OPERATIONAL RESULTS OF THE FIRST BIOMASS CHP PLANT IN ITALY BASED ON AN ORGANIC RANKINE CYCLE TURBOGENERATOR AND OVERVIEW OF A NUMBER OF PLANTS IN OPERATION IN EUROPE SINCE 1998

R. Bini, A. Duvia A. Schwarz, - Turboden srl, V.le Stazione 23, 25122 Brescia – I- tel. +39 030-3772341, fax +39 030-3772346, info@turboden.com
M. Gaia - Dipartimento di Energetica - Politecnico di Milano, P.za Leonardo da Vinci, 32 –20133 Milano – I, mario.gaia@polimi.it
P. Bertuzzi – Dipartimento di Economia Aziendale - Università degli Studi di Brescia, Contrada S. Chiara, 50 – 25122 Brescia – I segeaz@eco.unibs.it
W. Righini - T.C.V.V.V. spa –Teleriscaldamento Tirano – I -Via Polveriera 50, 23037 Tirano (SO) – I tel. +39 0342 – 706278 info@tcvvv.it

ABSTRACT: The first biomass CHP plant based on an Organic Rankine Cycle turbogenerator in Italy has been successfully put in operation on June 2003. A scheme already well proven in Switzerland and in Austria, composed of a biomass furnace, a thermal oil boiler, a Turboden ORC turbogenerator, was implemented.
The system provides heat and electricity to the Northern Italy town of Tirano, located in Valtellina (SO) and has been supported by funding from “Regione Lombardia”. The plant has an overall efficiency of about 89% considering the combined production of heat and electricity; a nominal electric capacity of 1100 kW with a net efficiency of 18% from thermal oil to electric power and of about 15% from biomass to electricity. A number of diagrams showing the operating parameters in terms of heat demand electric power output, efficiency at nominal and partial load operation are reported as well as an analysis on the economical convenience of the plant. A comparison of the CO2 emissions saved with an ORC CHP unit and with other biomass to energy uses is also included. Finally, a list of the Turboden ORC plants installed in Europe is presented.

Key words: Organic Rankine Cycle (ORC), Combined heat and power generation (CHP), CO2 emission reduction

1 DESCRIPTION OF THE SYSTEM

A biomass CHP plant supplies the town of Tirano with district heating and electricity. Figure 1 shows the simplified hydraulic system of the plant with ORC module. A biomass fired thermal oil boiler supplies heat through a thermal oil circuit to an ORC unit, which produces electricity and gives heat to a hot water circuit (district heating). Most of the biomass feeding the plant is supplied by local sawmills (saw dust, barks, wood chips).

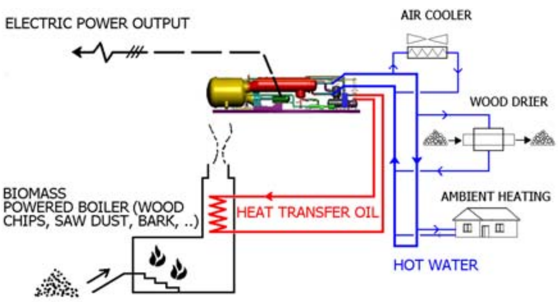

Fig.1 – Simplified scheme of a biomass boiler feeding an ORC turbogenerator. In the case of Tirano no wood driers are actually installed.

The biomass CHP plant in Tirano is equipped with two biomass fired hot water boilers and a biomass fired thermal oil boiler. The thermal oil boiler and the ORC cogeneration unit have been added in 2003 in order to cover the base load of the heat demand and to cogenerate green electricity thanks to the ORC unit. The increased installed power was designed to cover almost completely the expected future heat demand, related to the constant expansion of the district heating net. For the case a biomass boiler is not available due to any reasons or to cover peak loads when the district heating will be completed, an oil fired stand-by boiler is also provided. The main technical data of the biomass CHP plant in Tirano are shown in Fig.2 below.

Biomass cogeneration plant Tirano	
Nominal power of biomass fired hot water boilers	2 x 6 MW
Nominal power of biomass fired thermal oil boiler	8 MW
Nominal thermal oil power to ORC	6,2 MW
Nominal electric power ORC	1,1 MW_{el}
Nominal power of oil fired stand-by boiler	6 MW
Length of district heating net	about 21 km
Connected thermal load	about 39 MW
Nominal capacity of air coolers	5 MW

Fig.2 – Main technical data of the biomass CHP plant of Tirano

2 OPERATION OF THE SYSTEM

The plant in Tirano is mainly operated as CHP (combined heat and power) unit, controlled by the thermal power required by the district heating network. In winter period, due to the large demand of thermal power from the district heating, the biomass plant (and consequently the ORC turbogenerator) works at full load operation and all the thermal power recovered at the ORC condenser is used to feed the district heating (full CHP operation). When the heat demand is low, for example in summer period or during the night, it is possible to operate the plant mixing the CHP mode and the dissipation mode, wasting the excess heat to the atmosphere, thanks to the adoption of a 5 MW air cooler. Furthermore the partial utilization of the air cooler allows to manage low load operating conditions of the boiler that can occur in mid season periods.

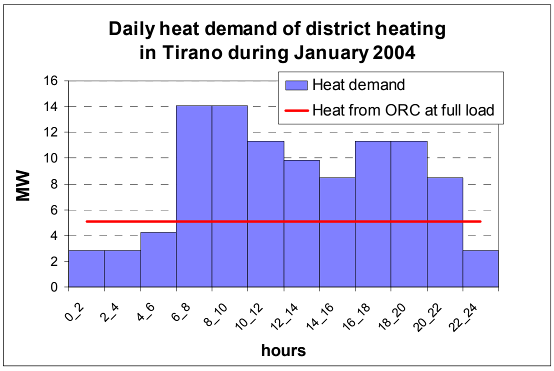

Fig.2 – Daily heat demand of district heating in Tirano on 5th January 2004

Figure 2 shows the daily variation of the thermal power demand of the district heating circuit during a typical winter day: the request is up to 14 MW in the morning and minimum 9 MW in the afternoon, while during the night only 3 MW were asked.

Considering that the thermal output at the ORC condenser is about 5 MW (see Fig.2), the plant can be operated with different criteria:

a) pure CHP mode, at full or partial load depending from the heat demand. The ORC can be automatically and efficiently operated down to 10% of its nominal capacity
b) CHP plus dissipation mode. In this case the electric output is decided according to the economic optimisation, see par.4b). The fraction of the thermal output at ORC condenser that is not required by the district heating is wasted through the air-coolers.

In Tirano the second operation criterion is seldom used. In the whole period considered (between October 2003 and March 2004) the overall amount of heat wasted through the air-cooler was in the range of 17% of the whole thermal energy delivered to the district heating.
For example, during the night of January 5th 2004, the ORC module has been operated at almost full load and the excess heat produced was used to warm up the district heating net (the net is used as buffer). Only when the water temperature reached the maximum acceptable value, the excess heat produced was sent to the air cooler. In other plants a dedicated hot water buffer is installed as a way to increase the utilization of the ORC in CHP mode. From the environmental point of view this is surely meaningful because it allows a more efficient utilization of the biomass resource as shown in paragraph 5.
Fig.3 shows the average electric power generation with the ORC unit in Tirano from October, 1st 2003 until March, 15th 2004. The plant was operated at almost constant electric power during the whole period (average power 1100 kW_{el}, peak power about 1200 kW_{el}). The generated electricity of the ORC module in this period is characterised by a very high constancy and availability (about 98%). The reduced electricity generation of the plant during some days was due to maintenance works mainly to the thermal oil boiler.

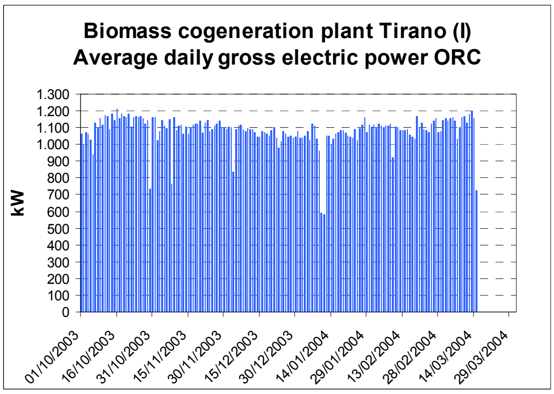

Fig.3 – Average gross daily electric power generation of the ORC plant in Tirano from October 2003 until March 2004

3 ORC OPERATING DATA AND EFFICIENCY

Figures 4 and 5 report two typical trends as acquired by the data acquisition system installed on the Tirano plant. Fig. 4 refers to a summer day operation (July, 30th 2003) while Fig.5 to two slightly cold spring days (May 1st and 2nd 2004).

On July, 30th the plant operated at a load between 650 and 950 kW_{el} (i.e. between 60 and 85 % of nominal load, line 1). The net electric efficiency (net electric power divided by thermal power input from thermal oil) was in the range 18-19% (line 4). Evaporation and water outlet temperatures are also reported (lines 3 and 2 respectively).

The ratio between the actual net efficiency of the ORC turbogenerator and the efficiency of an ideal cycle, working between the actual thermal oil and water temperatures, is also shown (line 5). The reference ideal cycle would have:

- heat sources with varying temperatures, characterized by constant thermal capacity
- no temperature difference in the heat exchange
- no machinery losses

Between May 1st and 2nd (Fig.5) the unit operated at a net power output between 950 and 1170 kW_{el} (line 1) (i.e. between 85 and 106 % of nominal load). The net electric efficiency (net electric power divided by thermal power input from thermal oil) was around 17.5% (line 4).

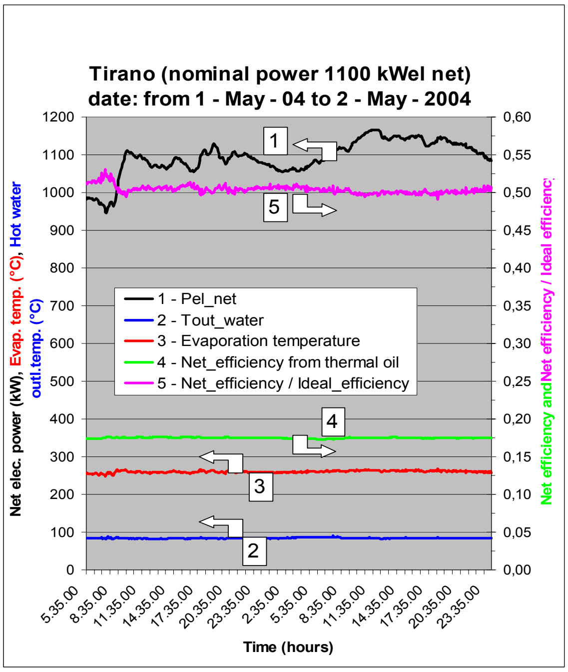

Fig.4 – Operation data of the ORC – July, 30th 2003

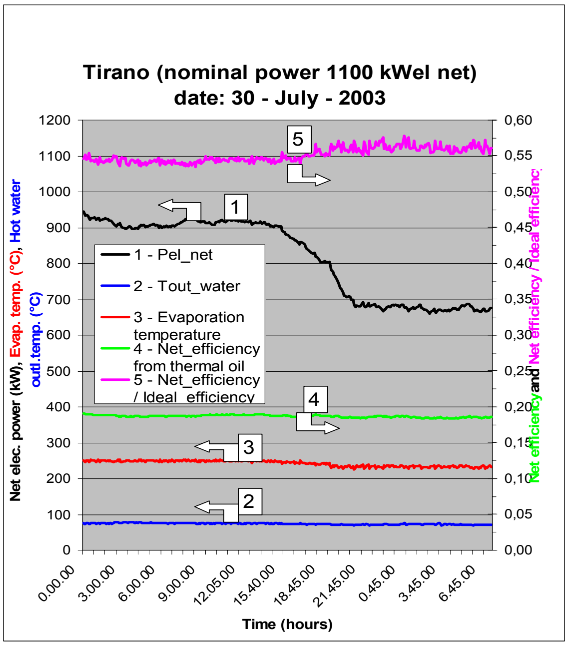

Fig.5 – Operation data of the ORC – May 1st and 2nd, 2004

This figure compared to the 18-19 % of previous diagram is a consequence of the increased water temperature (around 85 °C instead of 75 °C), that increases the condenser pressure. However, in ‘cold season’ it is required by the district heating circuit to supply hotter water, hence the water temperature has to be adapted to the heat user request.

The main results are the following:

- the ORC can reach an efficiency between 50% and 60 % of the ideal cycle efficiency
- this fraction increases at partial load. The reason for this behaviour is that at partial load the deltaTs in the heat exchangers decrease and the shape of the cycle becomes more ‘rectangular’ (in a Temperature – Entropy diagram) due to the increased distance from fluid critical temperature. The final consequence is that the actual ORC efficiency keeps relatively constant also at partial load. Really the reduced temperature span of the cycle at partial load is compensated by the better shape of the cycle.

In Fig.6 a 2nd principle analysis was carried out taking into consideration a typical operating point of the ORC plant.

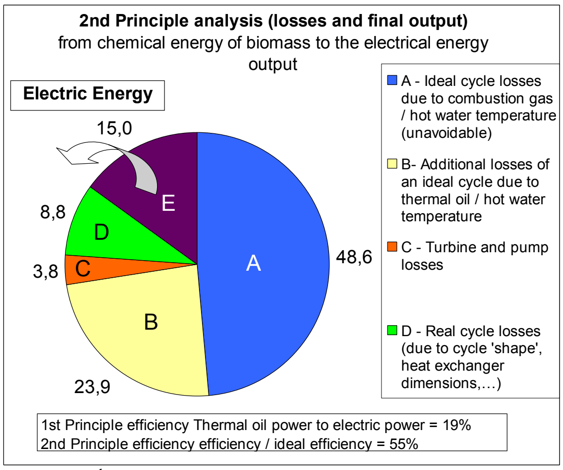

Fig.6 – 2nd Principle analysis of the ORC plant

Starting from a reference 100% available chemical energy of the biomass, the losses involved to arrive to the final output as electric energy are indicated:

- **A-** Ideal cycle losses (about 49 %) considering an ideal cycle as described above using the combustion gases (cooled from 1000 C to 60) to produce mechanical energy and heat between 60 to 75 C. The ideal cycle evolving between the indicated temperatures would have an efficiency of about 51 %.
- **B-** Additional losses (about 24 %) related to the fact that by producing thermal oil at lower temperature (250-300 C) the capacity to produce work decreases. These losses also include exergy losses due to residual heat in the exhaust gases
- **C** and **D** - Machinery losses (turbine and pump about 4 %) and real cycle losses (due to finite heat exchange surface and cycle ‘shape’, about 9 %)

The remaining fraction (region **E**, about 15%) represents the actual net electric output from the ORC system.

It has to be noted that the actual net efficiency value reported in previous diagrams (about 18-19%) is not in contrast with this figure because the former refers to the net efficiency considering the available heat to the thermal oil, hence does not consider the losses involved in producing the thermal oil flow at the required temperature level.

Furthermore, as already described in this article, the aim of the plant is not to produce only electricity but to use the renewable source in a CHP system. Hence most of the energy which could not be converted to electricity is used to feed the district heating system, as a consequence the First Principle efficiency is very high (about 89%). For this same reason in the present analysis, the hot water exergy has not been taken into account, too.

4 ECONOMIC EVALUATION OF PLANT

a) Economical advantage of the incremental investment in a CHP plant compared to a "heat only" district heating

An "incremental" economical analysis of the additional investment in a CHP system compared to a hot water boiler was performed. In this analysis we consider only the additional incomes and expenses that result from the addition of an ORC system for cogeneration (that is to say only the incomes and the expenses that would not exist if a heat-only system was implemented). In particular the following extra costs have been considered:

- Cost of the ORC module
- Extra costs for thermal oil boiler compared to the hot water boiler that would have been used in a heat-only system (including cost of the thermal oil circuit)
- Extra costs in civil works and plant engineering
- Extra running costs due to the additional biomass consumption
- Extra costs for operation and maintenance of the ORC unit

The following extra incomes have been considered:

- Sale (or saved expenses for the fraction of own consumption) of the produced electricity
- Sale of the green certificates awarded for green energy production (for the first 8 years only)

An operation in pure heat controlled cogeneration has been assumed, considering the safely estimated actual and future heat request of the grid. The financial value of time has been accounted for with an annual rate of 5 % during the estimated plant life of 20 years. Finally the investment grant of 33% awarded by the Regional Authority of "Regione Lombardia" has been considered. The resulting discounted cash flows are reported in Figure 7.
The economical results of the evaluation are:

Total additional investment = 1400 k€ (net of subsidies)
NPT (Net present Value) = 1987 k€
PBT (Discounted Pay back time) = 4,1 Years
IRR (Internal rate of return) = 25,0 %

The analysis shows that, with the frame conditions valid for Tirano, the additional investment in cogeneration has a good economical return with a discounted pay back slightly over 4 Years and an internal rate of return of 25%.

Moreover, the analyzed solution shows that the incremental income continues also after the first 8 years period in which green certificates are obtained, continuing to generate economical value during the whole plant life.

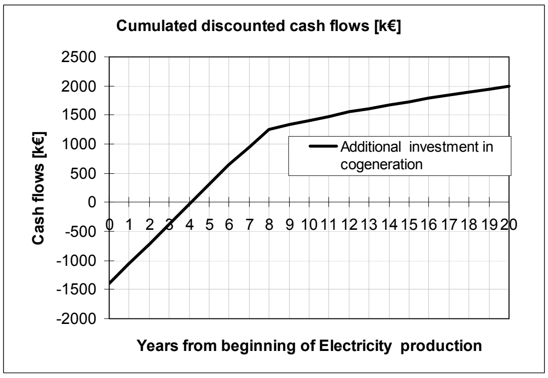

Fig.7 – Cumulated discounted cash flows of the additional investment for cogeneration in Tirano

b) Economical advantage of operation in dissipation mode

The biomass CHP plant in Tirano is equipped with an air cooler allowing a flexible plant operation during the year. Besides a heat controlled operation of the plant an electricity controlled operation is possible at any time because the excess heat can be removed by the air cooler. Whether an operation of the CHP plant in dissipation mode makes good economic sense or not depends on different boundary conditions. The main parameters effecting the cost effectiveness of using the air coolers are:

- The biomass costs (which can fluctuate during the year)
- The selling price of the electricity produced
- The variation of electric energy feed-in tariffs at different day-hours
- The presence and the value of Green Certificates (according to Italian law, during the first 8 years of operation only).

The biomass CHP plant in Tirano burns wood chips bought at a price of 12 €/std-m^3 constant along the year, guaranteed by a long term contract. The calorific value of the delivered wood chips varies during the year and depends on the origin of the biomass. The average calorific value is about 700 kWh_{th}/std-m^3. This corresponds to an average biomass costs for wood chips of about 1,7 €c/kWh_{th} over the year.

Fig. 8 shows the feed-in tariff during a winter day compared to the fuel costs for the production of one additional kWh electric net in dissipation mode (no valorization of produced heat). The shown fuel costs have been evaluated by deducting the additional electricity consumption of the biomass boiler, thermal oil circuit, air cooler and pump for the hot water circuit from the additional gross power generated. The fuel costs for the biomass are shown over a range from 1,0 to 2,0 €c/kWh_{th}. The actual biomass costs in Tirano are 1,7 €c/kWh_{th}. This corresponds to fuel cost of about

16 €c to produce one additional net kWh electric, in dissipation mode. The diagram clearly shows that for Tirano in winter an operation of the plant in dissipation mode makes almost no economic sense. Only between 9 and 11 a.m. and 5 and 7 p.m. the remuneration is slightly higher than the bare fuel costs.

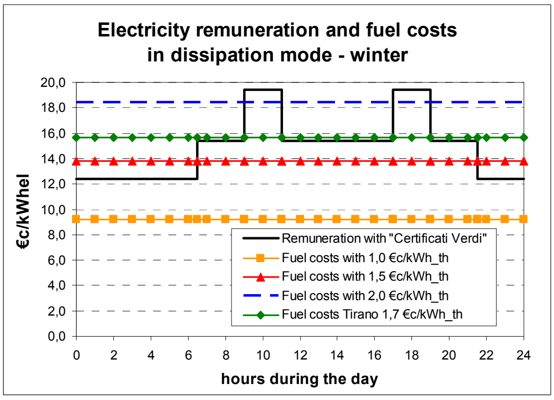

Fig.8 – Electricity remuneration and fuel costs in dissipation mode for the plant in Tirano during winter

In summer the actual remuneration of electricity is slightly less than in winter, hence an operation of the plant in dissipation mode is uneconomical (Fig. 9).

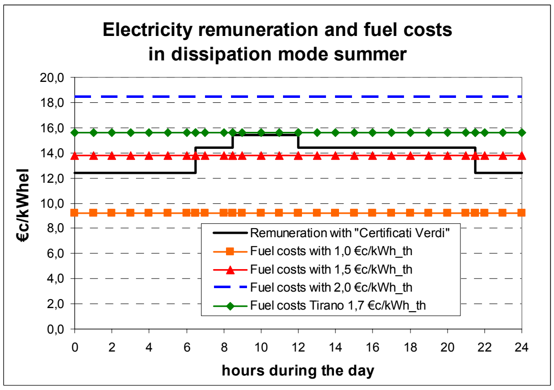

Fig.9 – Electricity remuneration and fuel costs in dissipation mode for the plant in Tirano during summer

Hence the decision to invest in a biomass plant using virgin wood and to be operated mainly in dissipation mode (with low or no use of the discharged heat), should be considered very carefully because relatively small changes in biomass costs can lead to uneconomical operation of the plant. In any case after the first 8 year period, in which the Green Certificate remuneration is awarded, the situation becomes even worse and only very low prices of the wood fuel can be accepted to operate economically the plant.

On the contrary, the Tirano plant, and all the plants that are conceived and designed first to supply heat to a suitable district heating, will feature a good, stable and satisfactory return of the investment and remuneration also after the first 8 year period as shown in the previous point a). This choice represents in our idea the correct solution both from economical and environmental points of view, as the renewable source is more completely utilized.

5 ENVIRONMENTAL EVALUATION OF DIFFERENT USES OF BIOMASS FOR ELECTRICITY PRODUCTION

The authors believe that virgin biomass is a limited resource and therefore should be used as efficiently as possible. In order to compare the efficiency of different technologies and uses of biomass, the global carbon dioxide emissions that can be avoided by using biomass with 1 kWh energy content for energy production compared to the existing fossil fuelled energy production plants have been evaluated. This comparison allows to evaluate in which way the available biomass can be used in order to avoid as much CO_2 emissions as possible.
In the comparison the possible uses (heat only, cogeneration, electricity only) and cogeneration technologies have been considered.

The substituted energy production has to be assumed in order to evaluate the emissions that can be avoided in any energy project. In this paper two different cases have been considered:

Case 1 -Actual reference situation :
Electricity production: steam plants; efficiency: 35%; energy source: oil
Heat production: oil boilers; efficiency: 90% ; energy source: oil

Case 2- Future reference situation :
Electricity production: combined cycle plants;
Efficiency: 55%; energy source: natural gas
Heat production: gas boilers; efficiency: 90%; energy source: natural gas

Fig. 10 reports the efficiency assumptions adopted for the different uses and technologies that have been considered.

	Thermal efficiency	Electric efficiency
Heat only boiler	85,0%	0,0%
Steam motor (100% heat use)	74,0%	11,0%
Cogeneration with ORC (100% heat use)	70,0%	15,0%
Condensing steam turbine (5 MW_{el};No heat use)	0,0%	26,0%
Backpressure steam turbine (5MW_{el};50% heat use)	31,7%	21,6%
Backpressure steam turbine (5MW_{el};100% heat use)	68,0%	17,0%

Fig.10 – Assumptions on efficiency of the energetic uses of biomass analysed [3]

The avoided emissions of the different options analysed are reported in Fig.11. The results show that a complete heat use in heat controlled cogeneration mode is the key point for an optimal use of the biomass resource concerning CO_2 emissions. This is especially true in the future situation, in which the emissions of the substituted electricity generation are lower, due both to the higher efficiency of the combined cycle power plants and to the prevalent use of natural gas as energy source. This clearly justifies from an environmental point of view a higher remuneration for electricity from biomass obtained in pure cogeneration mode (as recently proposed in Germany in the new Renewable Energy law) or subsidies for this type of plant.

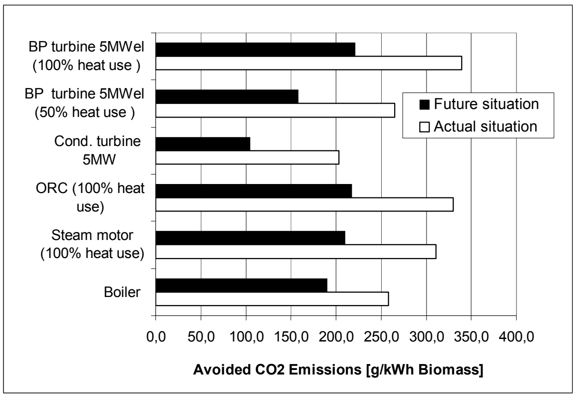

Fig.11 – Avoided CO_2 per kWh Biomass utilized for various energetic uses of biomass

For example compared to a $5MW_{el}$ steam condensing plant a cogeneration plant based on a cogenerating ORC unit allows to avoid 62 % more emissions in the actual situation (330 g/kWh compared to 203 g/kWh) and 107% more emissions in the future situation (217 g/kWh compared to 105 g/kWh) per kWh of used biomass. Compared to a hot water boiler the avoided emissions per kWh biomass of an ORC cogeneration plant are 27 % higher in the actual situation (330 g/kWh compared to 258 g/kWh) and 14% higher in the future situation (217 g/kWh compared to 190 g/kWh). Also large steam cogeneration plants or other systems with high electric efficiency obtain lower avoided emissions, if the heat is not used completely for cogeneration.

Larger cogeneration systems (>5 MW_{el}) based on steam turbines have slightly higher avoided emissions if the heat can be used completely and if enough biomass is available near the production site, in order to avoid excessive emissions due to biomass transport from the production sites of biomass residues to the cogeneration plant. This is especially true if the unit is operated with an almost constant power request from heat users allowing the unit to maintain the higher nominal efficiency for most of the time, and avoiding the necessity of quick load changes that are difficult to follow with this type of systems. On the contrary Cogeneration systems with ORC units have the advantage of easy regulation and good efficiency at part load that are vital in heat controlled operation of a cogeneration plant [1],[2]. Moreover, small scale solutions allow to find many applications with sufficient heat use near to the production sites of the biomass residues (for example mountain district heating plants, saw mills, etc.). Hence, small scale cogeneration plants based on ORC units are a very promising technical solution also from the point of view of efficient biomass use.

6 OTHER BIOMASS ORC PLANTS IN EUROPE

Starting from 1998 a number of medium scale biomass projects based on ORC turbogenerators designed and constructed by Turboden Srl, Brescia, Italy have been commissioned and run successfully. The units actually in operation and construction are reported below:

Units in operation:

- Biere (Switzerland) 300 kW el (1998)
- Admont (Austria) 400 kW el (1999)
- Crissier (Switzerland) 500 kW el (2002)
- Lienz (Austria) 1000 kW el (2002)
- Bregenz (Austria) 1000 kW el (2002)
- Tirano (Italy) 1100 kW el (2003)
- Dobbiaco (Italy) 1500 kW el (2003)
- Neckarsulm (Germany) 1000 kW el (2004)
- Sauerlach (Germany) 500 kW el (2004)
- Plössberg (Germany) 1000 kW el (2004)

Units under construction:

- Längenfeld (Austria) 1100 kW el (2004)
- Thal Aue (Austria) 1000 kW el (2004)
- Lofer (Austria) 600 kW el (2004)
- Grossarl (Austria) 600 kW el (2004)
- Siezenheim (Austria) 1500 kW el (2004)
- Abtenau (Austria) 1100 kW el (2004)
- Leoben (Austria) 3 x 1500 kW el (2005)
- Hall (Austria) 1100 kW el (2005)

The operating experience of more than 100.000 hours of this plants has confirmed that the ORC plants can be run automatically, without permanent supervision and with high availability, exceeding 98%. The unit installed at Admont has reached in Mai 2004 more than 36.000 hours of successful operation. Most of the stops have been due to the normal boiler cleaning operations and the availability of the ORC unit has been higher than 98%.

The ORC technology applied in small size (0.5 –1.5 MW_{el}) CHP biomass plants has demonstrated to be a mature 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. For the future the main research goals are the development of units with increased efficiency and an extension of the production range towards smaller units.

7 REFERENCES

[1] Bini R., Manciana E., Organic Rankine Cycle turbogenerators for combined heat and power production from biomass , Proceedings of the 3rd Munich Discussion meeting 1996, ZAE Bayern (ed) Munich, Germany, 1996

[2] Obernberger I., Hammerschmid A., Bini R., Biomasse- Kraft – Wärme – Kopplungen auf Basis des ORC –Prozesses – EU THERMIE Projekt Admont (A), VDI-BERICHTE NR. 1588, 2001

[3] IZES , Leprich U. el al, Auswirkungen des "Erneuerbare-Energien-Gesetzes" (EEG) auf die Wirtschaftlichkeit von Regenerativanlagen an Hand konkreter Fallbeispiele im Saarland. Studie im Auftrag der Saar Energie GmbH, der VSE AG und der Stadtwerke Saarbrücken AG, April 2001

[4] Werner S., Rewarding energy efficiency: the perspective of emissions trading , AIRU Bulletin, 2003