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ANALYSIS OF A BIOMASS TRI-GENERATION SYSTEM IN AN URBAN AREA

Rafal Strzalka*, Roman Ulbrich*, Ursula Eicker**, Eric Duminil**
*Technical University Opole, St.Mikolajczyka 5, PL-45-271 Opole, Poland
Tel.: +48/77/4006192, Fax: +48/77/4006317, Email: r.strzalka@po.opole.pl
**Stuttgart University of Applied Sciences, Schellingstr. 24, D-70174 Stuttgart, Germany
Tel.: +49/77/8926-2674, Fax: +49/711/8926-5698, Email: ursula.eicker@hft-stuttgart.de

ABSTRACT: Energy systems based on decentralised biomass CHP plants represent an economically interesting solution for municipal and commercial energy supply. Among the modern technologies used for decentralised heat and power generation from biomass, ORC (Organic Rankine Cycle) plants are commercially available systems for biomass utilisation, which ensure good conversion efficiencies. However, there are still unsolved problems related to the lack of practical experience in the integration of ORC plants in the energy management systems of urban areas. The biomass CHP plant located in Ostfildern/Germany is a practical example for the utilisation of the ORC technology for the energy supply of municipal areas. The CHP plant operates in heat driven mode and covers 80% of the heat demand and 50% of the power demand of an urban area, which has 7.000 inhabitants. Due to the fact that the heat demand of the supplied area is determined mostly by residential buildings, there are strong fluctuations in the heat demand related to changing weather conditions and heat customers' behaviour. The practical experience that has been gathered during the five years of the plant operation was used for the system performance analysis as well as for the optimisation of the energetically and ecological parameters of the plant operation.

KEYWORDS: trigeneration, organic rankine cycle (ORC), biomass combustion

1 INTRODUCTION

The energy supply is currently dominated by fossil fuels (approx. 80% of total energy production). Nevertheless, about 10-15% of the global energy demand is covered by biomass resources, making biomass by far the most important renewable energy source used to date. The present amount of biomass used for energy generation is already significant, but the production of heat, electricity and cooling from biomass is anticipated to provide a large contribution to the primary energy supply of many European countries [1].

In many countries large power plants provide most of the electrical energy used. Such plants are expensive systems with high fuel demand and therefore long transport distances if biomass is used as a combustible. The advantage of decentralised biomass, besides reasonable fuel transport distances is also the possibility to supply urban areas with district heating and cooling combined with the production of electricity. Decentralised bioenergy plants built reasonably close to the demand load will reduce transmission losses and can also improve the energy security by producing additional and alternative resources [2].

In recent years a great deal of effort has been put into research and development of new technologies for decentralised co-generation in biomass-fired plants. A typical obstacle for decentralised wood CHP plants are the installation costs. The most promising alternative to solve these problems is the ORC (Organic Rankine Cycle) process, as it combines high efficiency with relatively low investment costs.

The ORC technology is based on the Rankine process with the difference that instead of water an organic medium is used. The special advantages of the ORC technology are robustness (long service life, low maintenance costs), fully automatic and unmanned operation (personnel requirements only 3 to 5 hours per week) and excellent part load behaviour [3].

Although the ORC process is already well known from geothermal applications, the combination of an ORC module with biomass furnace is more complex. The technology is well described in the literature [4], [5] and approx. 130 biomass-fired ORC plants were installed all over Europe. Examples on the evaluation of experience from existing ORC plants can be found in [3] and [6]. However, there is still a lack of long-term experience with regard to conversion efficiency, emissions, reliability and ease of operation of this technology.

Although biomass ORC plants are an interesting alternative for energy supply of urban areas, there is still a problem with the utilisation of condenser heat in the summertime. Possible solution is the production of cold through absorption cooling integrated to the district heating network. The paper describes a pilot project where cold is produced by waste heat from a biomass CHP plant. The results show that the cogeneration plant in Scharnhauser Park can be operated with higher operating hours throughout the year, particularly when the cold production in summer is installed.

2 TECHNICAL DESCRIPTION OF THE BIOMASS-FIRED CO-GENERATION PLANT

The biomass plant Scharnhauser Park is located in Ostfildern, near Stuttgart, Germany and provides an urban quarter with 7000 inhabitants with heat. The main goal of the project was the achievement of 80% fraction on the covering of heat demand of the supplied area. Due to reduced carbon dioxide balance such plants are an interesting alternative for municipal and commercial heat supply. The decentralised cold generation through absorption cooling, driven by the heat from the biomass-fired plant can replace conventional cooling equipment and reduce the electricity consumption peak in summer.

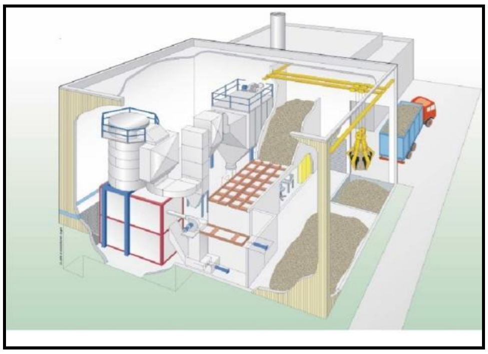

Figure 1: Biomass co-generation plant

Table I: Technical parameters

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

The core of the plant is a biomass fired grate furnace with a nominal capacity of 6.3 MW_{th}. The plant is fired mainly by natural wood-scraps and forested wood is burned additionally. The heating emission is transferred to a heat carrier (thermal-oil) in the thermal-oil boiler followed by a thermal oil economiser. Thermal oil acts as a heat transport agent between the furnace and the ORC module, where electricity is produced.

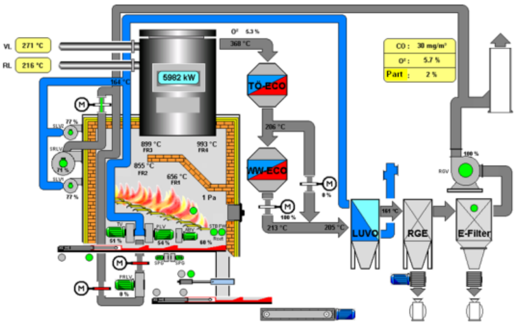

Figure 2: Biomass furnace

The working principle of the ORC module is similar to the classical water-steam process, with the main difference that instead of water an organic fluid (silicone-oil) is used as the working medium. The use of silicone-oil has the advantage that the production of electricity is realised at much lower temperature and pressure and therefore the investment and the maintenance costs of the plant can be reduced significantly.

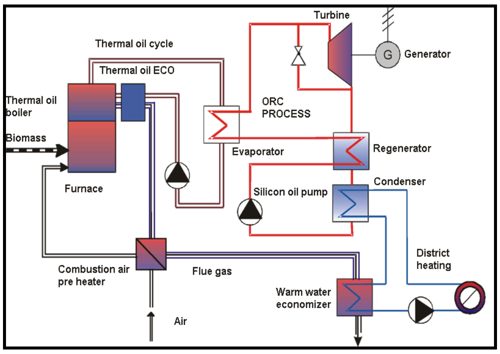

Figure 3: ORC module [6]

The ORC module is a closed system connected with the furnace via a thermal-oil cycle. The hot thermal oil generates superheated organic steam in the evaporator. The steam is then expanded in a single-stage turbine, which is connected to a generator. The condensation of the vapour takes place in the condenser and the waste heat from the electricity generation process is utilised as district heat, or with the use of an absorption chiller for the production of cold. The electrical efficiency of the ORC process lies between 6% and 17%. This efficiency is linked with the maximum heat recovery and the thermal efficiency of the boiler [7].

The district heating network of the area has been modernised and extended and spreads over a length of 13 kilometres. The houses and apartments in the Scharnhauser Park area have to be connected to the heating network, which results in a high heat density and therefore good prerequisites for an economically attractive district heating system. The main demand for heat in the area is covered by biomass and additionally gas boilers were installed at the plant to cover the peak demands of Scharnhauser Park.

The energy supply system of the area gives the possibility for biomass-trigeneration. Trigeneration is the simultaneous generation of electricity, heat and cooling, and is considered to be an extension of the cogeneration (CHP), with the addition of absorption chillers. It is also known as combined cooling, heating and power generation (CCHP). Absorption chillers have the ability to easily integrate with cogeneration systems and have lately gained widespread acceptance, together with the significant reduction of their price [7].

In the course of the planning for a new office building, cooling generated by 100% renewable energy sources can be offered by heat supplier at a relatively low price. The cold is produced by a lithium-bromine absorption chiller with a cooling capacity of 105 kW, which was installed in the cellar of the office building. Due to the fact that the cooling machine needs a feed water mass flow of 7.2 kg/s and creates a temperature spread of only 5K, the common connection between feed and return of the heat net would lead to high return temperatures in the heat net in the summertime and could negatively influence the performance of the ORC module. The problem was solved by an integrated connection of the cooling machine within the feed line of the heat net. The installation has a pilot project character and could serve to extent the availability of information related to implementation of modern biomass CCHP systems.

3 PRACTICAL EXPERIENCE

The biomass-fired ORC plant started its operation 2004. The installation was equipped with a monitoring system for the continuous measurements of the process parameters (e.g. electric and thermal performance, biomass combustion parameters, and pollutant emissions). Data gained from the ORC plant show that the installation achieves an overall efficiency of about 15% at nominal load, which is a relatively high value for decentralised biomass plants. The ORC plant operates with high efficiency even at part-load operation, which underlines the suitability of this technology for heat driven operation in combination with a district heating network.

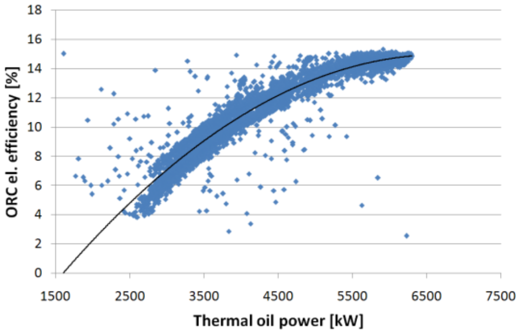

Figure 4: Electric efficiency in relation to the thermal oil power

At the start-phase of the plant operation 2005 several technical disturbances occurred and the electricity was not produced every month. One of the main reasons for the sub optimal performance of the plant was the non-stable operation of the ORC module. After the retrofit of the evaporator (the distance between the heat exchanger plates was changed) and the modernisation of the turbine and generator, the reliability and the performance of the ORC module has been increased. However, one of the main project goals, the production of 4500 MWh electricity per year has not been achieved yet. The lower as expected colonisation of the quarter can be given as the main reason for the lower amounts of produced electricity during the first years of plant operation. All of the expected plant customers will be connected to the system in 2011 and until that time the performance of the plant and the amount of produced electricity will be lower due to the limited heat intake of the district heating network.

Table II: Energy production

Year	Gas [MWh/a]	Biomass [MWh/a]	Electricity [MWh/a]	Biomass [%]
2004	19 899	10 802	1 103	54.3
2005	23 306	17 220	1 212	73.9
2006	24 255	19 716	278	81.3
2007	23 544	19 441	3 308	82.6
2008	26 810	16 924	3 527	63.1

The heat generated in the biomass plant is transferred to the customers via a district heating network. Hot water with an average volume flow of 100 m^3/h and feed temperatures from 75 to 95 degrees is used as a transfer medium. In regular operation the return temperature of the heat station is bellow 60°C and the total heat loss occurring in the net are approx.15%. The biomass-fired co-generation plant was installed as the alternative to the ageing gas-fired district heating system while considering the future fossil fuels price rises and the potential of biomass utilisation as a CO_2-neutral and renewable energy source. Due to its operational characteristics and higher capital costs the biomass-fired plant is designed to provide the base load and additional natural gas boilers were installed at the plant to cover the peak demands. The gas furnaces are also used during times when the heat load is lower than 30% of the nominal load (1.5 MW_{th}) of the plant to avoid inefficient operation of the biomass unit.

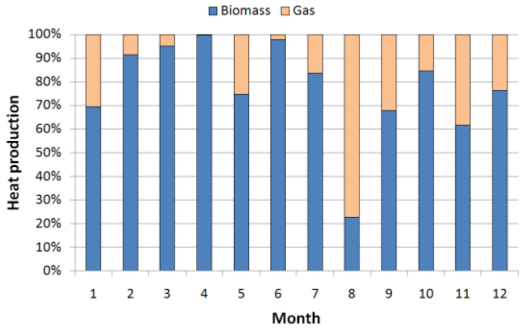

Figure 5: Heat generation 2007

Each year 80% of the heating energy and approx. 50% of the electrical power are produced from biomass in the cogeneration plant. The heat generation for the whole district in a single large plant allow a level of efficiency, automation and exhaust gas cleaning that would not be possible in smaller plants. The main advantage of modern biomass-fired plants is the possibility of part-load operation in the range between 30 and 100% of full load. The energy demand of a district heating system is not constant over the daytime. The heat load varies during the day in dependency of the outside temperature and heat customers' behaviour. Regarding fluctuations of the heat demand, a pc-based control system was installed in order to control the biomass-fired thermal oil boiler. The control of the amounts of air fed to the combustion chamber allows an efficient reduction of the output performance down to about 25 per cent of the nominal performance. The next figure shows the smooth reduction of the output performance of the furnace in relation to the ambient temperature.

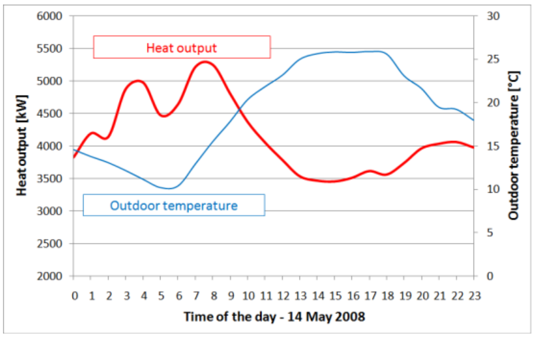

Figure 6: Part load operation

There are large changes in the thermal output of the biomass plant during the year, with a minimum during summer and maximum during winter. During summer the space heating demand can be considered very low or non-existent and the demand for hot water is approximately the same, independent of season. The biomass boiler installed in Scharnhauser Park is not able to operate bellow 1.5 MW_{th} thermal output. To achieve a sufficient furnace load in summertime an emergency cooler was installed. In the 2 MW cooling unit a part of the thermal energy generated in the furnace can be released to the ambient as waste heat. In order to reduce the amounts of waste heat from the electricity production process an absorption cooling machine has been integrated to the energy supply system of the area Scharnhauser Park.

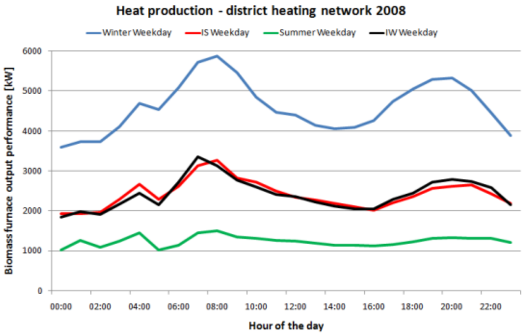

Figure 7: Heat production (winter, intersection, summer)

4 COMBINED GENERATION OF HEATING AND COOLING

Decentralised biomass co-generation plants in combination with a district heating network are an interesting alternative for utilisation of biomass potentials. However, apart from technical issues there is always a big challenge with finding a heat demand that would be suitable for an economically operation of a biomass CHP unit. Due to the fact that in summertime the heat demand decreases significantly, a suitable and economically feasible operation of the plant cannot always be achieved during the whole year round. Possible solution is the integration of an absorption chiller within a district heating network in order to increase the energy amount produced in the co-generation plant. As the result of recent development and reduction of cost, absorption cooling machines are an interesting alternative to combine heat and power production with the supply of cooling.

The analysis presents a case study based on historical data for the energy production at the biomass CHP plant for the whole year 2008. The heat and cooling customer is the local community Scharnhauser Park in Stuttgart/Ostfildern (Germany). The results obtained provide visibility to the increased biomass potential utilisation when an absorption cooling machine will be integrated within the district heating network. The cooling unit was installed in a newly constructed office building in order to realise a sustainable coverage of the heating demand. The office building is planned to be a pilot building using thermal cooling for air condition of offices and the IT structure. Heat produced by the CHP unit may be used for heating purposes or it may be transformed to cooling by the absorption cooling machine.

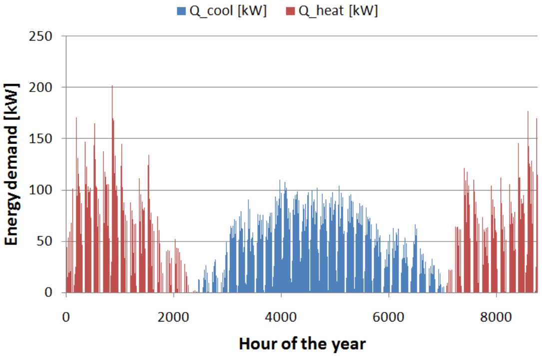

Figure 8: Load profile of the absorption cooling machine.

The output performance of the bioenergy plant is determined by the heating and cooling demand. The installation of the absorption chiller in the building has the advantage, that heating and cooling demand may overlap. As it can be seen on the chart bellow, the installation of an absorption cooling machine causes a significant increase in the output capacity of the bioenergy boiler.

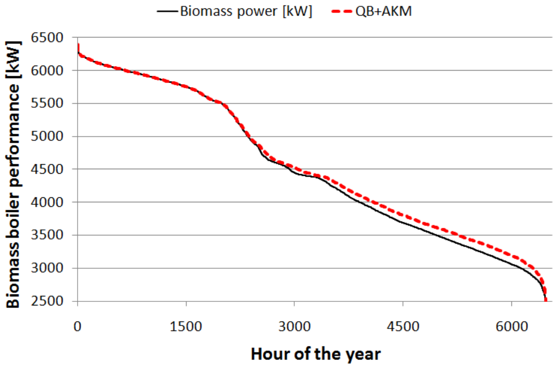

Figure 9: Biomass power after installation of the absorption cooling machine.

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 in year 2008, the relation between the electric capacity of the co-generation plant and the biomass boiler can be established.

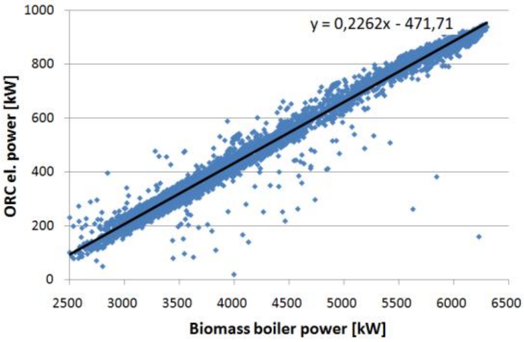

Figure 10: Relation between electric power and biomass boiler capacity.

On the basis of these calculations the potential for the increased electricity production, which can be achieved through installation of an absorption cooling machine, can be estimated.

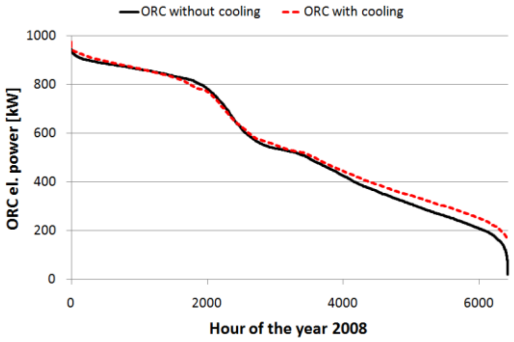

Figure 11: Electricity generation

When the co-generation plant operates with high capacity, the energy output performance of the ORC module is almost equal for the both cases. During part load operation, when the output performance is lower than 600 kW_{el} the installation of an absorption cooling machine results in increased electricity generation. As the electricity is the main income source of the plant owner, the increase of the electricity production is of great interest for the investor. Additionally increased income from district heating consumed by the absorption cooling machine in summertime can be responsible for good economic results

5 CONCLUSIONS

- The heat capacity of the biomass furnace can efficiently match the heat demand of the area
- There are strong fluctuations in the daily structure of the heat demand of the urban area due to changing weather conditions and customers' behaviour
- There is a linear relation between the electricity production and the heat capacity of the biomass boiler
- The integration of an absorption chiller within the heating network increased the output performance of the biomass plant
- The installation of an absorption cooling machine results in increased electricity generation during part-load operation

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7 ACKNOWLEDGEMENT

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