

## “ORGANIC RANKINE CYCLE (ORC) IN BIOMASS PLANTS: AN OVERVIEW ON DIFFERENT APPLICATIONS“

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**ABSTRACT:** The ORC technology in cogenerative systems has by now reached a level of full maturity in biomass applications. In Europe, there are over 120 plants in operation with sizes between 0.2 and 2.5 MW electric.

ORC systems are very flexible and can be used in different applications like district heating systems, pellet production factories, sawmills and tri-generation systems with absorption chillers.

In this article we summarize the possible application of ORC units in biomass field, focusing the attention on the possibility to use the ORC modules in processes that are not directly tie to electricity production like sawmills, pellet factories, district heating systems, etc. optimizing the global efficiency of the plant using the waste biomass coming from these existing production processes to produce, thanks to the ORC technology, hot water for internal use (belt driers, district heating, etc) and electricity.

With this target we have collected the results of different studies, presented in various exhibitions, in order to make an overview on the different biomass solutions with ORC modules.

### 1 ORC SYSTEM DESCRIPTION

Over the last 15 years the ORC turbogenerators has demonstrated to be a well proven industrial technology for application in small decentralized biomass CHP plants (0,2 – 2,5 MWe).

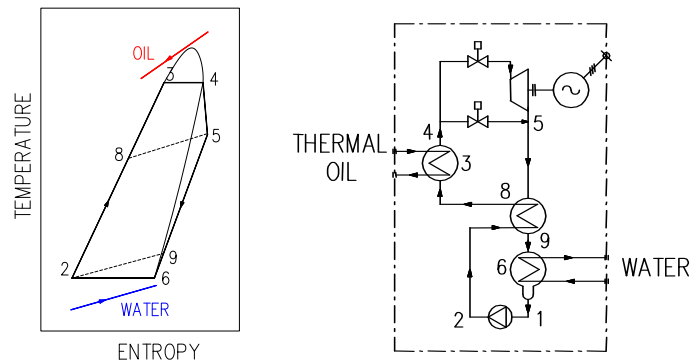
Typical systems are based on the following main items:

- biomass fuel is burned in a combustor made according to the well established techniques also in use for hot water boilers. These combustors with their set of accessories (filters, controls, automatic ash disposal and biomass feed mechanism etc.) are nowadays safe, reliable, clean and efficient;
- hot thermal oil is used as heat transfer medium, providing a number of advantages, including low pressure in boiler, large inertia and simple adaptability to load changes, automatic and safe control and operation. Moreover, the adopted temperature (about 310°C) for the hot side ensures a very long oil life. The utilization of a thermal oil boiler also allows operation without requiring the presence of licensed operators as for steam systems in many European countries;
- an Organic Rankine Cycle turbogenerator is used to convert the available heat to electricity. Thanks to the ORC, that is thanks to the use of a properly formulated working fluid and to the optimization of the machine design, both high efficiency and high reliability are obtained. The condensation heat of the turbogenerator is used to produce hot water at typically 80 – 120°C, a temperature level

suitable for district heating and other low temperature uses (i.e. wood drying and cooling through absorption chillers etc.).

The ORC unit is based on a closed Rankine cycle performed adopting a suitable organic fluid as working fluid. In the standard units for biomass cogeneration silicon oil is used as working fluid [1]. The first ORC adopting this fluid was tested in 1986 by Turboden.

The thermodynamic cycle and the relevant scheme of components are reported in Figure 1.



**Figure 1:** Thermodynamic cycle and components of an ORC unit

The turbogenerator uses the hot temperature thermal oil to pre-heat and vaporise a suitable organic working fluid in the evaporator (8→3→4).

The organic fluid vapour powers the turbine (4→5), which directly drives the electric generator through flexible coupling.

The exhaust vapour flows through the regenerator (5→9) where it heats the organic liquid (2→8).

Finally, the vapour is condensed in a water cooled condenser (9→6→1).

The organic fluid liquid is then pumped (1→2) to the regenerator and then to the evaporator, thus completing the sequence of operations in the closed-loop circuit.

Compared to other competing technologies (i.e. steam turbines), the main advantages obtained from the ORC technology are the following:

- high cycle efficiency (especially if used in cogeneration plants);
- very high turbine efficiency (in excess of 85%);
- low mechanical stress of the turbine, thanks to the low peripheral speed;
- low RPM of the turbine allowing the direct drive of the electric generator without reduction gear;
- no erosion of the turbine blades, thanks to the absence of moisture in the vapour nozzles;
- very long operational life of the machine due to the characteristics of the working fluid that, unlike steam, is non eroding and non corroding valve seats, tubing and turbine blades;
- no water treatment system is necessary.

There are also other relevant advantages, such as simple start-stop procedures, quiet operation, minimum maintenance requirements and good partial load performance [2]. The main advantage of ORC technology is that no particular qualification or know how is required for the personnel operating the CHP plant. This means that also customers without a specific background in electricity generation can easily evaluate an investment in a CHP plant using our ORC turbogenerator.

Due to these main reasons the standard range of ORC units is considered an optimal solution for small biomass cogeneration systems in the power range up to 3 MWeI per unit. This is confirmed by more than 120 ORC plants in operation for a total installed power of more than 120 MWeI that are showing very good results in terms of reliability (average availability of the ORC units > 98% over more than 2.000.000 hours of operation) and in terms of reduced operational and maintenance costs.

## 2 FEASIBILITY IN EXISTING DISTRICT HEATING NETWORKS [3]

Many large district heating networks are present in Northern Europe. The most common situation is an high temperature network fed by coal or gas, with the possibility of an increase of the efficiency revamping the existing network. In the last few years the most common activities proposed are the optimization of the grid for lower heating temperatures, the substitution of coal with cleaner energy sources (i.e. gas or biomass) and the installation of CHP solutions in grids where heat only solutions exist.

The flexibility of the ORC allows to work at partial load, down to 10% of the nominal thermal load, in order to follow the heat requested by the grid. Another operation scheme is to supply the base load that the grid needs during the year with the thermal output of the ORC and to cover the peak loads with other boiler/boilers fed by biomass or others kind of fuels.

Starting from these assumptions the feasibility of the investment can be evaluated according to the biomass cost and the remuneration for the electric energy produced.

An example of sensitivity of PBT is reported here below, showing the influence of the selling price of the electric energy.

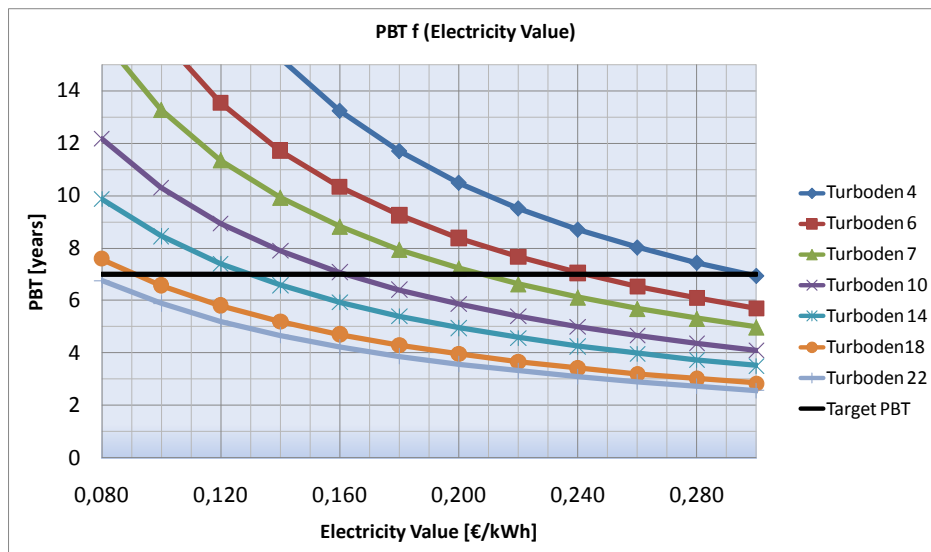
Main assumptions for the examples are:

	Boiler	ORC
Own consumption	3%	
Thermal efficiency	87%	80%
Net Electric efficiency	-	18%
Thermal and electric losses		2%
Value of electric energy	140 €/MWh	
Biomass humidity	40%	
Biomass lower heating value	2,9 kWh/kg	
Value of thermal energy supplied	30 €/MWh	
Biomass price	10 €/MWh lower heating value	
Annual average number of full load operational hours	5500 h/year	
Water outlet temperature from CHP system	90°C	

**Table 1:** Main assumptions for boiler and ORC unit

### 2.1 Sensitivity to variations in electricity value

The variations of this very important factor for a cogeneration plant are mainly linked to the Country where the plant is built. This is due to the different incentive schemes for green electricity production implemented in different Countries and, in Countries where no incentive schemes for the production of green electricity are adopted, to the different value of electricity on the national market. Figure 2 shows the discounted payback time depending on the cogeneration plant size and for values of the produced electric energy between 8 and 28 €/kWh.



**Figure 2:** Influence of the electricity value on the PBT of the cogeneration plant

Figure 2 shows that, entering the diagram with a given electricity value, the achievement of a project feasibility acceptable for bank financing depends strongly on the plant size, because of its strong influence on the specific investment costs.

### 2.2 Influence of additional heat used by absorption chiller on plant feasibility [4]

The use of chillers for air-conditioning of residential and commercial buildings is leading to a rapid increase in the electrical load during summer months. Consequences include a need for additional installed electric power (the yearly peak power request is shifting from winter to summer) and increase in CO<sub>2</sub> emissions. Absorption chillers are a mature technical solution that allow to use heat instead of electricity to produce cold water for space cooling. In particular, single stage absorption chillers allow to use hot water at about 90°C for cooling purposes.

With this background, trigeneration projects based on absorption chillers are an interesting alternative to traditional chiller plants because they give the possibility to add an important heat user during the “non-peak” season, achieving a much better distribution of the yearly heat load. From a strategic point of view these plants are particularly interesting because they substitute a valuable electric energy consumption, due to compressor chillers, with an easily available thermal energy consumption required by absorption chiller.

### 2.3 Real case: Ostrow wielkopolski [3]

The district heating plant of the Polish city of Ostrow Wielkopolski serves the city of Ostrow through a 50 km long grid. The heating energy requested by the network is about 190 GWh/year. The users are mainly residential buildings but about 10% of the heat is supplied to industrial customers.

The heating plant was based on 5 coal boilers rated 12 MW<sub>th</sub> each and on 2 natural gas peak load boilers rated 15 MW<sub>th</sub> each. In 2000 a gas Turbine rated 5,2 MW<sub>el</sub> and 11,6 MW<sub>th</sub> was added in order to cover the base load and increase both energetic and economical performance of the heating plant. In 2005 the possibility to add a Biomass cogeneration system was evaluated. Different technical solutions (steam turbine, gasification system, ORC system) and plant sizes were carefully evaluated and a solution based on a 1,5 MW<sub>el</sub> ORC unit was selected. The economical feasibility, the ease of operation, the high reliability of the ORC solution, and the high number of references in Europe in this

plant size where the main reasons for this decision. It was decided to dismantle one of the coal boilers and to substitute it with the new biomass cogeneration system. The investor decided to apply for a grant from the polish Ecofund.

The nominal data of the ORC unit are the following:

- total input power from Thermal oil: 10000 kWth
- gross electric power: 1750 kWel
- net electric power: 1670 kWel
- Thermal power to hot water: 8200 kWth
- Hot water temperatures: 60/85°C
- Net electric efficiency: 16,7 %

The new cogeneration plant was put into operation in September 2007 and is in successful operation since then.

### **3 APPLICATION OF ORC UNITS IN THE PELLETT PRODUCTION FIELD [5]**

Different configurations of wood pellet plants based on biomass combustion can be used coupled with ORC units.

The biomass fired combustion system of a typical pellet production plant is usually fed with raw material such as bark and low quality wood chips coming from sawmill and wood processing industry close to the pellet plant.

Wood pellets are manufactured from untreated wood wastes, mostly sawdust and shavings, without any addition of chemical gluing agent.

After a preliminary sorting process, only wood material which respects tight quality standards and with a suitable granulometry flows into the dryer, where evaporation of sawdust water content takes place.

From a technical point of view the different drying technologies are usually based on the generation of a hot drying air or gas stream which comes in contact directly with the wet material, drying it up to the optimal moisture content required by the following stages of pellet pressing process.

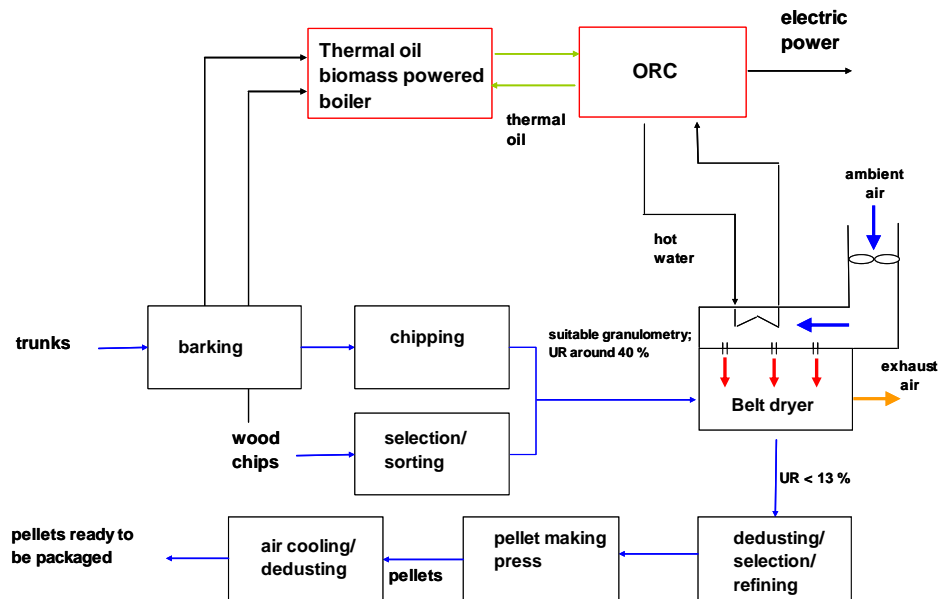
#### *3.1 CHP plant with ORC units coupled to belt dryers*

Depending on market boundary conditions, a CHP solution within a pellet manufacturing plant can be profitable. In the following part of this article a CHP solution based on biomass ORC unit and belt dryer is described.

A typical pellet production plant based on a biomass combustion system and an ORC unit does not lead to significant changes to conventional heat only plant for pellet production with belt dryer.

This means that, in addition to the new installation of CHP biomass pellet plant, retrofitting of already existing pellet plant based on hot water boiler coupled to belt dryer can easily be implemented as well, just replacing hot water boiler with thermal oil boiler feeding ORC unit. Hot water will be actually available downstream the ORC condenser.

In Figure 3 a block diagram of the process performed in a CHP biomass plant for pellet production based on belt drying system and ORC unit is shown.



**Figure 3** Schematic diagram of a CHP biomass plant for pellet production based on belt dryer coupled to an ORC unit.

## 4 APPLICATION OF ORC UNITS IN SAWMILLS [6]

A typical application in sawmills with drying chambers based on a biomass combustion system and an ORC unit is reported.

This application of ORC units is particularly interesting because additional income can be obtained from electricity generated by the ORC unit without significant changes to the typical sawmill. Part of the electricity generated is used for the own consumption of the plant and the remaining part is sold to the grid, according to the market conditions about electricity value and possible subsidies (Green Certificates or feed-in tariffs) for renewable energy applied in the different countries. For this reason many of the new sawmill plants recently built or under construction are based on CHP solutions with ORC units.

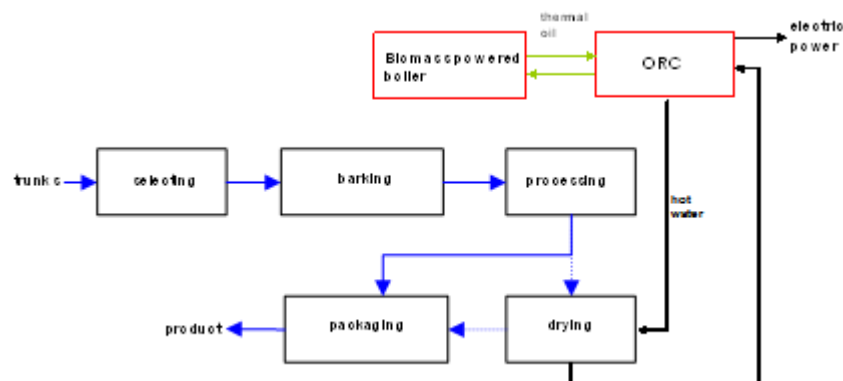
### 4.1 CHP plants with ORC units coupled to drying chambers in sawmills

Depending on market boundary conditions, a biomass CHP solution within a drying chamber plant can be profitable. In the following part of this paper a CHP solution based on biomass ORC units and drying chambers is shown.

A typical application in sawmills with drying chambers based on a biomass combustion system and an ORC unit does not lead to significant changes in conventional heat only solutions.

This means that retrofitting of already existing drying chambers plant based on a hot water boiler can easily be implemented as well, just replacing the hot water boiler (fed by natural gas or biomass) with a biomass boiler heating thermal oil in order to feed an ORC unit. Hot water will be available downstream the ORC condenser.

Figure 4 shows a block diagram of the process that occurs in a CHP biomass plant for sawmills based on drying chambers and an ORC unit.



**Figure 4** Schematic diagram of a CHP biomass plant for sawmills with drying chambers and an ORC unit.

## 5 APPLICATION OF ORC IN THE MDF AND PARTICLEBOARD SECTOR [7]

In MDF production plants the heat request of the process is often covered partly or completely by large biomass boilers using waste material from the production process as fuel. The heat is used mainly as thermal oil for the presses and as hot combustion gases for fiber drying. The integration of the ORC in the MDF production process will be analysed in particular considering the possibilities of using the thermal power available downstream the ORC units inside the process, therefore obtaining an operation in CHP mode.

### 5.1 Cogeneration with ORC units in MDF plants

The MDF process also has a high internal consumption of electricity mainly for the chipping and refining of the raw material. This makes the possibility of biomass CHP production particularly attractive not only in countries where subsidies for renewable energy production are available but also in countries where it just helps to reduce the electricity purchase costs for the plant own demand. This possibility has been seldom exploited in MDF plants due to the fact that biomass cogeneration systems based on the traditional steam process require high pressure generators that would lead to a complication of the process. Furthermore the typical size where steam plants are economically competitive ( $> 5 \text{ MW}_{el}$ ) leads in most cases to mainly non cogenerative process schemes because the available heat downstream the CHP plant is too high to be used completely inside the process.

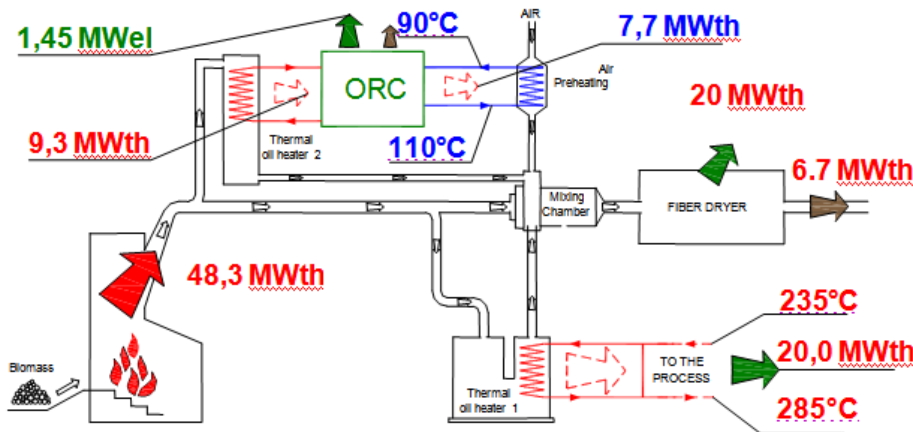
### 5.2 Process scheme with ORC unit

With reference to the following Figure 5 the proposed process scheme is based mainly on the following additional components :

- An additional thermal oil heater placed in parallel to the main heater and to the flue gas bypass that leads directly to the mixing chamber .
- A standard ORC unit
- A hot water/air heat exchanger used to preheat the air supplied to the mixing chamber.

Figure 5 illustrates the proposed scheme for a typical system with the same process requirements ( $20 \text{ MW}_{th}$  for drying and  $20 \text{ MW}_{th}$  for process heat users) assumed for an hypothetical base case without ORC. The operating conditions allow to transfer about  $7,7 \text{ MW}_{th}$  to the ambient air before the mixing chamber in the case of a hot water temperature of  $110^{\circ}\text{C}$  at ORC outlet and a pinch point of  $10^{\circ}\text{C}$  in

the hot water air heat exchanger. Assuming thermal oil temperatures of 300/250 °C at ORC inlet/outlet a net electric power of 1,45 MW<sub>el</sub> can be produced by the ORC unit in completely heat driven operation (CHP mode).



**Figure 5:** Proposed scheme for energy plant with ORC cogeneration unit in Metso Panelboard factory [10]

## 6 CONCLUSIONS

This paper shows that biomass cogeneration systems based on ORC units can have a good feasibility with frame conditions typical for the whole European area. The electricity value required in order to reach feasibility compatible with bank financing of these projects is around 10 €/kWh for plants with installed power above 1,5 MW<sub>el</sub>. Therefore projects in this scale can be feasible under normal frame conditions in most European countries. Plants in the range around 1 MW<sub>el</sub> are also feasible with the electricity values around 14 €/kWh, that can be achieved with support schemes for renewable electricity generation implemented in different European countries. In general it can be observed that the required electricity value increases steeply with lower size plants therefore higher guaranteed electricity values are required in order to exploit also more distributed renewable cogeneration.

The flexibility of ORC also permits a large kind of CHP applications, as shown in this paper, mainly in district heating and in the wood industry. This mean that wood industries can use waste wood, coming from internal process, to feed biomass boiler increasing the global efficiency of the factory using the hot water coming from the ORC for the production processes instead of using fossil fuels; in the same way biomass boiler coupled with an ORC can replace fossil fuel systems in already district heating grids with big benefits for the environment.

For the actual average European specific emissions of CO<sub>2</sub> for electricity generation, biomass cogeneration is the heat supplier that promises the highest emissions reduction. The advantage of biomass cogeneration towards other heat supply solutions will increase in the future when specific emissions of CO<sub>2</sub> for electricity generation will decrease.

The real cases described in this paper shows that ORC is a mature and reliable technology with an high level of flexibility due to the possibility to being integrated in already existing grid or industrial processes.

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