Biomass-fired Organic Rankine Cycle-based CHP for Community-Scale Applications

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Abstract—The growing energy demand, depleting fossil fuel reserves, and global warming concerns call for a further increase in biomass energy utilization. At present, biomass is mostly used in small-scale applications where the production of electricity is technically and economically disadvantageous. On the other hand, district or community-scale CHP applications with higher efficiencies and lower specific investment costs are a better alternative. Biomass combined heat and power (BCHP) systems can reduce GHG emissions and also have the potential for higher overall energy efficiencies than conventional home heating methods. In this research, an organic Rankine cycle (ORC)-based BCHP for community-scale applications is investigated concerning technical and economic aspects. MDM (Octamethyltrisiloxane) is selected as the ORC working fluid, taking into account the cycle efficiency and system design. The heat of biomass combustion in the boiler is used to vaporize the organic working fluid in the evaporator. The working fluid vapor drives the turbine that spins an alternator. A mathematical model for the community-scale ORC BCHP system is developed to predict its operational performance. Various costs for the BCHP plant are analyzed and the cost of electricity (COE) is calculated. The community-scale or district BCHP plant generates 520.9 kW_e electricity with the electrical efficiency reaching 17.24 % at a turbine inlet temperature of 250 °C, and provides hot water with a heating load of 2365.7kW_{th} at a temperature of 79.2 °C. The COE of the BCHP plant is 98.2 $/MWh when not including CO_2 credit.

Keywords—Biomass, organic Rankine cycle, BCHP, model, working fluid

I. Introduction

Biomass is a renewable energy source that stores solar energy by adsorbing CO_2 and fixing it into cellulose in photosynthetic processes. The CO_2 absorbed is released during the energy conversion. This would make biomass a CO_2-neutral energy source. Using locally available biomass is regarded as one of the solutions to the problems with climate change and energy security. In other words, biomass-to-energy is a sustainable solution that can reduce greenhouse-gas emissions to the atmosphere. Agricultural and forest-based industries generate a substantial amount of biomass residue and waste that could be used for energy production.

Biomass is currently mostly used in small-scale applications where the production of electricity is technically and economically disadvantageous. On the other have, district or community-scale combined heat and power (CHP) applications with higher efficiencies and lower specific investment costs are a better alternative. For instance, average thermal demand of district heating amounts to about 1.5-2 MW_{th}. Conventional Rankine cycles have demonstrated strong limitations for power sizes below 1 MW due to the reduced performance and the increased specific investment cost. For this reason, in many cases the residual biomass was used for heat-only applications. Biomass-fired organic Rankine cycle (ORC) CHP is showing increased potential, and is quickly becoming identified as a promising endeavour due to its uncomplicated operation under lower temperatures and pressures at favorable investment and operating costs. For instance, the intuition and efforts made by the company Turboden (Italy) to apply ORC technology to community-scale biomass plants have opened up a new market of biomass combined heat and power (BCHP) applications. However, the design of a BCHP system requires careful preparation. Jenkins [1] presented an optimal sizing methodology for a biomass utilization facility and the author considered constant and variable economy-of-scale investment cost scaling as well as costs for collection and transportation of biomass. Perlack et al. [2] presented a probabilistic approach to optimal biomass power plant design considering multiple normally distributed biomass costs and proposed a profitability index distribution. The index is the net present value divided by the total investment and can be used for investment decisions. A similar study was conducted by D'Ovidio and Pagano [3]. Taljan et al. [4] presented a model for optimal sizing of biomass-fired ORC CHP system with heat storage. The proposed BCHP setup with heat storage is shown not to be economically viable and their results show that an ORC plant without heat storage is viable when annual heat demands are higher than 5 GWh and biomass prices are lower than 17 EUR/MWh. Kumar et al. [5] assessed biomass power cost of an agricultural residues-, whole forest biomass- and forest harvest residues-fired power plant in Western Canada. The results show that the whole forest biomass, straw and forest harvest residues could generate power at the price levels of 47 $/MWh, 50 $/MWh and 63 $/MWh, respectively, at the time when their study took place. Their study assumed a remote location of the plant and did not consider heat sales, which should have improved the economics of the plant on a populated location. A district or community-scale BCHP plant size may be smaller than the most cost-effective size of a biomass power plant. However, actual cases show certain flatness in the profile of power cost vs. plant capacity. This is due to the fact that the reduction in capital cost per unit capacity with rising capacity is offset by increasing biomass transportation cost since the area where biomass is acquired increases. This means that smaller than optimum plants (e.g. medium scale applications or district heating) can be built with only a minor cost penalty. Meinel et al. [6] conducted economic comparison of ORC processes at different scales and highlighted thermodynamic and economic benefits of the investigated regenerative pre-heating process. Working fluids pay an important role in the performance of ORC systems, the sizes of the system components, the design of expansion machine and cost. Recently, a refrigerant R1233zd had been introduced as a low GWP ORC working fluid [7]. This fluid was used as a drop-in for R245fa into a 75 kW variable-speed ORC system. Mikielewicz and Mikielewicz [8] proposed a thermodynamic criterion to select the most suitable working fluids for small-scale ORC-based CHP units. Different working fluids were comparatively assessed by Tchanche et al [9] with regards to efficiency, volume flow rate, mass flow rate, pressure ratio, toxicity, flammability, ODP and GWP, and it has been reported that R134a and R152a seem to be the most suitable for low temperature ORC applications.

In this study, ORC-based BCHP for district or community-scale applications is investigated concerning technical and economic aspects. A mathematical model for a district-scale BCHP system has been developed to evaluate its operational performance. Specific investment cost for the BCHP plant is estimated and various costs for the BCHP plant are analyzed. The cost of electricity (COE) of the BCHP plant is calculated as well.

II. ORC-BASED BCHP PLANT AND MODELING

Figure 1 shows the basic configuration of an ORC BCHP system. The working fluid is preheated in the economizer and evaporated in the evaporator. The vapour of working fluid enters the turbine and it spins a generator. The low-pressure vapour exhausted from the turbine enters the condenser. The condensation takes place in the water-cooled condenser where the vapour's heat is transferred to circulating water that is subsequently used for district heating. The recuperator is used to recover a portion of heat from the vapour of working fluid exhausted from the turbine. And then, the low-pressure vapour is condensed, pressurized and directed to the economizer. The cooling water loop is operated close to the desired temperatures and a control system independent from the turbine controls the water loop. The biomass-fired boiler transfers the heat content in the combustion gas to thermal oil. The thermal oil is used as a medium to transfer the combustion heat to the ORC. The outlet temperature of the thermal oil directed to the ORC can rise up to 310°C, due to the use of high quality synthetic oil such as the one consisting of diphenyl and diphenylether. The thermal oil boiler can have different configurations. A traditional and still effective solution consists of a coil as radiant section with the hot gas passing in the center, while the convective section is composed of concentric coils with the hot gas passing in the center and between them. The main advantage of the thermal oil boiler using coils is the high reliability with a wide range of low quality biomass [10].

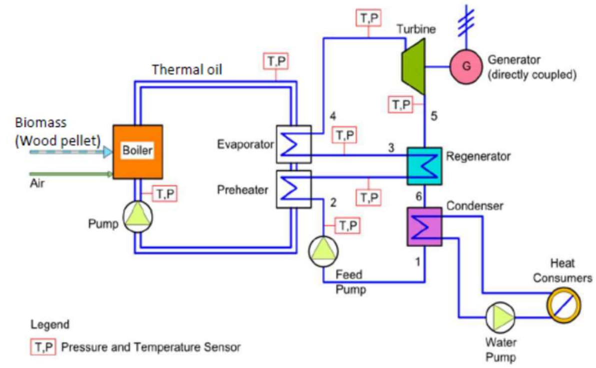

Figure 1. Schematic diagram of a BCHP system using ORC

District heating needs an installed thermal capacity which will be fully used during the peak hours in cold winters. The rest of the time the thermal demand will be partial. Therefore, a thermal demand should be found. For instance, the excess thermal energy produced by the BCHP during the summer could be used for a pellet production process. In this way, it would be possible to operate the plant at full load for 7500 (or more) hours per year. Such an operation is of interest since the produced pellets during the summer could be used to feed additional thermal users in the following winter [10].

The ORC efficiency can be derived based on the energy balance in the system. The work done by the pump is given by

$$W_{pump} = \dot{m}(h_2 - h_1)/\eta_{pump} \tag{1}$$

where η_{pump} is the pump efficiency, h is the working fluid enthalpy and $\dot{m}$ is the working fluid mass flow rate. The heat transferred to the ORC working fluid in the evaporator is

$$Q_{ev} = \dot{m}(h_4 - h_3) \tag{2}$$

The high-pressure vapor expands through the turbine, generating power. Ideally, this should be an isentropic process 4–5s. However, in practice, the process is not an isentropic one. In other words, the efficiency of the energy conversion in the turbine device cannot reach 100%. The state of the working fluid at the exit of the turbine is represented by 5. The power generated by the turbine is

$$W_t = \dot{m}(h_4 - h_{5s})\eta_s \eta_{me} = \dot{m}(h_4 - h_5)\eta_{me} \tag{3}$$

where η_s is the isentropic efficiency of the turbine device and η_{me} is the turbine's mechanical efficiency. η_s can be expressed as

$$\eta_s = \frac{h_4 - h_5}{h_4 - h_{5s}} \tag{4}$$

The vapor after the expansion process enters a condenser where it is condensed at a constant low pressure to become a saturated liquid (Process 6 to 1).

The net cycle electrical efficiency is then obtained from

$$\eta_{cyc} = \frac{W_{out}}{Q_{in}} = \frac{W_t - W_{feedpump} - W_{waterpump}}{Q_{in}} \tag{5}$$

where Q_{in} is the heat input, W_{out} is the net power output, W_t is the total power output, $W_{feedpump}$ is the working fluid pump power consumption and $W_{waterpump}$ is the water pump power consumption. The energy utilization efficiency is defined as:

$$\eta_{sys} = \frac{W_{out}+Q_{out}}{Q_{fuel}} = \frac{Q_{fuel}-Q_{loss}}{Q_{fuel}} \times \frac{W_{out}+Q_{out}}{Q_{in}} = \eta_{boiler}(\eta_{cyc} + \eta_{heat}) \tag{6}$$

where Q_{loss} is the boiler heat losses, Q_{fuel} is the fuel combustion heat, η_{boiler} is the efficiency of the boiler and η_{heat} is the efficiency of the BCHP heat production.

In this study, MDM (Octamethyltrisiloxane**)** is selected as the working fluid in the biomass-fired ORC system, taking into account the potential cycle efficiency, process design and turbine design. With MDM being the ORC fluid, it is relatively straightforward to design a turbine with a low rotational speed. MDM is classified as a linear siloxane with the molecular formula of $C_8H_{24}O_2Si_3$ and has a critical pressure of 14.2 bar and a critical temperature of 290.9 °C. For given operating conditions, heat transfer coefficients, working fluid properties and turbine parameters, the aforementioned equations can be solved for power output and efficiency. In the present study, the ORC process has been simulated using the software IPSEpro. Figure 2 shows the model for the ORC of the BCHP plant.

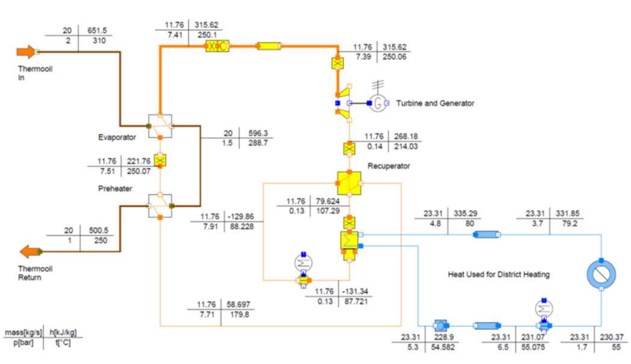

Figure 2. Schematic diagram of the model for the ORC of the BCHP plant

III. ECONOMIC ANALYSIS.

For a sustainable future, an electricity generation system must be environmental friendly and cost-effective as well. The economic analysis of the BCHP system has been conducted in this research. It is known that the specific investment cost for an ORC-based BCHP plant varies with the plant capacity. It is worth noting that Turboden has developed a biomass-fired ORC with a 600 kW electric and 2.4 MW thermal plant. Turboden, a Mitsubishi Heavy Industries group company, is an Italian firm and a global leader in designing and manufacturing ORC systems that are very suitable for distributed power generation. For a community-scale BCHP plant with an average thermal demand of 2-2.5 MW_{th} and an electrical power output of 500-750kWe, the specific investment costs is estimated at 3560$/kWe [6].

The cost of electricity (COE) for a power generation plant can be estimated using the following expression:

$$COE = \frac{C_{capital} + C_{O\&M} + C_{fuel} + C_{disposal}}{tW_{out}} \tag{7}$$

where $C_{capital}$ is the annual capital cost, $C_{O\&M}$ is the annual operating and maintenance costs, C_{fuel} is the annual fuel (biomass) cost of the combined cycle power unit, $C_{disposal}$ is the annual ash disposal cost and t is the annual operation time. The annual capital cost is calculated from:

$$C_{capital} = C_{RF} C_{investment} \tag{8}$$

where $C_{investment}$ is the total investment cost of the power plant including equipment and installation, C_{RF} is the capital recovery factor which is defined as the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. With an interest rate i, the capital recovery factor is

$$C_{RF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{9}$$

with n being the expected power plant lifetime, i.e., the number of annuities received. Costs involved in the equipment, construction, operation and maintenance of the BCHP plant outlined above have been estimated based on the obtainable data [4-6].

IV. RESULTS AND DISCUSSIONS.

A. *ORC BCHP performance*

The ORC-based BCHP plant with MDM used as the working fluid has been simulated using the software IPSEpro. Simulations were performed on the assumption that thermal oil temperature at the inlet to the ORC module is constant. The influences of certain key operating conditions on the performance have been examined. Table 1 presents the values of the main variables and the modeling results. The BCHP plant generates 520.9 kWe electricity with the electrical efficiency reaching 17.24 % at a turbine inlet temperature of

250 °C. The BCHP plant provides hot water at a temperature of 79.2 °C for district heating with a heating consumption of 2365.7kW$_{th}$ at the typical operating conditions being considered.

TABLE 1. THE VALUES OF MAIN VARIABLES AND MODELING RESULTS

Parameter	Value	Unit
Turbine inlet temperature	250	°C
Turbine enthalpy drop	557.8	[kW]
Cycle electricity power output	541	kW
Net electricity power output	520.9	kW
Internal power consumption	20.19	kW
HRVG heat input	3020.5	kW
Gross cycle electricity efficiency	17.91	%
Net cycle electricity efficiency	17.24	%
Energy utilization efficiency	87.4	%
Condenser duty	2480.2	kW
District heating consumption	2365.7	kW
Heating water outlet temperature	79.2	°C
Turbine mass flow	11.8	kg/s
Turbine inlet volumetric flow	197.4	l/s
Turbine outlet volumetric flow	14295.6	l/s
Thermal oil inlet volumetric flow	85.3	m^3/h

Figure 3 shows the modelling results of the electric efficiency as a function of turbine inlet temperature when using MDM as the ORC working fluid. The efficiency increases with the turbine inlet temperature due to a rise in enthalpy drop through the turbine. The electric efficiency increases from 15.6% to 21.1% as the turbine inlet temperature rises from 210°C to 285°C. As a result, a higher-grade heat source will improve the electric efficiency and power output as well. Figure 4 presents the relation between the electric efficiency of the BCHP system and heating hot water outlet temperature. The electric efficiency of the system is quite sensitive to the variations of the heating network temperature. The electric efficiency decreases as the supply water temperature increases, resulting from an elevated working fluid temperature and pressure in the condenser. This leads to a lower expansion pressure ratio. It should be noted that electricity selling price varies during the day. Usually, the production of electricity from biomass could receive financial support whereas the production of heat may not be supported. Hence, the stabilization of the operating conditions of the condenser is important to annual energy and economic performance of the plant.

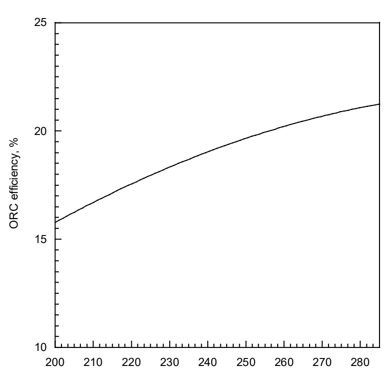

Figure 3. Modeling results of the ORC efficiency as a function of turbine inlet temperature.

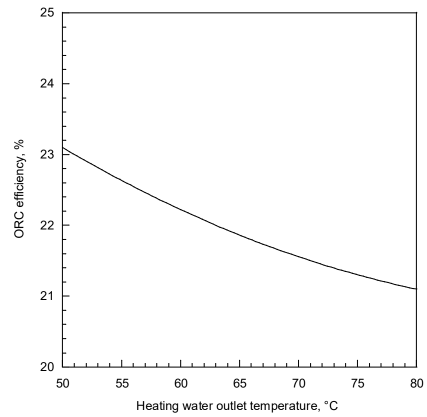

Figure 4. Modeling results of the ORC efficiencies as a function of heating water outlet temperature.

B. *Cost characteristics*

Table 2 presents the cost characteristics and COE for the ORC BCHP. The annual capital cost was calculated from Equations (8) and (9). Here, the interest rate is assumed to be 3.5% and expected power plant lifetime to be 25 years. The investment cost for the BCHP plant is calculated at 1851.2 k$. The COE that is obtained from Equation (7) is 98.2 $/MWh.

TABLE 2 COST CHARACTERISTICS AND COST OF ELECTRICITY (COE) FOR THE ORC BCHP PLANT

Item	Description	Value	$/MWh
1	Investment cost,	1851.2 k$	/
2	Annual capital cost,	112.3 k$/y	28.8
3	O&M	74.9 k$/y	25.6
4	Biomass cost*	217.4 k$/y	41.8
5	Ash disposal cost	7.8 k$/y	2
6	Total annual cost	411.7 k$/y	/
7	COE	/	98.2
8	Power output, kWe	520	
9	Thermal output for district heating, kW$_{th}$	2365	
10	Operating hours, h/y	7500	
10	Biomass capacity, ton/y	5430	

*Biomass price: 48$/ton biomass (5MWh), or 9.6$/MWh

It is noted that the COE of 98.2 $/MWh from biomass does not appear economic at this time but would become so when the value of produced heat and increasing carbon credits are considered. An important parameter that affects the overall economics of a BCHP plant is the biomass cost or the biomass market price. Table 2 indicates that the biomass price affects the COE to a large extent. The biomass mainly include whole forest biomass, straw and forest residues. Several factors will affect the biomass price including transportation cost, biomass yield, heating value, nutrient replacement cost for certain biomass fuels and BCHP capacity. Among them, biomass yield per gross hectare is a major factor in the cost of power from biomass. Figure 5 shows the average price of biomass feed stocks and its projection in the U.S. from 2017 to 2040 [10]. In this study, the biomass price is assumed to be 48$/ton (dry).

One dry ton biomass has an approximate heating value of 5MWh.

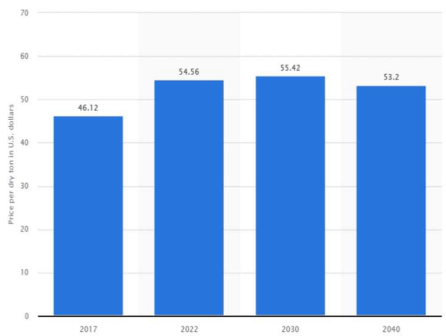

Figure 5. The average price of biomass feed stocks and its projection in the U.S. from 2017 to 2040 (in U.S. dollars per dry ton)

V. CONCLUSION

This study provides an ORC-based BCHP system design and simulation for community-scale applications. A mathematic model is built to predict the BCHP performance and optimize design and operation parameters. An ORC working fluid MDM (Octamethyltrisiloxane**)** that has a critical pressure of 14.2 bar and a critical temperature of 290.9 °C is selected in the ORC BCHP system with the cycle efficiency and system design taken into consideration. The key parameters considered include heat transfer characteristics, working fluid properties, cycle efficiency and costs for components and system. A higher-grade heat source is capable of improving the electric efficiency and power output. Therefore, the ORC efficiency increases with the temperature of working fluid at the turbine inlet. Simulations show the electric efficiency of the BCHP plant increases from 15.6% to 21.1% as the turbine inlet temperature rises from 210°C to 285°C. The community-scale BCHP plant generates 520.9 kWe electricity with the electric efficiency being 17.24 % at a turbine inlet temperature of 250 °C. The plant provides hot water at a temperature of 79.2 °C for district heating with a heating consumption of 2365.7kW_{th}. The obtained COE is 98.2 \$/MWh when not including CO_2 credit. The electricity generated from BCHP could receive financial support from the government but the heat production may not be supported. The excess thermal energy produced by the BCHP during the summer should be utilized as much as possible. For instance, the heat could be used for a pellet production process. The stabilization of the operating conditions of the condenser is important to the economic performance.

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