emissions	~7.000 tons/year

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The burner is equipped with an exhaust heat recovery system. After the hot exhaust has transferred its heat to the thermo oil, even more heat is drawn out of it. This takes place in a fume economizer, in which the exhaust fumes first release their heat to the thermo oil and then heat the water of the

district heating network. The exhaust heat recovery allows fuel consumption degrees of over 80%.
Cogeneration of electrical and thermal power takes place in an ORC (Organic Rankine Cycle) module. The ORC system is similar to the water-steam process for producing electricity. The main innovation is the use of an organic fluid as the working medium instead of water. In the ORC module at the "Scharnhauser Park" cogeneration plant silicon oil was used as the working medium. The use of silicon oil allows the production of electricity at much lower pressure and temperatures and therefore the ORC module can be installed and operated with relatively low operating and personnel costs. ORC units in general are characterized by a good partial load performance, a fact that is particularly important when the plant is operating within a heating network.

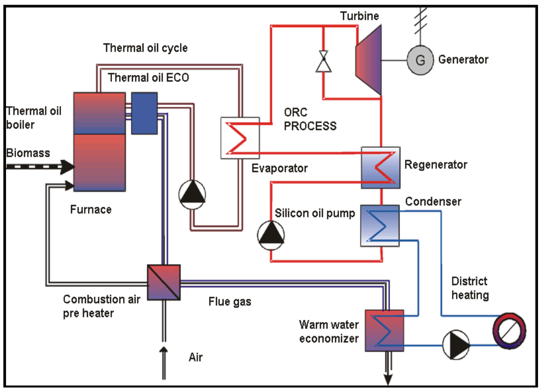

Figure 2: ORC Process [3].

The local heating network of the Scharnhauser Park area has been substantially modernized and extended. The network spreads over a length of more than 13 km and enables all the inhabitants of the area to use environmentally-friendly energy. The local heating network is fed with waste heat from the electricity generation process in the ORC module. The heat energy is transferred to the heating network in its condenser. The main demand for heat in the area is covered by biomass. Additional gas boilers were installed at the plant to cover the peak demands of Scharnhauser Park. Each year 80% of the heating energy and approximately 50% of the electrical power are produced CO_2 neutral in the cogeneration power plant.

Table 2: Produced quantity of heat.

Year	Total heat produced	Biomass precentage
2004	19899 MWh	54.3%
2005	23306 MWh	73.9%
2006	24255 MWh	81.3%
2007	23544 MWh	81.03%

The core of the plant is the 6 MW_{th} biomass furnace. Modern feed grate firing is equipped with a fully automated control system, which makes a clean and complete combustion possible.

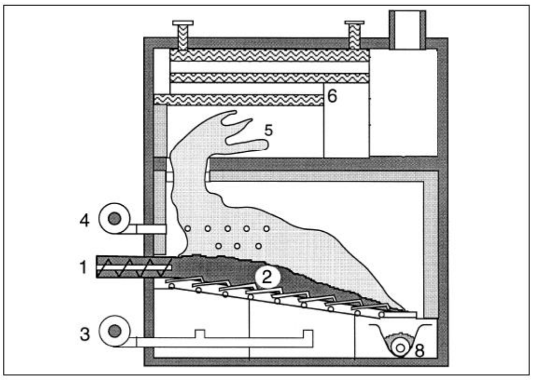

Figure 3: Scheme of the grate furnace [4].

1-fuel feed, 2-grate, 3-primary air, 4-secondary air, 5-burning chamber, 6-heat exchanger.

The combustion chamber is separated into two different zones (primary and secondary) in order to optimize the process of thermal utilization of wood. In the primary combustion zone, the wood chips are gasified under sub-stoichiometrical ($\lambda<1$) conditions. The main steps in the thermal decomposition of wood in the primary combustion zone are drying, devolatilization, gasification and char combustion. The gasification products from the primary combustion zone are transferred to the secondary zone where they are burned under over-stoichiometrical ($\lambda>1$) conditions.

Automatic biomass furnaces are operated continuously and all steps of the thermal decomposition of wood occur simultaneously in different sections of the combustion chamber. Every step of the combustion process takes place in a separate zone of the furnace and every zone is equipped with a separate combustion air fan. This advanced combustion air management achieves low emissions of unburned components as well as high energy conversion efficiencies. The complex control system enables a plant operation with a variable performance depending on the requirements of the district heating network.

The installation of complex filter equipment at the plant contributes to a significant reduction in combustion-related emissions. After the exhaust fumes have released their heat to the thermo oil and the heating network, they are ducted to the cyclone and electro filter where dust is removed. Additionally a permanent emission monitoring system was installed at the plant in order to control the emissions of pollutants from the combustion process.

3. PRACTICAL EXPERIENCE

Presently the use of biomass and derived solid biofuels by combustion for the production of heat and electricity represent about 98% of the total primary energy utilized from this energy source that accounts for about 55 EJ/year [5]. However, there are strong needs to improve biomass combustion in terms of efficiency enhancement. The reduction of the emission limits by new legislative regulations in the 1980's forced the manufacturers to reduce emissions and increase the thermal efficiency of their wood-fired systems. Further development of modern installations for energy generation from wood has to be based on the practical experience from existing plants. In this context the data from Scharnhauser Park can serve as a basis for the analysis of efficiency of modern energy management systems and can provide useful knowledge and information for the development of modern energy supply systems.

3.1 Part load operation

The structure of the energy demand of Scharnhauser Park is mostly determined by residential buildings and therefore there are high variations in the energy demand during the daily operation of the plant. Biomass combustion devices with low output performance and simplified technology commonly operate with high emissions of unburned components under part load conditions as well as low energy conversion efficiencies. The combustion of biomass in furnaces equipped with advanced combustion air management systems make the adaptation of the system output performance to variable heat energy demand possible. The combustion process parameters in complex biomass furnaces can be adapted to changing fuel quality and variations of the heat demand. The division of the furnace into zones adequate for the various steps of the combustion process makes the application of complex combustion control systems easier and above all more effective. The combustion of biomass in two steps, in the primary and secondary combustion zone, also allows the reduction of temperatures of the grate zone and therefore prevents the ash from sintering during combustion. Figure 4 shows a daily structure of the heat output capacity of the furnace. As can be seen the furnace output performance can be effectively adjusted to the actual levels of heat demand.

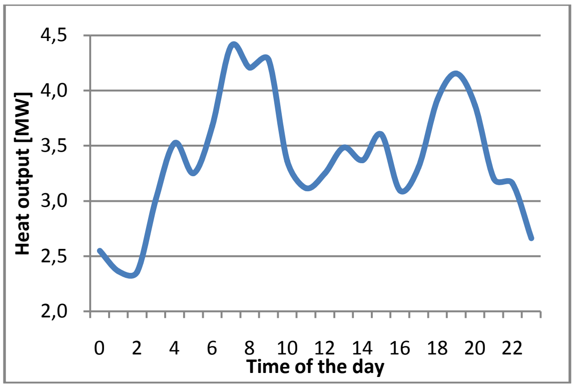

Figure 4: Thermal output.

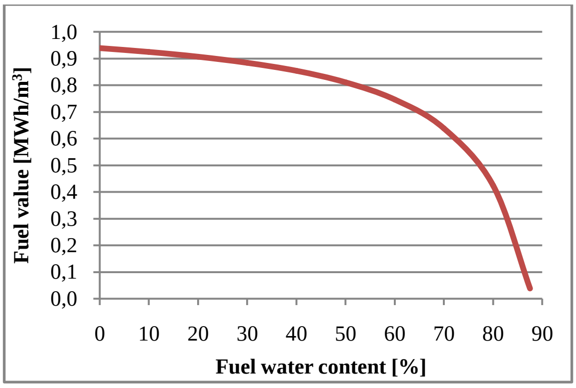

Figure 5: Fuel value in function of humidity.

If good adaptation of the output performance of the furnace to the actual heat demand is achieved, the efficiency of biomass utilization can be increased significantly. This efficiency of the operation of the furnace can be estimated depending on degree of efficiency. The overall degree of efficiency for the Scharnhauser Park CHP was calculated on the basis of the comparison between the amounts of generated energy and the amounts of fuel energy. The plant has its own energy metering system for the acquisition of amounts of produced and sold energy. The measured amounts can be used for estimating the amount of heat generated in the biomass furnace and it also contains the amounts of combusted wood chips. Fuel energy can be calculated with a simplified method in which the wood type and wood humidity are estimated. The fuel value was determined on the basis of average fuel values taken from literature [6]. The fuel value of wood chips depends clearly on their humidity and can be calculated as a function of humidity for a given wood type (Figure 5). Fresh wood chips with an approximately water content of 65% are used as combustible at the Scharnhauser Park CHP. For wood chips with a water content of 65% the fuel value achieves 0.70 MWh/m^3.

The results of the evaluation of the amount of generated energy and the amount of fuel energy enable the calculation of the overall degree of efficiency for the biomass furnace.

Table 3: Plant efficiency.

Overall degree of efficiency	
Combusted wood chips	135376 m^3
Fuel value	0.70 MWh/m^3
Fuel energy	94768 MWh
Generated energy (heat + electricity)	73456 MWh
Overall degree of efficiency	82.38 %

The overall degree of efficiency allows the evaluation of plant performance while operating under non stable working conditions. For that reason the calculated value enables the determination of the “quality” of the entire biomass combustion system in Scharnhauser Park over a defined time span. The calculated degree of efficiency can be compared with reference values given in the literature. In [7] the overall degrees of efficiency were calculated for 30 biomass heating systems in Switzerland. Most of the analyzed combustion systems achieved degrees of efficiency of between 70 and 80%. The calculated overall degree of efficiency of 82.38% for the biomass furnace can be described as relatively high in respect of those reference values.

3.2 Environmental impact of the biomass combustion

The main task of the biomass furnace is to generate heat by a complete oxidation of the combusted substance to H_2O and CO_2. The flue gases generated as a result of combustion of biomass also contains undesirable pollutants. Different types of pollutants from biomass combustion can be distinguished:

- unburnt pollutants such as CO, C_XH_Y, PAH, tar, soot, unburnt carbon, H_2, HCN, NH_3 and NO_2;
- pollutants from complete combustion such as NO_X (NO and NO_2), CO_2, and
- ash and contaminations such as particles (KCL, etc.), SO_2, HCL, PCDD/F, Cu, Pb, Zn, Cd, etc. [8].

If a modern biomass furnace is operated competently, a clear reduction of the emission values can be achieved. The emission values of a biomass furnace should serve as an essential factor for the analysis of the environmental impact of energy supply concepts based on biomass combustion. The emission values from a biomass furnace can be evaluated on the basis of a comparison with typical emission values of heating oil and natural gas furnaces (Table 4). These decentralized furnaces with an overall performance of up to 100 kW can be treated as alternative heat supply systems for residential buildings.

Table 4: Typical emission values of fuel oil and natural gas furnaces [9].

Parameter	Emissions in mg/Nm^3 Fuel oil boiler	Natural gas boiler
CO	approx. 8.6	approx. 8.6
C_{total}	<2.2	<2.2
NO_x	43-65	22-39
Particles	up to 0.2	-

The typical emission values for decentral heating systems fed with biomass (Table 5) can also be used as reference values for the evaluation of measured emission values in Scharnhauser Park.

Table 5: Average emission values for biomass furnaces (50-100 kW) [9].

Parameter	Emissions in mg/Nm^3 Wood chip boiler	Wood pellet boiler
CO	95	32
C_{total}	2	1
NO_x	123	123
Particles	27	24

The installation of complex flue gas cleaning systems would be uneconomical in the case of heating systems fed with biomass with relatively low output performance. The biomass combustion in furnaces like the firing in Scharnhauser Park makes the installation of complex flue gas cleaning systems possible. Additionally the permitted emission values for furnaces with higher output performance are very strict in comparison to these allowed for installations with lower output performance. Table 6 contains the emission limit values and the emission measurement results for the biomass combustion system investigated in Scharnhauser Park.

Table 6: Permitted and measured emission values for CHP Scharnhauser Park.

Parameter	Emissions in mg/Nm^3 Emission limit values	Measured emissions
CO	150	8.1
C_{total}	10	0.15
NO_x	250	199
Particles	20	6.1

According to the measurement results of the emission values shown in Table 6, it can be said that all emissions are lower than the limit values for biomass combustion in such systems as the furnace in Scharnhauser Park.

3.3 NO_X emissions

The application of two-stage combustion with primary air injection in the fuel bed and secondary air injection in the combustion chamber enabled a significant reduction of NO_X emissions. Besides staged combustion, partial recirculation of exhaust gases was used in the researched furnace for an additional reduction of NO_X emissions. Formed NO_X can be decomposed if the exhaust gases are returned back to the hot combustion chamber. The measured NO_X emissions are higher than the typical NO_X emission values for furnaces with a lower output performance (Table 5). The higher NO_X values can be explained by the relatively high amount of undesirable fuel contents like grass, which can be found in the combustible at CHP Scharnhauser Park. The combustion of herbaceous biomass, which has higher contents of N, causes higher emissions of NO_X. The typical emission values of NO_X measured for combustion of herbaceous biomass like grass are in a range of (478 mg/Nm^3 [9]) in comparison.

3.4 CO emissions

The achievement of a complete combustion is one of the most important conditions for low emissions in biomass furnaces. The CO emissions can serve as an indicator for the evaluation of thoroughness and quality of the combustion. The plant in Scharnhauser Park is equipped with a measuring system for a continuous monitoring of CO emissions. Figure 6 shows the CO emissions measured during the daily operation of the plant. The emission values were calculated on the basis of a reference oxygen content of exhaust gases of 13%.

The CO emissions measured are very low in comparison to the limit values for biomass combustion as shown in Table 6. The optimized injection of secondary air in modern furnaces enables good mixing of combustion air with combustible gases in the combustion chamber. If a good mixing is achieved, the concentrations of unburnt pollutants can be reduced to levels close to zero [8].

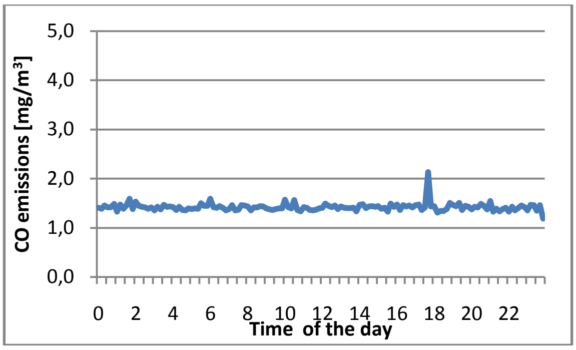

Figure 6: CO emissions (at 13 vol% O_2).

3.5 Particulate emissions

The reduction of the emissions of particles has a high priority for the limitation of the environmental impact of biomass combustion. The priority must be put on the reduction of particles smaller than 10 µm (PM10) which can be inhaled and cause severe health problems. The emission limit values for PM10 particles have been frequently exceeded in the region of Stuttgart.

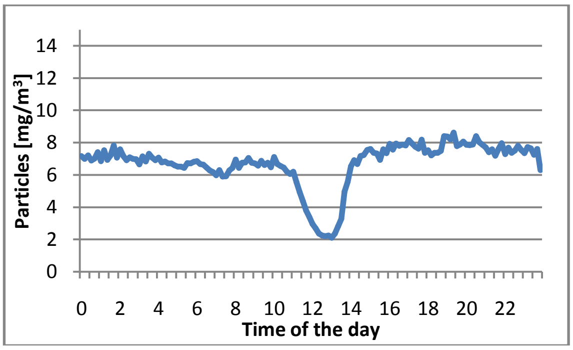

Figure 7: Measured particulate emissions (at 13 vol% O_2).

The Scharnhauser Park CHP is equipped with an exhaust gas control system which enables a continuous monitoring of particulate emissions. The particulate emissions are low in comparison with the emission limit values for particles (Table 6). The removal of particles in a multicyclone followed by an electro filter leads to a significant reduction in particulate emissions at Scharnhauser Park CHP. Therefore the measured emission values are relatively low in comparison to typical particulate emissions from biomass furnaces with lower output performance (Table 5).

4. CONCLUSION

The analysis of the practical experience and results gathered during the first four years of operation of the Scharnhauser Park CHP made the evaluation of the efficiency of the utilized energy management concept possible. The results showed a high efficiency of the part load operation of the plant. The efficient adaptation of thermal output performance to the instantaneous value of heat demand of the residential area enabled the achievement of a relatively high fuel consumption degree of over 82%. The implementation of a complex combustion control system in combination with an effective flue gas cleaning system made significant reduction of emission values in comparison to biomass furnaces with lower output performance possible. Energy generation from biomass in plants like Scharnhauser Park CHP is promising, as it combines high efficiency with low emissions. The results showed that the energy supply concept in Scharnhauser Park is a reasonable alternative to common energy concepts.

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