

“Technical and economic aspects of Biomass fuelled CHP plants based on ORC turbogenerators feeding existing district heating networks “

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ABSTRACT

In the last 10 years the TURBODEN ORC technology applied in small size (0.4 – 2.2 MWe) CHP biomass plants has demonstrated to be a ripe industrial product with exceptional results in terms of reliability, ease of operation, low maintenance together with a good conversion efficiency allowing to implement cost effective plants.

The concept is based on modular plants using thermal oil as heat source with feeding temperature around 300°C and delivering heat at a temperature level between 80 and 120°C to heat users.

The company Turboden s.r.l., world leader in biomass fired ORC applications, has installed more than 50 turbogenerators feeding district heating networks in Central, Southern and Eastern Europe.

In Europe many large district heating plants powered with various fossil fuels (mainly coal, heavy oil and gas) are in operation. In this paper the economic feasibility of the addition of a biomass fuelled cogeneration plant with ORC technology as a heat source covering the base load in existing district heating plants is discussed. The study is based on an “incremental economic feasibility” approach that considers additional investment costs and incomes for the CHP solution in comparison with the existing heat supply solution.

The sensitivity of the economic results to the main parameters (biomass price, full load operating hours, electricity, heat sales prices and plant size) will be analyzed.

Furthermore a relation between both peak thermal power and yearly energy requested by the district heating network and the full load operating hours will be presented.

Also the environmental benefits of Biomass CHP will be presented in particular in terms of CO₂ emission reductions depending on the substituted fuel mix.

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BIOMASS COGENERATION SYSTEMS BASED ON TURBODEN ORC UNITS: HISTORY AND SYSTEM DESCRIPTION

Over the last 10 years the ORC technology has demonstrated to be a well proven industrial product for application in small decentralized biomass CHP plants (0,4 – 2,2 MWel).

Typical systems are based on the following main steps:

- 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, 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 insensitivity to load changes, simple and safe control and operation. Moreover, the adopted hot side temperature (below 315°C) ensures a long oil life. The utilization of a thermal oil boiler also allows operation without the presence of licensed operators as requested for steam systems in many European countries;

- an Organic Rankine Cycle turbogenerator is used to convert the available heat into electricity. Thanks to the Turboden ORC technology both high efficiency and high reliability are obtained: this could be obtained by using a properly formulated working fluid and by optimizing the machine design. The condensation heat of the turbogenerator is used to produce hot water at a temperature between 80 and 120°C, a level suitable for district heating and other low temperature uses (i.e. wood drying in drying chambers, sawdust drying in belt driers, 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 developed by Turboden 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.

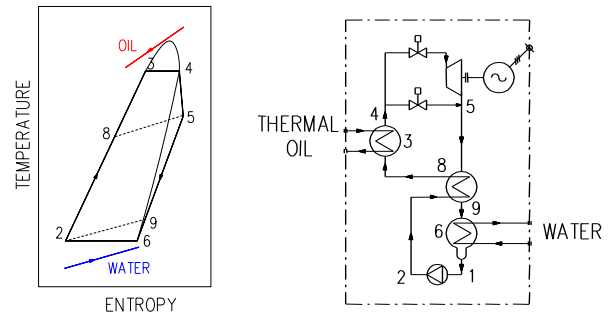


Figure 1: Thermodynamic cycle and components of an ORC unit

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

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

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

Finally, the vapor 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.

This ORC unit shows the following favorable characteristics:

- High cycle efficiency (especially if used in cogeneration plants);
- Very high turbine efficiency (up to 90%)
- 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, due to the absence of moisture in the vapor nozzles
- Very long operational life of the machine

- No water treatment system is necessary.
- Automatic operation of plants without need of onsite attendance by licensed operators.

There are also other advantages, such as simple start-stop procedures, quiet operation, minimum maintenance requirements and good partial load performance [2].

Currently there are 90 Turboden biomass fed ORC plants for CHP (Combined Heat and Power) in operation, mostly in Germany, Austria and Italy. Further 30 plants are under construction. The Turboden ORC modules have demonstrate an availability greater than 98 % and more than 2.000.000 operating hours have been reached.

FEASIBILITY IN EXISTING DISTRICT HEATING NETWORKS

Many large district heating networks are present in Central, Northern and Eastern Europe. The most common situation is a high temperature network fed by coal or gas, with possibilities of increase of efficiency with revamping of the existing network and the old boiler systems. In the last few years the most common activities proposed in this field are the optimization of the network 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. In this paragraph the possibility to install a biomass cogeneration system with ORC technology in an existing district heating network is analyzed from a technical and economical point of view.

Method of investigation and main assumptions

The economical investigations in this article are based on the method of discounted cash flow. The economical parameter used in the comparison of the different solutions is the discounted payback time. Only the investment cost of the total biomass power plant was considered, without taking into account the price of the district heating network. This assumption reflects the case of revamping an already existing power plant or permits to evaluate different solutions independently from

the length and the special conditions (e.g. pumping levels differences, soil composition) present in different networks.

The main assumptions considered:

Biomass cost:

The wood used is usually bark, sawdust, and wood chips with high humidity levels. Transport costs have a high impact on the cost of biomass. The amount of wood required by plants in the power range between 500 and 2000 kW_{el} (10.000 – 50.000 t/year) can be usually sourced locally. Therefore the assumed value of 10 €/MWh¹ is a reasonable value for areas where unused biomass resources exist.

Thermal energy value:

Due to the fact that a part of the required thermal energy is provided by the biomass cogeneration plant with ORC technology, the value of thermal energy used as input was calculated as the avoided cost in the existing heating plant. Main avoided costs that were here considered are the saved fuel and avoided variable operation and maintenance costs. The value used in this paper is 3,0 €/kW_{th}, which is an average value considering to substitute natural gas as primary fuel.

Electricity value:

The value of the electricity production considered takes into account both the sales value (or avoided costs for own consumption of the heating plant and district heating network operation) and incentives for renewable energy production or energy efficiency (feed in tariffs, green certificates, efficiency certificates and CO₂ certificates from ETS as applicable in the specific site). As base value of electricity 14 €/kWh has been assumed. This value is an average value of typical frame conditions in Europe.

Full load operation hours:

The assumed value of full load operation hours (6000 h/year) is consistent with the assumption

¹ This value corresponds to 25 €/t considering an average lower heating value of 2,5 kWh/kg. This value is referred to low quality biomass at high humidity level (about 40%). With lower humidity levels (about 10%) an average lower heating value of 4 kWh/kg can be considered, with a corresponding value of 40 €/t.

that the biomass cogeneration system based on ORC technology is designed in order to cover the base load of a big district heating network in Europe.

Hot water feeding temperature:

The assumed hot water feeding temperature of 90°C from the biomass cogeneration unit can usually suit a network working with hot water feeding temperature at higher levels in winter, when peak loads are reached. This can be reached in multiple heat source heating plants when the cogeneration system is placed directly on the hot water return with the other boilers placed in series.

Operation and maintenance costs

On the basis of existing plants, the expected personnel driving the biomass boiler and ORC plant can be assumed as one worker, added to the personnel working in the existing power plants. Thus the operation costs have been considered as a fixed value of about 30.000€.

The maintenance costs have been calculated as one per cent of the total investment costs.

Investment grants:

All financial calculations have been made without considering the possibility of investment grants. In many actual cases the economical results of the investment in a biomass cogeneration system can be considerably improved if access to investment grants either from the local government or from EU structural funds (up to 40% investment grant are a typical value for this case) can be achieved.

Target payback time:

Of course in the decision on the financing of a project also other factors play an important role. Above all the risk associated to the project (variability of the key economical frame conditions such as value of electricity, heat and biomass cost, technological risk, financial strength of the investor, own capital, etc.). In this analysis a PBT time of 7 years as target value has been considered. This reflects the fact that cogeneration plants based on Turboden ORC units are a mature and proven technology and with the assumption that the main economical values have been fixed for a time frame longer than the target payback time by the investor. The heat load of the district heating (and therefore the full load operating hours in

heat driven operation) can normally be supported by historical values, the electricity value is either guaranteed by law or should be defined in a long term contract . Heat value and biomass cost should also be fixed by long term contracts.

Following please find a resuming table with the main assumptions:

| | Boiler | ORC |
|------------------------------------------------------|------------------------------|-------------------|
| Own consumption | 3 % ² | |
| Thermal efficiency | 87 % ³ | 80 % ⁴ |
| Net Electric efficiency | - | 18 % ⁵ |
| Thermal and electric losses | | 2% |
| Value of electric energy | 14 €/kWh | |
| 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 | 6000 h/year | |
| Water outlet temperature from CHP system | 90°C | |

Table 1: Main assumptions boiler and ORC unit

In the following table the assumed values for the evaluation of the approximate cost of the biomass power station (in €/kWel) are reported together with the calculated net electric power of the installation and the biomass consumption [kg/hour] for each standard size of Turboden ORC units.

² Ratio between electrical own consumption of boiler and thermal power supplied to thermal oil

³ Thermal efficiency of the boiler defined as ratio between thermal power output from thermal oil and thermal power input from biomass

⁴ Thermal efficiency of the ORC defined as ratio between thermal power output and thermal power input from thermal oil

⁵ Electric efficiency defined as the ratio between net electric power output after deduction of internal consumptions of the module and thermal power input from thermal oil

| | Price [€/kW _{el}] ⁶ | Net ⁷ power of CHP plant [kW _{el}] | Biomass consumption |
|----------------------|---------------------------------------------|------------------------------------------------------------------------|------------------------|
| Turboden 22 Split | Ca. 4500 €/kW _{el} | 1803 kW _{el} | 4753 kg/h |
| Turboden 18 Split | Ca. 4900€/kW _{el}] | 1469 kW _{el} | 3871 kg/h |
| Turboden 14 Split | Ca. 5900 €/kW _{el} | 1007 kW _{el} | 2655 kg/h |
| Turboden 10 Split | Ca. 6700 €/kW _{el} | 771 kW _{el} | 2032 kg/h |
| Turboden 7 Split | Ca. 7900 €/kW _{el} | 572 kW _{el} | 1508 kg/h |
| Turboden 6 Split | Ca. 8800 €/kW _{el} | 486 kW _{el} | 1281 kg/h |
| Turboden 4 Split | Ca. 10200 €/kW _{el} | 345 kW _{el} | 909 kg/h |

Table 2: Assumptions about costs and performances of power plant

Note: All evaluations in this paper are for a heat driven power plant. Discount rate and analysis period were the same for all cases (respectively 5% and 15 years).

Economical sensitivity analysis

The first important value influencing the economical feasibility of a biomass cogeneration plant is the plant size, due to the influence on the specific investment costs reported in table 2. Therefore in all the following sensitivity calculations the PBT is reported for all the plant sizes. In addition one of the main economical conditions (electricity value, thermal energy value, equivalent full load operation hours and biomass price) has been varied while all other parameters were kept constant.

⁶ Including ORC, biomass furnace, thermal oil boiler, fuel handling, civil works, connection to the grid, engineering

⁷The net electricity value has been considered as a the electric energy produced minus the ORC own consumption and thermal oil circuit own consumption.

Sensibility to variations of biomass value:

In the following table the biomass price was varied from 0 €/ton up to 20 €/MWh.

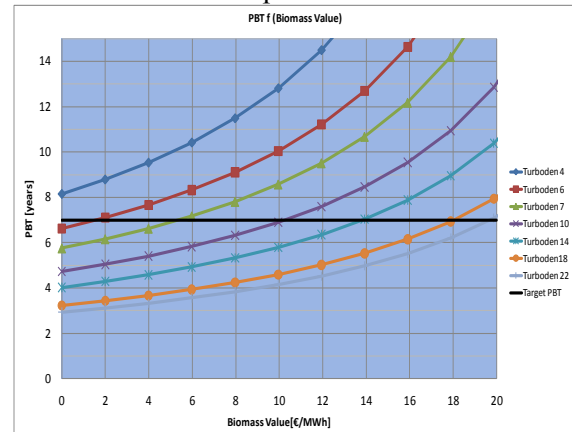


Figure 2: Influence of the biomass value on the PBT of the ORC plant

The figure shows that, using the assumptions described in the previous chapter, the maximum value of biomass considered in order to have a project feasibility acceptable for bank financing depends strongly on the plant size due to the strong influence of the size of this variable on the specific investment costs.

Considering a target payback time of 7 years, Figure 1 shows that:

- Plants with installed power between 1,5 and 2 MW_{el} are feasible until a biomass value of 18 €/ton (Turboden 18) and 20 €/MWh (Turboden 22)
- Plants with installed power between 1 and 1,5 MW_{el} are feasible until a biomass value of 14 €/ton (Turboden 14) and 11€/MWh (Turboden 10).
- Plants with installed power between 0,5 and 0,8 MW_{el} are feasible starting from an electricity value of between 5 €/ton (Turboden 7) and 2 €/ MWh (Turboden 6).
- The Turboden 4 unit cannot reach the target PBT with the considered conditions. The feasibility of this plant can be increased either with a higher valorization of electricity and/or with a higher value of the heat.

Sensibility to variations of full load operating hours:

In the following table the sensibility of the payback time to the variation of full load operation hours is presented. The value of the full load operating hours has been varied between 5000 hours and 8000 h/year. The first value can correspond to a district heating network built in South Europe (Mediterranean Area) and a 8000 h/year can be related to an existing district heating network in which the ORC cover the heat demand basis load (e.g. in revamping of existing bigger district heating network).

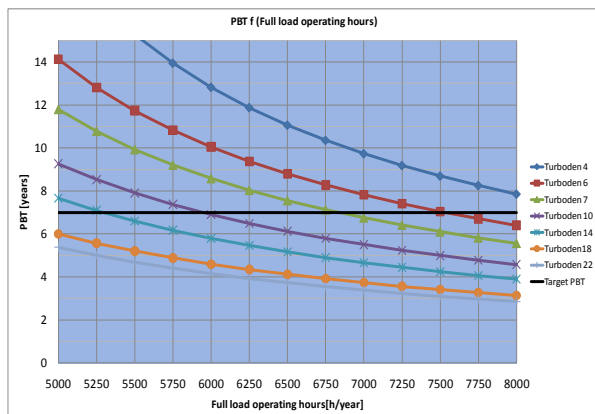


Figure 3: Influence of the full load operating hours on the PBT of the ORC plant

Considering, as above, a target payback time of 7 years, it can be noticed that:

- Plants with installed power between 1,5 and 2 MWeI are feasible also with lower full load operating hours. With 5000 full load operating hours per year they have a payback time of 5,4 years (TURBODEN 22) and 6 years (TURBODEN 18)
- Plants with installed power between 1 and 1,5 MWeI are feasible starting from 5250 full load operating hours per year (Turboden 14) and 6000 full load operating hours per year (Turboden 10).
- Plants with installed power between 0,5 and 0,8 MWeI are feasible starting from 6500 full load operating hours per year (Turboden 7) and 7500 full load operating hours per year (Turboden 6).
- The Turboden 4 unit needs higher electricity values or higher heat values in order to reach the target PBT

Sensibility to variations of electric power valorization:

The variations of this crucial value for a cogeneration plant are mainly linked to the country where the plant is realized. This is due to the different incentive schemes for green electricity production implemented in the different countries or to the different value of electricity on the national market for countries where no incentives are present. The following figure (Figure 3) shows the discounted payback time depending on the cogeneration plant size and with value of the produced electric energy between 4 and 28 €/kWh.

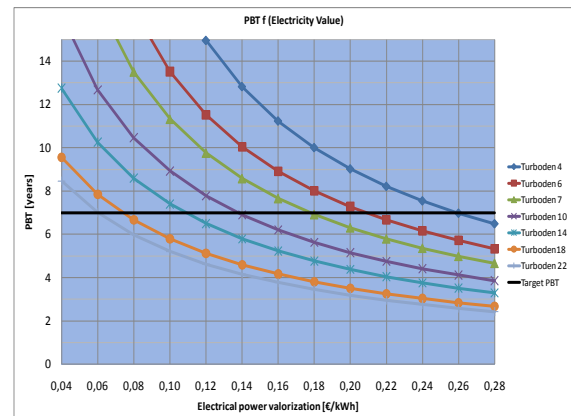


Figure 4: Influence of the electricity value on the PBT of the ORC plant

Considering, as above, a target payback time of 7 years it can be noticed that:

- Plants with installed power between 1,5 and 2 MWeI are feasible starting from an electricity value between 6 €/kWh (Turboden 22) and 8 €/kWh (Turboden 18)
- Plants with installed power between 1 and 1,5 MWeI are feasible starting from an electricity value of between 11 €/kWh (Turboden 14) and 14€/kWh (Turboden 10).
- Plants with installed power between 0,5 and 0,8 MWeI are feasible starting from an electricity value of between 18 €/kWh (Turboden 7) and 21 €/kWh (Turboden 6).
- The Turboden 4 unit needs an electricity value of 26 €/kWh in order to reach the target PBT

Sensibility to variations of thermal power valorization:

In the figure below the thermal power value is varied between 1,5 €/kWh and 7,5 €/kWh. The first value could correspond to the price of avoided costs in regions where biomass or gas are available in great quantities and at a low price compared to the European average. Values like 7,5 €/kWh could be considered in European regions where no fuels are available at average values.

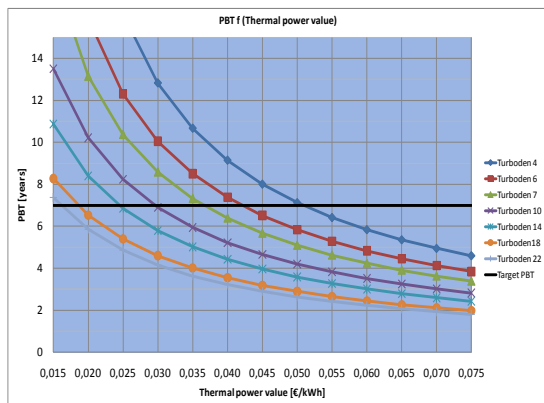


Figure 5: Influence of the thermal power value on the PBT of the ORC plant

The figure above (Figure 5) shows that the values of thermal energy has a strong impact on the feasibility of the plant.

Considering the target payback time of 7 years it can be noticed that:

- Plants with installed power between 1,5 and 2 MWel are feasible starting from an electricity value between 1,5 €/kWh (Turboden 22) and 2 €/kWh (Turboden 18)
- Plants with installed power between 1 and 1,5 MWel are feasible starting from an electricity value of between 2,5 €/kWh (Turboden 14) and 3 €/kWh (Turboden 10).
- Plants with installed power between 0,5 and 0,8 MWel are feasible starting from an electricity value of between 4 €/kWh (Turboden 7) and 4,5 €/kWh (Turboden 6).
- The Turboden 4 unit needs an electricity value of 5 €/kWh in order to reach the target PBT

RELATION BETWEEN BOTH PEAK THERMAL POWER AND YEARLY ENERGY REQUESTED BY THE DISTRICT HEATING NETWORK AND THE FULL LOAD OPERATING HOURS

The following figure (Figure 5) shows the relationship between full load operating hours and cumulated power of an existing district heating network for different ORC sizes.

The cumulated load curve used for this relationship reflects the heating load of a village in the Italian Alps, with mainly small domestic users.

The cumulated load curve was designed considering a fixed value for each months (given by the sum of the heat consumption of the whole village), with a daily variation with two major peaks, one in the morning and one in the evening that was kept constant for every month.

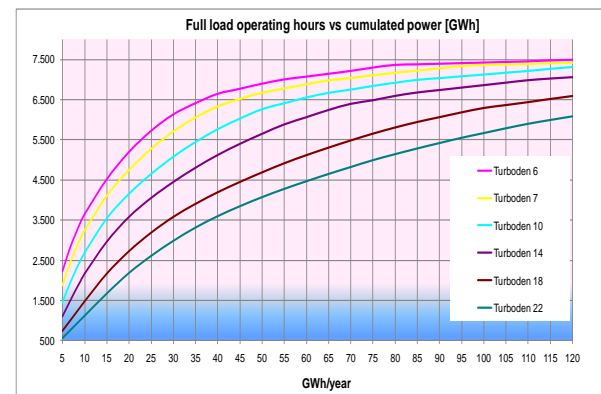


Figure 6: Full load operating hours vs. cumulated power

This relationship can be helpful to preliminarily dimension the size of the ORC to be implemented in district heating network for all alpine/mountain area in Southern Europe and plain areas in Central Europe, given the cumulated power of a district heating network.

The following figure (Figure 6) shows that there is a relationship between the full load operating hours and the ratio between the peak load of a district heating network and the thermal power of the ORC. This means

that given a number of full load operating hours it is possible to know the ratio between peak load and thermal power of the ORC.

The values for the district heating network used for this evaluation are the same used above, with the same assumptions.

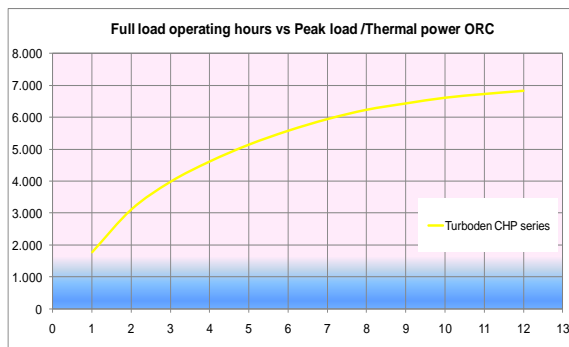


Figure 7: Full load operating hours vs. peak load divided by the thermal power of the ORC

ENVIRONMENTAL BENEFITS DUE TO A BIOMASS ORC COGENERATION PLANT

In this paragraph the environmental benefits in terms of CO₂ emissions savings, that can be obtained by a biomass cogeneration system with ORC technology, are analyzed and compared with the savings that can be obtained with fossil fuel cogeneration systems.

The substituted energy production has to be assumed in order to evaluate the emissions that can be avoided in any energy project. In particular concerning the evaluation of a biomass cogeneration project the main assumptions that need to be taken into account are the specific CO₂ emissions for electricity generation related with the saved electricity production.

This parameter is variable mainly depending on the country. In this paper the reduction in CO₂ emissions has been analyzed as a function of this variable and for different types of district heating system heat suppliers.

Table 3 reports the efficiency assumptions adopted for the different heat suppliers taken into account in this paper.

| | Electric Efficiency | thermal efficiency |
|------------------|---------------------|--------------------|
| DH nat gas | 0% | 90% |
| DH nat gas | 0% | 90% |
| DH biomass | 0% | 85% |
| CHP natural gas | 43% | 43% |
| CHP diesel | 43% | 43% |
| CHP Turboden ORC | 15,6% | 70% |

Table 3: Assumptions on efficiency of heat suppliers to the district heating system

In the picture below (figure 8) the avoided CO₂ emissions per MWh supplied with a biomass cogenerations system are represented as a function of specific CO₂ emissions for electricity generation.

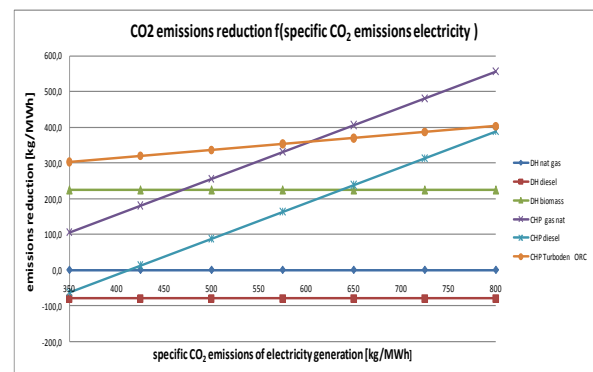


Figure 8: Avoided CO₂ emissions per MWh supplied with a biomass cogeneration system as a function of specific CO₂ emissions for electricity generation

The results show that in district heating systems supplied by fossil fuel the production of electricity causes a global increase in CO₂ emissions.

A natural gas cogeneration system is the solution with the highest decrease in global CO₂ emissions (550 kg/MWh) if high values of specific emissions of the substituted electricity generation are considered (800 kg/MWh). This is due to the high electricity/heat ratio which allows to overcompensate the local CO₂ emissions with the much higher saved emissions in the system if the substituted electricity

generation is very carbon intensive. This is the case in countries with inefficient power plants using carbon intensive fuels (especially coal).

For specific energy consumptions of the substituted energy generation below 600 kg/MWh a distributed biomass cogeneration system allows the highest decrease in CO₂ emissions thanks to the fact that no CO₂ emissions are generated locally due to carbon neutral fuel.

At the moment the average CO₂ emissions of the EU are evaluated to be slightly above 500 kg/MWh. In any case in future the average CO₂ emissions of energy generation will decrease constantly. Therefore biomass cogeneration is the most effective way of reducing the CO₂ emissions for producing electricity already now and the advantage compared to fossil fuel cogeneration will increase in the future.

In the following figure (Figure 9) the avoided CO₂ emissions are reported as a function of the specific CO₂ emissions of heat generation (specific CO₂ emission for EE generation 550 kg/MWh).

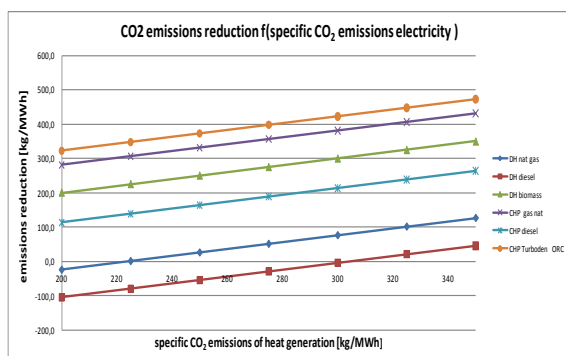


Figure 9: Avoided CO₂ emissions per MWh supplied with a TURBODEN ORC cogeneration as a function of specific CO₂ emissions of heat generation (specific CO₂ emissions for electricity generation = 550 kg/MWh)

The sensibility analysis shows that the substitution of traditional cogeneration with biomass cogeneration with ORC technology is advantageous, assuming the

actual average European emissions for electricity generation, also if gas cogeneration systems are used. Biomass cogeneration remains the solution which allows the highest emission reductions regardless of the specific CO₂ emissions of heat generation.

REAL CASES: OSTROW WIELKOPOLSKI

Ostrow Wielkopolski (P)

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_{th} each and on 2 natural gas peak load boilers rated 15 MW_{th} each. In 2000 a gas Turbine rated 5,2 MW_{el} and 11,6 MW_{th} 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 evaluated carefully and a solution based on a 1,5 MW_{el} ORC unit supplied by Turboden 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 and an international tender was issued in order to determine the suppliers for the different parts of the cogeneration plant.

The nominal data of the ORC unit are the following:

total input power from Thermal oil: 10000 kW_{th}

gross electric power: 1750 kW_{el}

net electric power: 1670 kW_{el}

Thermal power to hot water: 8200 kW_{th}

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.

CONCLUSIONS

This paper shows that biomass cogeneration systems based on Turboden 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 MWe_l. Therefore projects in this scale can be feasible under normal frame conditions in most European countries. Plants in the range around 1 MWe_l 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, as for example in Italy, UK, Croatia, Slovenia, Spain, Germany, Belgium, Switzerland, the Netherlands and Romania. 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.

For the actual average European specific emissions of CO₂ 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 CO₂ for electricity generation will decrease.

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