Description and evaluation of the new 1,000 kW$_{el}$ Organic Rankine Cycle process integrated in the biomass CHP plant in Lienz, Austria

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1 Abstract

The ORC (Organic Rankine Cycle) process represents an economically interesting technology for decentralised biomass-fired combined heat and power plants (biomass-fired CHP plants). The ORC technology is based on the Rankine process with the difference that instead of water an organic working medium is used. A newly developed ORC technology with a nominal electric capacity of 1,000 kW was implemented in the biomass CHP plant Lienz (A) in the framework of an EU demonstration project. This plant has been in operation since February 2001.

The biomass CHP plant in Lienz supplies the town of Lienz with district heat (about 60,000 MWh/a after completion of the network of pipes) and feeds the electricity produced (about 7,200 MWh/a) into the public grid. Biomass combustion takes place in a thermal oil boiler followed by a thermal oil economiser with a nominal capacity of 6.5 MW$_{th}$ and in a hot water boiler with a nominal capacity of 7.0 MW$_{th}$. The flue gases of both biomass-fired boilers pass through a heat recovery unit (economiser) with a nominal capacity of 1.5 MW$_{th}$ in order to optimise the overall efficiency of the CHP plant. Moreover, a solar collector panel with a nominal capacity of 0.35 MW$_{th}$ has been implemented and an oil-fired peak load boiler with a nominal capacity of 11.0 MW$_{th}$ has been installed.

The special advantages of the ORC technology are robustness (long service life, low maintenance costs), fully automatic and unmanned operation (personnel requirements only 3 to 5 hours per week), excellent partial load behaviour, and electric efficiency (= net electric power produced / thermal power input) of approximately 18%, which is relatively high for decentralised biomass-fired CHP plants. The ORC is a closed cycle process connected to the thermal oil boiler by a thermal oil cycle (thermal power input at nominal load 5,560 kW) and to the district heating network (thermal power output at nominal load 4,450 kW) as well as to the electric grid (net electric power at nominal load 1,000 kW). Using a new and improved coupling of the thermal oil boiler with a thermal oil economiser and an air pre-heater, the thermal efficiency of this system has been considerably improved and amounts to about 82% (= thermal power output / fuel power input [NCV]), which is about 10% higher than corresponding values from conventional biomass-fired thermal oil boilers. This increased thermal efficiency also raises the overall electric efficiency of the CHP plant to about 15% (= net electric power produced / fuel power input into the biomass-fired thermal oil boiler [NCV]). Furthermore, the overall process control system of the CHP plant will be optimised by a newly developed Fuzzy Logic control which will go into operation in autumn 2002.

Economic evaluations based on the experiences and data already gained from this project show that a biomass-fired CHP plant based on a 1,000 kW$_{el}$ ORC cycle can achieve specific electricity production costs between 0.09 and 0.14 EUR/kWh$_{el}$ depending on the specific framework conditions concerning fuel price and capacity utilisation of the ORC process. These specific electricity production costs enable an economically viable application of this

technology to be made in all countries which run special funding programmes for promoting electricity production from renewable energy sources (such as Austria, Germany, Switzerland, Italy and Denmark). Another basic requirement for an ecological and cost-effective operation of the process is that not only the electricity but also the heat produced by the CHP plant can be utilised as process or district heat (heat controlled operation of the overall system).

The greatest application potential of biomass-fired CHP plants based on ORC cycles is represented by medium-sized wood manufacturing and wood-processing enterprises, decentralised waste-wood combustion plants and biomass district heating plants (newly erected or adapted existing plants).

2 Introduction and technical description of the biomass-fired CHP plant in Lienz

The biomass CHP plant in Lienz is located in the east of Tyrol in Austria (see Figure 1) and supplies the town of Lienz with district heat [1]. It started operation in autumn 2001 and will cover the heat requirement of approximately 70 % of all buildings in the supply area by the end of 2003. The residential and industrial heating systems replaced are mainly oil-fired boilers; this therefore results in a considerable CO_2 reduction on the part of the new biomass CHP plant (see section 7). The owner and operator of the plant is Stadtwärme Lienz Produktions- und Vertriebs-GmbH.

Figure 2 shows the annual heat and electricity output line as well as the energy supply of the different units installed.

The CHP plant essentially consists of two biomass-fired boilers, an ORC process, a solar collector panel and an oil-fired peak load boiler as well as a heat recovery unit combined with a flue gas cleaning plant.

The fuel conversion unit is composed of the two biomass combustion plants, a hot water boiler with a nominal capacity of 7,000 kW_{th} and a thermal oil boiler with a nominal capacity of 6,000 kW_{th}. The thermal oil boiler supplies the ORC process with a nominal net electric power of 1,000 kW. The heat recovery unit with a nominal capacity of 2,000 kW_{th} increases the overall plant efficiency and covers a thermal oil economiser, located behind the thermal oil boiler, and a hot water economiser which recovers energy from the flue gases of both biomass-fired boilers. The solar collector panel is installed on the roof of the CHP plants and consists of a 630 m² collector surface and achieves a thermal power of up to 350 kW An oil-fired boiler with a nominal capacity of 11,000 kW_{th} is installed for peak load coverage and as a stand-by system (see Table 1).

In the final development stage the CHP plant Lienz will produce about 60,000 MWh of district heat and about 7,200 MWh of electricity which is fed into the public grid.

Forest and industrial wood chips, sawdust and bark (average water content between 40 and 55 wt.% w.b.) from the regional forestry and wood industries are utilised as biomass fuel. The total annual biomass fuel consumption will amount to about 100,000 bulk m^3 in the final development stage. The oil-fired peak load boilers cover only approximately 4 % of the entire thermal energy production. Concerning biomass storage, an open and a roofed area with a total storage capacity of 15,000 bulk m^3 has been planned.

The network of pipes covers three stages of development, with a final total length of 37.5 km and about 900 units connected.

The flue gas cleaning unit consists of two stages. In the first stage the coarse fly ash particles are precipitated in multi-cyclones which are placed downstream of each biomass-fired boiler. In the second stage, fine fly-ash and aerosol precipitation take place in a wet electrostatic filter integrated in a heat recovery and flue gas condensation unit. In this plant configuration, dust emissions in the clean flue gas of about 10 mg/Nm³ (dry flue gas, 13 Vol.% O_2) and the avoidance of water vapour formation at the chimney outlet at temperatures above -5°C are achieved.

3 ORC process description

The main innovative part of the new biomass CHP plant is the ORC process with a nominal electric capacity of 1.0 MW and a nominal thermal capacity of 4.4 MW. The relevant technical data of the ORC process are listed in Table 2. The ORC was manufactured and supplied by TURBODEN Srl, Brescia, Italy.

The principle of electricity generation by means of an ORC process corresponds to the conventional Rankine process. The substantial difference is that instead of water an organic working medium with favourable thermodynamic properties is used - hence the name Organic Rankine Cycle (ORC) [2, 3]. The working principle and the different components of the ORC process are shown in Figure 3 and 4. The ORC process is connected with the thermal oil boiler via a thermal oil cycle. The ORC unit itself operates as a completely closed process utilising a silicon oil as organic working medium. This pressurised organic working medium is vaporised and slightly superheated by the thermal oil in the evaporator and then expanded in an axial turbine which is directly connected to an asynchronous generator (see Figure 5). Subsequently, the expanded silicon oil passes through a regenerator (where in-cycle heat recuperation takes place) before it enters the condenser. The condensation of the working medium takes place at a temperature level which allows the heat recovered to be utilised as district heat (hot water feed temperature about 80 to 90°C). The liquid working medium then passes the feed pumps to again achieve the appropriate pressure level of the hot end of the cycle.

4 Optimised integration of the ORC unit in the overall process

The design and integration of the ORC process in the entire plant took place with the objective to achieve a high capacity utilisation (large number of full load operating hours), a high overall electric efficiency and economical operation [4, 5].

A high capacity utilisation of the ORC in heat-controlled operation can be achieved by an appropriate dimensioning of the CHP system (see Figure 2). The CHP unit should be able to operate the whole year in order to achieve at least 5,000 full load operating hours. The ORC in Lienz is dimensioned to achieve 7,000 full load operating hours at the final development stage of the district heating network.

In order to obtain a high electric efficiency (= net electric power produced / thermal power input) of the ORC unit itself, it is necessary to keep the back-pressure of the turbine as low as possible and thus to minimise the necessary temperature for district heat utilisation at the condenser of the ORC plant (approximately 80 °C feed water temperature). This can be achieved by optimising the operation and control of the district heating network in order to keep the necessary feed-water temperature as low as possible as well as by an optimised hydraulic integration of the ORC in the district heating network. In order to achieve this goal, the ORC should be directly connected to the return of the district heating network and the feed water temperature at the ORC outlet should be kept as low as possible by placing the hot water economiser and the hot water boiler in series after the ORC. Following this approach, the ORC can be operated at feed-water temperatures of about 80°C the whole year round, although the feed-water temperature required for the district heating network amounts to 90 to 95 °C in winter.

The overall electric efficiency of the CHP plant (= net electric power produced / fuel power input into the biomass-fired thermal oil boiler [NCV]) has been considerably increased by a new and improved coupling of the thermal oil boiler with a thermal oil economiser and an air pre-heater (see Figure 3). Using this approach, the thermal efficiency of the biomass-fired thermal oil boiler reaches 82% (= thermal power output / fuel power input [NCV]), which is about 10% higher than corresponding values from conventional biomass-fired thermal oil boilers [4]. This increased thermal efficiency correspondingly also raises the overall electric efficiency of the CHP plant (= net electric power produced / fuel power input into the biomass-fired thermal oil boiler [NCV]) to about 15% (see Figure 6).

5 Safety aspects, process control and personal demand

The high safety aspects of the ORC plant are to be particularly emphasised. All welding seams of the pressure vessels of the ORC plant are 100% X-ray and pressure tested by an approved technical inspection authority (TUEV), which also implies, according to the European pressure vessel regulations, that no repetitions of the tests over the whole lifetime of the plant are necessary.

Due to strong fluctuations of the fuel quality and the heat demand in a district heating network, an optimised process control system of the CHP plant is of importance. The ORC process itself is controlled by an SPS, which ensures automatic start-up and shutdown procedures (without the necessary presence of an operator) as well as a smooth load control guided by the feed water temperature at the condenser outlet between 10 and 100% of nominal load. Due to this fully automatic operation, the personnel demand is reduced to checking and maintenance work, which does not exceed 5 hours per week on average. Possible malfunctions of the process are visualised, automatically stored and forwarded to the operator via telecommunication.

Regarding a constant thermal oil feed temperature, the biomass-fired thermal oil boiler is more difficult to control. As the thermal oil feed temperature directly influences the load of the ORC unit, a newly developed Fuzzy Logic control system for biomass CHP plants has been installed, with the aim of stabilising and smoothening the operation of the biomass combustion plant and, consequently, of the entire CHP plant. This system is in its test phase at the moment.

Due to the fact that the biomass furnace is coupled with a thermal oil boiler operated at atmospheric conditions, no steam boiler operator is needed and the steam boiler operation law does not apply. Thus, the personnel costs are reduced in comparison to steam boilers.

The silicon oil used as a working medium in the ORC cycle is environmentally friendly (see section 7). Furthermore, due to the favourable thermodynamic properties of the silicon oil, there is no danger of droplet erosion on the turbine blades. As the working medium is flammable, the ORC process is equipped with a special detection system for organic compounds whereby a small amount of air over all the flanges is sucked in and subsequently analysed using a flame ionisation detector. Through this safety measure the ORC is monitored continuously for leaks.

6 Operational experience

The ORC unit in the biomass CHP plant in Lienz has been in successful continuous operation since February 2002. Within the framework of the EU demonstration project a comprehensive monitoring programme is performed during the first year. According to operation data already evaluated, the net electrical efficiency of the ORC plant amounts to 18% at nominal load and about 16.5% at 50% partial load at feed water temperatures of 85°C (see Figure 7). This underlines the excellent partial load behaviour of this technology and its suitability for heat-controlled operation.

The internal electric power demand of the ORC for the feed pumps amounts to about 60 kW at nominal load and forms the difference between the gross and the net electric power output of the plant. Thus, the gross electric efficiency of the ORC is about 19% at nominal load.

Furthermore, the measurement data already gained clearly show that the ORC plant can be operated at up to 120% of its nominal electric power, which is an additional advantage during the winter months. In Figure 9 a typical operation of the ORC during a winter day is depicted. This graph shows how the electric power output follows the heat demand of the district heating network and how quick load changes are possible with the ORC unit.

ORC plants are relatively silent (the highest noise emissions occur at the encapsulated generator and amount to about 80 dB(A) at a distance of 1 m.

The start-up of the plant took place without any problems. In the first six months of operation no substantial disturbances of the ORC plant occurred.

The biomass-fired thermal oil boiler, the thermal oil economiser and the air pre-heater are equipped with an automatic cleaning system based on pressurised air. This system has already proved itself since during the first nine months of operation no manual boiler cleaning was necessary and boiler operation took place without rising flue gas temperatures at the boiler outlet. This aspect is also of great relevance for a high availability of the overall CHP plant.

The first biomass CHP plant based on an ORC cycle put in operation within the EU is situated at the STIA wood processing company in Admont (A). This plant has now been working for almost three years and has been running for more than 20,000 operating hours, which stresses the reliability and high availability of this technology [4, 7].

Since the cycle of the ORC process is closed and thus no losses of the working medium are possible, the operating costs are low. Only moderate consumption-based costs (lubricants) and maintenance costs are incurred. Regarding the necessary maintenance, periodic weekly checks by the operator excepted, a routine one to two day examination is recommended once a year by the manufacturer. The usual lifetime of ORC units is greater than twenty years, as has been proven by geothermal applications. The silicone oil used as working medium has the same lifetime as the ORC since it does not undergo any relevant ageing.

7 Economic evaluation of the CHP plant in Lienz

Based on the project in Lienz and on experiences with other biomass CHP applications, comprehensive investigations concerning the economy of decentralised biomass CHP plants have been performed. In this paper the electricity production costs of a biomass CHP plant based on a 1,000 kW_{el} ORC process are outlined.

The calculation of the production costs for electricity is based on the VDI guideline 2067. This cost calculation scheme distinguishes four types of costs:

- capital costs (depreciation, interest costs),
- consumption based costs (fuel, consumables),
- operation-based costs (personnel costs, costs for maintenance) and
- other costs (administration, insurance).

Technical data and important side constraints for the cost calculations are shown in Table 3 and 4. These data are taken from implemented or pre-designed plants in order to secure realistic figures. For a more detailed presentation of the calculation of electricity production cost see [2].

The capital costs are based on additional investment costs, and consider only the surplus investment costs of a CHP plant in comparison to a conventional biomass combustion plant with a hot water boiler and the same thermal output. The additional investment costs form the correct basis for the calculation of the electricity production costs of a CHP plant (excluding costs for buildings). This approach seems to be meaningful because decentralised biomass CHP plants (nominal electric capacity below 2.0 MW) primarily produce process or district heat. An electricity-controlled operation of decentralised biomass-fired CHP plants is neither economically nor ecologically meaningful due to the limited electrical efficiencies achievable with such systems. In contrast, the overall efficiency of a heat controlled biomass CHP plant can be very high (up to 90%). Consequently, electricity production is an alternative and implementation depends mainly on the profitability of the additional investment necessary. Additionally, it is possible to separate costs for electricity production from costs for heat production and to make them independent of the combustion system used. This approach makes possible clear comparisons of costs for heat only and CHP applications and forms the basis for a correct calculation of the electricity production costs.

The additional investment costs of a biomass CHP plant based on a 1,000 kW_{el} ORC cycle compared to a conventional biomass heating plant with the same thermal output are shown in Table 3 and do not consider subsidies. Table 4 gives an overview of the electricity production costs calculated from the total annual surplus costs for a biomass CHP plant in comparison to a conventional biomass heating plant with the same thermal output.

An average fuel price of 15 €/MWh (NCV), an interest rate of 6% p.a. and a service life of the CHP unit of 10 years were taken as a basis. The service life is derived from the fact that the feed-in tariffs for electricity from biomass are secured for 10 years according to present Austrian regulations. The biomass fuel price represents the price of a mixture of bark, industrial wood chips and forest wood chips, which is a representative fuel blend for Austrian conditions taking a secured long-term fuel availability into consideration. Only the amount of additional fuel needed for electricity production is considered (see Table 3), taking into account that the overall average efficiency of a biomass CHP plant is usually slightly lower than that of a heat only application (80% instead of 85%). The annual costs for consumables (such as lubricants and sealings), maintenance and other expenditures are calculated by taking a percentage of the additional investment costs based on operational experience [2, 7]. The personnel costs and the amount of electricity needed for the thermal oil circulation are derived from experiences already gained from the Lienz CHP plant as well as from the CHP plant in Admont [7]. Concerning the capacity utilisation of the ORC unit, 5,000 full load operating hours have been considered for the base case scenario.

As shown in Figure 4 the specific electricity production costs calculated amount to 120 €/MWh(el). For an ORC unit with a nominal electric capacity of 500 kW and the same basic conditions, the specific electricity production costs increase by approximately 15% mainly due to higher specific investment costs (economy-of-scale effect). The most relevant cost factor is the capital costs, representing more than 60% of the overall specific electricity production costs. The contribution of the fuel costs, as a second relevant influencing parameter, to the specific electricity production costs amounts to about 20%.

The capacity utilisation of the CHP plant influences the electricity production costs to a high extent (see Figure 9) and represents the most important influencing variable. 5,000 full load operating hours per year can be recommended as a minimum value for economic operation. In heat controlled CHP systems this requirement makes a correct design of the plant capacity, based on the annual heat output line, essential. Of special interest are decentralised biomass CHP units for the wood processing and wood manufacturing industry (where high amounts of process heat are required) as well as for larger biomass district heating plants (where the base load boiler could be changed to a CHP unit).

Another important factor influencing the electricity production costs is the fuel price (see Figure 9). Consequently, it is recommended that the feed-in tariffs for electricity from biomass should be defined according to the fuel used, as the prices for bark (7 to 9 €/MWh NCV), industrial wood chips (12 to 16 €/MWh NCV) and forest wood chips (18 to 22 €/MWh NCV) vary strongly.

By comparing the specific electricity production costs calculated with the feed-in tariffs granted in different central European countries (investment subsidies have also to be taken into account, if available), an economically viable operation of such plants is possible in Austria, Germany, Switzerland and Northern Italy, if the framework conditions pointed out are fulfilled (heat controlled operation and high capacity utilisation).

Concerning future objectives, a further reduction of the investment costs of ORC plants seems realistic based on the experiences and the optimisation potential gained from demonstration projects, especially when a small series production can be achieved.

8 Aspects of ecology

The thermal utilisation of biomass corresponds to the criteria of actual environmental protection, since biomass is a renewable and CO_2-neutral source of energy. The enhanced production of electricity from biomass is a clear objective of the European and Austrian environmental and energy policy. The project contributes to the achievement of the CO_2 reduction target planned in the Kyoto protocol as well as to the goal defined in the Austrian Electricity Supply Act, which aims at an amount of 4% of electricity to be provided from renewables (excluding hydro power) out of the total electricity production in Austria in the year 2007.

Measurements of emissions carried out at the biomass-fired CHP plant in Lienz showed that the prescribed limiting values (in each case related to dry flue gas and 13.0 Vol.% O_2) of 100 mg/Nm^3 for CO, 20 mg/Nm^3 for C_xH_y, 200 mg/Nm^3 for NO_x (measured as NO_2) and 20 mg/Nm^3 for dust, both at nominal load and partial load operation, can be adhered to without problems.

Based on an emission prediction performed for the biomass Lienz CHP plant, approximately 29,900 t/a of CO_2, 58 t/a of CO, 24 t/a of SO_2, 4.2 t/a of NO_x and 1.4 t/a of dust can be prevented, mainly by the replacement of old oil-fired furnaces with district heat from biomass. Therefore, a clear improvement of the regional environmental situation is achieved.

Most of the ashes from biomass combustion (a mixture of bottom ash and cyclone fly ash, representing about 90% of the overall ash produced) can be used as an additive in compost production or as a secondary raw material with fertilising and liming effects on forest or agricultural soils. The third ash fraction, the filter fly ash, precipitated in the wet ESP as sludge, has to be separately collected and disposed of due to its high heavy metal concentrations. Following this approach, the mineral cycle in the course of thermal biomass utilisation can almost be closed and heavy metals, accumulated in the ecosystem by environmental pollution, can be efficiently extracted.

The condensate from the flue gas condensation unit is pH stabilised (the pH value is kept at 7.5 by alkali addition in order to minimise the dissolution of heavy metals) and is then separated from the sludge in a sedimentation tank. In this way, the condensate can be directly discharged into rivers or into a sewer.

The ORC process does not cause any solid, liquid or gaseous emissions, since it is completely closed.

9 Application potential and future development targets

Summing up, it can be stated that the new biomass CHP technology based on the ORC process is an economically and technologically interesting solution for decentralised applications [6, 7]. The potential for such plants in Austria is very large if one considers that more than 400 biomass district heating plants are in operation and that about 50 biomass-fired boilers with a nominal capacity above 1.0 MW_{th} are installed in Austria.

A basic requirement for an ecological and cost-effective operation of such CHP plants is that not only the electricity but also the heat produced by the ORC process can be utilised as process or district heat (heat-controlled operation of the overall system). The greatest application potential of biomass-fired CHP plants based on ORC cycles is represented by medium-sized wood manufacturing and wood processing enterprises, decentralised waste-wood combustion plants as well as biomass district heating plants (newly erected or adapted existing plants).

Compact ORC modules are available in container size with nominal capacities between 400 and 1,500 kW_{el}.

Further biomass CHP projects based on the ORC technology already implemented or in the implementation stage are located in Fussach (A), where a combined electricity and cold production from biomass takes place (nominal electric capacity 1,100 kW_{el}), and near Vienna (nominal electric capacity 1,000 kW_{el}). A third project with a nominal electric capacity of 1,500 kW will be realised in the year 2003 in Toblach (I). Future development aims focus on a further improvement of the electrical efficiency by two-stage ORC cycles as well as by combined hot air turbine - ORC cycles.

Acknowledgement

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Figure 1: The new biomass CHP plant in Lienz

Figure 2: Annual heat and electricity output line for the final stage of development of the district heating network – biomass CHP plant in Lienz

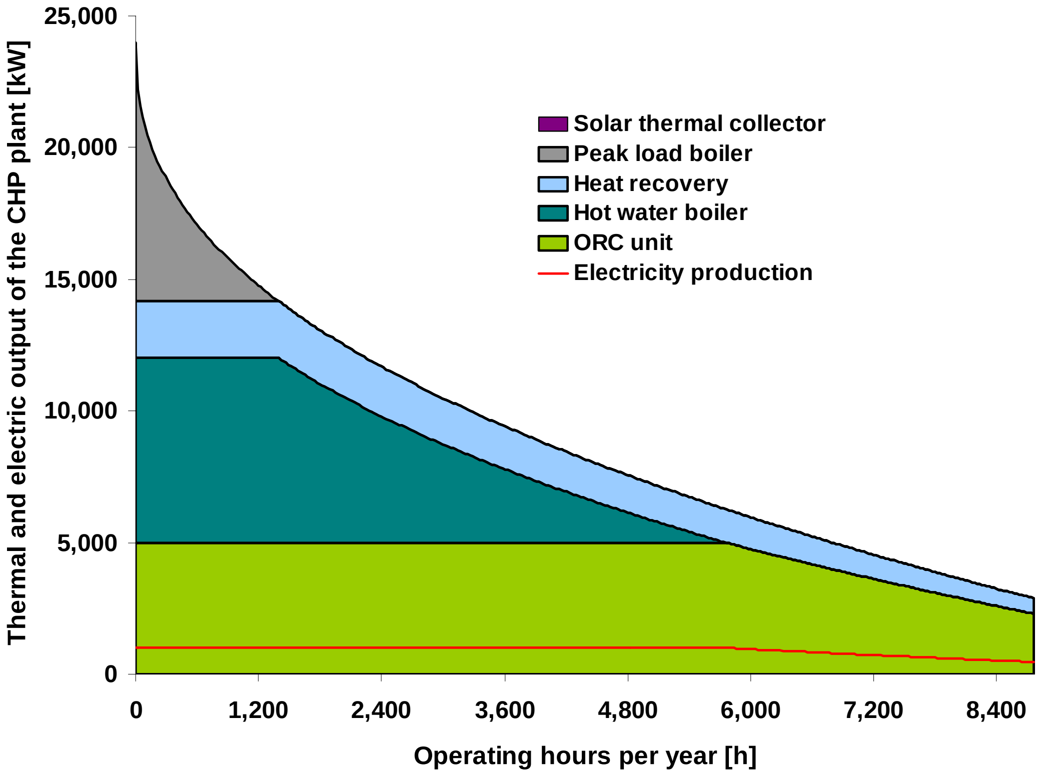


Figure 3: Working principle of the biomass-fired ORC process in Lienz

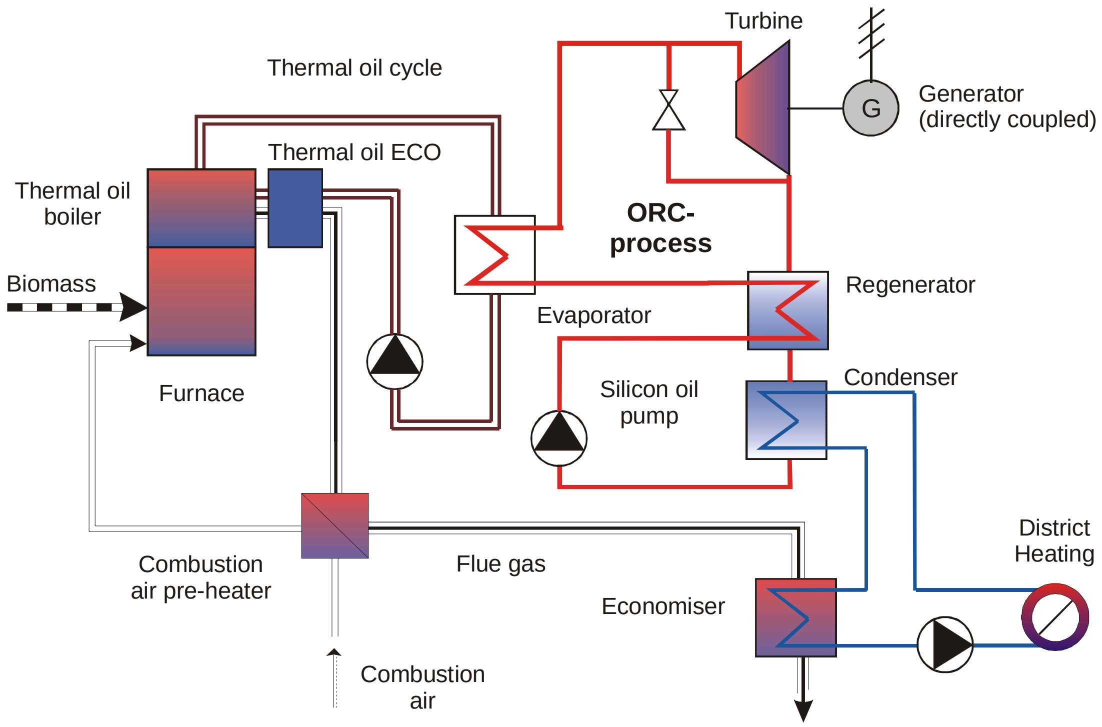
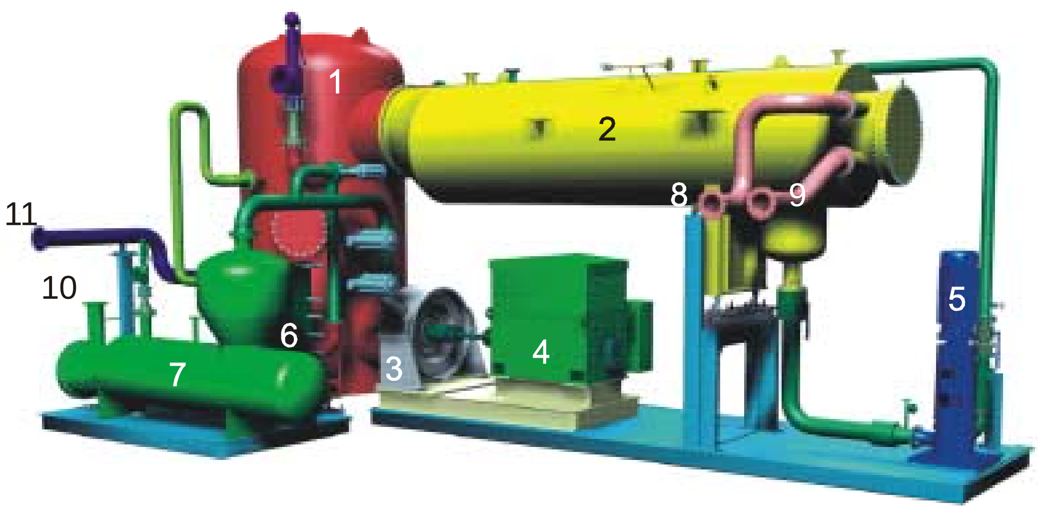


Figure 4: View of the 1,000 kW_{el} ORC plant

Explanations: source: TURBODEN Srl, Brescia, Italy



1 Regenerator
2 Condenser
3 Turbine
4 Electric generator
5 Circulation pump
6 Pre-heater
7 Evaporator
8 Hot water inlet
9 Hot water outlet
10 Thermal oil inlet
11 Thermal oil outlet

Figure 5: View of the evaporator (left picture), the turbine and the generator (right picture)

Figure 6: Energy balance of the biomass CHP plant in Lienz

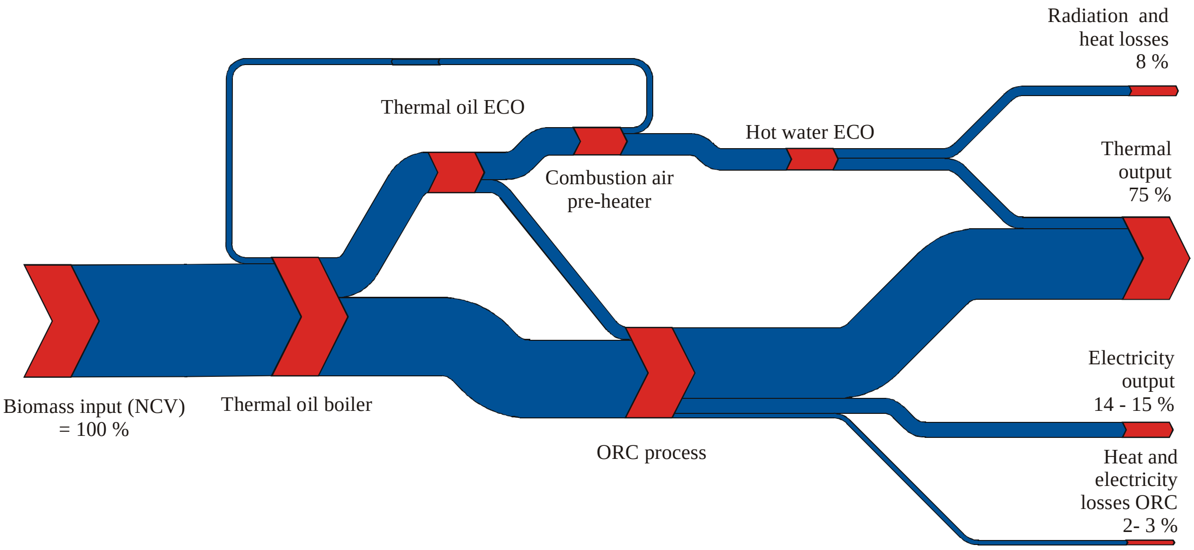


Figure 7: Net electric efficiency vs. load of the ORC unit according to measured data – biomass CHP plant in Lienz

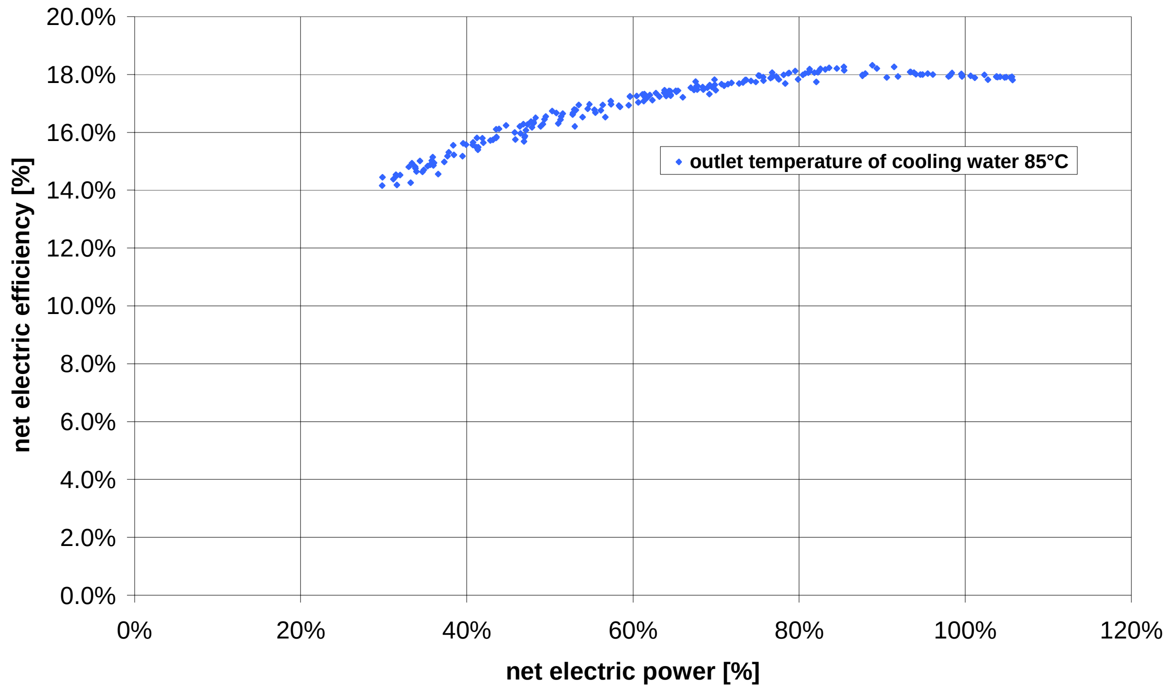


Figure 8: Net electric power produced vs. the thermal power required for a typical winter day – biomass CHP plant in Lienz

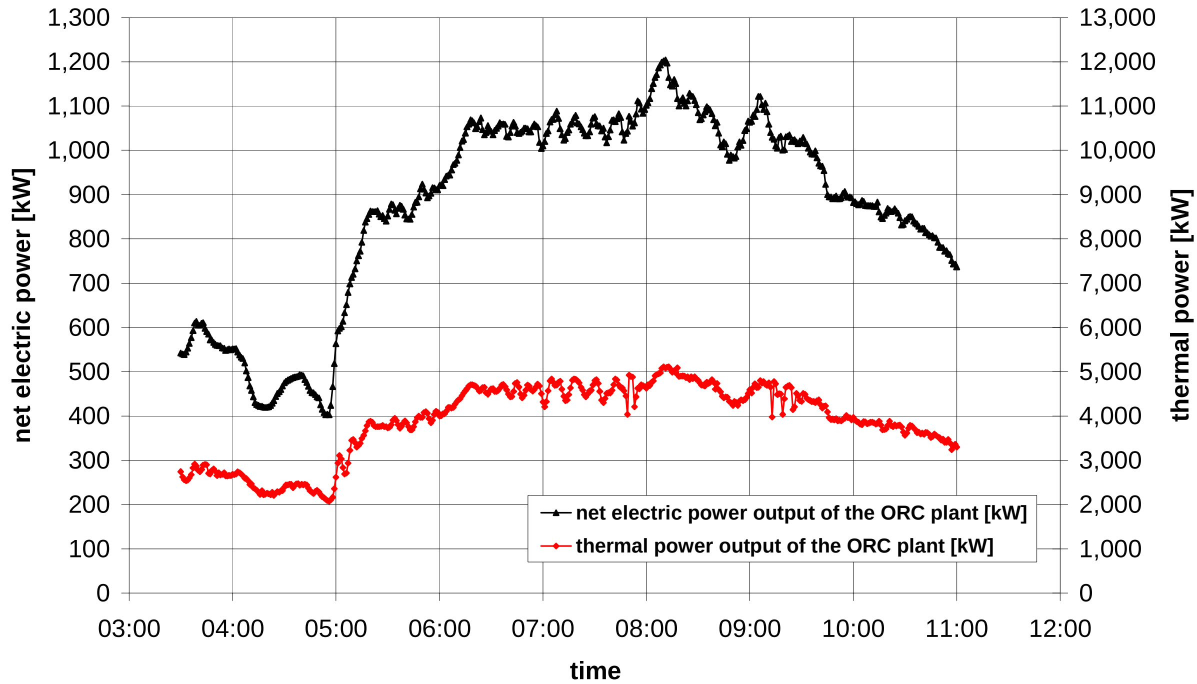
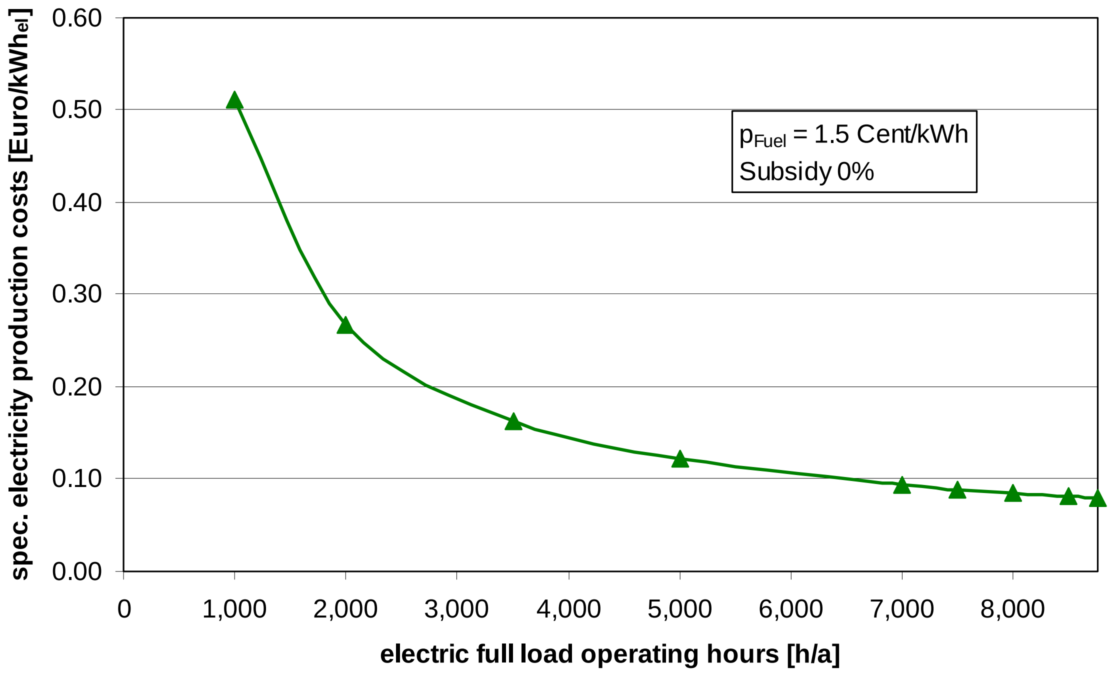


Figure 9: Specific electricity production costs vs. the capacity utilisation (full load operating hours) and the biomass fuel costs for a 1,000 kW_{el} ORC plant in heat controlled operation



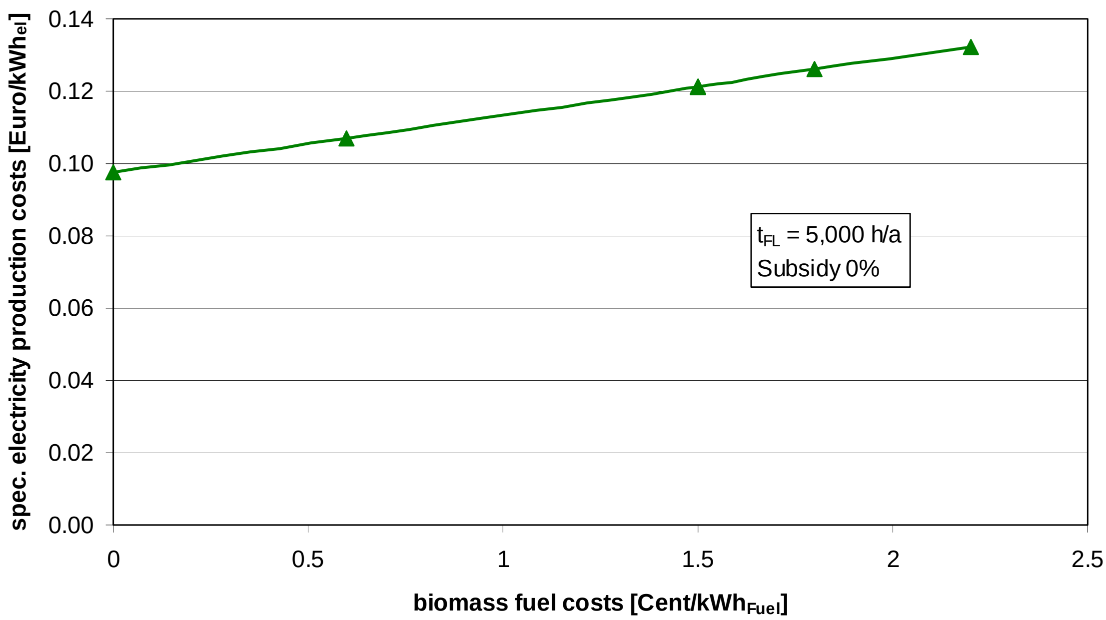


Table 1: Technical data of the biomass CHP plant Lienz

Roofed storage capacity	5,000 Srm
Open storage capacity	10,000 Srm
Solar thermal collector	630 m²
Nominal power - thermal oil boiler	6,000 kW
Nominal power - thermal oil ECO	500 kW
Nominal power - hot water boiler	7,000 kW
Nominal power - hot water ECO	1,500 kW
Nominal power - oil boiler (peak load coverage)	11,000 kW
Maximum thermal power - solar collector	350 kW
Net electric power - ORC	1,000 kW
Production of heat from biomass	60,000 MWh/a
Production of heat from solar energy	250 MWh/a
Production of electricity from biomass	7,200 MWh/a

Table 2: Technical data of the ORC process – Lienz biomass CHP plant

Heating medium	Thermal oil
Inlet temperature	300 °C
Outlet temperature	250 °C
Working medium - ORC	Silicon oil
Cooling medium	Water
Inlet temperature	80 °C
Outlet temperature	60 °C
Thermal power (thermal oil) input – ORC at nominal load	5,560 kW
Net electric power output at nominal load	1,000 kW
Thermal power output (ORC condenser) at nominal load	4,440 kW
Net electrical efficiency at nominal load	18.0 %
Thermal efficiency at nominal load	80.0 %
Electric and thermal losses	2.0 %

Table 3: Overview of the technical data and surplus investments of a biomass-fired CHP plant based on a 1,000 kW_{el} ORC process in comparison to a conventional biomass-fired heat only plant (hot water boiler) with the same thermal power output

TECHNICAL DATA			
Nominal electric capacity	P_{el}	[kW_{el}]	1,000
Overall net electric efficiency - CHP plant	ν_{el}	[%]	15
Total efficiency (heat and electricity)		[%]	80
Total thermal efficiency of a biomass heating plant (reference)		[%]	85
Full load operating hours of the CHP plant		[h/a]	5,000
Annual electricity production	Q_{el}	[kWh/a]	5,000,000
Generated amount of heat	Q_{th}	[kWh/a]	21,666,700
Total primary energy input	Q_{Fuel}	[kWh/a]	33,333,300
Primary energy needed for electricity production	$Q_{Fuel\text{-}CHP}$	[kWh/a]	7,843,100
ADDITIONAL INVESTMENT COSTS			
(compared to a conventional biomass heating plant)			
Thermal oil boiler, thermal oil cycle and economiser		[€]	650,000
Installation incl. fittings		[€]	65,000
ORC-module		[€]	1,360,000
Generator		[€]	included
Control system		[€]	36,000
Grid connection (transformer, etc.)		[€]	130,000
Engineering		[€]	204,000
Others (buildings, hydraulics)		[€]	320,000
Investments costs	I	**[€]**	**2,765,000**
Spec. investment costs	I_{spec}	**[€/kW_{el}]**	**2,765**

Table 4: Calculation of the specific electricity production costs of a biomass-fired CHP plant based on a 1,000 kW_{el} ORC process as surplus costs in comparison to a conventional biomass-fired heat only plant (hot water boiler) with the same thermal power output

Explanations: basic data see Table 3; no investment subsidies considered; costs for maintenance, consumption and operation based costs derived from experience [4, 7]; calculation based on VDI guideline 2067

Capital costs			
Real interest rate	i_r	[%/a]	6
Useful life of CHP	n	[a]	10
Total capital costs	K_k	**[€/a]**	**375.675**
Spec. capital costs		**[€/kWh$_{el}$]**	**0,075**
Consumption based costs			
Fuel costs (15.0 €/MWh $_{Fuel}$)		[€/a]	117.647
Consumables - ORC (0.3 % of I)		[€/a]	8.295
Electricity demand - thermal oil cycle		[€/a]	18.000
Total consumption based costs	K_v	**[€/a]**	**143.942**
Spec. consumption based costs		**[€/kWh$_{el}$]**	**0,029**
Operation based costs			
Personnel costs (400 hours; 30 €/h)		[€/h]	12.000
Maintenance costs (2.0 % of I)		[€/a]	55.300
Total operation based costs	K_b	**[€/a]**	**67.300**
Spec. operation based costs		**[€/kWh$_{el}$]**	**0,013**
Other costs			
Administration and insurance costs (0.7 % of I)		[€/a]	19.355
Total other costs	K_s	**[€/a]**	**19.355**
Spec. other costs		**[€/kWh$_{el}$]**	**0,004**
Total electricity production costs	K_{ges}	**[€/a]**	**606.271**
Spec. total electricity production costs		**[€/kWh$_{el}$]**	**0,121**