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IEA Bioenergy Task 32 project
Techno-economic evaluation of selected decentralised CHP applications based on biomass combustion with steam turbine and ORC processes

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Abbreviations and definitions

Abbreviations

A	Austria
BOP	balance of plant
CHP	combined heat and power production
CO	carbon monoxide
d.b.	dry base
DE	direct exchange
DH	district heating
ECO	economiser
ESP	electrostatic precipitator
EST	Estonia
Gross	electricity output of the generator
h.p.a.	hours per year
HT	high temperature
HWB	hot water boiler
IEA	International Energy Agency
LT	low temperature
NCV	net calorific value
Net	electricity output of the generator reduced by electricity own demand of the plant
NH_3	ammonia
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O	oxygen
ORC	Organic Rankine Cycle
PLB	peak load boiler
SNCR	Selective non catalytic reduction
SO_2	sulphur dioxide
SO_x	sulphur oxide
ST	steam turbine
TOC	total organic carbon
vol.%	volume percent
w.b.	wet base
wt.%	weight percent

Definitions

$$\text{electric flow index} = \frac{\text{electric capacity}}{\text{themal capacity}}$$

$$\text{annual total efficiency} = \frac{\text{energy production p.a.}}{\text{fuel energy input}\left(\text{NCV}\right)\text{p.a.}}$$

$$\text{annual electric efficiency} = \frac{\text{electricity production p.a.}}{\text{fuel energy input}\left(\text{NCV}\right)\text{p.a.}}$$

$$\text{annual thermal efficiency} = \frac{\text{heat production p.a.}}{\text{fuel energy input}\left(\text{NCV}\right)\text{p.a.}}$$

Abstract

Since the first CHP plant based on biomass combustion has been launched, the technologies in the field of power generation have continuously developed. To give an overview about recent technological developments and demonstration activities regarding small-scale biomass CHP systems a project called „Decentralised CHP technologies based on biomass combustion – state of development, demonstration activities, economic performance (IEA-CHP)“ has been launched within the IEA Bioenergy Agreement Task 32 in 2004. The main objective was to perform technological and economic evaluations of innovative small-scale biomass CHP technologies in a capacity range of up to 20 MW_{el}. Now, 10 years later an update of the most successful and market relevant CHP approaches, the steam turbine and the ORC technology has been made under consideration of the technological development which took place within the last ten years but also under regard of the economic framework conditions given at present.

In general it turned out that for an efficient biomass-fired small-scale CHP application a heat-controlled operation seems to be the best option not only from an efficiency point of view but also from an economic perspective (heat is the main product and electricity is a valuable by-product). Under this perspective representative best practice case studies for small-scale biomass CHP applications which also represent the latest state of technological development have been chosen for the techno-economic evaluation performed. Regarding steam turbine based systems the main issue within the last ten years was to increase the electric efficiency by stepwisely increasing the life steam temperatures based on the experiences gained regarding material selection and high temperature corrosion. Within the present study a steam turbine based process representing the present state-of-the-art based on a backpressure turbine system with a buffer storage tank and a nominal capacity of 5.7 $MW_{el,gross}$ from Austria has been chosen. Regarding the ORC technology, its successful first demonstration took place in 1999 within an EU demonstration project. From this time on a successful market introduction and market penetration took place. Now over 200 ORC units are in operation in biomass CHP plants. But within the last decade also further technological developments have taken place and are still ongoing in order to increase the electric efficiency and to reduce the investment costs. The so-called “split cycle” has been introduced in the market with the main objective to increase the efficiency of the ORC and therefore one best practice case study has been chosen based on this technology with a nominal electric capacity of 2.4 $MW_{el,gross}$ located in Estonia. The split cycle enhances the heat transfer from the flue gas to the ORC by an additional flue gas economizer integrated in a low temperature loop of the ORC working fluid. Moreover, a further technological approach, the so-called direct exchange ORC system, has been developed for biomass applications. This technology is based on an ORC system without the need of an intermediate circuit (e.g. a thermal oil cycle) and can be seen as a promising future approach to reduce the investment costs of this technology. For this reason also a case study based on the direct exchange ORC system in a biomass plant in Slovakia with an electric capacity of 130 $kW_{el,gross}$ has been investigated.

The evaluation of the CHP technologies is covering a technological as well as an economic evaluation based on real life figures of the case studies selected. The plants themselves, their process flow sheets including mass and energy balances as well as the specific differences between the technologies concerning operation behaviour, personal demand and process control are pointed out. Moreover, the plant efficiencies (electric, thermal and overall) are discussed and ecological aspects (emissions) are illustrated. Finally, based on the VDI guideline 2067

economic calculations have been performed using the operating data and economic side constraints of the individual plants in order to determine und compare the electricity, heat and energy generation costs of the different technologies. In addition, within a sensitivity analysis the main influencing parameters (investment costs, fuel price, electricity feed-in tariff, heat price and full load operating hours of the CHP plant) have been analysed in order to show their influence on the economic performance.

Summing up, the techno-economic evaluation performed provides an overview of the most relevant small-scale CHP technologies based on biomass combustion relevant for the market at present. It points out the differences between the technologies available, their meaningful integration in heat supply systems based on real-life case studies and a technological as well as economic evaluation and comparison between the technologies. The results provide valuable information about the necessary constraints for a meaningful application of these technologies and a good basis for future design, application and operation of such plants but also for meaningful further developments.

The results showed, that the heat generation costs of the different CHP plants investigated vary between 43.7 €/MWh$_{th}$ (steam turbine) to 21.1 €/MWh$_{th}$ (direct exchange ORC system) and the electricity generation costs are in a range of 108.8 €/MWh$_{el}$ (direct exchange ORC) and 98.6 €/MWh$_{el}$ (steam turbine). The main cost factors are the capital costs as well as the consumption costs (fuel costs). The economy-of-scale-effect is obvious when comparing the specific investment costs of the plants investigated and also clearly emphasises the need for selective feed-in tariffs depending on the scale or a combination of feed-in tariffs and investment subsidies. Heat utilisation and correct dimensioning of the CHP plant in order to achieve a large number of full load operating hours in heat controlled operation is another key issue.

1 Introduction and objectives

In 2004 the project “Decentralised CHP technologies based on biomass combustion – state of development, demonstration activities, economic performance (IEA-CHP)” had been performed within the IEA Bioenergy Agreement Task 32. The main objectives of that project were to gain an overview of technological developments and demonstration activities regarding small-scale biomass CHP systems based on biomass combustion and to perform technological and economic evaluations of innovative small-scale biomass CHP technologies. In the meantime the CHP technologies available on the market have developed. For this reason the evaluations made in this report shall give an overview of the current state of the art by evaluating selected decentralised CHP applications based on biomass combustion.

As decentralised CHP applications based on biomass combustion are seen plants with nominal electric capacities below about 20 MW_{el}. Co-combustion applications can, however, also have higher nominal electric capacities, but the share covered by biomass is usually also in the capacity range (below about 20 MW_{el}). Only a few biomass CHP plants, especially in Scandinavia, exist with higher nominal electric capacities.

Different technologies are in principle available for electricity production from biomass. Based on biomass combustion these are:

- steam turbine process,
- steam piston engine process,
- screw type engine process,
- ORC process (with or without intermediate heat transfer circuit),
- Stirling engine process,
- directly fired gas turbine process,
- indirectly fired gas turbine process.

According to the current state-of-the-art, the following technologies based on biomass combustion are well suited and highly developed for decentralised biomass CHP plants and are commercially available on the market:

- ORC processes in a capacity range up to 6,000 kW_{el},
- steam turbine processes for capacities of more than 2,000 kW_{el} (although some applications with lower capacities are in operation).

The other technologies mentioned above are still not fully developed for market introduction, but there are some promising demonstration plants.

Therefore, biomass CHP plants based on biomass combustion applying steam turbine processes (case study 1) and ORC processes (case study 2 and 3) have been investigated in detail in this report.

Biomass CHP based on gasification technologies have not been considered in this report.

2 Methodology

The study presented has been performed based on reliable technological and economic data of three different, actually operated CHP plants in Europe. Where applicable and necessary, missing data has been added based on experience values and reference projects. The plants selected are an Austrian biomass CHP project based on a steam turbine, an Estonian ORC process plant and a Slovakian CHP plant based on the innovative direct exchange ORC system.

For the description of the technologies investigated the following issues are discussed for each case study:

- Basic process description
- Interface between the CHP technology and the combustion plant
- Operating behaviour
- Control system
- Maintenance demand
- Special (technology related) operation costs
- Ecological aspects
- Technological maturity
- Weak points
- Fuel characterisation and handling

The economic calculations in section 4 have been performed based on the guideline VDI 2067 [1], distinguishing between heat, electricity and total energy generation (electricity and heat) costs. A detailed description of the method applied is shown in section 4.1.

Moreover, based on the results achieved, a sensitivity analysis considering relevant influencing parameters on the heat and electricity generation costs has been executed. Finally, conclusions and recommendations are derived.

3 Description of the technologies investigated

3.1 Case study 1: Biomass CHP plant based on a steam turbine process (Austria)

3.1.1 Basic process description

A schematic diagram of the CHP plant investigated is shown in Figure 1, the technical data are shown in Table 1. The CHP plant is the main heat supplier for the district heating network. Additional heat demand is met by a gas-fired peak load boiler with a nominal capacity of 8 MW_{th} (the heat produced by this boiler will not be taken into account within the economic evaluation).

For lowering the heat demand fluctuations in the district heating network and to raise the minimum load of the plant a buffer storage with a water content of 231 m^3 has been installed. During wintertime the CHP plant is operated heat controlled. In the summertime small heat demand of the district heating network would cause a low partial load of the system and decrease the plant efficiency and deteriorate the gaseous emissions. For this reason an air cooler has been installed.

The biomass fuels used in the CHP plant are wood chips, bark and saw dust from the regional forestry and wood industry with water contents in a range of 30 – 55 wt.% w.b.. In case of delivery bottlenecks wood logs stored at the plant site can be chopped by a mobile chipper to maintain fuel and heat supply.

The plant is located in Austria and was started up in December 2012. The net electric capacity of the CHP plant is 5 MW_{el}, the heat produced is used in a district heating network, the net electricity produced is fed into the public grid. The plant, which is operated heat controlled, uses a back pressure steam turbine (manufacturer: MAN Diesel und Turbo, DE).

Table 1: Main technical data of the Austrian biomass CHP plant based on a backpressure steam turbine

Parameter	Value
Fuel energy input CHP	27,860 kW_{NCV}
Electric capacity (gross) CHP	5,700 kW_{el}
Electric capacity (net) CHP	5,000 kW_{el}
Useful heat capacity CHP	17,000 kW_{th}
Steam pressure	90 bar
Steam temperature	525°C
Steam flow	30 t/h
Kind of turbine	Back pressure
Back pressure	0.5 – 2.3 bar_a
Operation mode	Heat controlled

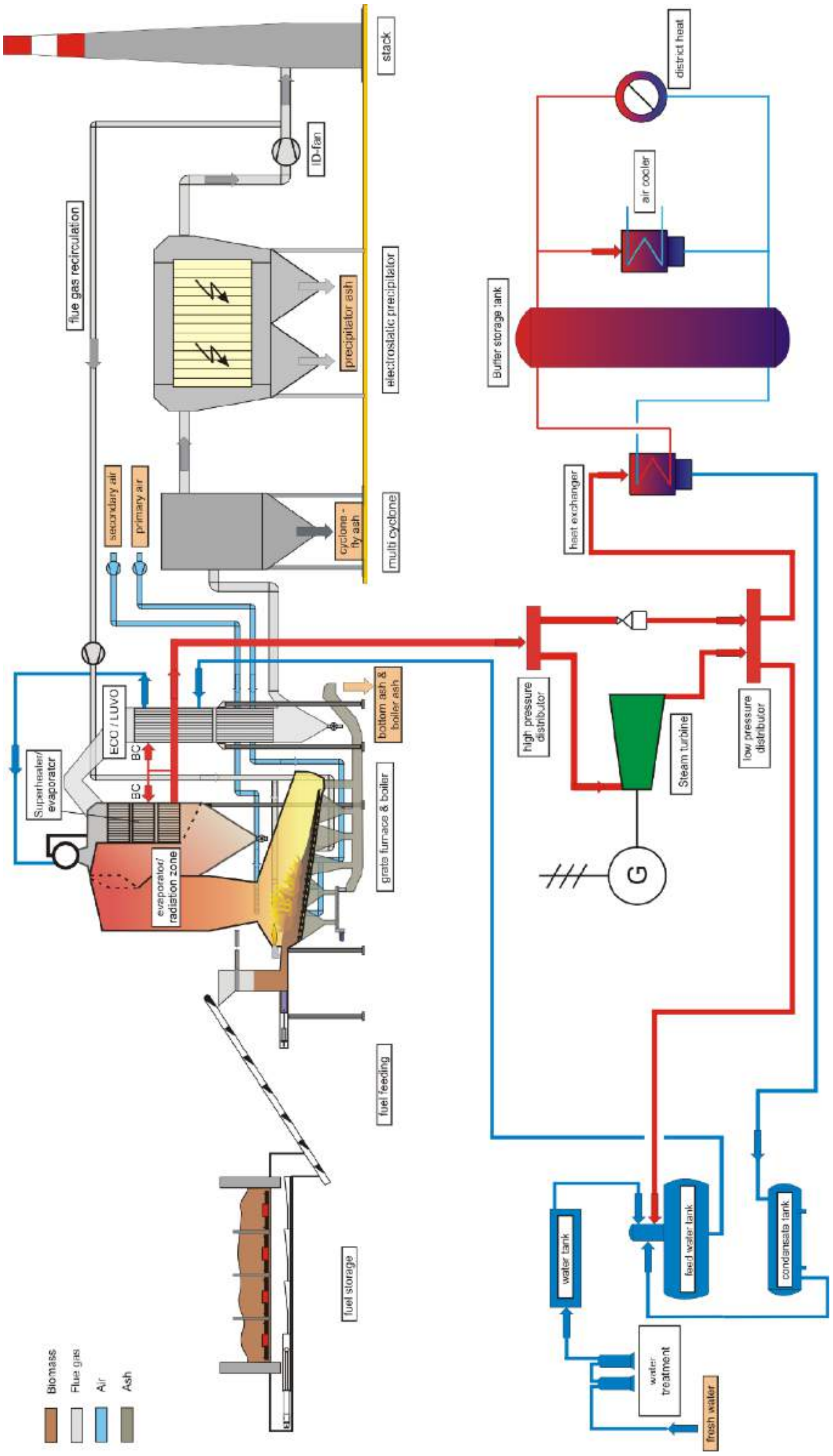

Figure 1: Schematic diagram of the overall biomass CHP plant based on steam turbine in Austria

Explanations: ECO … economiser; LUVO … air pre-heater; BC … boiler cleaning; G … generator; data source BIOS BIOENERGIESYSTEME GmbH

The wood logs for emergency fuel supply are stored in a separate storage area. The biomass is transported with a wheel loader to the short term storage and afterwards automatically fed to the moving grate furnace. Downstream the furnace a water tube steam boiler including a superheater is installed. Subsequently, the flue gas passes through a feed water economiser and an air pre-heater to the flue gas cleaning unit including a cyclone and an electrostatic precipitator (ESP). Downstream the ESP a side stream of the flue gas is used for flue gas recirculation to the furnace, the remaining flue gas passes into the chimney. Due to low emission limits for NO_x, the CHP plant is also equipped with a SNCR-system (selective non catalytic reduction) for flue gas cleaning.

The steam turbine used in the CHP plant is a back pressure turbine and the heat supply for district heating is realised by three heat condensers.

3.1.2 Interface between the CHP technology and the combustion plant

The steam is produced in a water tube steam boiler (manufacturer: Weiss GmbH, DE) including a superheater. Steam pressure and steam temperature are 90 bar and 525°C, respectively. Since the steam turbine requires a very constant operation, the steam parameters must be kept as constant as possible. In order to fulfil these requirements, the fuel mixture must be kept as homogeneous as possible (as different biomass fuel fractions with different water contents are used). This is managed by the wheel loader using the different fractions available for filling the daily fuel storage and thus achieving a good mixture.

3.1.3 Operating behaviour and efficiencies

The CHP plant in Austria had a construction time of about 1 year and was started up at the end of 2012.

Start-up of the entire plant is done by the use of natural gas in a separate natural gas burner mounted at the wall of the combustion chamber. This gas burner has a nominal capacity of 4,100 kW and needs at maximum 800 Nm^3/h of natural gas. The start-up period can last between 10 minutes to 1 hour until the gas burner can be turned off and the regular operation of the furnace and feeding of the wood fuel can be started. Usually an operation of the gas burner for about 10 minutes at 2.0 MW are enough to ignite the biomass fuel. The start-up procedure is computer controlled and happens fully automatically. On average, about 2 start-up procedures are needed per year.

The CHP plant is operated almost uninterrupted all year long. In winter the heat produced in the CHP plant is used in the district heating network. Additional heat demand is covered by the natural gas fired peak load boiler. In the summertime the thermal production exceeding the customers' heat demand and the capacity of the buffer storage tank will be cooled down by an air cooler to keep the load of the CHP plant high and to increase electricity production. The average feed and return temperature from the district heating network is 125°C and 60°C, respectively.

Within an average operating year the minimum load of the CHP plant is about 67% (20 t/h), which is quite high due to the installation of the buffer storage tank and the cooling system. The minimum load that can be reached by the biomass furnace is 30% of nominal boiler load.

The efficiencies of the biomass CHP plant investigated are shown in Table 2. It can be seen that the nominal total gross efficiency is about 81.5%. The annual total efficiency is about 68.8% due to the fact that a certain amount of heat is cooled off.

The availability of the plant is 96% and the CHP plant can therefore be considered as very reliable. Usually the plant can be operated without any unexpected outages. Planned stops for plant maintenance take place on approximately 8 days per year.

Table 2: Efficiencies of the Austrian biomass CHP plant based on a steam turbine

Explanations: The efficiencies are calculated from the nominal and annual electricity and thermal production related to the fuel energy input to the furnace.

Parameter	Value [%]
Total efficiency CHP plant at nominal load (gross)	81.5
Annual electric efficiency gross	22.3
Annual electric efficiency net	20.3
Annual thermal efficiency	46.5
Annual total efficiency gross	68.8

3.1.4 Control system and personnel demand

The complete operation of the plant is controlled and supervised by a computer based system. Changes in operation condition can be supervised and immediately changed via the computer monitors in the control room. According to Austrian law an unattended operation of a steam system up to 72 hours is permitted, if special regulations are obeyed. In order to this the biomass plant is equipped with special additional safety precautions. The control system enables automatic operation of the plant and is connected to another biomass plant of the operator where the personnel can receive alarms and malfunction notifications and can in order to this react if necessary. The stand-by operators will also be contacted automatically in case of alarms.

The main tasks of the personnel during normal plant operation are the fuel handling with wheel loader and the supervision of the plant including small repair work. Regular walk arounds (at least every 72 hours) in the plant as well as check-ups of the safety equipment are necessary for an operation without permanent supervision.

Due to the additional safety equipment and adapted process control the personnel demand of the steam turbine plant can be reduced to about 6,800 hours per year, which reduces the personnel costs significantly. Boiler attendants need to have a special education for supervising a steam boiler which rises the hourly rate of working costs.

3.1.5 Maintenance demand

Maintenance and service work increase the personnel effort temporarily. These jobs are however not part of the daily work routine and will therefore be considered separately in the economic evaluation of the plant.

Once a year, usually during summertime, a revision of the CHP plant has to be done. During that time the plant will be cleaned, repair work takes place and if necessary plant components will be replaced or improved. On average these revisions last for about 8 days.

3.1.6 Special (technology related) operation costs

In a steam process special requirements to feed water quality exist. Due to this water conditioning is necessary (see section 3.1.7). Therefore additional, technology related operation costs occur due to the desalination and blowdown needed for the boiler water and are considered in the operation costs.

In addition the plant is equipped with a SNCR system for flue gas cleaning, for which a urea solution is needed and has to be considered in the operation costs.

3.1.7 Ecological aspects

The emissions of the plant as well as the emission limits to be met are shown in Table 3. The emission limits shown are valid for plants operated with biomass fuels in a capacity range between 10 and 50 MW in Austria. The limits for TOC and dust for this special case study plant are more rigorous than usually.

It can be seen, that the emissions of CO, TOC and dust are easily met by the plant. Only the NO_x emissions of the plant are close to the emission limit.

Table 3: Plant emissions and emission limits to be met by the Austrian steam turbine based biomass CHP plant

Explanations: values in mg/Nm^3_{dry}, 13 vol.% O_2; data source: emission test report

Parameter	Emission limit [mg/Nm³]	Plant emissions [mg/Nm³]
CO	100	15
NO_x (NO_2)	200	191
particulate emissions	20	8
TOC	20	< 4.0
NH_3	10	2.7

During steam production nearly clean water in form of steam is discharged. Salts in the water remain in the boiler water. In order to avoid a high salt content, periodic desalination is required. In addition, blowdown of sludge in the boiler formed from carbonates and abrasion from ducts must be done periodically. The waste water from the desalination, the blowdown and the water treatment are only slightly contaminated and can therefore be discharged in the sewer without any further neutralisation.

Bottom ash from grate, cyclone ash and fly ash from the ESP are transported in wet de-ashing systems and collected in ash containers. The ash disposal will cause additional operating costs, which have been taken into account.

The sound pressure level of the steam turbine is 85 dB(A) in 1 m distance. Appropriate noise insulation measures were considered to keep the noise emissions of the plant low.

3.1.8 Technological maturity

The steam process is a well-known and well developed technology and commercially available. The boiler and superheater section as well as the steam turbine itself have been optimised in the last years whereby the developments declined. The main focus on further investigations is based on steam parameters to increase the plant efficiency. In state-of-the-art steam turbine processes of this size the steam temperature reached is about 500°C – 525°C.

Steam turbines in general have a large range of application. Combined with decentralised biomass combustion plants electric capacities of 500 kW_{el} up to ~25 MW_{el} are reachable.

According to a country analysis of wood chips plants performed by the “Biomass Availability and Sustainability System” [2] the number of CHP plants based on biomass wood chips in Europe is about 630. Approximately 250 of these plants are based on the ORC technology [database: Turboden srl and Adoratec]. Therefore the number of CHP plants based on steam turbines in Europe is about 380.

In former years many steam turbines have been used in power-only plants to produce a high amount of electricity while the heat production of the plant has been cooled off. Nowadays, due to rising biomass prices, high plant efficiencies have become more and more important and a main requirement for legally granted feed-in tariffs. For this reason heat controlled CHP applications have become the state-of-the-art for steam processes. During summertime, however, when the heat demand is low, the electric efficiency of a steam turbine decreases strongly due to the rather poor part load behaviour. For this reason buffer storage tanks are installed to smoothen fluctuations.

Due to the high pressure in a steam turbine process, the operation requires a special education which increases the personnel costs. At the same time the maturity of the technology and the fully automatic control enables an operation without continuous supervision. By installing additional safety equipment, the plant will reach a safe operation state in case of failure operation without the need of external intervention, which can limit the personnel demand.

3.1.9 Weak points

Changing fuel composition and quality have an impact on the steam quality and in consequence on the performance of the steam turbine. This fact has to be taken into account at the design of the biomass furnace and the fuel selection.

The performance of the plant is limited by the steam parameters. Further rising of temperature leads to the need of special materials and increases the high temperature corrosion risk and the specific investment costs. The high steam pressure is a safety risk causing special requirements to equipment and personnel.

3.1.10 Fuel characterisation and handling

Forest and industrial wood chips, sawdust and bark (average water content between 30 and 55 wt.% w.b., particle size between 3 – 100 mm) from the regional forestry and wood industries are utilised as biomass fuels.

The biomass is stored in a 4,500 bulk m³ roofed fuel storage. The wood logs for emergency supply are stored in a separate area of 18,000 bulk m³. If necessary a mobile wood chipper will be rented to chip these wood logs.

The transport of the biomass fuel is done by wheel loader. If possible the biomass delivered will be directly transported to the roofed storage with trucks. To ensure a homogeneous fuel quality the different fuel fractions with varying water content are mixed using the wheel loader.

The biomass storage itself is equipped with two push floors (nine hydraulic pull rods each) that transport the fuel to one common belt conveyor. The fuel then passes an inclined conveyor and a disc screen, where too large wood parts are separated. Two further belt conveyors transport the biomass to the stoker unit of the biomass combustion plant.

3.2 Case study 2: Biomass CHP plant based on an ORC process (Estonia)

3.2.1 Basic process description

A schematic diagram of the CHP plant investigated (ORC plant in Estonia) is shown in Figure 2, the main technical data of the plant are shown in Table 4. The CHP plant supplies the closer region with district heating, the electricity produced is fed into the local electricity network. The net electric capacity is about 2 MW_{el}. The plant, which is operated heat controlled mainly consists of the biomass furnace (manufacturer: Polytechnik, AT), a thermal oil boiler and two thermal oil economisers, an air pre-heater for heat recovery, a flue gas cleaning unit consisting of a multi-cyclone and a flue gas condensation plant, the ORC (manufacturer: Turboden srl, IT) and the BOP.

Table 4: Main technical data of the Estonian biomass CHP plant based on an ORC process

Explanations: The thermal capacity in the table below is the capacity of the ORC unit without taking the condensation unit into account.

Parameter	Value
Fuel energy input CHP	14,200 kW_{NCV}
Boiler efficiency	84.5%
Thermal oil input to ORC	12,000 kW_{th}
Electric capacity CHP (gross)	2,400 kW_{el}
Electric efficiency ORC module (gross)	20.0%
Electric capacity CHP (net)	2,050 kW_{el}
Thermal capacity ORC	9,580 kW_{th}
Operation mode	Heat controlled

The plant is the main heat supplier for the district heating network. In addition an old wood fired heating plant exists as a stand-by system for the CHP plant. This old plant was not taken into account in the evaluation of the system.

Wood chips, sawdust and bark (average water content between 25 and 55 wt.% w.b.) from the regional forestry and wood industries are utilised as biomass fuel in varying composition. The fuel conversion unit covers a biomass combustion system and the thermal oil boiler with a nominal capacity of 9,800 kW_{th}. In addition two thermal oil economisers with a nominal capacity of 2,200 kW_{th} are used for heat recovery and for increasing the overall plant efficiency. In total the thermal oil capacity is 12,000 kW which feeds the ORC. The heat for supplying customers is produced in the ORC condenser with a nominal capacity of 9,580 kW_{th} and the flue gas condensation unit.

The biomass-fired thermal oil boiler, the thermal oil economisers and the air pre-heater are equipped with an automatic cleaning system based on pressurised air. This system has already proved its efficiency due to the fact that manual boiler cleaning is necessary only once a year and boiler operation takes place without rising flue gas temperatures at boiler outlet. This aspect is of great relevance for a high availability and overall efficiency of the CHP plant.

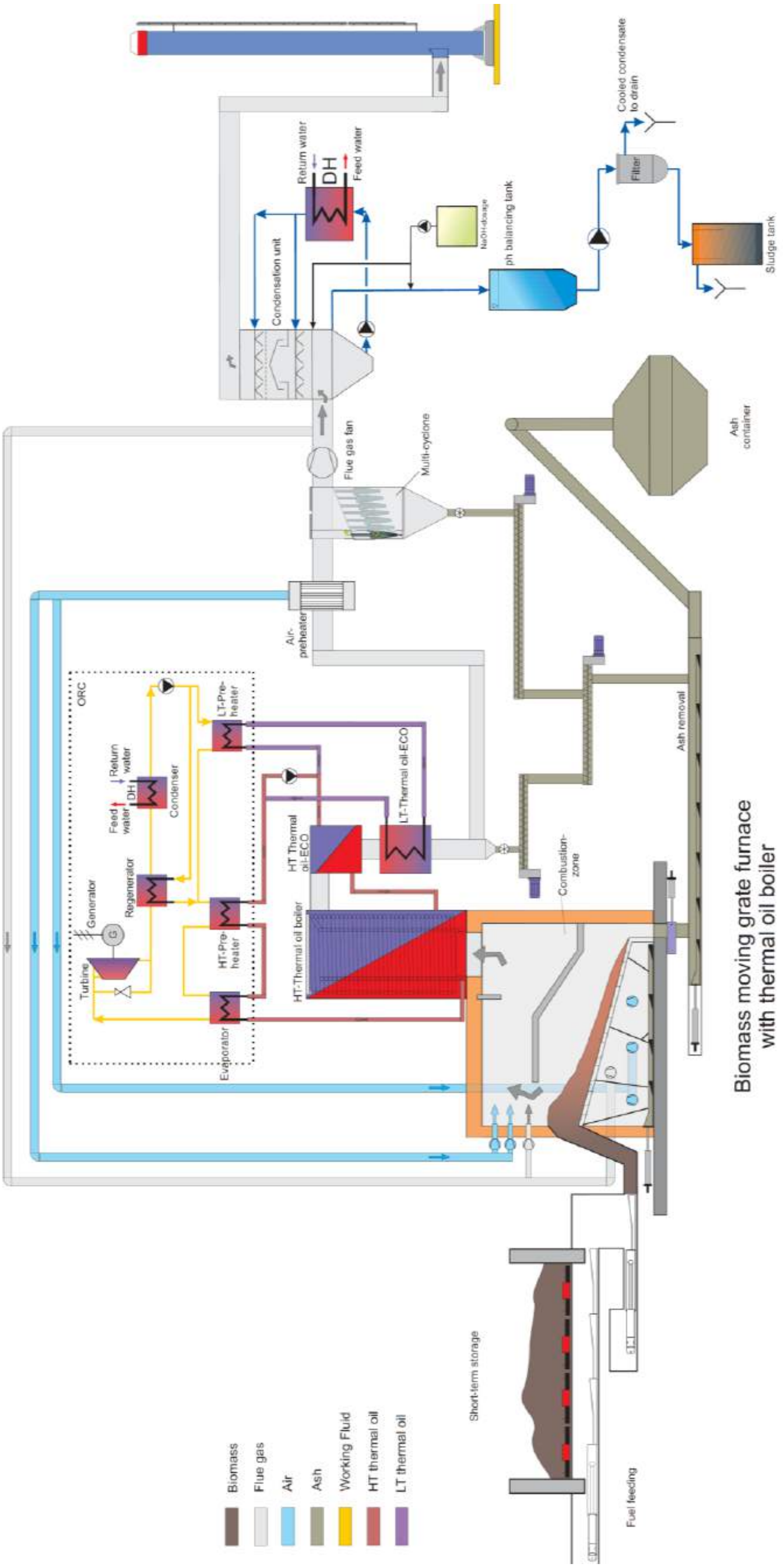

Figure 2: Schematic diagram of the biomass boiler section of the CHP plant in Estonia

Explanations: data source BIOS BIOENERGIESYSTEME GmbH

The flue gas cleaning unit consists of two stages. In the first stage the coarse fly ash particles are precipitated in a multi-cyclone which is placed downstream the air pre-heater. In the second stage, fine fly-ash and aerosol precipitation takes place in the flue gas condensation unit.

The main part of the biomass CHP plant is the ORC process with an electric capacity of 2.4 MW_{el} and a nominal thermal capacity of 9.6 MW. The principle of electricity generation by means of an ORC process corresponds to the conventional Rankine process (see Figure 3). The substantial difference is that instead of water an organic working fluid with favourable thermodynamic properties is used – hence the name Organic Rankine Cycle (ORC). 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 fluid. This pressurised organic working fluid 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. 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 fluid 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 fluid then passes the feed pump to again achieve the appropriate pressure level of the hot end of the cycle. By installing a thermal oil economiser, the heat transfer from the flue gas to the thermal oil cycle and the overall plant efficiency can be increased. The state-of-the-art of ORC processes is the realisation of a so-called split-cycle where a second thermal oil economiser is used at a lower temperature level. A part flow of thermal oil passes the low temperature economiser and transfers the heat to an ORC working fluid LT-pre-heater (LT… low temperature). Due to the split-cycle more energy can be transferred from the thermal oil to the ORC and thus the electric efficiency of the overall process rises.

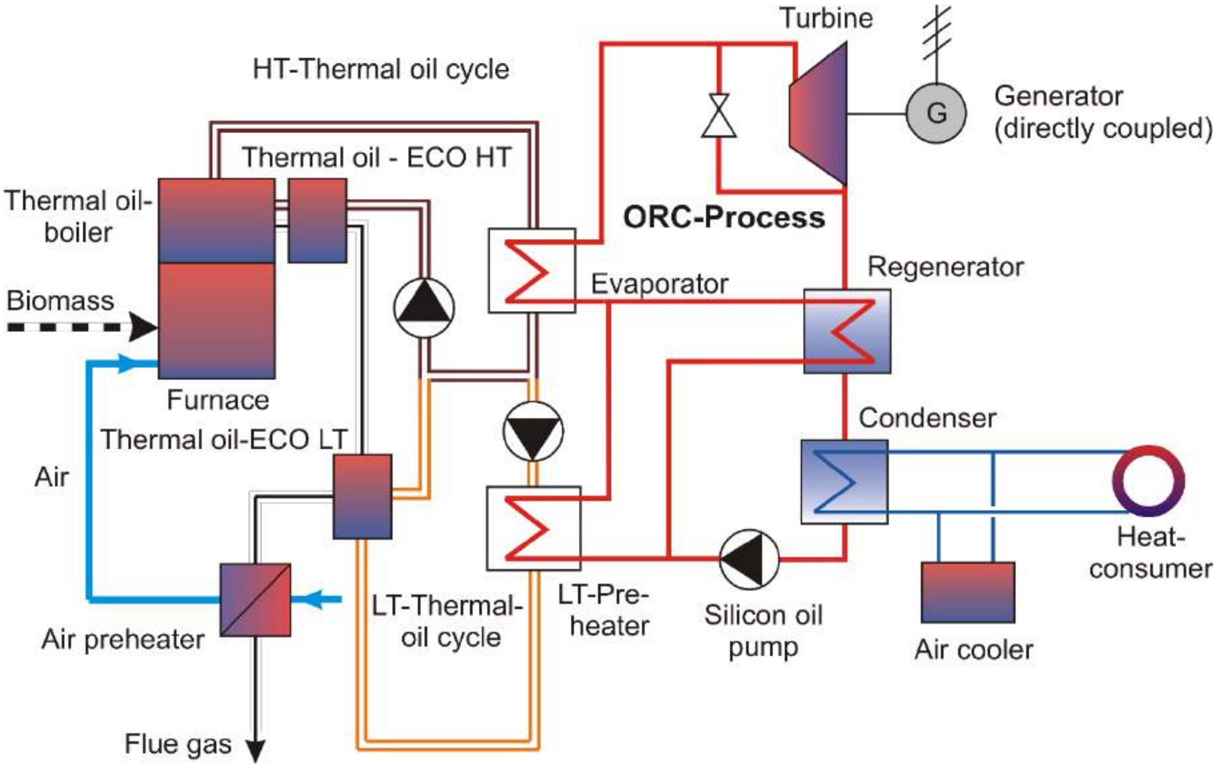

Figure 3: Working principle of a biomass-fired ORC process with split cycle

3.2.2 Interface between the CHP technology and the combustion plant

The ORC process is connected to the thermal oil boiler and the thermal oil economisers via a thermal oil cycle which is divided into a HT and a LT circuit (see Figure 2). This intermediate thermal oil cycle is chosen in order to achieve a high level of security for the ORC cycle (constant feed temperatures at the ORC evaporator) and to make an operation of the boiler at atmospheric pressure possible, which reduces personnel costs (no steam boiler operator necessary). The thermal oil cycle is a closed cycle which is equipped with appropriate security measures like expansion vessels and an emergency cooling system. The lifetime of the thermal oil is at least 15 years if the nominal operating temperatures are kept (usually about 310°C feed temperature).

Usually the ORC power units are delivered as compact modules. The interfaces to the combustion plant are mainly the connection to the thermal oil cycle on the one hand and the connection to the district heating water cycle on the other hand.

3.2.3 Operating behaviour and efficiencies

The plant in Estonia is operated heat controlled. In the summertime the heat demand in the district heating network is very low. To enable a good part load operation of the ORC module an air cooler has been installed to dissipate excess heat produced in the ORC module.

Start-up and shutdown procedures as well as the operation of the entire CHP plant are controlled fully automatic, which minimises the demand of personnel. Due to the excellent partial load behaviour of ORC units and the possible rapid load changes, this CHP technology is very suitable for decentralised biomass CHP systems in heat controlled operation.

The efficiencies of the biomass CHP plant in Estonia are shown in Table 5. It can be seen, that the annual electric efficiency is smaller compared to case study 1. The annual thermal efficiency and the annual total efficiency however are higher. In the calculations the nominal efficiency has been calculated by relating the thermal and electricity production of the CHP unit to the fuel input based on the net caloric value (without consideration of the heat recuperation of the flue gas condenser). The annual total efficiency of the system includes the condensation unit and is therefore higher than the total efficiency of the CHP unit at nominal load.

The ORC unit in the biomass CHP plant in Estonia is in successful operation since November 2012, the construction time was about 1.5 years. The plant can operate between 20 – 100% of the nominal load.

In 2014 the planned working hours of the boiler were 7,700 hours. Due to 60 hours of unplanned outages the availability of the thermal oil boiler achieved 99.2%. In the same period the planned working hours ORC were 7,500 hours. Due to 150 hours of unplanned outages the availability of the ORC achieved 98.0%. The difference between 7,700 hours and 8,760 (full year) were due to planned maintenance and non-operation due to low heat demand in summer.

Table 5: Efficiencies of the Estonian biomass CHP plant based on ORC process

Explanations: The efficiencies are calculated from the nominal and annual electricity and heat production related to the fuel energy input to the furnace. The thermal output of the system considers the heat production of the ORC unit as well as of the flue gas condensation unit.

Parameter	Value [%]
Total efficiency at nominal load (without condensation) (gross)	84.4
Annual electric efficiency (gross)	16.5
Annual electric efficiency (net)	12.3
Annual thermal efficiency	74.8
Annual total efficiency (with condensation) (gross)	91.2

3.2.4 Control system and personnel demand

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 a PLC, 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 ORC condenser outlet. Due to this fully automatic operation of the ORC process, the personnel demand is considerably reduced and mainly covers routine checks and maintenance. Possible malfunctions of the process are visualised, automatically stored and forwarded to the operator via telecommunication. The operation of the entire CHP plant requires about 6,600 annual working hours.

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 standards do not apply. Thus, the personnel costs are reduced in comparison to steam boilers.

3.2.5 Maintenance demand

Regarding the necessary maintenance for the ORC module, periodic weekly checks by the operator (some hours) as well as an annual routine examination which lasts about one day is recommended by the manufacturer. The usual lifetime of ORC units is greater than twenty years, as has been proven by many geothermal applications. The silicone oil used as working fluid was in the past said to have the same lifetime as the ORC since it does not undergo any relevant ageing. In fact experiences with ORC modules showed, that the quality of the silicone oil decreases during the years of operation. Impurities like lubricants can enrich in the silicone oil which leads to a decrease of the ORC performance. For this reason the periodic cleaning of silicone oil can provide a high electric efficiency of the ORC module continuously. For the biomass combustion and boiler system the maintenance demand is similar to the system described in case study 1.

3.2.6 Special (technology related) operation costs

Since the cycle of the thermal oil and the ORC process is closed and thus no losses of the working fluid are possible, the operating costs are low. Only moderate consumption-based costs (lubricants) and annual maintenance costs have to be considered.

The flue gas condensation unit causes additional costs for sludge and condensate treatment and disposal.

3.2.7 Ecological aspects

Measurements of emissions carried out at the biomass-fired CHP plant in Estonia showed that the prescribed limiting values according to Table 6 can be kept without problems both at nominal load and partial load operation. Only the particulate emissions exceeded the limits slightly which requires some optimisation in the combustion system.

Table 6: Emission limits to be met by the Estonian ORC based biomass CHP plant

Explanations: values in mg/Nm^3_{dry}, 13 vol.% O_2; data source: air emission measurement report

Parameter	Emission limit [mg/Nm³]	Plant emissions full load [mg/Nm³]	Plant emissions part load [mg/Nm³]
CO	100	7	3
NO_x (NO_2)	200	88	118
particulate emissions	56	60	71
TOC	25	< 1	< 1

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

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 filter. In this way, the condensate can be directly discharged into rivers or into a sewer.

The ash (bottom and boiler ash, as well as cyclone ash) are collected in a single ash container. Ash disposal causes additional operating costs, which have been taken into account.

Table 7: Properties of the thermal oil used in the Estonian plant

Explanations: The data is based on the safety data sheet of the thermal oil. [3]

Parameter	Value [%]
Name	Marlotherm® SH
Chemistry	Dibenzyltoluene
Boiling point (at 1,013 hPa)	390°C
Flash point	200°C
Ignition temperature	450°C
Vapour pressure (at 20°C)	< 0.01 hPa
Explosive properties	No explosion limits at normal conditions

As already mentioned, the ORC process uses an intermediate thermal oil cycle for transferring the heat from the thermal oil boiler and the economisers to the ORC unit. In case of the Estonian plant about 32,000 litres of the thermal oil Marlotherm® SH are used. The most important properties of this fluid are given in Table 7. Due to the flammability of the thermal oil special safety precautions and additional safety equipment like an emergency cooling or an additional emergency thermal oil pump to ensure a permanent thermal oil flow and to avoid an overheating in the thermal oil boiler are necessary. An explosion risk, however, is not given under normal conditions. The extremely low vapour pressure of the thermal oil ensures, that the fluid is in a liquid state in normal operation and can therefore be stored in non-pressurized vessels.

The silicon oil used as a working fluid in the ORC cycle is Octamethyltrisiloxane which is environmentally friendly. Furthermore, due to the favourable thermodynamic properties of the silicon oil, there is no danger of droplet erosion on the ORC turbine blades. As the working fluid is flammable and may form explosive mixtures with air, 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. The most important properties of the silicon oil can be seen in Table 8.

The ORC working fluid can be stored in non-pressurized vessels due to its low vapour pressure.

Table 8: Properties of the silicon oil used in the Estonian plant

Explanations: The data is based on the safety data sheet of the silicon oil. [4]

Parameter	Value [%]
Name	Xiameter® PMX-200 Silicone Fluid 1CS
Chemistry	Octamethyltrisiloxane
Boiling point (at 1,013 hPa)	152°C
Flash point	30°C
Ignition temperature	340°C
Vapour pressure (25°C)	5.3 hPa
Explosive properties	Vapours may form explosive mixtures with air

3.2.8 Technological maturity

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 was realised in 1999 and is still operated successfully [5].

A few different suppliers are specialised on highly efficient ORC systems, which can be used for biomass, heat recovery, geothermal energy and other applications. At the moment about 250 CHP plants in Europe are operated based on biomass combustion with an ORC process.

Since 1999 the ORC technology is commercially available but has been continuously improved. Technology suppliers provide the ORC technology in complete and compact modules which only have to be connected to the thermal oil cycle, the water cycle and the electricity interfaces.

At present the ORC process in single modules is commercially available (in a capacity range up to 6,000 kW_{el}). Some custom-built ORC systems however are also available above this capacity range. The gross electric efficiency (related to the thermal oil input to the ORC system) of these ORC plants is in a range of 17.9 to 19.9% in case of the classic ORC system and up to 19.6% in case of split systems. Split ORC systems have a slightly lower efficiency related to the thermal oil input, but can increase the total electric efficiency (related to the fuel input) significantly.

The state-of-the-art in ORC systems is the realisation of a split cycle. By using a second thermal oil economiser at a low temperature level, lower flue gas temperatures than in a classic ORC process can be reached, which increases the overall plant efficiency.

The ORC process is a well analysed and studied process and reaches a high level of availability. One main issue however is the need of the thermal oil cycle which needs special safety precautions. The high temperatures (about 310°C) and the flammability are the issue. Additionally the intermediate cycle causes heat losses between the flue gas and the ORC process which reduce the overall plant efficiency. Furthermore the quality of silicone oil can decrease after some time of operation due to impurities, which leads to a decrease of ORC performance. This can be reduced by regular or continuous cleaning of the ORC working fluid.

Further attention of the ORC process should be laid on the intermediate cycle to further improve efficiency and decrease the safety risks due to the hot and flammable thermal oil. Newest research is based on an ORC process without any intermediate cycle. This topic will be discussed in chapter 3.3.

3.2.9 Weak points

Due to the limited operation (feed) temperature of thermal oil and silicone oil, the electric efficiency is also limited. Further development and optimisation potential towards higher electric efficiencies is, however, given. The plant efficiency and the heat transfer from the flue gas to the ORC module has already been improved by realising ORC split-cycles.

In common the state-of-the-art ORC process needs an intermediate thermal oil cycle. This cycle is operated at ambient pressure but high temperatures. Furthermore, the thermal oil is flammable and therefore needs different safety equipment and precautions to enable a safe operation compared to steam cycles like case study 1.

3.2.10 Fuel characterisation and handling

Forest and industrial wood chips, sawdust and bark (average water content between 25 and 55 wt.% w.b., particle sizes between 3 – 10 mm) from the regional forestry and wood industries are utilised as biomass fuels. For biomass storage an open intermediate storage with an area of about 400 m² has been installed.

The transport of the biomass fuel from the intermediate storage to the roofed daily storage (about 1,000 m³) is usually done by wheel loaders. If possible the biomass delivered will be directly transported to the daily storage with trucks. The daily storage itself is equipped with four push floors (with five hydraulic pull rods each) that transport the fuel to one chain scraper conveyor. A stoker unit is used for fuel feeding of the biomass furnace. This stoker is equipped with the necessary backfiring protection and creates a compression zone at the entry of the firebox, where the fuel is pre-heated and compressed to a fuel barrier which assures air tightness in case of overpressure in the combustion chamber.

3.3 Case study 3: Biomass CHP plant based on a direct exchange ORC process (Slovakia)

3.3.1 Basic process description

The third case study is based on a Slovakian biomass fired CHP plant based on a direct exchange ORC process as shown in Figure 4, the main technical data can be seen in Table 9.

The plant was started up in 2014 with a construction time of about 20 weeks and has been designed for an annual operation of about 8,000 hours. Data of a representative operation year were not available yet and due to this the annual heat and electricity production as well as the overall operating behaviour have been estimated based on experience of the manufacturer.

The fuel energy input is about 1,110 kW using untreated wood processing residues with a water content of about 40 – 55 wt.% w.b.. The heat produced in the plant is used for supplying a sawmill process for drying purpose and electricity produced is used for covering the sawmill's own consumption. The efficiency of the direct exchange ORC system (manufacturer: Triogen, NL) analogous to the conventional ORC system depends on the temperature of the cooling medium. The lower the temperature is, the higher the electricity production of the module. With a water outlet temperature of 55°C, the gross electric capacity of the plant would be 165 kW_{el} at a thermal capacity of 660 kW_{th} at the ORC condenser. The feed temperature necessary in the sawmill process is about 80°C. For this reason the gross electric capacity in this plant reaches 130 kW_{el} only (see Table 9).

The cooler in the water circuit is installed only for emergency reasons, so that usually all heat produced in the plant can be used for drying purposes.

Table 9: Main technical data of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: The electric capacity in the table below is based on a water outlet temperature of 80°C downstream the ORC condenser.

Parameter	**Value**
Fuel energy input CHP	1,110 kW_{NCV}
Boiler efficiency	81.1%
Thermal input to ORC	900 kW_{th}
Electric capacity CHP (gross)	130 kW_{el}
Electric efficiency ORC module (gross)	14.4%
Electric capacity CHP (net)	90 kW_{el}
Thermal capacity CHP	660 kW_{th}
Operation mode	Heat controlled

The boiler efficiency (thermal input to the ORC related to fuel energy input) of the direct exchange ORC system is 81.1%. This derives from the flue gas losses due to the high flue gas temperature at the stack (about 200°C) as well as from the temperature losses due to long and hot flue gas ducts. The gross electric efficiency of the ORC module (electric capacity related to thermal input to ORC) amounts to 14.4%. The total gross efficiency of the ORC module is about 87.8% deriving from internal thermal losses in the ORC cycle. Both the boiler efficiency as well as the electric and total efficiency of the direct exchange ORC module show a potential for further improvement. Despite these facts the technology however is well suited for small scale applications in decentralised systems.

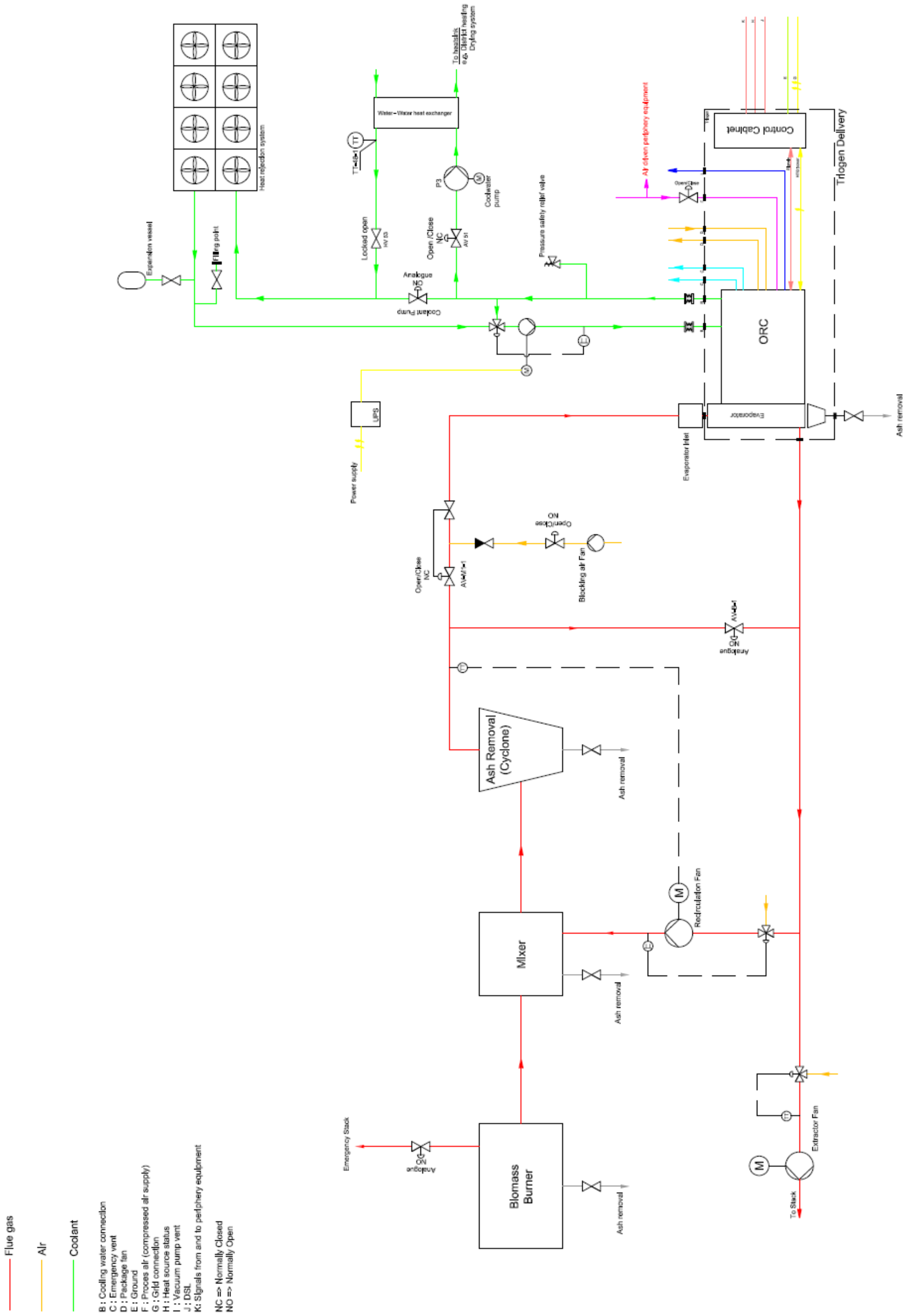

Figure 4: Schematic diagram of the overall biomass CHP plant based on a direct exchange ORC process

Explanations: data source TRIOGEN

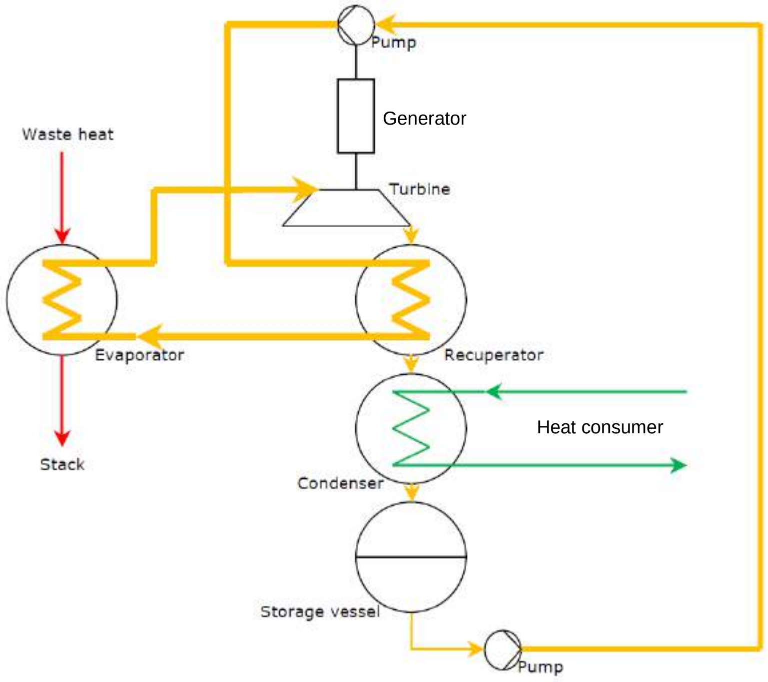

Figure 5: Principle of the direct exchange ORC system

Explanations: data source TRIOGEN

The heart of a CHP plant of this kind is the ORC process, whose principle is shown in Figure 5. It can be seen, that the ORC system equals the conventional ORC process described in chapter 3.2, but instead of a silicone oil toluene is used as working fluid. The toluene is circulated in a closed cycle which is separated into a low and a high pressure part. The liquid working fluid is transported from a storage vessel at a pressure of about 4 bar to the main pump, which raises the working pressure to approximately 30 bar. In the following high pressure part, the toluene passes a recuperator, where it is pre-heated and is afterwards led into the evaporator in which it is evaporated and superheated. The gaseous toluene is expanded in the turbine which produces electricity on the one hand and drives the main pump on the other hand. In the low pressure part of the closed toluene cycle the working fluid is internally used for pre-heating the toluene coming from the storage vessel. Downstream the recuperator the still gaseous toluene passes a heat exchanger, where it is condensed transferring the heat to the heat consumer. The cycle is closed by leading the working fluid back into the storage vessel. (data source TRIOGEN, [6])

Instead of the conventional ORC process, which needs an intermediate thermal oil cycle for transferring the heat from the flue gas to the ORC system due to the thermal stability of the working fluid, the direct exchange ORC process is designed for high temperatures and can be continuously operated at flue gas temperatures at the evaporator inlet between 350°C and 530°C.

The ORC module is equipped with a special evaporator which can be heated by hot flue gas. The biomass is burned in a conventional biomass furnace (manufacturer: Fiedler, CZ) resulting in a dust loaded flue gas at temperatures of up to 1,000°C. To secure the evaporator and avoid an overheating of the working fluid, the flue gas temperature has to be reduced before passing the heat exchanger. For this reason flue gas from downstream the evaporator is recirculated reducing the temperature to at least 530°C. The temperature of the flue gas at the chimney is about 180 – 220°C.

The high dust load of the flue gas could cause fouling and erosion of the evaporator. For this reason a high temperature multi-cyclone is located upstream the evaporator to reduce the dust emissions to a dust content of maximum 200 mg/Nm³. A regular cleaning of the heat exchanger is necessary anyway to remove depositions and avoid a reduced heat transfer. [6]

3.3.2 Interface between the CHP technology and the combustion plant

The direct exchange ORC process does not need an intermediate thermal oil loop as it is used in conventional ORC plants. For this reason the evaporator can directly be connected to the flue gas line of the combustion plant. Compared to hot water boiler or thermal oil boiler plants, the flue gas line between the furnace and the evaporator is much longer and has to be of high temperature stable material due to the high temperature. This has to be considered in the plant design.

The ORC module itself and the evaporator are delivered in a compact unit including a support frame and only have to be connected to the flue gas line on the one side and the cooling cycle on the other. The control cabinet of the ORC is delivered separately and has to be connected to the biomass plant PLC. The communication between the biomass combustor and the direct exchange ORC module is made via Modbus.

3.3.3 Operating behaviour and efficiencies

The plant in Slovakia was started up in 2014 and is planned to be operated for about 8,000 hours per year. The missing hours to 8,760 (which equals the hours of a whole year) is the downtime due to planned maintenance of the ORC and the biomass furnace. In the last 12 months the entire plant has been operated for 8,124 hours a year with a downtime of 35 hours caused by the ORC. This means that the technology can be considered as reliable.

The concept of the ORC supplier TRIOGEN is that the direct exchange ORC module is operated heat controlled. The minimum load of the CHP plant is about 50% of full load. According to this the heat production of the plant varies between 300 and 660 kW_{th}.

The efficiencies of the CHP plant can be seen in Table 10. The annual efficiencies have been estimated based on the efficiencies at nominal and partial load conditions and full load operating hours of 7,500 hours per year.

Table 10: Efficiencies of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: The efficiencies are calculated from the nominal and forecasted annual electricity and thermal production related to the fuel energy input to the furnace and not based on measured data due to the short operation period of the plant.

Parameter	Value [%]
Total efficiency at nominal load (gross)	71.2
Annual electric efficiency (gross)	10.8
Annual electric efficiency (net)	7.5
Annual thermal efficiency	58.3
Annual total efficiency (gross)	69.1

For starting up the biomass plant based on the direct exchange ORC system, the evaporator is by-passed until the biomass furnace is in stable operation. This procedure can take up to 5 hours if the furnace is cold and can be reduced to 20 minutes if the furnace is still warm. After that the flue gas is re-directed to the evaporator and the working fluid is pre-heated. When all components and the toluene have reached the working temperature the normal operation of the CHP plant can be started.

3.3.4 Control system and personnel demand

The direct exchange ORC module is fully automatically controlled. The control cabinet is connected to the control system of the biomass plant and adjusts the heat production of the plant to the demand of the clients.

To avoid an overheating of the working fluid special safety requirements are considered. The flue gas line between the biomass furnace and the evaporator is equipped with tight flaps which are controlled by electric actuators with emergency function. In case of a malfunction of the ORC system or if no heat can be dissipated, these flaps, controlled by the boiler PLC, close automatically to stop the flue gas from passing the evaporator. At the same time an emergency chimney opens releasing the hot flue gas to the environment.

Due to the small size, the plant’s high level of automation (also fuel feeding from the sawmill to the daily feed storage is automated) as well as due to the full maintenance contract the personnel demand of the Slovakian CHP plant with estimated 183 hours per year is very low. The main work consists of regular checks of the plant.

3.3.5 Maintenance demand

The biomass based direct exchange ORC plant in Slovakia has signed a full maintenance contract for the entire CHP plant which amounts to 15,000 €/a. The direct exchange ORC system has to be inspected quarterly. Furthermore, regular checks of the plant are necessary to indicate malfunctions or wear as soon as possible.

The dust loaded flue gas can induce erosion or fouling of the evaporator surface. For this reason the heat exchanger is equipped with an automatic cleaning system, which periodically removes dust depositions from the surface of the heat exchanger tubes. Additionally the surface of the evaporator should be cleaned manually within a certain period of time to prevent heat exchanger damage and leakage of working fluid, which may cause safety risks.

3.3.6 Special (technology related) operation costs

The direct exchange ORC system doesn’t have special requirements for water treatment like in a steam turbine process or other specific operation costs beside the common demand of lubricants or comparable. The only technology related difference to other CHP technologies is the usage of toluene which has a lifetime of about 5 years and has to be changed within this period of time to avoid a decrease of the ORC performance. These costs, however, are included in the maintenance contract.

3.3.7 Ecological aspects

As every biomass fired CHP plant, the plant in Slovakia causes gaseous emissions like NO_x, CO and particles. Measurements of these emissions carried out at the plant showed that the limiting values according to Table 11 can be kept.

The low dust emissions, like they have to be met in many other countries however, are unlikely to be met with a multi-cyclone only. For this reason it will be necessary to install an electrostatic precipitator or a baghouse filter in addition in order to keep dust emission limits below 50 mg/Nm³ or even lower. If the ORC unit has to be by-passed, the flue gas does not pass the flue gas cleaning unit and therefore the dust emissions will increase, but this happens only in emergency cases.

Table 11: Emission limits to be met by the Slovakian biomass CHP plant

Explanations: values in mg/Nm^3_{dry}, 11 vol.% O_2; data source: TRIOGEN

Parameter	**Emission limit [mg/Nm³]**
CO	400
NO_x (NO_2)	350
particulate emissions	150
TOC	50

The ash (bottom and boiler ash, as well as cyclone ash) are collected in a single ash container. Ash disposal causes additional operating costs, which have been taken into account.

The ORC process itself does not have an impact on the flue gas emissions of the plant. But it is operated with about 800 kg toluene which has to be considered. Toluene is not a greenhouse gas and has a global warming potential of zero. The main properties of toluene are given in Table 12. The ORC process is a closed hermetic cycle and due to this no toluene emissions should occur during normal plant operation. In fact small amounts of toluene can be lost due to the evacuation of condensable gases from the storage vessel. The maximum allowable concentration of toluene for workspaces is about 25 mg/Nm³. This limit has to be kept. The working fluid is flammable and the concentration in the air has to be kept low for not reaching the explosion level. For this reason the concentration of toluene in the air as well as the level of toluene in the storage vessel are continuously measured leading to a process shutdown if critical values are reached [Data source: TRIOGEN].

The vapour pressure of toluene enables a storage in non-pressurized vessels. The flashpoint, however, is 4°C and thus below the ambient temperature. For this reason special safety-precautions are necessary when handling with toluene.

During maintenance the ORC system has to be opened leading to toluene emissions to the atmosphere due to vaporescence. For this reason it is important to minimise the opening time of the system.

Table 12: Properties of the working fluid used in the Slovakian plant

Explanations: The data is based on the safety data sheet of the working fluid. [7]

Parameter	**Value [%]**
Chemistry	Toluene
Boiling point (at 1,013 hPa)	111°C
Flash point	4°C
Ignition temperature	480°C
Vapour pressure (at 20°C)	3.5 kPa
Explosive properties	Vapours may create explosive mixtures with air

3.3.8 Technological maturity

The usage of direct exchange ORC systems to use low temperature waste heat for power production is a technology that has been applied about 30 times by the manufacturer TRIOGEN up to now.

The usage in combination with a biomass furnace, however is quite new due to the high temperature (1,000°C downstream furnace, up to 530°C upstream evaporator) and dust load of the flue gas which causes a special plant design and safety concept. At present 4 plants of the same size as the one in Slovakia have been built and another 4 plants are under construction.

Also other manufacturers of conventional ORC processes have started to research on an efficient and safe operation of a direct exchange ORC process to avoid an intermediate thermal oil loop and therefore decrease the plant complexity and investment costs. These processes however did not reach market introduction yet but seem close to first demonstration plants.

3.3.9 Weak points

Concerning the direct exchange ORC system as realised in the Slovakian CHP plant, a few disadvantages have already been discovered which need further research and development.

The first main weak point of the technology is the limited feed water temperature of about 80°C. In many processes higher temperatures are required. By raising the feed water temperature the fields of application for direct exchange ORC systems could be increased.

The second weak point that has to be mentioned is the low electric efficiency of the ORC module (electric capacity related to thermal input to the ORC module; 14.4%) as well as the quite low total efficiency of the module (electric and thermal capacity related to thermal input to the ORC; 87.8%) due to high internal losses of the direct exchange ORC system. A potential for improvement and reduction of these losses exists and in the future higher electric efficiencies should be reachable.

In addition the boiler efficiency (thermal input to the ORC related to fuel input; 81.1%) further decreases the electric efficiency of the overall plant. This efficiency derives from the flue gas losses due to high flue gas temperatures at the stack (no air pre-heater or economiser is used for heat recovery) as well as from the temperature losses of the flue gas ducts upstream the evaporator. A reduction potential for these losses exists. A reduction can enhance the plant profitability and reduce the biomass demand.

Despite these weak points it has to be mentioned, that the direct exchange technology shows advantages compared to other CHP technologies when it comes to small-scale applications due to its low personnel demand.

3.3.10 Fuel characterisation and handling

The direct exchange ORC system in Slovakia uses residual wood from a sawmill process at an average water content between 40 – 55wt.% w.b.. The particle size of the fuel changes depending on the untreated wood processing residues available. The main deliverer of the fuel is a nearby sawmill. The fuel is transported from the sawmill process to the daily fuel storage of the furnace via a conveyor, which reduces fuel transport costs. If this daily fuel storage is full, the biomass will be stored in the nearby open storage area, from where it has to be transported to the daily fuel storage using wheel loaders.

Screw conveyors are used to transfer the residual wood to the moving grate furnace. For avoiding backfiring of the fuel, the furnace is equipped with an automatic extinguishing device [Data source: TRIOGEN].

4 Economic evaluations of the technologies investigated

4.1 Economic calculations according to the guideline VDI 2067

The guideline VDI 2067 [1] provides the basis for the heat, electricity and energy production cost calculations of the different processes compared. According to this guideline, the different types of costs are divided into 4 cost groups, which are

- capital costs,
- consumption costs,
- operating costs,
- other costs.

The annual capital costs (annuity) can be calculated by multiplying the capital recovery factor (CRF, see Equation 1) with the investment costs. They are calculated for each unit of the process, taking the different utilisation periods into account.

Equation 1:

$$\mathrm{CRF} = \frac{(1+\mathrm{i})^{\mathrm{n}} \cdot \mathrm{i}}{(1+\mathrm{i})^{\mathrm{n}} - 1}$$

Explanations: CRF…capital recovery factor; i…real interest rate [% p.a.]; n…utilisation period [a]

All costs in connection with the process, e.g. the fuel costs and the electricity costs, are included in the group of consumption costs.

The operating costs comprise costs originating from the operation of the plant, e.g. personnel costs and maintenance costs. The annual maintenance costs are calculated in percent of the whole investment costs on the basis of guiding values or of practical experiences and are evenly spread over the years of the utilisation period. They are calculated for each unit of the process, taking the different wear and utilisation periods into account.

The other costs include costs such as insurance rates, overall dues, taxes and administration costs and are calculated as a percentage of the overall investment costs.

4.2 Methodology for the calculation of the electricity, heat and energy generation costs

For combined heat and power production (CHP) the heat and the power production should be considered separately. The capital costs for electricity production should therefore be 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. This approach seems to be meaningful because decentralised biomass CHP plants primarily produce process or district heat. Electricity production is an alternative and implementation depends mainly on the profitability of the additional investment necessary. Moreover, it is possible by this approach to separate costs for electricity production from costs for heat production. This approach makes clear comparisons of costs for heat only and CHP applications possible and forms the basis for a correct calculation of the electricity generation costs.

The method to be followed was therefore to take the additional annual costs of the electricity production in comparison to a heat-only plant with the same thermal power output into consideration and to calculate heat generation costs and electricity generation costs separately. For the calculation of the heat generation costs the heat distribution system has not been taken into account. Therefore, the heat generation costs shown in the following sections are heat generation costs ex CHP plant. This means that also the investment costs for the network of pipes have not been taken into account for the economic calculations. Therefore, the heat related investment costs stated in the following sections are related to the CHP plant only.

Additionally, the specific energy generation costs have also been calculated by dividing the total annual costs (capital costs, consumption costs, operating costs and other costs) by the total annual energy sold (heat and electricity) according to Equation 2 for each process to be compared.

Equation 2:

$$C_{spec.} = \frac{C_{tot}}{Q_{el} + Q_{th}}$$

Explanations: C_{spec}… specific energy generation costs [€/kWh]; C_{tot}… annual energy generation costs [€/a]; Q_{el}… annual electricity production sold [kWh_{el}/a]; Q_{th}… annual heat production sold [kWh_{th}/a]

Finally, the total income, calculated by taking the annual heat and electricity sold and the possible sales revenues for heat and electricity into consideration, can be compared with the total costs of energy generation.

4.3 General economic data

Table 13: Utilisation periods and maintenance costs for the different units of biomass CHP plants

Explanations: I...investment costs; the utilisation period "CHP related" is based on the period of the granted feed-in tariff for green electricity of the country; data source [own inquiries]

Unit	Heat related		CHP related			
	Utilisation period [a]	Maintenance costs [(% of I)/a]	Utilisation period [a]			Maintenance costs [(% of I)/a]
			Austria	Estonia	Slovakia	
Construction						
Civil worcs, infrastructure	25	1.0	15	12	15	1.0
Fuel storage unit	25	1.0	15	12	15	1.0
Weighbridge	25	1.0	15	12	15	1.0
Mechanical engineering						
Furnace and boiler	15	2.0	15	12	15	2.0
Flue gas cleaning	15	2.0	15	12	15	2.0
Ash container and conveyor	15	2.0	15	12	15	2.0
Heat recovery	15	2.0	15	12	15	2.0
Fuel conveyor	15	2.0	15	12	15	2.0
Electric installations	15	2.0	15	12	15	2.0
Hydraulic installations	15	2.0	15	12	15	2.0
Steelworks	15	1.0	15	12	15	1.0
CHP module	-	-	15	12	15	2.0
Vehicles	8	3.0	8	8	8	3.0
Planning	15	0.0	15	12	15	0.0
Other investment costs	15	2.0	15	12	15	2.0

Utilisation periods and maintenance costs of the process units have been chosen according to usual depreciation periods for energy generation units (see Table 13). Due to the fact, that the feed-in tariffs for electricity from biomass are secured for a specific period of time regarding the projects investigated (15 years in Austria, 12 years in Estonia and 15 years in Slovakia), the utilisation periods of all electricity related units have been chosen according to these time frames, because an amortisation of the investment must be reached within this period of time.

4.4 Case study 1: Biomass CHP plant based on a steam turbine process (Austria)

The technical data of the Austrian biomass CHP plant based on a steam turbine process described in section 3.1 are shown in Table 14. The electric gross capacity of the plant amounts to 5,700 kW_{el}, the electric capacity net is 5,000 kW_{el}. The thermal capacity is 17,000 kW_{th}. Approximately 7,800 full load operating hours can be achieved with the CHP plant, leading to an annual gross electricity production of 44.5 GWh/a. Within the calculation it was stated, that the electricity consumption surplus of the CHP plant will be covered by the electricity production of the steam turbine which reduces the electricity sold to the grid to 42.2 GWh/a. The auxiliary demand of the heat related part will be covered by an external electricity supply. The electricity sold to the grid is rated with a feed-in tariff of 122 €/MWh leading to an annual income of 5.1 mill. €.

The heat production of the plant amounts to 93 GWh/a. Taking into account the internal distribution losses of about 3.2%, the useful heat sold to the clients is 90 GWh/a. With a heat price of 55 €/MWh the annual income of heat sold is approximately 5 mill. €. Together with the electricity sold the specific income of the steam turbine plant is 76.4 €/MWh of the total energy sold.

The investment costs related to the electricity production amount to about 15.5 mill. € or about 62% of the total investment costs (see Table 15). The main costs occur due to the steam turbine and the extensive steam system. This leads to specific electricity related investment costs of 3,100 €/kW_{el}. Investment subsidies are not granted within the Austrian framework conditions for electricity related parts of biomass CHP plants due to the increased feed-in tariffs of such plants.

Table 14: Technical data of the Austrian biomass CHP plant based on a steam turbine process

Explanations: The specific electricity consumption of the CHP plant is related to the heat and electricity produced in the CHP plant. The specific electricity consumption of the heat related part is the auxiliary demand of a hot water boiler with the same heat production as the CHP plant. Data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	**Unit**	**ST-A**
Combined heat and power plant (CHP)		
Fuel energy input CHP (nominal conditions)	[kW_{NCV}]	27,860
Electric capacity CHP gross (nominal conditions)	[kW_{el}]	5,700
Electric capacity CHP net (nominal conditions)	[kW_{el}]	5,000
Useful heat capacity CHP (nominal conditions)	[kW_{th}]	17,000
Full load operating hours CHP	[h/a]	7,807
Annual electric efficiency gross	[%]	22.3
Annual total efficiency	[%]	66.8
Electrical flow index	-	0.29
Specific electricity consumption CHP (total)	[kWh_{el}/MWh_{th}]	29.1
Specific electricity consumption (heat related)	[kWh_{el}/MWh_{th}]	18.0
Total electricity consumption CHP	[kWh_{el}/a]	4,000,000
Electricity consumption heat related	*[kWh_{el}/a]*	*1,674,000*
Electricity consumption - CHP surplus	*[kWh_{el}/a]*	*2,326,000*
Electricity production gross	[kWh_{el}/a]	44,500,000
Electricity sold	[kWh_{el}/a]	42,174,000
Total fuel energy input CHP	[kWh_{NCV}/a]	200,000,000
Fuel energy input heat related	*[kWh_{NCV}/a]*	*107,500,000*
Fuel energy input - CHP surplus	*[kWh_{NCV}/a]*	*92,500,000*
Heat production CHP	[kWh_{th}/a]	93,000,000
Distribution losses (network of pipes)	[%]	3.2
Useful heat (sold to clients)	[kWh_{th}/a]	90,000,000

Table 15: Electricity related investment costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Plant unit	Unit	ST-A
Civil works and infrastructure	[€]	1,340,000
Furnace and boiler	[€]	7,160,000
Flue gas cleaning	[€]	included
Ash container and conveyor	[€]	included
Heat recovery	[€]	included
Fuel conveyor	[€]	260,000
Electric installations	[€]	310,000
Hydraulic installations	[€]	1,540,000
Steelworks	[€]	included
CHP module (incl. generator, grid connection, transformer)	[€]	2,910,000
Planning	[€]	630,000
Fuel storage unit	[€]	310,000
Other investment costs	[€]	1,040,000
Investment costs CHP	**[€]**	**15,500,000**
Specific investment costs CHP	**[€/kW$_{el}$]**	**3,100**
Funding	[%]	-
Funding	[€]	-
Specific investment costs CHP (incl. funding)	[€/kW$_{el}$]	3,100

Table 16: Electricity related annual costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: I… Investment costs; the electricity demand of the CHP related part is covered by the electricity produced in the plant; data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	ST-A
Interest rate	[%/a]	4.0
Capital costs	**[€/a]**	**1,394,087**
Specific capital costs	**[€/MWh$_{el}$]**	**33.06**
Fuel price	[€/MWh$_{NCV}$]	21.5
Ash disposal costs	[€/a]	112,000
Fuel costs	[€/a]	1,988,750
Electricity price (own needs)	[€/MWh$_{el}$]	0.0000
Electricity costs	[€/a]	0
Share of general consumption costs	[(% of I$_{CHP}$)/a]	0.7
General consumption costs	[€/a]	108,500
Consumption costs	**[€/a]**	**2,209,250**
Specific consumption costs	**[€/MWh$_{el}$]**	**52.38**
Hourly rate - personnel costs	[€/h]	55
Annual working hours CHP	[h/a]	1,700
Personnel costs	[€/a]	93,500
Management CHP	[€/a]	26,500
Total personnel costs CHP	[€/a]	120,000
Maintenance costs	[€/a]	280,900
Operation costs	**[€/a]**	**400,900**
Specific operation costs	**[€/MWh$_{el}$]**	**9.51**
Share of other costs	[(% of I$_{CHP}$)/a]	1.0
Other costs	**[€/a]**	**155,000**
Specific other costs	**[€/MWh$_{el}$]**	**3.68**
Total electricity generation costs	**[€/a]**	**4,159,237**
Specific electricity generation costs	**[€/MWh$_{el}$]**	**98.62**
Specific electricity generation costs (incl. funding)	**[€/MWh$_{el}$]**	**98.62**

Table 16 shows the calculation of the annual electricity generation costs as well as of the specific electricity generation costs. The interest rate has been chosen with 4%, based on realistic Austrian framework conditions. The fuel price is an average price for the fuel mixture used (bark, wood chips and sawdust, see section 3.1.10).

The costs for man-hours of work are comparatively high (55 €/h), which is due to the fact, that steam boiler operators are required. The man hours needed for electricity generation are 1,700 h/a, which is quite low. The reason for this is the additional equipment of the plant according to Austrian law that enables an operation of the plant without continuous supervision for up to 72 hours and reduces the personal demand.

The general consumption costs have been calculated based on a percentage of investment costs. These consider the water treatment as well as the urea costs needed for the denitrification plant.

The electricity related part of biomass CHP plants in Austria is not eligible. Therefore, no decrease of the specific electricity generation costs is possible by funding.

The most important cost factors are the consumption costs (including the fuel costs) covering about 53% of the electricity generation costs and the capital costs with about 34%. The operation costs with about 9.5% and the other costs with 3.5% of the electricity generation costs are of minor importance.

Table 17: Heat related investment costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Plant unit	Unit	ST-A
Civil works and infrastructure	[€]	3,370,000
Furnace and boiler	[€]	1,600,000
Flue gas cleaning	[€]	600,000
Ash container and conveyor	[€]	140,000
Heat recovery	[€]	included
Fuel conveyor	[€]	940,000
Electric installations	[€]	390,000
Hydraulic installations	[€]	500,000
Steelworks	[€]	included
Planning	[€]	370,000
Fuel storage unit	[€]	740,000
Other investment costs	[€]	620,000
Vehicles	[€]	included
Investment costs (heat related)	**[€]**	**9,270,000**
Funding	[%]	25.0
Funding	[€]	2,317,500
Investment costs (heat related, incl. funding)	[€]	6,952,500

The heat related investment costs of the plant amount to 9.3 mill. € (see Table 17). Investment subsidies of 25% of the total heat related investment costs have been taken into account and reduce the investment costs to about 7 mill. €.

The calculation of the annual and the specific heat generation costs is shown in Table 18. The general assumptions correlate to the parameters used for the calculation of the CHP related costs. As can be seen the personnel hourly rate, however, is smaller because no special boiler attendants are needed. Other costs have been calculated based on a percentage of the heat related investment costs. Additionally 70.000 € have been considered for the rental of land. The consumption costs account for 68.5% of the heat generation costs, followed by the capital costs covering 17.5% of the heat generation costs. The operation costs cover about 10% and the other costs about 4% of the heat generation costs.

The specific heat generation costs ex plant amount to 43.7 €/MWh$_{th}$. Taking the investment subsidy into account, they can be reduced by 4.3% to 41.8 €/MWh$_{th}$.

The total energy generation costs of the Austrian biomass CHP plant based on a steam turbine process are shown in Table 19. The total investment costs of the plant amount to about 24.8 mill. €. The annual energy generation costs amount to about 8.1 mill. €/a, the specific energy generation costs to 61.2 €/MWh. They can be reduced to 60 €/MWh taking the investment subsidy into consideration. The most important cost factors are the capital costs and the consumption costs, covering about 86% of the energy generation costs. The operation costs cover about 10% and the other costs about 4% of the energy generation costs.

Table 18: Heat related annual costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: I … Investment costs; data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	ST-A
Interest rate	[%/a]	4.0
Capital costs	**[€/a]**	**679,816**
Specific capital costs	**[€/MWh$_{th}$]**	**7.55**
Fuel price	[€/MWh$_{NCV}$]	21.5
Ash disposal costs	[€/a]	131,000
Fuel costs	[€/a]	2,311,250
Electricity price (own needs)	[€/MWh$_{el}$]	120
Electricity costs	[€/a]	200,880
General consumption costs	[€/a]	46,350.0
Consumption costs	**[€/a]**	**2,689,480**
Specific consumption costs	**[€/MWh$_{th}$]**	**29.88**
Hourly rate - personnel costs	[€/h]	45
Annual working hours	[h/a]	5,100
Personnel costs	[€/a]	229,500
Management	[€/a]	44,000
Total personnel costs CHP	[€/a]	273,500
Maintenance costs	[€/a]	129,500
Operation costs	**[€/a]**	**403,000**
Specific operation costs	**[€/MWh$_{th}$]**	**4.48**
Share of other costs	[(% of I$_{th}$)/a]	1.0
Other costs	[€/a]	70,000.0
Other costs	**[€/a]**	**162,700**
Specific other costs	**[€/MWh$_{th}$]**	**1.81**
Total heat generation costs	**[€/a]**	**3,934,996**
Specific heat generation costs	**[€/MWh$_{th}$]**	**43.72**
Specific heat generation costs (incl. funding)	**[€/MWh$_{th}$]**	**41.83**

Table 19: Total energy generation costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	ST-A
Total investment costs	[€]	24,770,000
Total investment costs (incl. funding)	[€]	22,452,500
Capital costs	[€/a]	2,073,903
Specific capital costs	[€/MWh]	15.69
Capital costs (incl. funding)	[€/a]	1,903,949
Specific capital costs (incl. funding)	[€/MWh]	14.40
Consumption costs	[€/a]	4,898,730
Specific consumption costs	[€/MWh]	37.06
Operation costs	[€/a]	803,900
Specific operation costs	[€/MWh]	6.08
Other costs	[€/a]	317,700
Specific other costs	[€/MWh]	2.40
Total energy generation costs	**[€/a]**	**8,094,233**
Specific energy generation costs	**[€/MWh]**	**61.24**
Specific energy generation costs (incl. funding)	**[€/MWh]**	**59.95**

It can be summarized, that the specific heat generation costs of the plant are 43.7 €/MWh$_{th}$ respectively 41.8 €/MWh$_{th}$ if subsidies are taken into account. Compared to the heat price of the plant of 55 €/MWh$_{th}$ it can be stated, that the heat related costs can be covered by the heat related income which means, that the heat related part of the plant can be economically operated. The specific electricity generation costs of 98.6 €/MWh$_{el}$ are lower than the feed-in tariff of 122 €/MWh$_{el}$ granted for this CHP plant based on a steam turbine. This means that the electricity related part is economic as well. Concluding the specific energy generation costs of 61.2 €/MWh respectively 60 €/MWh (with subsidies) can be covered by the specific income of 76.4 €/MWh and the heat price as well as the feed-in tariff are well suited for this application.

4.5 Case study 2: Biomass CHP plant based on an ORC process (Estonia)

Table 20 shows the technical data of the Estonian biomass CHP plant based on an ORC process as described in section 3.2. About 5,140 annual full load operating hours can be achieved with the plant. Based on a gross electric capacity of 2,400 kW$_{el}$, this leads to an annual gross electricity production of about 12.3 GWh/a. The auxiliary demand of the CHP unit will be covered by the electricity produced in the plant. This reduces the amount of electricity sold to the grid to 10.4 GWh/a. With a feed-in tariff of 89.9 €/MWh the annual income is 0.93 mill. €/a.

The heat production of the CHP plant amounts to about 55.9 GWh/a consisting of the thermal output of the ORC unit as well as the thermal production of the flue gas condensation unit. The distribution losses of the pipe network are about 1%, which leads to a useful heat of about 55.4 GWh/a. Taking a heat price of 45 €/MWh into account this leads to an annual income of about 2.5 mill. €/a. Together with the electricity sold the specific income of the plant is 52.1 €/MWh of total energy sold.

The electricity related investment costs are shown in Table 21. They amount to about 7.2 mill. € and cover about 56% of the total investment costs. The specific investment costs amount to 3,500 €/kW$_{el}$ and are related to the net electric nominal power. The investment of the electricity related parts has been supported by subsidies by almost 38% of the investment costs which reduces the investment costs to 4.5 mill. €.

Table 20: Technical data of the Estonian biomass CHP plant based on an ORC process

Explanations: The specific electricity consumption of the CHP plant is related to the heat and electricity produced in the CHP plant. The specific electricity consumption of the heat related part is the auxiliary demand of a hot water boiler with the same heat production as the CHP plant. Data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	ORC-EST
Combined heat and power plant (CHP)		
Fuel energy input CHP (nominal conditions)	[kW$_{NCV}$]	14,200
Electric capacity CHP gross (nominal conditions)	[kW$_{el}$]	2,400
Electric capacity CHP net (nominal conditions)	[kW$_{el}$]	2,050
Useful heat capacity CHP (nominal conditions)	[kW$_{th}$]	9,580
Full load operating hours CHP	[h/a]	5,140
Annual electric efficiency gross	[%]	16.5
Annual total efficiency	[%]	87.0
Electrical flow index	-	0.21
Specific electricity consumption CHP (total)	[kWh$_{el}$/MWh$_{th}$]	46.1
Specific electricity consumption (heat related)	[kWh$_{el}$/MWh$_{th}$]	20.9
Total electricity consumption CHP	[kWh$_{el}$/a]	3,145,000
Electricity consumption heat related	*[kWh$_{el}$/a]*	*1,170,000*
Electricity consumption - CHP surplus	*[kWh$_{el}$/a]*	*1,975,000*
Electricity production gross	[kWh$_{el}$/a]	12,336,000
Electricity sold	[kWh$_{el}$/a]	10,361,000
Total fuel energy input CHP	[kWh$_{NCV}$/a]	74,830,000
Fuel energy input heat related	*[kWh$_{NCV}$/a]*	*58,887,368*
Fuel energy input - CHP surplus	*[kWh$_{NCV}$/a]*	*15,942,632*
Heat production CHP	[kWh$_{th}$/a]	55,943,000
Distribution losses (network of pipes)	[%]	1.0
Useful heat (sold to clients)	[kWh$_{th}$/a]	55,383,570

The calculation of the annual and specific electricity generation costs is shown in Table 22. The interest rate chosen with 3% p.a. is based on realistic Estonian framework conditions. The fuel price of 12.3 €/MWh is an average price for the fuel mixture used (see section 3.2.10).

The costs for man-hours of work are considerably lower (10 €/h) compared to the steam turbine process described in section 3.1, because no steam boiler operators are needed to operate the plant and due to lower price level in Estonia. Unattended operation of the CHP plant is possible and the work to be done is confined to ongoing maintenance and supervision in an amount of a few hours per week. The low amount of personnel needed is due to the fully automatic operation of the CHP unit and due to the fact that a thermal oil boiler operating under atmospheric conditions is applied.

The general consumption costs are 0.1% of the CHP related investment costs and consider minor consumables.

The most important cost factor are the capital costs covering about 70% of the electricity generation costs, followed by the consumption costs covering about 19.5%. The operation costs cover 9% and the other costs cover 1.5% of the electricity generation costs.

Table 21: Electricity related investment costs of the Estonian biomass CHP plant based on an ORC process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Plant unit	Unit	ORC-EST
Civil works and infrastructure	[€]	420,000
Furnace and boiler	[€]	3,020,000
Flue gas cleaning	[€]	220,000
Ash container and conveyor	[€]	20,000
Heat recovery	[€]	20,000
Fuel conveyor	[€]	90,000
Electric installations	[€]	310,000
Hydraulic installations	[€]	170,000
Steelworks	[€]	70,000
CHP module (incl. generator, grid connection, transformer)	[€]	2,360,000
Planning	[€]	310,000
Fuel storage unit	[€]	100,000
Other investment costs	[€]	65,000
Investment costs CHP	**[€]**	**7,175,000**
Specific investment costs CHP	**[€/kW$_{el}$]**	**3,500**
Funding	[%]	37.9
Funding	[€]	2,720,000
Specific investment costs CHP (incl. funding)	[€/kW$_{el}$]	2,173

Table 22: Electricity related annual costs of the Estonian biomass CHP plant based on an ORC process

Explanations: I… Investment costs; the electricity demand of the CHP related part is covered by the electricity produced in the plant; data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	ORC-EST
Interest rate	[%/a]	3.0
Capital costs	**[€/a]**	**720,815**
Specific capital costs	**[€/MWh$_{el}$]**	**69.57**
Fuel price	[€/MWh$_{NCV}$]	12.3
Ash disposal costs	[€/a]	520
Fuel costs	[€/a]	196,094
Electricity price (own needs)	[€/MWh$_{el}$]	0.0000
Electricity costs	[€/a]	0
Share of general consumption costs	[(% of I$_{CHP}$)/a]	0.1
General consumption costs	[€/a]	6,900
Consumption costs	**[€/a]**	**203,514**
Specific consumption costs	**[€/MWh$_{el}$]**	**19.64**
Hourly rate - personnel costs	[€/h]	10
Annual working hours CHP	[h/a]	1,700
Personnel costs	[€/a]	17,000
Management CHP	[€/a]	42,100
Total personnel costs CHP	[€/a]	59,100
Maintenance costs	[€/a]	32,500
Operation costs	**[€/a]**	**91,600**
Specific operation costs	**[€/MWh$_{el}$]**	**8.84**
Share of other costs	[(% of I$_{CHP}$)/a]	0.2
Other costs	**[€/a]**	**16,639**
Specific other costs	**[€/MWh$_{el}$]**	**1.61**
Total electricity generation costs	**[€/a]**	**1,032,569**
Specific electricity generation costs	**[€/MWh$_{el}$]**	**99.66**
Specific electricity generation costs (incl. funding)	**[€/MWh$_{el}$]**	**73.29**

Table 23 shows the heat related investment costs of the plant, amounting to about 5.7 mill. €. No subsidies are granted for the heat related part.

The calculation of the annual and specific heat generation costs is shown in Table 24. It can be seen, that the most important cost factors are the consumption costs covering more than 56% of the heat generation costs and the capital costs covering about 25.5%. The operation costs cover 15.5% and the other costs about 3% of the heat generation costs.

The specific heat generation costs amount to 28.7 €/MWh$_{th}$.

Table 23: Heat related investment costs of the Estonian biomass CHP plant based on an ORC process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Plant unit	Unit	ORC-EST
Civil works and infrastructure	[€]	1,540,000
Furnace and boiler	[€]	1,090,000
Flue gas cleaning	[€]	810,000
Ash container and conveyor	[€]	80,000
Heat recovery	[€]	60,000
Fuel conveyor	[€]	350,000
Electric installations	[€]	590,000
Hydraulic installations	[€]	240,000
Steelworks	[€]	260,000
Planning	[€]	240,000
Fuel storage unit	[€]	340,000
Other investment costs	[€]	55,000
Vehicles	[€]	included
Investment costs (heat related)	**[€]**	**5,655,000**
Funding	[%]	-
Funding	[€]	-
Investment costs (heat related, incl. funding)	[€]	5,655,000

Table 24: Heat related annual costs of the Estonian biomass CHP plant based on an ORC process

Explanations: I … Investment costs; data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	**Unit**	**ORC-EST**
Interest rate	[%/a]	3.0
Capital costs	**[€/a]**	**404,658**
Specific capital costs	**[€/MWh$_{th}$]**	**7.31**
Fuel price	[€/MWh$_{NCV}$]	12.3
Ash disposal costs	[€/a]	2,100
Fuel costs	[€/a]	724,315
Electricity price (own needs)	[€/MWh$_{el}$]	125
Electricity costs	[€/a]	146,250
General consumption costs	[€/a]	30,000
Consumption costs	**[€/a]**	**902,665**
Specific consumption costs	**[€/MWh$_{th}$]**	**16.30**
Hourly rate - personnel costs	[€/h]	10
Annual working hours	[h/a]	4,900
Personnel costs	[€/a]	49,000
Management	[€/a]	86,100
Total personnel costs CHP	[€/a]	135,100
Maintenance costs	[€/a]	110,500
Operation costs	**[€/a]**	**245,600**
Specific operation costs	**[€/MWh$_{th}$]**	**4.43**
Share of other costs	[(% of I$_{th}$)/a]	0.7
Other costs	[€/a]	0.0
Other costs	**[€/a]**	**38,700**
Specific other costs	**[€/MWh$_{th}$]**	**0.70**
Total heat generation costs	**[€/a]**	**1,591,622**
Specific heat generation costs	**[€/MWh$_{th}$]**	**28.74**
Specific heat generation costs (incl. funding)	**[€/MWh$_{th}$]**	**28.74**

Table 25 shows the total investment costs for the Estonian biomass CHP plant based on an ORC process to be about 12.8 mill. € and the annual energy generation costs to be about 2.6 mill. €/a. The specific energy generation costs amount to 39.9 €/MWh and can be decreased by about 10% to 35.8 €/MWh, when the investment subsidy is taken into consideration. The most important cost factors are the capital costs covering 43% of the energy generation costs followed by the consumption costs (including the costs for neutralisation of the flue gas condensation unit) covering about 42%. The operation costs cover about 13% and the other costs about 2% of the energy generation costs.

Table 25: Total energy generation costs of the Estonian biomass CHP plant based on an ORC process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	ORC-EST
Total investment costs	[€]	12,830,000
Total investment costs (incl. funding)	[€]	10,110,000
Capital costs	[€/a]	1,125,473
Specific capital costs	[€/MWh]	17.12
Capital costs (incl. funding)	[€/a]	852,216
Specific capital costs (incl. funding)	[€/MWh]	12.96
Consumption costs	[€/a]	1,106,179
Specific consumption costs	[€/MWh]	16.83
Operation costs	[€/a]	337,200
Specific operation costs	[€/MWh]	5.13
Other costs	[€/a]	55,339
Specific other costs	[€/MWh]	0.84
Total energy generation costs	**[€/a]**	**2,624,191**
Specific energy generation costs	**[€/MWh]**	**39.91**
Specific energy generation costs (incl. funding)	**[€/MWh]**	**35.76**

Summing up, the specific heat generation costs of the plant are 28.7 €/MWh$_{th}$ and can be covered by the heat price of 45 €/MWh$_{th}$. The heat related part of the plant can therefore be operated economically. The specific electricity generation costs of 99.7 €/MWh$_{el}$, however, are higher than the feed-in tariff granted of 89.9 €/MWh$_{el}$. This means, that the specific costs of the electricity related part of the plant would need to be covered partly by the income of the heat sold. In case of the Estonian CHP plant though, subsidies are granted for the electricity related part of the plant which reduce the specific electricity generation costs to 73.3 €/MWh$_{el}$ and enable an economic operation of the electricity generation plant as well. As a result the total energy generation costs of 35.8 €/MWh (incl. subsidies) can be covered by the specific income of 52.1 €/MWh and the heat price as well as the feed-in tariff and the subsidies can be seen as suitable for this application and allow an economic operation of the CHP plant based on an ORC process.

4.6 Case study 3: Biomass CHP plant based on a direct exchange ORC process (Slovakia)

The technical data of the Slovakian biomass CHP plant based on a direct exchange ORC process described in section 3.3 are shown in Table 26. The gross electric capacity of the plant amounts to 130 kW$_{el}$, the net electric capacity is 90 kW$_{el}$. The capacity of useful heat is 660 kW$_{th}$ whereas the nominal fuel energy input is 1,100 kW$_{NCV}$. About 7,500 full load operating hours can be achieved with the plant, leading to an annual gross electricity production of 0.98 GWh/a. The CHP surplus is subtracted from the electricity production of the direct exchange ORC unit reducing the electricity sold to clients to about 0.78 GWh/a. A feed-in tariff of 110 €/MWh is granted in Slovakia leading to an annual income of about 86,000 €/a.

The heat production of the plant amounts to 5.3 GWh/a. Taking the distribution losses of about 1% into account, the useful heat sold will be about 5.2 GWh/a. With a heat price of 32 €/MWh the annual income of heat production is about 167,000 €/a resulting in a total specific income of about 42.2 €/MWh.

Table 26: Technical data of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: The specific electricity consumption of the CHP plant is related to the heat and electricity produced in the CHP plant. The specific electricity consumption of the heat related part is the auxiliary demand of a hot water boiler with the same heat production as the CHP plant. Data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	**Unit**	**DE-ORC**
Combined heat and power plant (CHP)		
Fuel energy input CHP (nominal conditions)	[kW_{NCV}]	1,110
Electric capacity CHP gross (nominal conditions)	[kW_{el}]	130
Electric capacity CHP net (nominal conditions)	[kW_{el}]	90
Useful heat capacity CHP (nominal conditions)	[kW_{th}]	660
Full load operating hours CHP	[h/a]	7,500
Annual electric efficiency gross	[%]	10.8
Annual total efficiency	[%]	65.8
Electrical flow index	-	0.14
Specific electricity consumption CHP (total)	[kWh_{el}/MWh_{th}]	48.0
Specific electricity consumption (heat related)	[kWh_{el}/MWh_{th}]	20.0
Total electricity consumption CHP	[kWh_{el}/a]	299,520
Electricity consumption heat related	*[kWh_{el}/a]*	*105,300*
Electricity consumption - CHP surplus	*[kWh_{el}/a]*	*194,220*
Electricity production gross	[kWh_{el}/a]	975,000
Electricity sold	[kWh_{el}/a]	780,780
Total fuel energy input CHP	[kWh_{NCV}/a]	9,028,000
Fuel energy input heat related	*[kWh_{NCV}/a]*	*6,581,250*
Fuel energy input - CHP surplus	*[kWh_{NCV}/a]*	*2,446,750*
Heat production CHP	[kWh_{th}/a]	5,265,000
Distribution losses (network of pipes)	[%]	1.0
Useful heat (sold to clients)	[kWh_{th}/a]	5,212,350

Table 27: Electricity related investment costs of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Plant unit	Unit	DE-ORC
Civil works and infrastructure	[€]	4,000
Furnace and boiler	[€]	37,000
Flue gas cleaning	[€]	included
Ash container and conveyor	[€]	included
Heat recovery	[€]	included
Fuel conveyor	[€]	included
Electric installations	[€]	included
Hydraulic installations	[€]	10,000
Steelworks	[€]	included
CHP module (incl. generator, grid connection, transformer)	[€]	515,000
Planning	[€]	16,000
Fuel storage unit	[€]	included
Other investment costs	[€]	1,500
Investment costs CHP	**[€]**	**583,500**
Specific investment costs CHP	**[€/kW$_{el}$]**	**6,483**
Funding	[%]	-
Funding	[€]	-
Specific investment costs CHP (incl. funding)	[€/kW$_{el}$]	6,483

The investment costs related to the electricity production amount to 583,500 € or about 68% of the total investment costs (see Table 27). This leads to specific electricity related investment costs of 6,483 €/kW$_{el}$. Subsidies have not been taken into account for the CHP related investment costs.

Table 28 shows the calculation of the annual electricity generation costs as well as of the specific electricity generation costs. The interest rate has been chosen with 3%, based on experience. The fuel price has been assumed for the fuel used (untreated wood processing residues, see section 3.3.10) according the Slovakian conditions.

The hourly rate of man-power is very low (10 €/h) compared to case study 1 because no steam boiler operators are required and due to the lower price levels in Slovakia. Due to the small size of the CHP plant, the high level of automation (including an automated fuel feeding from the sawmill to the daily feed storage) as well as the full maintenance contract the demand of working hours is small resulting in a low personal demand of 53 hours per year for the CHP related part during normal operation.

The general consumption costs have been calculated based on a percentage of investment costs and consider minor consumables.

The most important cost factors are the capital costs, covering about 57.5% of the electricity generation costs. The consumption costs cover about 30.5%, and the operation costs about 10%

of the electricity generation costs. The other costs are with 2% of the electricity generation costs of minor importance.

Table 28: Electricity related annual costs of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: I… Investment costs; the electricity demand of the CHP related part is covered by the electricity produced in the plant; data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	**Unit**	**DE-ORC**
Interest rate	[%/a]	3.0
Capital costs	**[€/a]**	**48,878**
Specific capital costs	**[€/MWh$_{el}$]**	**62.60**
Fuel price	[€/MWh$_{NCV}$]	10.0
Ash disposal costs	[€/a]	100
Fuel costs	[€/a]	24,468
Electricity price (own needs)	[€/MWh$_{el}$]	0.000
Electricity costs	[€/a]	0
Share of general consumption costs	[(% of I$_{CHP}$)/a]	0.2
General consumption costs	[€/a]	1,167
Consumption costs	**[€/a]**	**25,735**
Specific consumption costs	**[€/MWh$_{el}$]**	**32.96**
Hourly rate - personnel costs	[€/h]	10
Annual working hours CHP	[h/a]	53
Personnel costs	[€/a]	525
Management CHP	[€/a]	540
Total personnel costs CHP	[€/a]	1,065
Maintenance costs	[€/a]	7,500
Operation costs	**[€/a]**	**8,565**
Specific operation costs	**[€/MWh$_{el}$]**	**10.97**
Share of other costs	[(% of I$_{CHP}$)/a]	0.3
Other costs	**[€/a]**	**1,751**
Specific other costs	**[€/MWh$_{el}$]**	**2.24**
Total electricity generation costs	**[€/a]**	**84,928**
Specific electricity generation costs	**[€/MWh$_{el}$]**	**108.77**
Specific electricity generation costs (incl. funding)	**[€/MWh$_{el}$]**	**108.77**

The heat related investment costs of the plant amount to about 276,500 € (see Table 29).

The calculation of the annual and the specific heat generation costs is shown in Table 30. The general assumptions correlate to the parameters used for the calculation of the CHP related costs. Other costs have been calculated based on a percentage of the heat related investment costs. The consumption costs account for 68% of the heat generation costs, followed by the capital costs covering 20.5% of the heat generation costs. The operation costs cover about 9% and the other costs about 2.5% of the heat generation costs. The specific heat generation costs ex plant amount to 21.1 €/MWh$_{th}$.

The total energy generation costs of the Slovakian biomass CHP plant based on a direct exchange ORC process are shown in Table 31. The total investment costs of the plant amount to 860.000 €. The annual energy generation costs amount to about 195,000 €/a, the specific energy generation costs to 32.6 €/MWh. The most important cost factors are the capital costs and the consumption costs, covering about 88% of the energy generation costs. The operation costs cover about 9.5% and the other costs about 2.5% of the energy generation costs.

Table 29: Heat related investment costs of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Plant unit	**Unit**	**DE-ORC**
Civil works and infrastructure	[€]	16,000
Furnace and boiler	[€]	100,000
Flue gas cleaning	[€]	30,000
Ash container and conveyor	[€]	20,000
Heat recovery	[€]	included
Fuel conveyor	[€]	50,000
Electric installations	[€]	included
Hydraulic installations	[€]	20,000
Steelworks	[€]	included
Planning	[€]	40,000
Fuel storage unit	[€]	included
Other investment costs	[€]	500
Vehicles	[€]	included
Investment costs (heat related)	**[€]**	**276,500**
Funding	[%]	-
Funding	[€]	-
Investment costs (heat related, incl. funding)	[€]	276,500

Table 30: Heat related annual costs of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: I … Investment costs; data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	DE-ORC
Interest rate	[%/a]	3.0
Capital costs	**[€/a]**	**22,740**
Specific capital costs	**[€/MWh$_{th}$]**	**4.36**
Fuel price	[€/MWh$_{NCV}$]	10.0
Ash disposal costs	[€/a]	400
Fuel costs	[€/a]	65,813
Electricity price (own needs)	[€/MWh$_{el}$]	70
Electricity costs	[€/a]	7,371
General consumption costs	[€/a]	1,382.5
Consumption costs	**[€/a]**	**74,966**
Specific consumption costs	**[€/MWh$_{th}$]**	**14.38**
Hourly rate - personnel costs	[€/h]	10
Annual working hours	[h/a]	130
Personnel costs	[€/a]	1,300
Management	[€/a]	910
Total personnel costs CHP	[€/a]	2,210
Maintenance costs	[€/a]	7,500
Operation costs	**[€/a]**	**9,710**
Specific operation costs	**[€/MWh$_{th}$]**	**1.86**
Share of other costs	[(% of I$_{th}$)/a]	1.0
Other costs	[€/a]	0.0
Other costs	**[€/a]**	**2,765**
Specific other costs	**[€/MWh$_{th}$]**	**0.53**
Total heat generation costs	**[€/a]**	**110,181**
Specific heat generation costs	**[€/MWh$_{th}$]**	**21.14**
Specific heat generation costs (incl. funding)	**[€/MWh$_{th}$]**	**21.14**

Table 31: Total energy generation costs of the Slovakian biomass CHP plant based on a direct exchange ORC process

Explanations: data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	DE-ORC
Total investment costs	[€]	860,000
Total investment costs (incl. funding)	[€]	860,000
Capital costs	[€/a]	71,618
Specific capital costs	[€/MWh]	11.95
Capital costs (incl. funding)	[€/a]	71,618
Specific capital costs (incl. funding)	[€/MWh]	11.95
Consumption costs	[€/a]	100,701
Specific consumption costs	[€/MWh]	16.80
Operation costs	[€/a]	18,275
Specific operation costs	[€/MWh]	3.05
Other costs	[€/a]	4,516
Specific other costs	[€/MWh]	0.75
Total energy generation costs	**[€/a]**	**195,109**
Specific energy generation costs	**[€/MWh]**	**32.56**
Specific energy generation costs (incl. funding)	**[€/MWh]**	**32.56**

The heat generation costs of the plant are 21.1 €/MWh$_{th}$ and the heat price is 32 €/MWh$_{th}$. This means that the costs of the heat related plant can be covered by the income of heat sold.

The feed-in tariff granted for the CHP plant based on a direct exchange ORC process is 110 €/MWh$_{el}$. Compared to the specific electricity generation costs of the plant of about 108.8 €/MWh$_{el}$ it has to be stated, that the feed-in tariff is sufficient for this CHP plant based on a direct exchange ORC process and that an economic operation of the plant is possible.

The specific energy generation costs of 32.6 €/MWh are lower than the specific income of 42.2 €/MWh which means that the local economic side constraints enable an economic operation of the entire plant.

As mentioned in section 3.3.9 the direct exchange ORC process still shows improvement potential regarding the electric efficiency of the ORC module and the overall CHP plant. Due to this optimisation potential is given regarding the economic performance.

4.7 Economic comparison of the case studies investigated

The technical data of the biomass CHP plants investigated, which have already been described in sections 3 and 4, are summarised in Table 32. The electric capacity gross of the CHP plants ranges from 130 to 5,700 kW$_{el}$, covering the most relevant capacity range for decentralised biomass CHP plants. The thermal capacities of the CHP units range from 660 to 17,000 kW$_{th}$. The annual total net efficiencies of the CHP plants investigated vary between 65.8% and 87.0%, the annual gross electric efficiencies increase with increasing electric capacities from 10.8% to 22.3%.

The biomass CHP unit covers the base load in all system. Additional heat producers for district heat supply (like peak load boilers) have not been taken into account in this comparison. The total heat production of the plants investigated varies between 5.3 and 93 GWh/a. Taking the heat distribution losses in the CHP plant into account, the useful heat is in a range of 5.2 and 90 GWh/a.

The annual gross electricity production of the biomass CHP plants investigated varies between 975 and 44,500 MWh$_{el}$/a. The annual full load operation hours of the CHP units vary between 5,140 and 7,807 hours per year. The specific electricity consumption of the CHP plants varies between 29.1 and 48 kWh$_{el}$/MWh$_{th}$ leading to an electricity consumption (auxiliary energy) between 9 and 31% of the overall electricity production.

Table 32: Technical data of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; The specific electricity consumption of the CHP plant is related to the heat and electricity produced downstream the steam turbine respectively the ORC. The specific electricity consumption of the heat related part is the auxiliary demand of a hot water boiler with the same heat production as the CHP plant. Data source: plant operator and BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

Parameter	Unit	DE-ORC	ORC-EST	ST-A
Combined heat and power plant (CHP)				
Fuel energy input CHP (nominal conditions)	[kW$_{NCV}$]	1,110	14,200	27,860
Electric capacity CHP gross (nominal conditions)	[kW$_{el}$]	130	2,400	5,700
Electric capacity CHP net (nominal conditions)	[kW$_{el}$]	90	2,050	5,000
Useful heat capacity CHP (nominal conditions)	[kW$_{th}$]	660	9,580	17,000
Full load operating hours CHP	[h/a]	7,500	5,140	7,807
Annual electric efficiency gross	[%]	10.8	16.5	22.3
Annual total efficiency	[%]	65.8	87.0	66.8
Electrical flow index	-	0.14	0.21	0.29
Specific electricity consumption CHP (total)	[kWh$_{el}$/MWh$_{th}$]	48.0	46.1	29.1
Specific electricity consumption (heat related)	[kWh$_{el}$/MWh$_{th}$]	20.0	20.9	18.0
Total electricity consumption CHP	[kWh$_{el}$/a]	299,520	3,145,000	4,000,000
Electricity consumption heat related	*[kWh$_{el}$/a]*	*105,300*	*1,170,000*	*1,674,000*
Electricity consumption - CHP surplus	*[kWh$_{el}$/a]*	*194,220*	*1,975,000*	*2,326,000*
Electricity production gross	[kWh$_{el}$/a]	975,000	12,336,000	44,500,000
Electricity sold	[kWh$_{el}$/a]	780,780	10,361,000	42,174,000
Total fuel energy input CHP	[kWh$_{NCV}$/a]	9,028,000	74,830,000	200,000,000
Fuel energy input heat related	*[kWh$_{NCV}$/a]*	*6,581,250*	*58,887,368*	*107,500,000*
Fuel energy input - CHP surplus	*[kWh$_{NCV}$/a]*	*2,446,750*	*15,942,632*	*92,500,000*
Heat production CHP	[kWh$_{th}$/a]	5,265,000	55,943,000	93,000,000
Distribution losses (network of pipes)	[%]	1.0	1.0	3.2
Useful heat (sold to clients)	[kWh$_{th}$/a]	5,212,350	55,383,570	90,000,000

Figure 6 and Figure 7 show the absolute and relative investment costs of the biomass CHP plants investigated. The highest investment costs with almost 24.8 mill. € are shown by the Austrian plant based on a steam turbine process (ST-A). The biomass CHP plant based on a direct exchange ORC process shows the lowest investment costs with 860,000 €. As the plants compared have different electricity and heat capacities as well as varying local side constraints, these figures are, however, not directly comparable.

Austrian legal framework conditions do not allow investment subsidies for the electricity related parts of biomass CHP plants (due to the subsidy of the electricity production by the increased feed-in tariffs). The investment subsidy for the heat related part of the plant leads to an overall investment subsidy of 10% for the Austrian plant investigated. In Estonia, opposite to Austrian law, investment subsidies are only granted for the CHP related part of the plant resulting in an overall subsidy of 21% of the investment costs. The direct exchange ORC plant in Slovakia has not been funded.

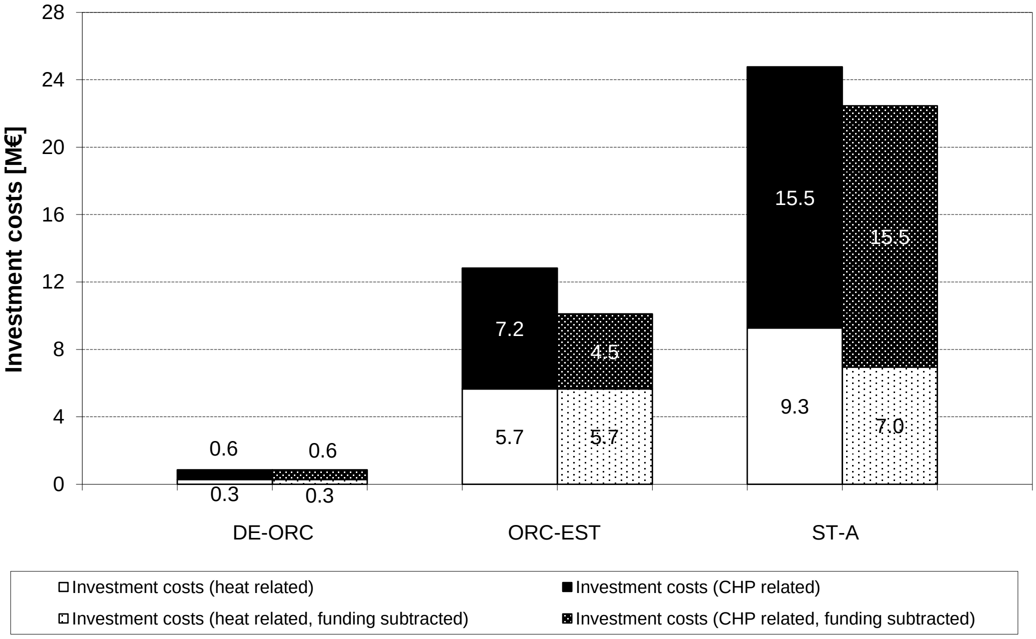

Figure 6: Investment costs of the biomass CHP plants investigated (absolute numbers)

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; left column: investment costs without funding; right column: investment costs funding subtracted

The biomass CHP plants investigated have different electric efficiencies and are based on different technologies, which can also be seen in the composition of investment costs. The heat related investment costs of the Slovakian plant cover about 32%, the electricity related costs amount to 68% of the total investment costs. In the Estonian case, the ratio of heat to electricity related investment costs is about 44% to 56%. The heat related costs of the Austrian steam turbine process investigated cover 37% of the total investment costs. It can be seen, that the share of heat related costs of the total costs is rather similar despite the different CHP processes.

The specific CHP related investment costs of the biomass CHP plants investigated are shown in Figure 8. The highest specific investment costs occur for the direct exchange ORC process. This is mainly due to the small electric capacity of the direct exchange ORC and its novelty for the use in biomass based CHP plants. The Austrian biomass CHP plant based on a steam turbine process shows the lowest specific CHP related investment costs, mainly due to the higher electric capacity (economy-of-scale-effect) and the fact, that the steam turbine process is a well proven technology. The ORC process under Estonian framework conditions is more expensive. However, due to the investment funding, which has been available for the CHP related part of this plant, the specific investment costs could be reduced to a level below the one for the Austrian steam turbine based plant.

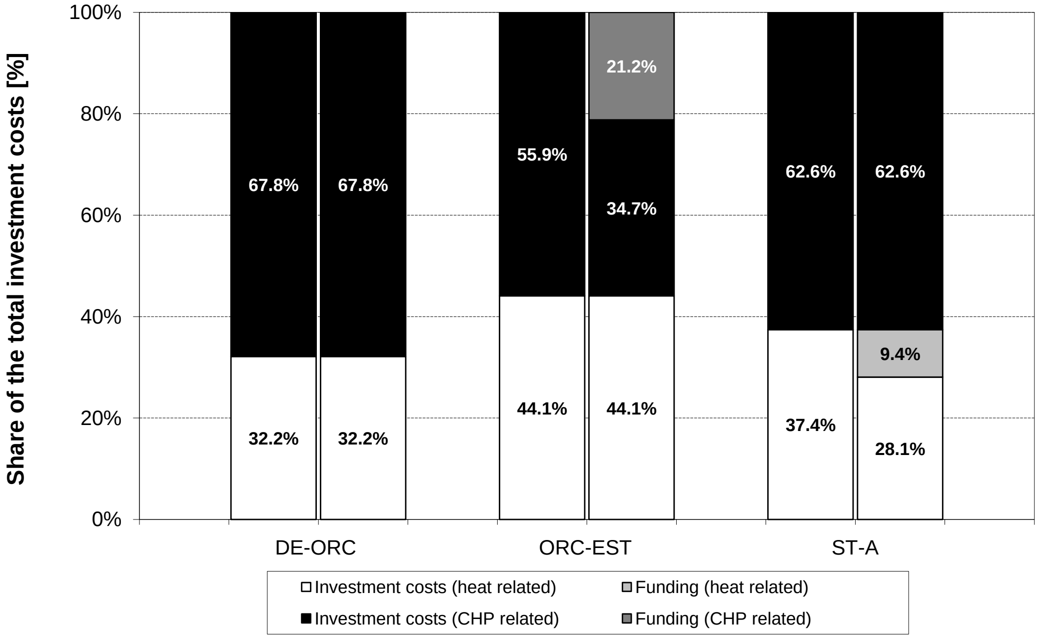

Figure 7: Share of the investment costs between heat and electricity related part

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; left column: investment costs without funding; right column: investment costs funding subtracted

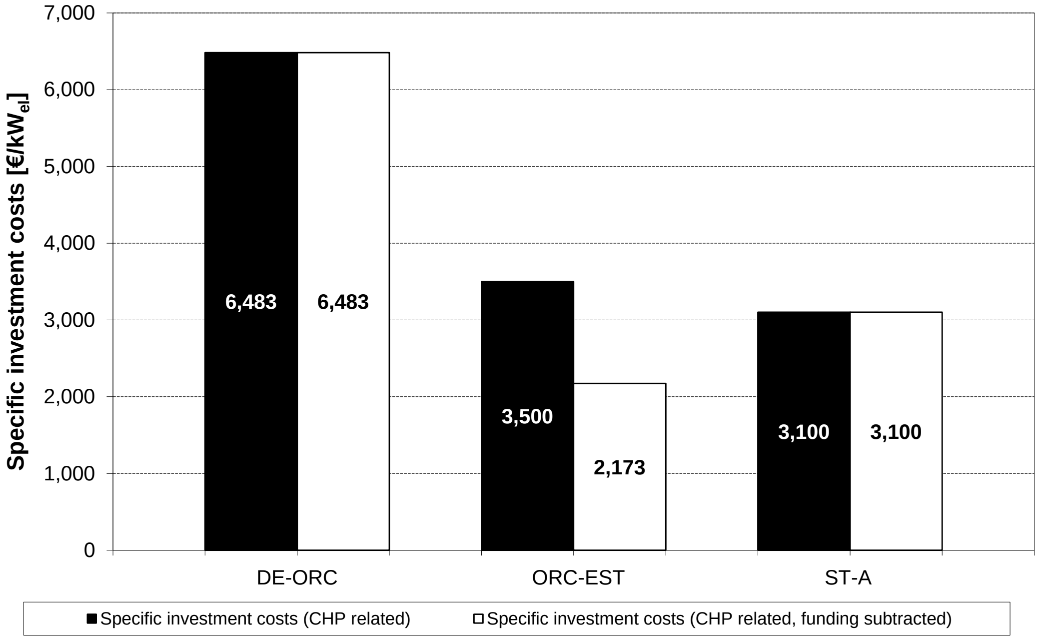

Figure 8: Specific CHP related investment costs of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the specific investment costs shown are related to the CHP related investment costs (additional investment costs of a CHP unit in comparison to a heat-only unit with the same nominal thermal capacity, see also Table 15, Table 21 and Table 27); left column: investment costs without funding; right column: investment costs with funding subtracted

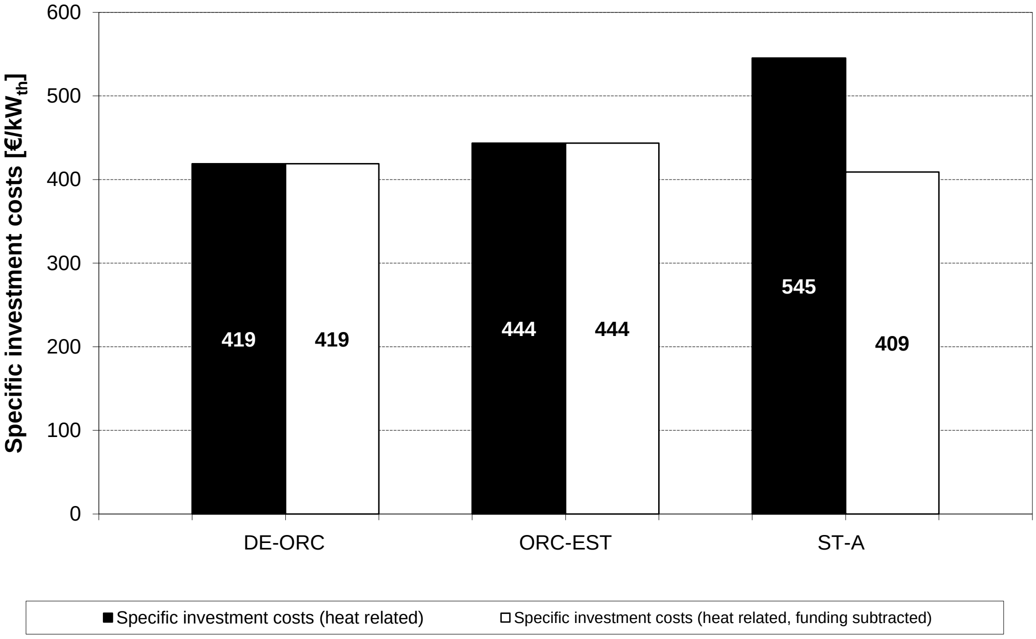

Figure 9: Specific heat related investment costs of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the specific investment costs shown are related to the heat related investment costs (only investment costs of a heat-only unit with the same nominal thermal capacity without consideration of the network of pipes for heat distribution (see also Table 17, Table 23, Table 29); left column: investment costs without funding; right column: investment costs with funding subtracted.

For the direct exchange ORC process a certain cost reduction potential exists due to the development potential concerning the electric and thermal efficiencies achievable.

The specific heat related investment costs of the biomass CHP plants investigated are shown in Figure 9. Peak load boilers or other heat producers beside the CHP plants investigated have not been taken into account for the calculation of the heat related investment costs. The investment costs have been related to the nominal thermal capacity of the CHP plants. The equipment of the reference hot water boiler plants has been adjusted to the one of the overall CHP plant. For this reason the hot water boiler plant of the direct exchange ORC process has no economiser, air-pre-heater or other heat recovery unit. Furthermore the flue gas will only be cleaned by a multi-cyclone. The ORC plant in Estonia has an air pre-heater as well as a flue gas condensation unit with neutralisation which increases the investment costs. The thermal capacity of the flue gas condensation unit has been considered within this comparison. The steam turbine plant in Austria has a nominal thermal capacity of 17 MW. This capacity would usually not be realised in a single hot water boiler because in this case special boiler and furnace suppliers would be necessary increasing the investment costs. Therefore the costs have been estimated for two hot water boilers of similar size. These differences have to be considered and make the specific costs not directly comparable.

The cost reduction potential concerning the heat related investment costs is low, as the biomass combustion technologies used are well proven state-of-the-art technologies. Therefore, a cost reduction potential of the total investment costs related to the useful heat capacity (see Figure 10) can most probably only be achieved by a reduction of the CHP related investment costs.

In Figure 10 it can be seen, that the specific total investment costs of the direct exchange ORC system are the highest due to the small plant size (economy-of-scale-effect). The specific costs of the ORC process are the smallest due to the maturity of the technology and the easier plant design compared to the steam process. Additionally it has to be considered, that the investment costs are based on the individual side constraints of the countries whereby the costs in Austria are higher than in Estonia or Slovakia. The funding of investment costs in case of the Austrian and Estonian plant leads to a further reduction of the specific investment costs.

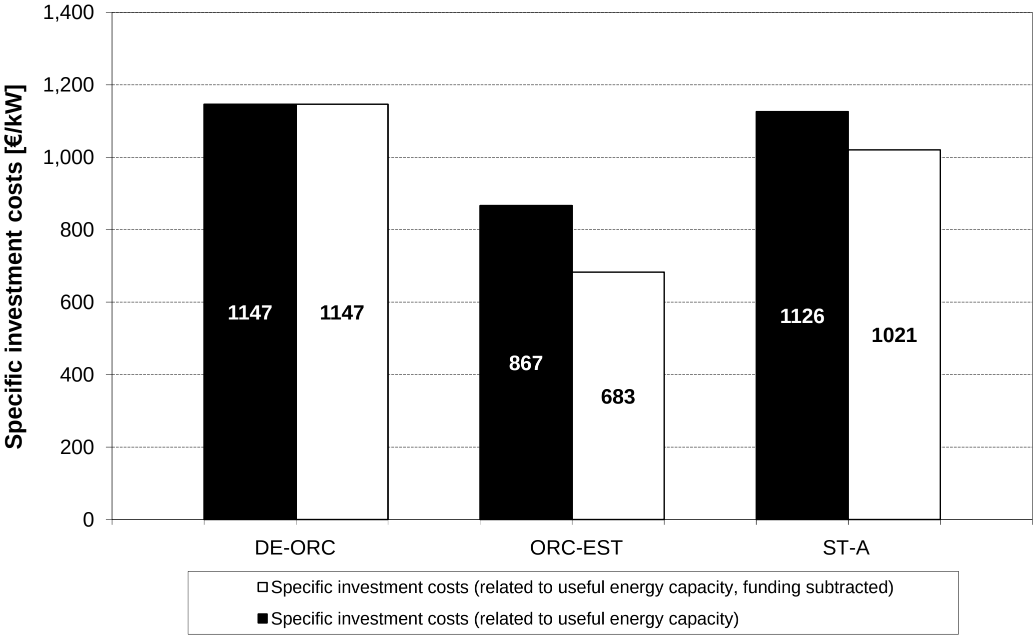

Figure 10: Specific total investment costs related to the useful energy capacity of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the specific investment costs shown are related to the total investment costs (without consideration of the network of pipes for heat distribution, see also Table 19, Table 25 and Table 31); specific investment costs are based on the sum of the thermal and electric capacities; left column: investment costs without funding; right column: investment costs with funding subtracted

The specific heat generation costs of the biomass CHP plants investigated are shown in Figure 11. These have been calculated by dividing the heat related costs by the total annual heat sold. In this case the heat production of the flue gas condensation unit in the ORC-EST plant has also been taken into account. The specific heat generation costs are heat generation costs ex plant without heat distribution costs.

It can be seen, that the heat generation costs of the CHP plant based on a steam turbine are the highest with 43.7 €/MWh_{th} respectively 41.8 €/MWh_{th} if funding is taken into account. The plant is located in Austria and therefore also Austrian economic conditions have been considered. Especially the fuel prices and personnel costs are much higher in Austria than in Eastern Europe which increases the specific costs compared to the other two CHP plants. The specific costs of the direct exchange ORC plant are the lowest with about 21.1 €/MWh_{th}. In all three cases the heat generation costs can be covered by the heat price.

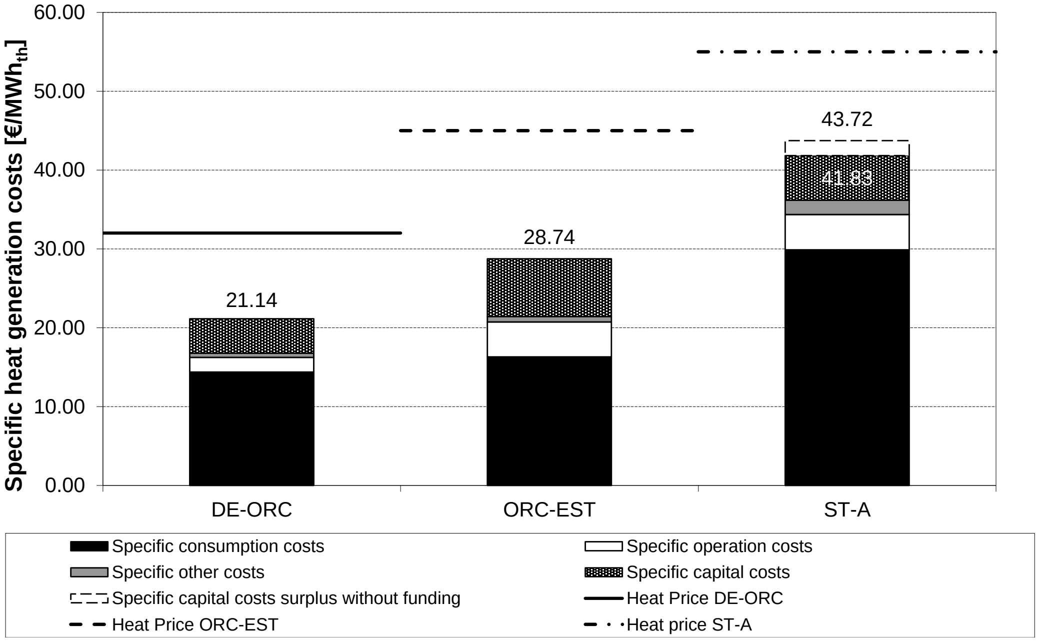

Figure 11: Specific heat generation costs of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the specific heat generation costs shown are costs ex plant, which means that heat distribution costs (costs of the network of pipes) are not considered

Figure 12 shows the specific electricity generation costs of the CHP plants investigated as well as their individual feed-in tariff. It can be seen that these costs vary between approximately 99 and 109 €/MWh$_{el}$ whereas the direct exchange ORC process shows the highest and the steam turbine process the lowest.

The specific electricity generation costs of the direct exchange ORC system are the highest due to the small plant size. Small CHP plants in general have higher energy production costs. That is the reason why feed-in tariffs for biomass CHP plants should be dependent of size (electric capacity).

The specific electricity generation costs of the direct exchange ORC system mainly derive from the investment costs including the ORC module and the additional costs for a high temperature multi-cyclone. The specific operation costs are dominated by the maintenance costs resulting from the full maintenance contract. The operating costs take the additional fuel costs for electricity production into account. Whilst the reference hot water boiler plant with the same thermal capacity has been calculated with a state-of-the-art thermal efficiency of about 80%, the total efficiency of the CHP plant is only 65.8% resulting in a higher fuel demand, which has been considered in the electricity related costs.

The feed-in tariff valid for the Austrian plant is above the respective electricity generation costs calculated. The specific consumption costs of 52.4 €/MWh$_{el}$ are quite high, because the steam turbine plant is equipped with a cooler to increase the annual electricity production which increases the fuel demand of the plant and thus the fuel costs. Additionally it has to be considered, that the economic data are based on Austrian framework conditions which also leads to higher specific consumption costs in comparison to the other two case studies. The specific investment costs, however, are lower due to the economy-of-scale-effect.

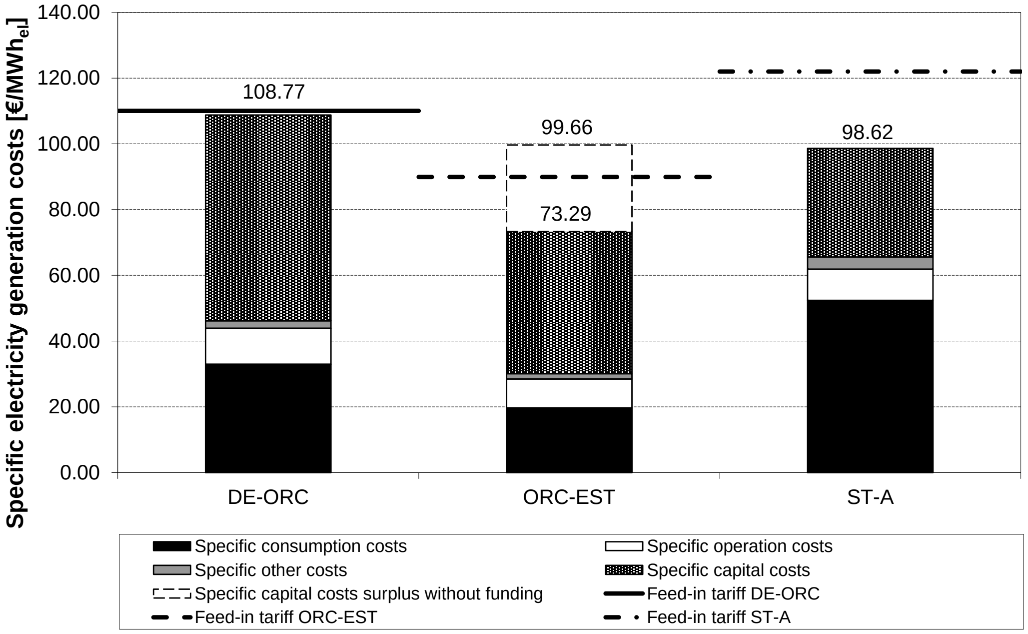

Figure 12: Specific electricity generation costs of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria;

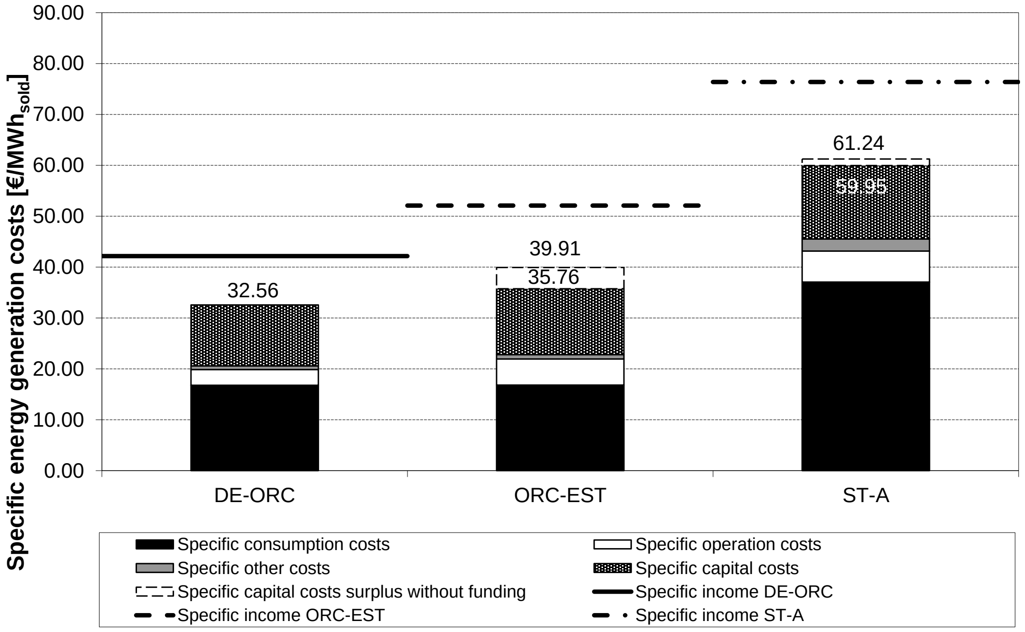

Figure 13: Specific energy generation costs of the biomass CHP plants investigated

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria

The Estonian CHP plant has low specific electricity generation costs compared to the direct exchange ORC plants due to the rather large plant size for ORC units, the small maintenance demand as well as the Estonian framework conditions. The electricity generation costs of 99.7 €/MWh$_{el}$ are higher than the feed-in tariff granted of about 89.9 €/MWh$_{el}$. In this case the funding of the CHP related part is necessary to cover the electricity generation costs by the electricity related income.

The specific total energy generation costs of the biomass CHP plants investigated are shown in Figure 13. They vary between 33 and 61 €/MWh (without taking funding into account) and between 33 and 60 €/MWh, when the investment subsidies granted are considered. The biomass CHP plant based on a steam turbine shows the highest and the plant based on a direct exchange ORC process shows the lowest specific energy generation costs.

The main cost categories of the total energy generation costs are the capital costs and the consumption costs. The capital costs are partly reduced by investment subsidies. The consumption costs are dominated by the fuel costs. Operation costs and other costs are of minor relevance. Once again it has to be considered, that the costs have been calculated based on the specific conditions of the countries where the CHP plants are located. For this reason the results cannot be directly compared.

4.8 Sensitivity analysis

The annual full load operating hours of the CHP plant and the fuel price are important influencing factors for the specific heat, electricity and energy generation costs. Therefore, in order to find out their influence, sensitivity analyses have been performed for these parameters, which are discussed in the following sections.

In addition also a variation of the investment costs has been considered within the sensitivity analyses. This variation of investment costs can also be considered similar to a variation of a possible investment subsidy (funding). Following, this sensitivity analysis also points out the influence of funding on the heat and electricity generation costs.

The heat price is a further important parameter which influences the economic result of a CHP plant. Therefore the impact of this parameter on the specific income and the coverage of the specific energy generation costs has also been investigated.

All calculations of heat and energy generation costs have been performed without consideration of the heat distribution costs.

4.8.1 Influence of the investment costs

The influence of the investment costs on the specific heat generation costs is shown in Figure 14. A variation of ± 10% leads to a variation of the specific heat generation costs between ± 2.1 and ± 2.6%.

It is not expected, that the heat related investment costs can significantly be reduced. Therefore, no major impact of the investment costs on the specific heat generation costs can be expected by cost reduction effects but subsidies could influence the heat generation costs in the same way.

The influence of the investment costs on the specific electricity generation costs in comparison to the respective feed-in tariffs is shown in Figure 15. The results show that the effect of the variation of investment costs for electricity generation is larger than in case of the heat generation costs. A variation of the investment costs by ± 10% would lead to a variation of the specific electricity generation costs between ± 4.3 and ± 7.0%.

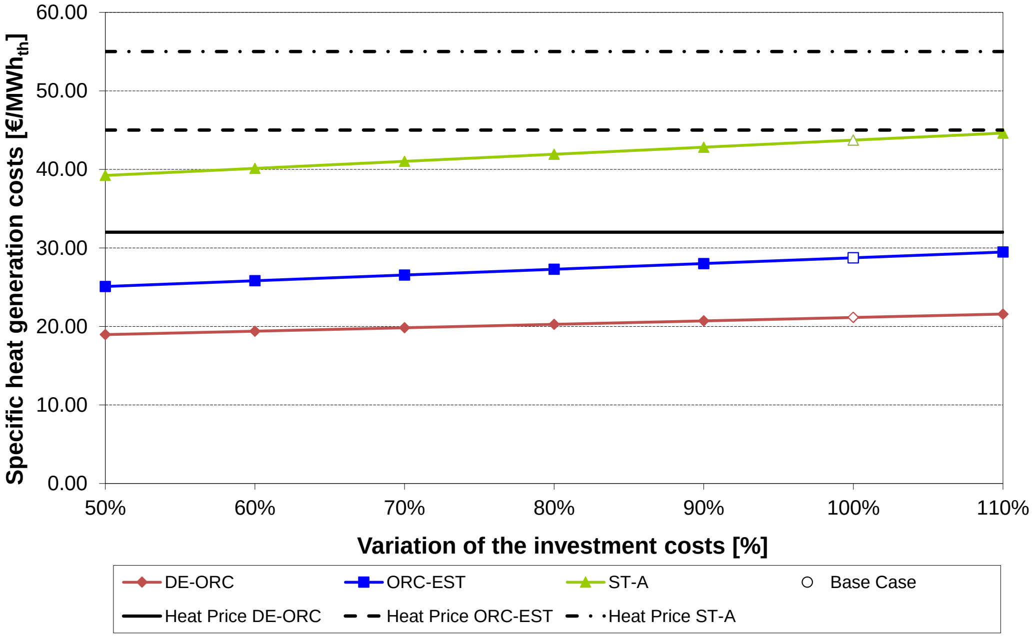

Figure 14: Influence of the investment costs on the specific heat generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all heat generation costs have been calculated without taking funding into account

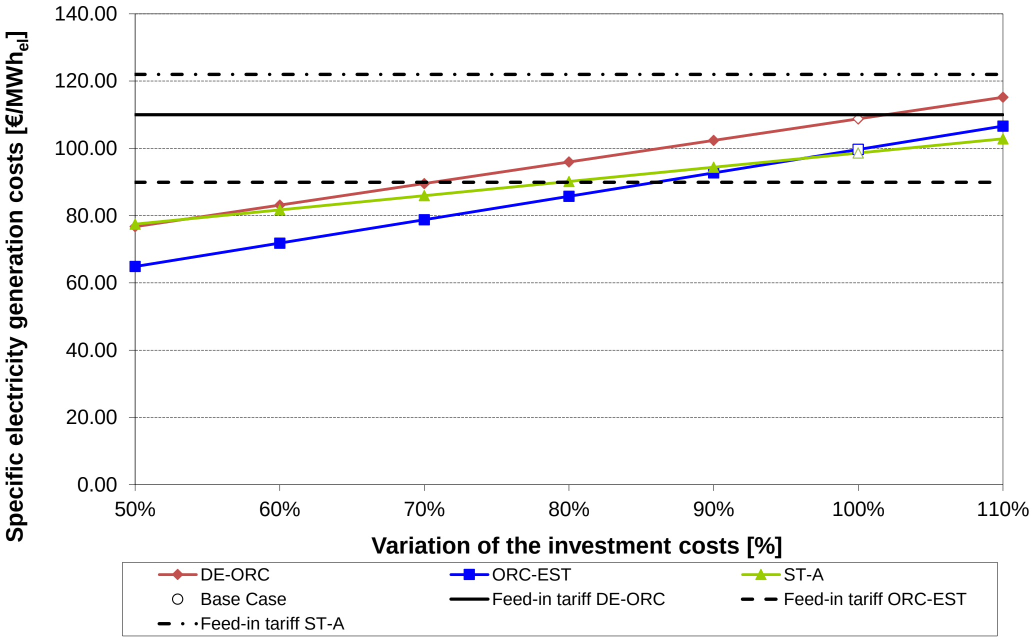

Figure 15: Influence of the investment costs on the specific electricity generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all electricity generation costs have been calculated without taking funding into account

Investment subsidies of the electricity related part, as granted in Estonia, are able to improve the economic result of the CHP plants.

The influence of the variation of the investment costs on the specific energy generation costs is shown in Figure 16. A variation of the investment costs by ± 10% would lead to a variation of the specific energy generation costs between ± 3.2 and ± 4.3%.

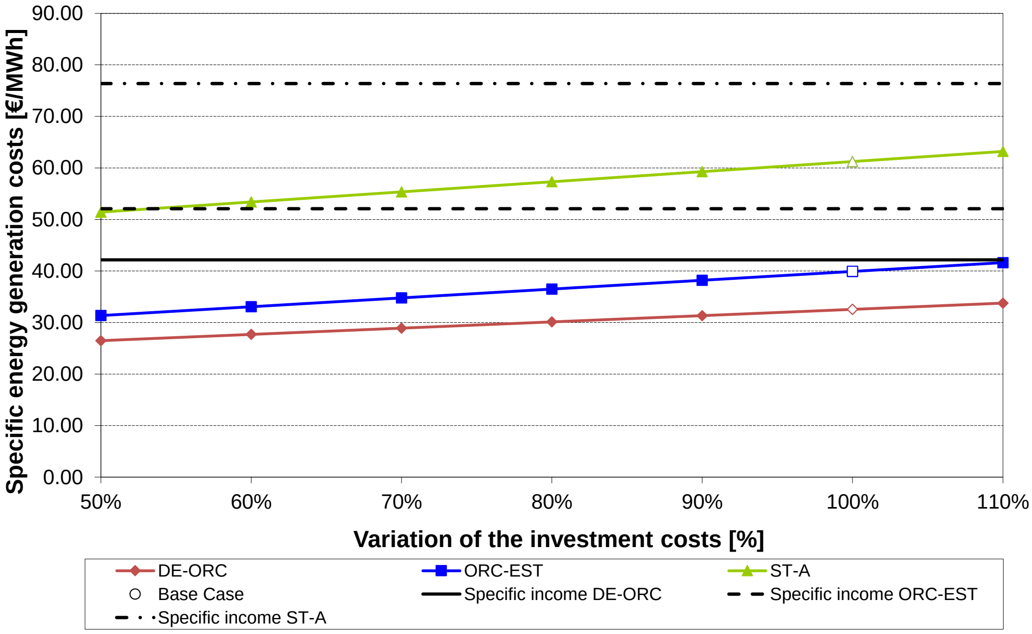

Figure 16: Influence of the investment costs on the specific energy generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all energy generation costs have been calculated without taking funding into account

4.8.2 Influence of the fuel price

The influence of the fuel price on the specific heat generation costs is shown in Figure 17. It can be seen that the specific heat generation costs can be significantly reduced by reducing the fuel costs.

In case of the Austrian and the Estonian CHP plant the fuel used is a mixture of wood chips, sawdust and bark. The large difference in the fuel price derives from the specific side constraints of the countries. The Slovakian CHP plant burns untreated waste wood, which enables lower fuel costs.

A variation of the fuel price of ± 10% leads to a variation of the specific heat generation costs between ± 4.6 and ± 6.0%.

The influence of the fuel price on the electricity generation costs can be seen in Figure 18. It shows, that the fuel price has the largest impact on the specific electricity costs in the Slovakian plant due to the lower total efficiency of the CHP plant and the therefore increased fuel demand for the CHP related plant. The same scenario occurs in case of the Austrian steam turbine plant. Due to the small additional fuel demand in case of the Estonian plant the impact is of minor importance.

An increase or reduction of the fuel price in the range of 10% changes the specific electricity generation costs between 1.9 and 4.8%.

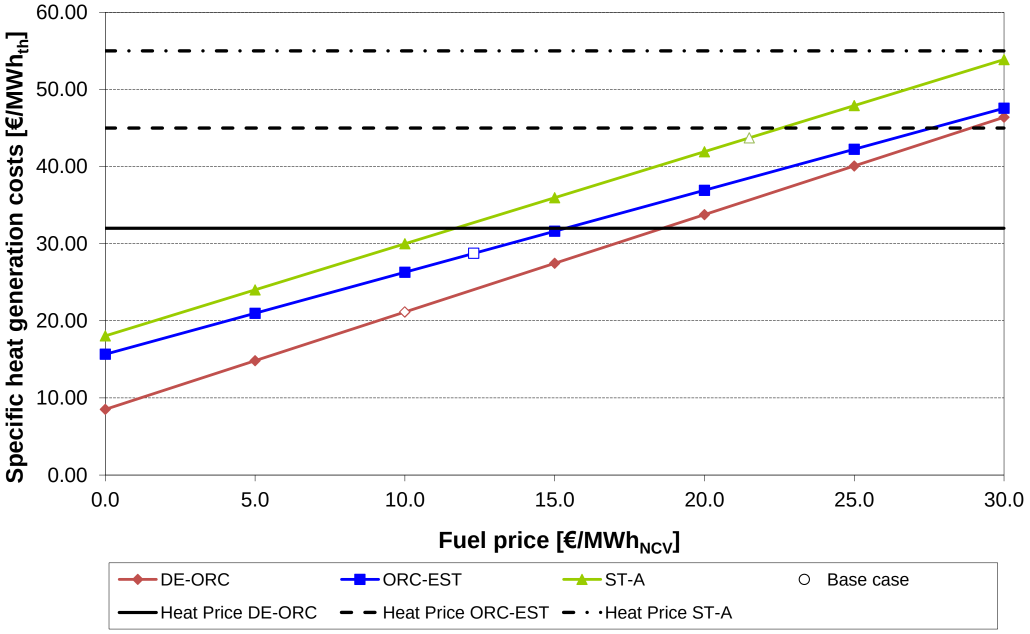

Figure 17: Influence of the fuel price on the specific heat generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all heat generation costs have been calculated without taking funding into account

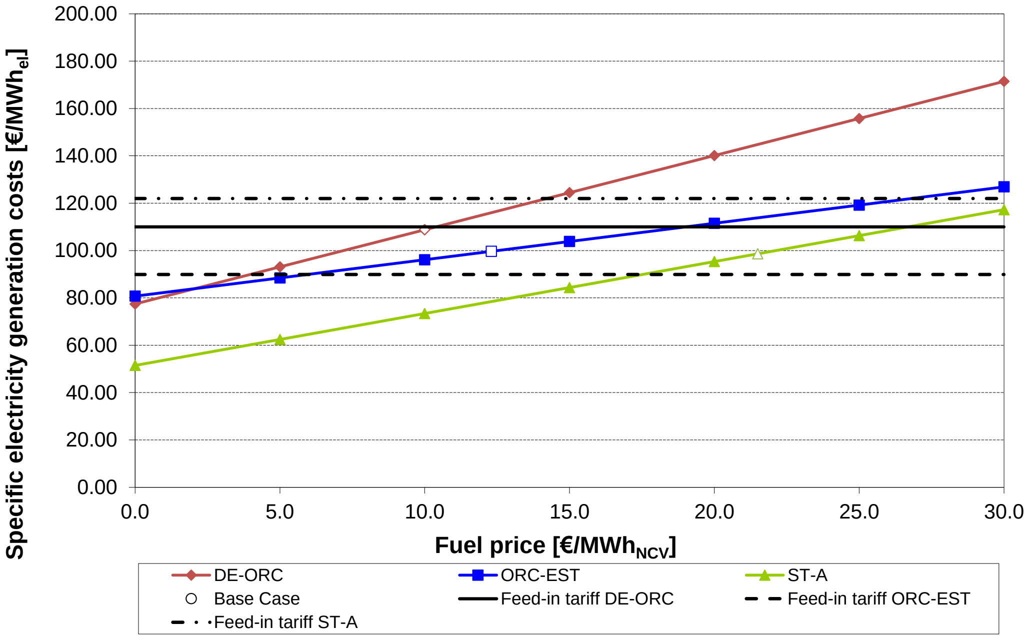

Figure 18: Influence of the fuel price on the specific electricity generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all electricity generation costs have been calculated without taking funding into account

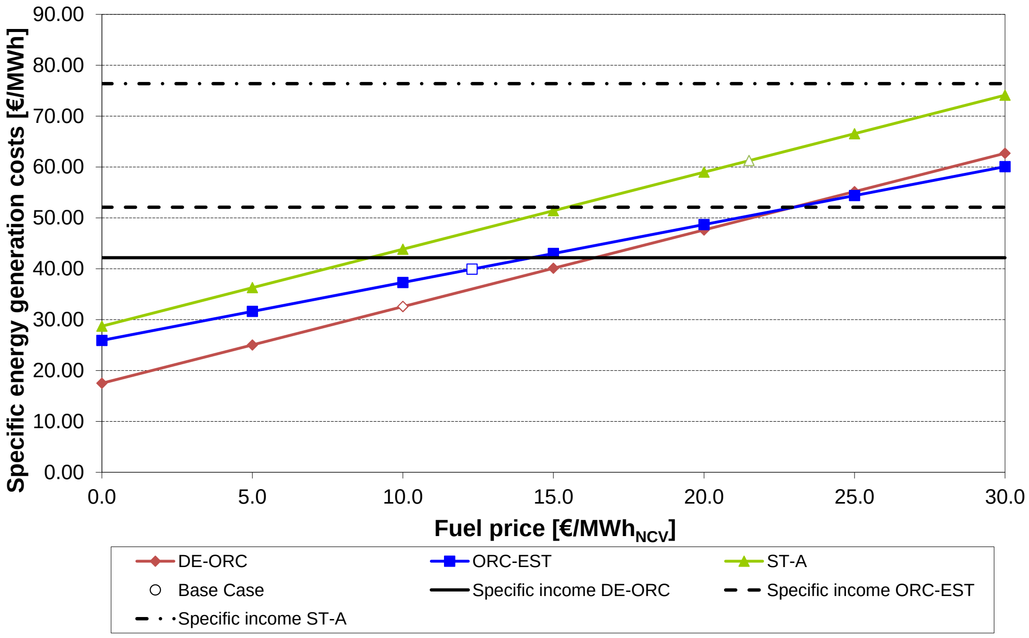

Figure 19: Influence of the fuel price on the specific energy generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all energy generation costs have been calculated without taking funding into account

Figure 19 shows the influence of the fuel price on the specific energy generation costs. A variation of the biomass fuel price by ± 10% leads to a variation of the specific energy generation costs between 3.5% and 5.3%.

4.8.3 Influence of the annual full load operating hours of the CHP unit

In the following sensitivity analyses the annual full load operating hours of the CHP plant have been varied. Their influence on the specific heat generation costs is shown in Figure 20.

In case of the Austrian steam turbine process two hot water boilers have been taken into account as a reference plant with the same thermal output because of the large thermal capacity of the CHP plant. According to this the heat generation costs show a strong dependence on the full load operating hours because of the high specific investment costs.

It is obvious, that the annual full load operating hours have a strong impact on the heat generation costs in every case study especially below about 3,000 full load hours. For this reason a proper dimensioning of the plant is recommended (from an ecological as well as an economic point of view).

An increase of the annual full load operating hours of the CHP plant by + 10% leads to a decrease of the specific heat generation costs of 2.8 – 3.9%. A decrease of the full load operating hours increases the specific costs between 3.7 – 5.2%.

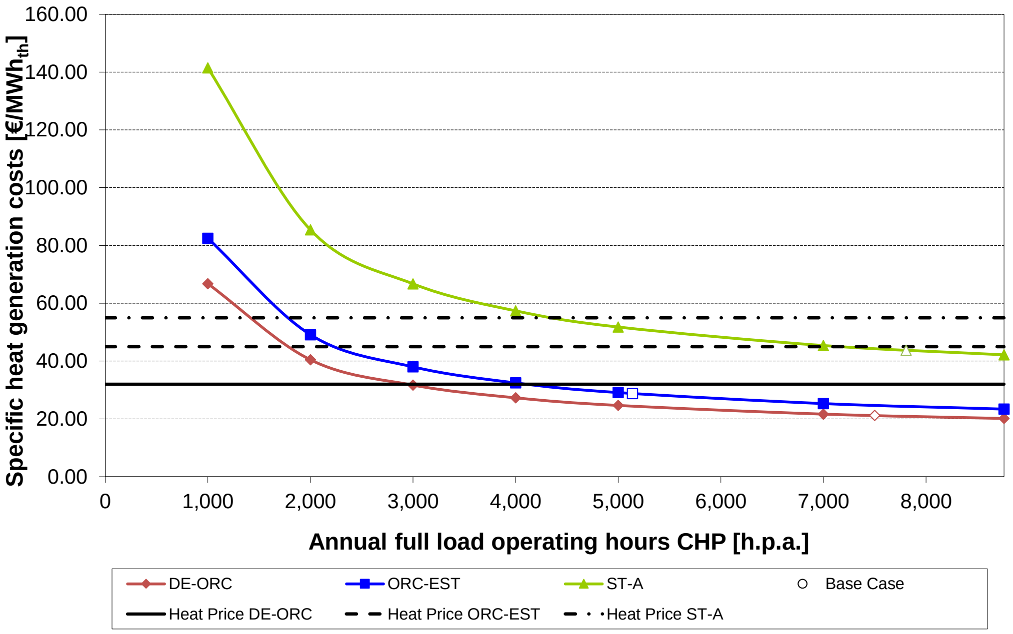

Figure 20: Influence of the annual full load operating hours on the specific heat generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all heat generation costs have been calculated without taking funding into account

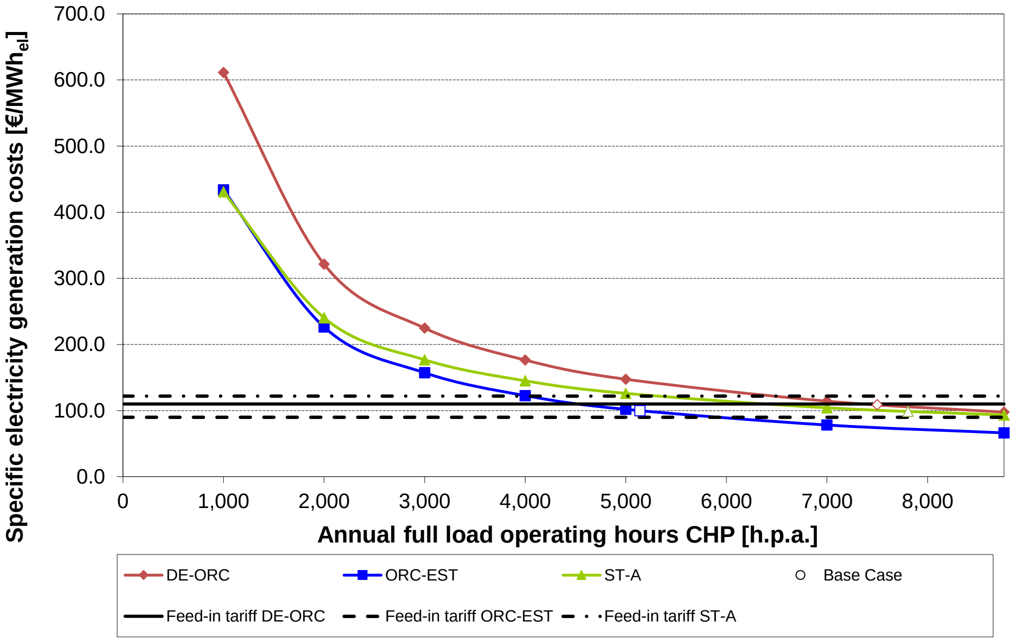

Figure 21: Influence of the annual full load operating hours on the specific electricity generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all electricity generation costs have been calculated without taking funding into account

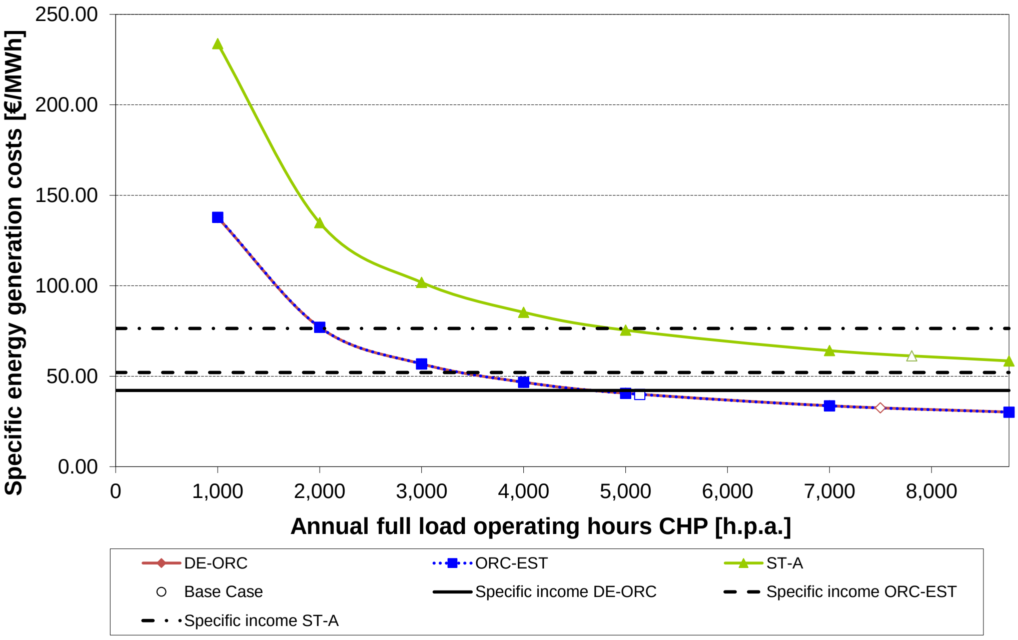

Figure 22: Influence of the annual full load operating hours on the specific energy generation costs

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all energy generation costs have been calculated without taking funding into account

Figure 21 shows the impact of a variation of the annual full load operating hours of the CHP plant on the electricity generation costs. It can be seen, that all three case studies show a strong dependence on the full load operating hours when decreasing below 3,000 hours per year because of the high specific capital costs. For this reason it is recommended to enable a minimum of about 6,000 full load operating hours by a proper dimensioning of a biomass CHP plant to ensure an economic operation of the CHP plant.

A decrease of the electricity generation costs in a range of 4.5 – 7.4% can be achieved by changing the full load operating hours of the CHP plant by +10%. A decrease of the full load hours by 10% increases the electricity generation costs by 5.5 – 8.9%

The variation of full load operating hours of the entire CHP plant and its influence on the specific energy generation costs is shown in Figure 22. A variation of the full load operating hours of + 10% leads to a decrease of the energy generation costs of 3.8 – 5.3% whereas a variation of - 10% increases the specific costs about 4.7 – 6.5%.

Figure 22 shows that the two case studies based on ORC processes show rather similar dependencies of the full load operating hours on the energy generation costs. The differences in plant size and efficiencies are compensated by local side constraints for the case studies investigated.

4.8.4 Influence of the heat price

The heat price is another important factor influencing the economy of the CHP plants and shall therefore be analysed within a sensitivity analysis (see Figure 23).

In case of the Estonian and the Slovakian CHP plant the variation of the heat price leads to a stronger influence on the specific income than in case of the Austrian CHP plant due to the lower electric efficiencies of the ORC units and thus the higher importance of the heat price.

An increase of the heat price of 10% leads to an increase of the specific income of about 4.9 – 7.3%. A decrease of the heat price of -10% reduces the specific income by 4.9 – 7.3%.

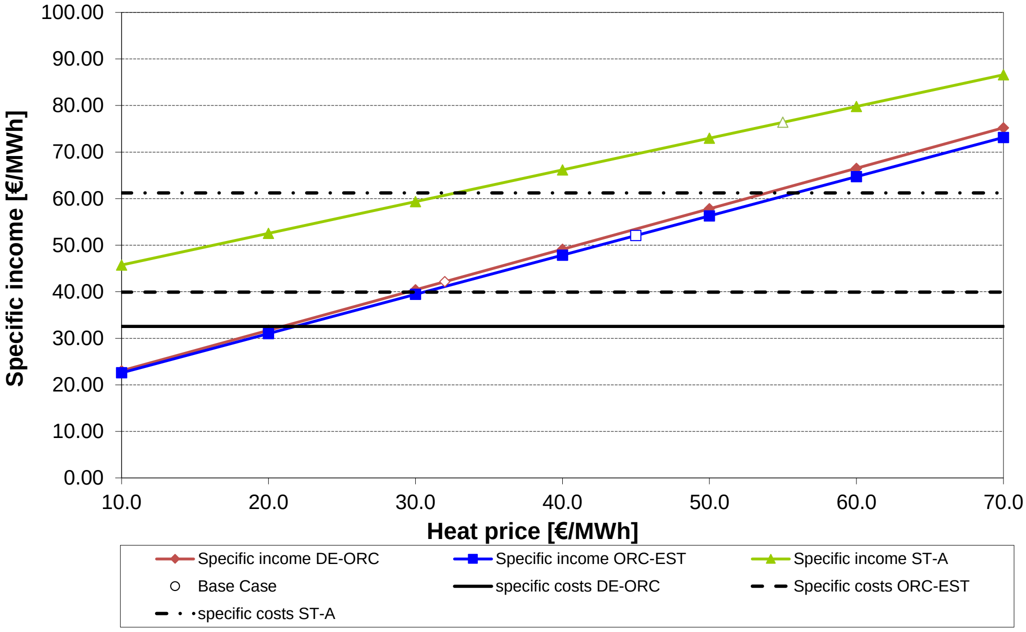

Figure 23: Influence of the heat price on the specific income

Explanations: DE-ORC … Direct exchange ORC process in Slovakia; ORC … Organic Rankine Cycle process; ST … steam turbine process; EST … Estonia; A … Austria; the empty dots indicate the base cases; calculations performed according to chapter 4; all energy generation costs have been calculated without taking funding into account

5 Summary, conclusions and recommendations

In 2004 the project “Decentralised CHP technologies based on biomass combustion – state of development, demonstration activities, economic performance (IEA-CHP)” had been performed within the IEA Bioenergy Agreement Task 32 to give an overview about recent technological developments and demonstration activities regarding small-scale biomass CHP systems. Now, 10 years later an update of the most successful and market relevant CHP approaches, the steam turbine and the ORC technology has been made under consideration of the technological development which took place within the last ten years but also under regard of the economic framework conditions given at present.

Within this report three case studies of biomass CHP plants have been investigated. Case study 1 (“Steam turbine”) is a biomass CHP plant based on a backpressure steam turbine process located in Austria. The thermal capacity of the plant (useful heat to the district heating system) is 17 MW and the gross electric capacity of the steam turbine is 5.7 MW. To raise the annual full load operating hours the CHP plant is equipped with a buffer storage tank smoothing fluctuations of the district heat demand and allowing higher heat production. Excess heat can be cooled in the installed air cooler, increasing the electricity production too.

Case study 2 (“ORC”) is a biomass fired CHP plant based on an ORC process in Estonia. The plant is equipped with a thermal oil boiler and an ORC unit with split-cycle which increases the overall efficiency. The gross electric capacity of the plant is 2.4 MW and the thermal capacity of the ORC condenser is 9.6 MW. An additional flue gas condensation unit increases the heat output of the CHP plant.

Case study 3 (“Direct exchange ORC”) is based on a Slovakian biomass fired direct exchange ORC system. In contrast to conventional ORC processes, the direct exchange system is equipped with a special evaporator transferring the heat from the flue gas to the ORC process. Due to this no intermediate thermal oil cycle is necessary. The gross electric capacity of this CHP plant is 130 kW and the thermal capacity is 660 kW. Due to recent start-up of this plant no long-term data regarding annual operation are available. For this reason the annual performance of the plant has been assumed according to experiences/expectations of the manufacturer.

Both the steam turbine as well as the conventional ORC process are well-known technologies which are commercially available since many years. The usage of a direct exchange ORC system in low temperature waste heat applications is also available in series production. The combination of the direct exchange ORC process with a biomass furnace however is quite new because of the special requirements of the process concerning the high temperature of the flue gas (about 1,000°C downstream the furnace which have to be reduced to at least 530°C before entering the ORC evaporator) as well as the dust load of flue gas (high-temperature multi-cyclone placed upstream the ORC evaporator). However, a few plants are already in operation respectively under construction using this new technological approach regarding ORC technology.

All plants investigated are fully automatically controlled which reduces the annual personnel demand and in order to this the operation and energy generation costs. The Austrian steam turbine plant is equipped with a special additional infrastructure regulated by law to enable a plant operation without continuous supervision for 72 hours. However, due to the steam process special boiler attendants are necessary which increases the hourly wages of the personnel.

In all three case studies it was assumed, that the auxiliary energy demand of the CHP related part of the plant can be covered by the electricity produced by the electric generator. The electricity sold to the public grid is reduced respectively.

Concerning the ecological point of view it can be stated, that all three biomass based CHP plants are appropriately equipped to keep the emission limits given by law. The biomass furnaces are optimised to reduce gaseous emissions. The steam turbine process is additionally equipped with a SNCR system to keep the strict NO_x emissions limits given. The dust emissions of the plants are all reduced by using multi-cyclones and if necessary additional dust precipitators like an electrostatic precipitator or a flue gas condensation unit. The liquid emissions due to waste water discharge are kept as low as possible by appropriate water treatment and the solid emissions (ash) are collected and disposed properly. The ashes can partly be used as an additive in compost production or as a secondary raw material with fertilising and liming effects on forest or agricultural soils (usually a mixture of bottom ash and cyclone fly ash). Moreover, decentralised biomass CHP plants offer the great advantage, that they can be designed and operated in a heat controlled way which results in high overall efficiencies (usually above 80%) and an efficient use of resources.

The overall annual efficiencies of the plants investigated vary between 65.8 and 87.0%. The annual gross electric efficiencies achieved are between 10.8 – 22.3%. The electricity produced in the CHP plants is thus a valuable by-product. Selling the heat produced, however, is absolutely necessary to cover the energy generation costs of the plant, enable an economic operation and ensure a certain flexibility regarding fluctuations in biomass fuel costs.

With respect to the economy of the processes investigated, the investment costs, the fuel price and the annual full load operating hours have been identified as the most important influencing factors. The kind of biomass used and the respective fuel price have a strong influence on the economy. 5,000 to 6,000 annual full load operating hours are recommended for decentralised biomass CHP plants in heat controlled operation. Following, the correct design of such plants (base load coverage) according to the annual heat output line of the system is of utmost relevance.

The specific CHP related investment costs of the plants investigated amount to about 6,500 €/kW_{el} for the direct exchange ORC process, to about 3,500 €/kW_{el} for the ORC process (2,200 €/kW_{el} taking subsidies into account) and to about 3,100 €/kW_{el} for the Austrian steam turbine process. These figures clearly outline the economy-of-scale effect given between the plant cases investigated. The electricity generation costs vary between 98.6 €/MWh_{el} (steam turbine process) and 108.8 €/MWh_{el} (direct exchange ORC process). The specific heat generation costs vary between 21.1 €/MWh_{th} (direct exchange ORC process) and 43.7 €/MWh_{th} (steam turbine process). Most important influencing variables for the electricity generation costs are the investment costs and the fuel costs. For the heat generation costs, the most important influencing variables are the fuel costs (first priority) and the investment costs (second priority). These costs, however, are based on the individual economic side constraints of the countries and are for this reason not directly comparable. The specific investment costs as well as the heat and electricity generation costs can significantly be reduced by a reduction of the investment costs or by investment subsidies.

Under the current framework conditions in the countries of the case studies the erection and operation of decentralised biomass CHP plants is economically meaningful and possible. However, investment subsidies and the feed-in tariffs available for biomass CHP plants are absolutely necessary in order to promote the market introduction of such systems, to contribute to the fulfilment of national and European targets concerning electricity production from biomass and CO_2 reduction as well as to utilise biomass resources efficiently in decentralised applications.

In general decentralised biomass CHP technologies which operate in heat controlled mode should be supported because they can contribute to a higher share of renewable electricity which can be provided on demand and ensure a high overall efficiency (high fuel utilisation ratio).

6 Literature

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