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# Techno-economic evaluation of selected decentralised CHP applications based on biomass combustion in IEA partner countries

# final report

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# Abbreviations and definitions

| | |
|---|---|
| A | Austria |
| CHP | combined heat and power production |
| CO | carbon monoxide |
| d.b. | dry base |
| DK | Denmark |
| ESP | electrostatic precipitator |
| h p.a. | hours per year |
| HWB | hot water boiler |
| IEA | International Energy Agency |
| NCV | net calorific value |
| $NO_2$ | nitrogen dioxide |
| $NO_x$ | nitrogen oxides |
| O | oxygen |
| ORC | Organic Rankine Cycle |
| PLB | peak load boiler |
| $SO_2$ | sulphur dioxide |
| $SO_x$ | sulphur oxide |
| ST | steam turbine |
| STE | Stirling engine |
| TOC | total organic carbon |
| vol.% | volume percent |
| w.b. | wet base |
| wt.% | weight percent |

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

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

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

# 1 Introduction and objectives

The evaluations made in this report have been performed within the IEA Bioenergy Agreement Task 32, project „Decentralised CHP technologies based on biomass combustion - state of development, demonstration activities, economic performance (IEA-CHP)".

The main objectives of the 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.

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,
- 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 for decentralised biomass CHP plants:

- Stirling engines up to an electric capacity of about 100 $kW_{el}$,
- ORC processes in a capacity range between 400 and 1,500 $kW_{el}$,
- steam turbine processes for capacities of more than 2,000 $kW_{el}$ (although some applications with lower capacities are in operation).

Both ORC processes and steam turbine processes have already reached market introduction. Stirling engines are already in operation in pilot plants, their market introduction is expected to be achieved in the near future. A small series production of Stirling engines is planned to be launched in the years 2004/2005. A first biomass CHP demonstration unit based on a screw-type engine is in operation since autumn 2003, market introduction can be expected in the near future (most probably 2004). However, the steam temperature is still limited to about 300 °C, leading to a low electric efficiency. Steam piston engines are also applied for biomass CHP plants based on biomass combustion. Their oil lubrication problems, however, increase the operation costs. Biomass CHP plants based on biomass combustion based on directly and indirectly fired gas turbine processes are still in a very low state of development.

Therefore, biomass CHP plants based on biomass combustion applying steam turbine processes (case study 1 and 2), ORC processes (case study 3) and Stirling engine processes (case study 4) have been investigated in detail in this report.

Beside biomass combustion, also biomass gasification can in principle be applied in the field addressed. The relevant technologies are:

- fixed bed gasification and gas engine,
- fluidised bed gasification and gas engine,
- fluidised bed gasification and gas turbine.

Biomass CHP systems based on gasification technologies have, however, not achieved market introduction yet (no mature technology). Moreover, they are not in the focus of IEA Bioenergy Task 32´s work. Therefore, they have not been investigated within the framework of this report.

# 2 Methodology

The study presented has been performed based on questionnaires as well as interviews. All partner countries of the IEA Bioenergy Agreement Task 32, in total 14 persons and institutions, have been invited to participate in the study. Those plants from where reliable and complete technological and economic data could be gained have been considered in this report. These are a Danish biomass CHP project based on a steam turbine process and three Austrian projects based on different biomass CHP technologies, namely the steam turbine, the ORC and the Stirling engine process.

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
- State of development
- Weak points
- Fuel characterisation and handling

The economic calculations in section 4 have been performed according to the guideline VDI 2067, 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 (Denmark)

### 3.1.1 Basic process description

A schematic diagram of the CHP plant investigated (i.e. the CHP plant at Assens Fjernvarme in Denmark) is shown in Figure 3.1, the technical data are shown in Table 3.1. For more details see section 4.4. Start-up of the plant has been in 1999. The electric capacity of the CHP plant is 4.4 $MW_{el}$, the heat produced is used in a district heating network. The plant, which is operated heat controlled, uses a back pressure steam turbine.

**Table 3.1:** Main technical data of the Danish biomass CHP plant based on a steam turbine process

| **Parameter** | **Value** |
|---|---|
| Fuel energy input CHP | 20,000 $kW_{NCV}$ |
| Electric capacity CHP | 4,700 $kW_{el}$ |
| Useful heat capacity CHP | 14,000 $kW_{th}$ |
| Steam pressure | 75 bar |
| Steam temperature | 525 °C |
| Steam flow | 20 t/h |
| Kind of turbine | back pressure |
| Back pressure | 0.81 bar |
| Operation mode | heat controlled |

The CHP plant is the main heat supplier for the district heating network. During coldest periods in wintertime the district heating network has a peak load demand of approximately 20 $MW_{th}$. For peak load coverage an old wood fired heating plant is utilised. This old plant also serves as a stand-by system for the CHP plant. For lowering the heat demand fluctuations in the district heating network, a big buffer storage is installed.

As the stand-by and peak load system is an existing old biomass heating plant, this plant has not been taken into account for the economic evaluation (see section 4.4).

The fuels used in the plant are pure and clean wood fuels (forest wood chips, wood chips from whole wood logs, dry wood waste from industry, sawdust, etc.) with a water content in the range of 5 to 55 wt.% (w.b.). Two pneumatic feeders – air spouts – intermittently blow the fuel (see section 3.1.10) into the combustion chamber, where the larger particles fall onto the grate. Small easy ignitable particles like dry sawdust burn in suspension. The air spouts use secondary air and/or recirculated flue gas. Combustion air can be pre-heated up to 200 °C in steam/combustion air heat exchangers.

The grate is water cooled and vibrating (in sequences of 3 seconds vibration for a period of 1,200 seconds occurs). When the grate is vibrated the bottom ash falls trough the grate into the dry ash transport system.

The flue gas passes from the combustion chamber through four sections of superheaters to a hot cyclone, where large fly ash particles are separated. The captured fly ash in the cyclone contains a high amount of unburned particles and is therefore pneumatically recycled to the combustion chamber. After the cyclone the energy remaining in the flue gas is utilised in an economiser for pre-heating the feed water of the steam cycle. Downstream the boiler an electrostatic precipitator (ESP) is used for efficient dust precipitation.

Finally, the flue gas may either pass through a combined wet scrubber/condenser unit cooled by the return of the district heating network, or pass directly into the 42 meter high chimney. The cooling in the wet scrubber decreases the flue gas temperature to a level below the dew point which makes it possible to increase the energy output as well as the overall efficiency of the plant considerably.

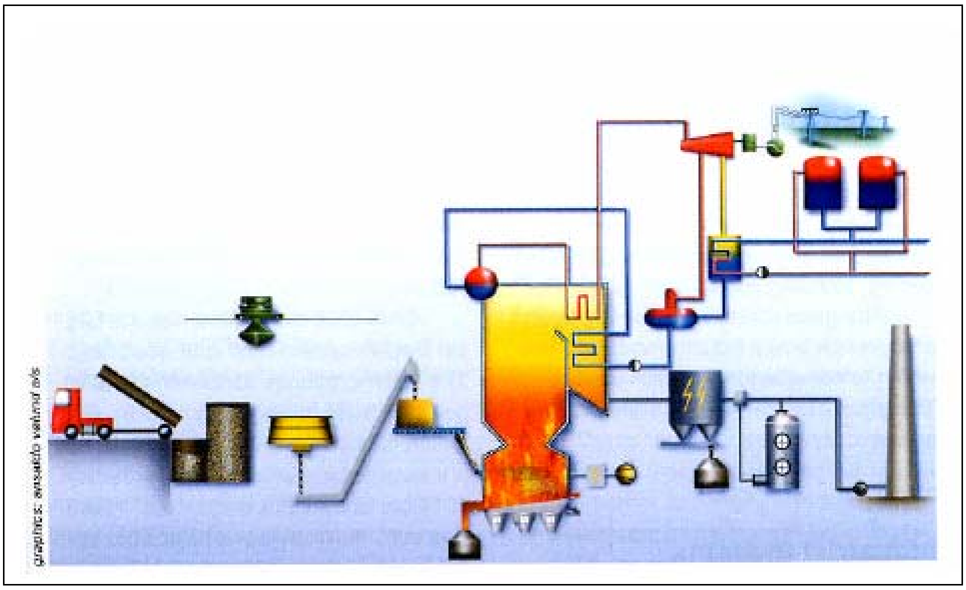

**Figure 3.1:** Schematic diagram of the biomass CHP plant at Assens Fjernvarme

Explanations : data source : Assens Fjernvarme

### 3.1.2 Interface between the CHP technology and the combustion plant

Since the water tube steam boiler supplies a turbine, for which a constant operation and electricity production are essential parameters, the operation of the boiler must be kept in a condition, where the steam data (mass flow of steam, temperature, pressure) are as accurate and 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).

The temperature of the superheated steam from the boiler, however, varies within 10%, which is not satisfying. The variation might be caused by too large variations in the energy content of the biomass fuel. Efforts will therefore be made to ensure a better mixing of the fuel in the transport system and the process control system should also be improved.

### 3.1.3 Operating behaviour and efficiencies

Start-up of the entire plant is done by the use of light fuel oil in a separate oil burner mounted at the wall of the combustion chamber. After a short start-up period which lasts 5 – 10 minutes, the feeding of wood fuel can be initiated and the oil burner is turned off. The start-up procedure is computer controlled and happens fully automatically. The oil burner igniting the fuel needs about 10 l oil per start-up. On average, about 150 start-up procedures are needed per year.

During summer the plant only runs part of the time because of the low heat demand. During periods of peak load / high load electricity payment the plant runs on full load in order to benefit from this high payment for the electricity produced. The heat produced during these periods is stored in accumulation tanks (buffer storage) with a capacity of 185 MWh (which is equal to about 70 hours of operation at high-summer load). The average feed and return temperature from the district heating network is 75 and 36 °C, respectively.

The plant operates only a few hours per year on partial load, if a stop would last for less than 4 hours.

The plant is operated heat controlled.

The efficiencies of the biomass CHP plant investigated are shown in Table 3.2.

**Table 3.2:** Efficiencies of the biomass CHP plant at Assens Fjernvarme

| Parameter | Value [%] |
|---|---|
| Annual total efficiency | 92.0 |
| Annual electric efficiency | 22.0 |
| Annual thermal efficiency | 70.0 |

### 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. The system enables automatic operation of the plant, thereby making unattended operation possible during evenings and nights. Therefore, the annual working hours needed to operate the entire plant are comparatively low, about 6,300 h p.a.. The operator in charge can carry out remote supervision of the plant with a laptop computer connected to the public telephone network.

### 3.1.5 Maintenance demand

The operation of the entire plant and the performance of the ongoing maintenance during the year is done by 4.5 employees (steam boiler attendants). Once a year in summertime a revision lasting about 14 days has to be done. Boiler cleaning, repairs, replacements and improvements are done during these revisions, where 8 people are working on average.

About 15 working days per year specialists for turbine maintenance, pressure tanks, cranes, etc. are needed.

Total maintenance costs amount to approximately 215,000 € per year, including approximately 54,000 € per year for experts and maintenance contracts.

### 3.1.6 Special (technology related) operation costs

Additional, technology related operation costs occur due to the desalination and blowdown needed for the boiler water (see section 3.1.7) and are 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 3.3. The emission limits shown are valid for plants operated with biomass fuels in a capacity range between 1 and 50 MW in Denmark.

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

**Table 3.3:** Plant emissions and emissions limits to be met (Danish biomass CHP plant based on a steam turbine process)

Explanations: values in $mg/Nm^3_{dry, 10 vol.\% O2}$; data source: Assens Fjernvarme

| parameter | plant emissions | emission limit |
|---|---|---|
| CO | 280 | 500 |
| $NO_x$ ($NO_2$) | 214 | 300 |
| $SO_x$ ($SO_2$) | 8 | 150 |
| particulate emissions | 40 | 40 |

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, 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 and the blowdown (appr. 4,500 $m^3$/a) and the flue gas condensation (appr. 3,500 $m^3$/a) must be discharged in the sewer.

Bottom ash from grate and fly ash from the ESP is collected in containers by a dry ash transport system. Before the ash is delivered to a dump water is added to ensure that no fire hazard exists.

The sound pressure level of steam turbines is comparatively high with 91 to 94 dB(A). Therefore, appropriate noise insulation measures are required.

### 3.1.8 State of development

Market introduction of the steam turbine process for biomass fired applications has already been performed. Start-up of the plant was in 1999. In total 25,000 operating hours have already been achieved from start-up since 1999. The average availability of the CHP plant in this period was 92%.

Potential for further optimisation and development has been identified through operating experience by the plant operator. Thus, the performance of the electricity production, the start-up procedure and the fuel logistics could be improved. In addition, more know how about firewood and wood chips should be gained (optimised fuel mixture, reason for different Cd contents in the ash, optimum water content, optimum height of the fuel layer on the grate, etc.).

### 3.1.9 Weak points

Several weak points of the plant evaluated have been identified according to experiences of the plant operators. One weak point is the fuel logistic (see section 3.1.10), which should be improved (about 150,000 $m^3$ wooden material is needed per year). The number of start-ups (approximately 150 per year) is too high and must be reduced. However, the high number of start-ups is due to the fact, that the operation of the plant is limited by the district heating consumers and it is not allowed to cool heat away. In addition, the start-up procedure should be improved as well. Each start-up lasts about 2 hours connected with reduced electricity production and non optimal combustion conditions during this period. Furthermore, each start-up reduces the lifetime of the plant.

The CHP plant is too expensive compared to conventional heating plants and an economic operation is only possible with public support to the production of green electricity. There is too much unburned carbon in the ash and the electric efficiency of the plant is too low.

### 3.1.10 Fuel characterisation and handling

The fuels used in the plant are pure and clean wood fuels with a water content in the range of 5 to 55 wt.% (w.b.). Different types of wood fuels (forest wood chips, wood chips from whole wood logs, dry wood waste from industry, sawdust, etc.) are used in combination and get mixed in a pre-defined ratio before the fuel mixture enters the combustion chamber. Depending on the circumstances on the fuel market also other qualities of wood residues might be taken into consideration.

The contracts with the wood chip suppliers include quality demands on the fuels. The size distribution must meet the requirement as announced in a physical size classification from 1987 settled by the Danish Forest Owners Association in 1987 (the classification is currently revised).

Furthermore the contract limits the content of the following compounds in the fuel:

- Sulphur: max 0.05 wt.% (d.b.)
- Chlorine: max 0.02 wt.% (d.b.)
- Total amount of ash: 1.5 wt.% (d.b.)

A mobile wood chipper rented from an individual contractor occasionally chips the stocks of wood logs. A general demand for all kind of wood delivered to the plant is that it must be free from any kind of non-wood material.

The outside storage of wood chips has a capacity of approximately 2,500 tonnes of wood chips (about 9,000 $m^3$ loose volume) and 5,000 tones of wood logs. This corresponds to about 50 days consumption at full load energy production.

The outdoor storage can receive fuel with both rear-unloading and side-unloading lorries, but wood chip trucks in Denmark use traditionally solely rear-unloading. The lorries, which carry up to 80 $m^3$ loose volume of chips a time, enter a receiving station at the plant. The driver uses an electronic card for identification and the weight of the vehicle including pay load is registered. The weight and the identification code are transmitted to a computer in the office of the administration.

Transport of fuel from the outdoor to the indoor storage is done by means of a wheel loader with a large shovel, or the lorries that arrives with fuel may unload directly in one of the four receiving bins. Each of the bins has a volume of app. 200 $m^3$. The bottom of the bins are approximately 4 meters below the level of the pathway, so the trucks can easily rear-unload their complete charge of 80 $m^3$ into the bin. The walls of the storage bins are equipped with heating pipes from the district heating system. The heated walls cause some drying of the stored wood chips and this has a positive influence at the angle of slope for the wood chips. This result in a more efficiently utilisation of the storage bins.

Behind the receiving bins the main indoor storage with a capacity of 5,800 $m^3$ of wood chips is located. This capacity allows about 10 days operation at nominal load. Two parallel lanes with identical automatically operated cranes are used for the transport of the fuel from the receiving bins to either the large main indoor storage or directly into the next fuel hopper in the handling system.

The industrial wood fuel and the wet forest wood chips are kept separated in the main storage. The separation in storage is required since the fuel later has to be mixed in a pre-defined and constant ratio. Each of the cranes have two of the four receiving bins within their working range. The partition of the storage is simply done by dedication of the receiving bins for different fuel types. One of the receiving bins is reserved for dry wood chips from industry and another bin for wet and/or dry saw dust. Those two receiving bins are within the range of one of the cranes. The two residual receiving bins are within the range of the other crane and are supplied with wet wood chips from forests or chips made of wood logs. Each of the cranes have a capacity of 1.5 times the need for maximum energy production and they are delivering fuel into two different fuel hoppers. The shovels of the cranes have a capacity of about 2.5 $m^3$ and are equipped with teeth to ensure a proper filling. A built-in scale between the cranes body and shovel records the weight of the received fuel. A radar sensor for distance measurement is mounted on the crane body and prevents overfilling of the main storage.

The two fuel hoppers above the belt conveyor are located in the centre of the storage building, adjacent to each other and along the centre line of the belt conveyor, which is situated underneath the fuel hoppers. When the fuel arrives on top of the fuel hoppers it gets in contact with a plane screen. It consists of two adjoining frames, both with a pattern of many approximately $200 \times 200$ mm rectangular holes. One of the frames is fixed while the other works by hydraulic cylinders in a horizontal reciprocating motion. Another hydraulic cylinder lifts frequently the whole screen into vertical position and empties it for oversize pieces.

The plane screens works satisfactory with the industrial wood and sawdust but not with forest wood fuels. Oversized pieces of wood are caught by the frames and stay there also after the screen has been lifted for emptying, or the oversized pieces can get into a position where they creep through the screen and continue further in the handling system.

In February 2000 two new disc screens replaced the two plane screens in order to get rid of these disturbances. Each of the new disc screens got a horizontal entry of approximately 3 × 3 meter. They were manufactured by an Estonian company.

In the fuel hoppers infrared sensors in horizontal position for measuring the height of the fuel layer are used. The sensors are equipped with an automatic pressurised air cleaning system to ensure stable operation. Correct function of the sensors is essential since they are used for control of the automatic cranes filling the hoppers. The push rod conveyors in the bottom of each of the hoppers have three hydraulic cylinders for operation of three reciprocating push rods. They are controlled in a mode where all three push rods at the same time move in the same direction. At the belt conveyor beneath the fuel hoppers a sandwich layer with forest wood chips in the bottom and by industrial wood chips and/or sawdust at the top is built. When the belt progresses from the storage to the boiler building the shaking and movements of the belt cause a mixing of the two types of fuel.

At the outlet of the belt conveyor the mixed fuel drops into a feed hopper ahead of the boiler.

A radar sensor carries out the height measurements of fuel in the hoppers. The continuous signal from the radar controls the conveyor belt and is also displayed at the computers in the control room. Furthermore, the feed hopper has a separate infrared sensor for height measurements as a security system against overfilling.

The operation of the belt conveyor is satisfactorily but the belt itself has to be properly aligned to the idlers in order to avoid leakage’s through which dust may escape to the ambient air. An automatic alignment system is considered. At the outlet of the belt there is a bottleneck, where the hazard for blocking exists.

The feed hopper is equipped with a parallel emergency loading system in case of failures of the conveyor belt. An always filled separate small hopper and an auger allow operation of the plant for 20 – 30 minutes. This capacity of the emergency loading system is inadequate in case of malfunctions of the belt conveyor beyond the normal working hour period. Since the plant is left in unattended operation during evenings and nights, an alarm caused by a belt conveyor failure requires a fast dispatch from home by the operator in charge. The hopper of the emergency system is supplied with fuel directly by the wheel loaders and enables the plant to stay in operation during the time needed for repair. At the bottom of one feed hopper four frequency controlled screw augers receive the fuel and transport it further to two pneumatic feeders, which intermittently move the fuel into the combustion chamber. The fuel is shot intermittently fuel into the combustion chambers. Larger particles fall down on the grate, small and easily ignitable particles, like dry sawdust, burn in suspension.

## 3.2 Case study 2: Biomass CHP plant based on a steam turbine process (Austria)

### 3.2.1 Basic process description

A schematic diagram of the CHP plant investigated (situated in a sawmill in Austria) is shown in Figure 3.2, the technical data of the plant are shown in Table 3.4. For more details see section 4.5. The plant is currently in the design stage, start-up is planned in the beginning of 2006. The electric capacity of the CHP plant will be 4.1 $MW_{el}$. The major part of the heat will be utilised as process heat (for the drying chambers), a part of it will be cooled by an air cooler. Following, the plant will be operated in heat controlled mode at a load between 50 and 100% of nominal power.

**Table 3.4:** Main technical data of the Austrian biomass CHP plant based on a steam turbine process

Explanations: all values related to nominal conditions

| Parameter | Value |
|---|---|
| Fuel energy input CHP | 19,500 $kW_{NCV}$ |
| Electric capacity CHP | 4,100 $kW_{el}$ |
| Useful heat capacity CHP | 12,100 $kW_{th}$ |
| Steam pressure | 60 bar |
| Steam temperature | 500 °C |
| Steam flow | 20 t/h |
| Kind of turbine | back pressure |
| Back pressure | 1 bar |
| Operation mode | mainly heat controlled |

The biomass fuels used in the CHP plant are wood chips, sawdust and bark, each about 50%, with an average water content of about 50 wt.% (w.b.) from the own plant. It is fed from a fuel hopper, where the different fuels from the plant are collected, to the furnace, which is equipped with a moving grate. 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). After the ESP a side stream of the flue gas is used for flue gas recirculation, the remaining flue gas passes into the chimney.

The base load is covered by the CHP plant shown in Figure 3.2. In addition, for peak load and stand-by a biomass hot water boiler (nominal capacity 8.0 $MW_{th}$) is used.

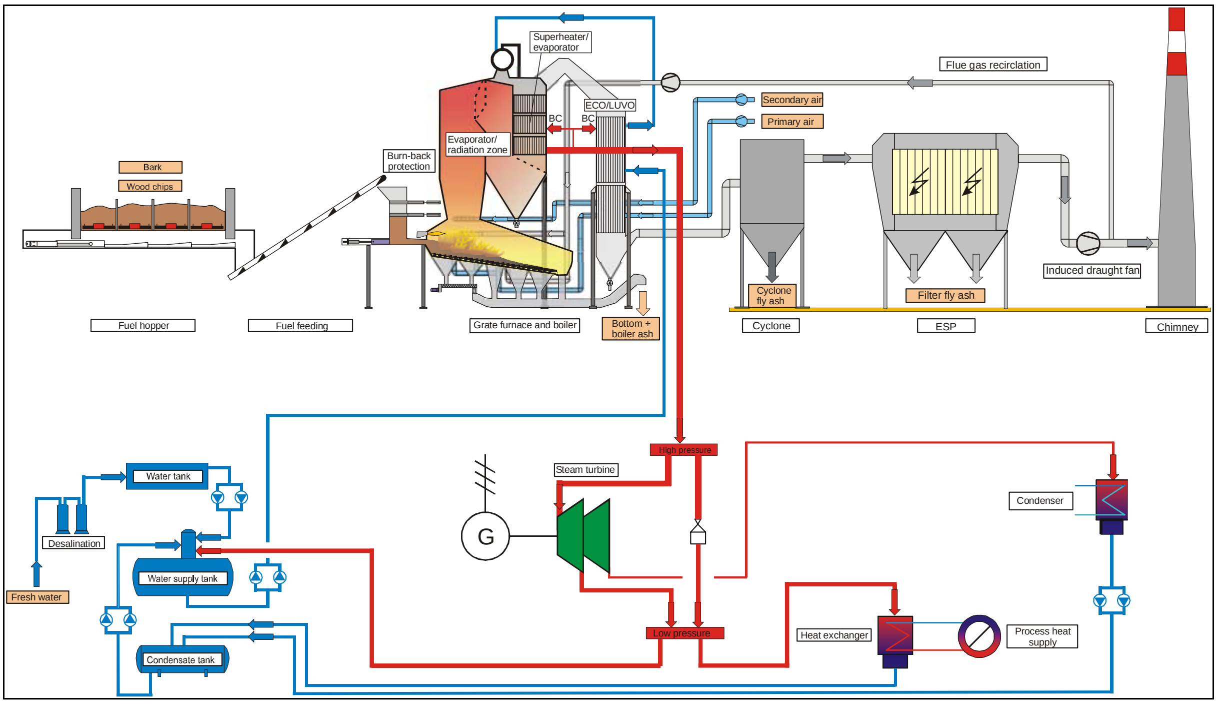


**Figure 3.2:** Schematic diagram of the overall biomass CHP plant of an Austrian sawmill

Explanations: ECO…economiser; LUVO…air pre-heater; BC…boiler cleaning; ESP…electrostatic precipitator; G…generator; data source BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

The annual heat and electricity output line as well as the energy supplied by the different units installed are shown in Figure 3.3.

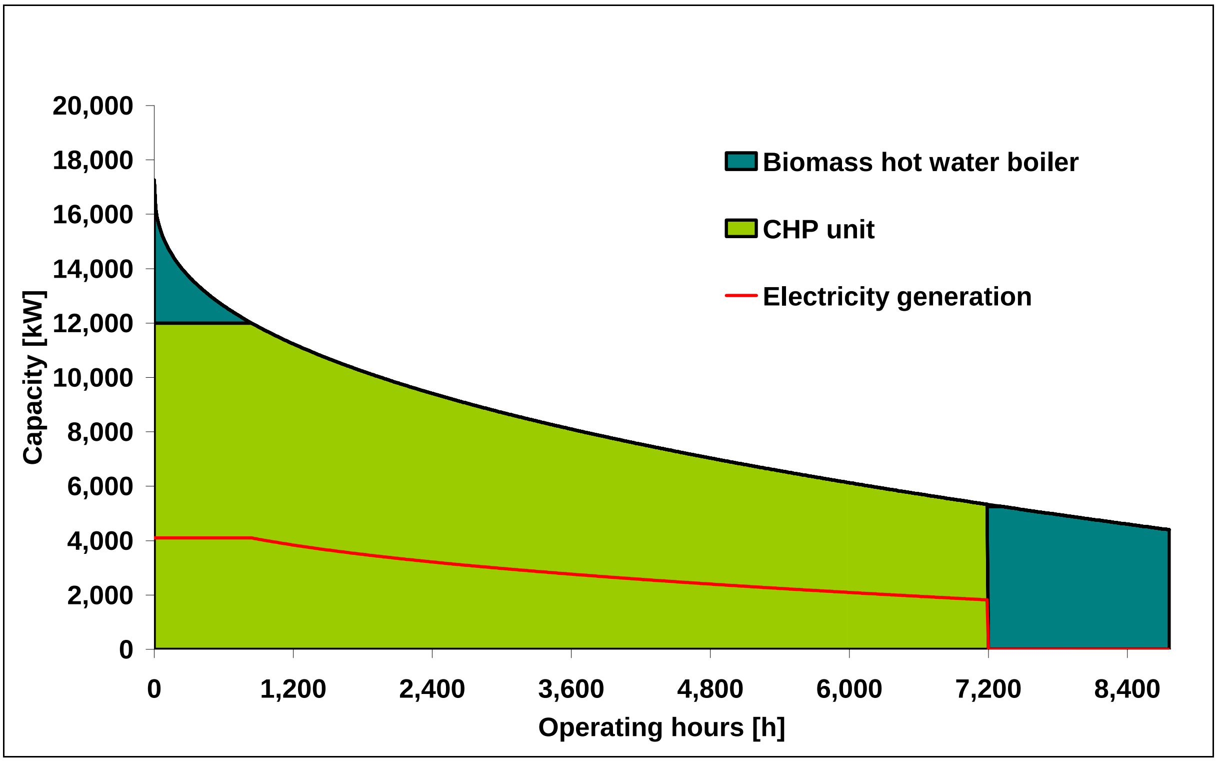


**Figure 3.3:** Annual heat and electricity output line for the Austrian biomass CHP plant based on a steam turbine process

### 3.2.2 Interface between the CHP technology and the combustion plant

The steam is produced in a water tube steam boiler including a superheater. Steam pressure and steam temperature are planned to be 60 bar and 500 °C, respectively. Since the steam turbine requires a very constant operation, the steam parameters must be kept as constant as possible. Therefore, large variations in the biomass fuel quality shall be avoided.

### 3.2.3 Operating behaviour and efficiencies

Start-up and operation of the entire plant is planned to be fully automatic. The start-up of the steam turbine can also be done fully automatic in a short time. The operation of the plant will be heat controlled. During summer time, when the heat demand of the drying chambers of the sawmill is lower, the plant will operate only at 50 to 70% of nominal load.

The efficiencies of the biomass CHP plant investigated are shown in Table 3.5.

**Table 3.5:** Efficiencies of the Austrian biomass CHP plant based on a steam turbine process

| Parameter | Value [%] |
|---|---|
| Annual total efficiency | 83.0 |
| Annual electric efficiency | 19.4 |
| Annual thermal efficiency | 63.6 |

### 3.2.4 Control system and personnel demand

The complete operation of the plant will be controlled and supervised by a computer based system. Unattended operation, e.g. during the night, will however not be realised. Therefore, continuous shift work with 1.4 persons per shift on average (3 shifts per day at 7 days per week) will be needed for the operation of the entire plant which leads to about 12,300 man hours per year in total. Personnel costs occurring due to maintenance of the plant are considered separately. A higher number of personnel is also needed, because fuel feeding from the intermediate storage in the sawmill to the daily fuel storage will be performed by wheel loaders.

### 3.2.5 Maintenance demand

As already mentioned, the operation of the entire plant requires 12,300 man hours per year. In addition, maintenance work causes additional personnel costs (which are not included in the personnel costs) as well as material costs. Maintenance includes ongoing maintenance during the year, revisions, boiler cleaning, repairs, replacements and realisation of improvements.

The total maintenance costs are expected to amount to approximately 337,000 € per year (approximately 1.7% of the investment costs p.a.).

### 3.2.6 Special (technology related) operation costs

In addition, technology related operation costs occur due to the desalination and blowdown needed for the boiler water (see section 3.2.7), which are considered in the operation costs.

### 3.2.7 Ecological aspects

The emission limits to be met by the plant according to Austrian legal framework conditions are show in Table 3.6. Based on experiences gained from several projects, the plant emissions are expected to be clearly below the limits to be met.

**Table 3.6:** Emission limits to be met by the Austrian steam turbine based biomass CHP plant

Explanations: values in mg/Nm$^3_{dry,\ 13\ vol.\%\ O2}$; TOC…total organic carbon; data source [1]

| parameter | emission limit |
|---|---|
| CO | 100 |
| $NO_x$ ($NO_2$) | 200 |
| particulate emissions | 50 |
| TOC | 20 |

Due to the necessary periodic desalination and blowdown of sludge from the boiler, waste water emissions are caused. From the desalination and the blowdown about 4,000 m$^3$ of waste water are expected per year, which will be discharged without further waste water treatment to the sewer. The waste water from the boiler water preparation will be neutralised and also discharged to the sewer.

The ash (bottom and boiler ash, cyclone fly ash and filter fly ash) will be collected in ash containers. Ash disposal will cause additional operation costs, which have been taken into account (worst case assumption as usually a mixture of bottom ash and cyclone fly ash could also be utilised on agricultural fields or in forests according to Austrian regulations, but the necessary ash logistics are difficult to manage due to the large ash amounts caused by bark combustion and due to the large size of the plant.

Steam turbines show a comparatively high sound pressure level of about 85 dB(A). Therefore, noise insulation measures are required.

### 3.2.8 State of development

The steam turbine process is a well developed technology and usually applied for power generation in medium- and large-scale power plants with nominal electric capacities greater than 5 MW$_{el}$. However, several plants, especially biomass CHP plants, are in the meantime in operation with capacities below this value. Efficient steam turbines are available for capacities from 3 MW$_{el}$ upwards at present.

### 3.2.9 Weak points

Due to the fact, that the water content of the biomass fuel can vary in a broad range, the steam quality (temperature, pressure, flow rate) can also vary. In order to keep the steam quality variation as low as possible, this fact must already be considered during the design phase of the fuel pre-treatment, the plant components and the process control system. In the specific case presented, the bark will be cut before firing in order to make the fuel feeding and the grate coverage more homogeneous.

### 3.2.10 Fuel and ash handling

The biomass fuels used in the CHP plant will be wood chips, sawdust and bark from own production with an average water content of about 50 wt.% (w.b.). Due to economic reasons, bark will be used preferably.

The storage capacity amounts to about 2 weeks (just in time fuel supply).

The transport of the biomass fuel from the intermediate storage to the daily storage will be done by wheel loaders. The daily storage will be equipped with a sliding bar conveyor, from there the biomass fuel will be transported by piston feeders directly into the furnace.

## 3.3 Case study 3: Biomass CHP plant based on an Organic Rankine Cycle (ORC) process (Austria)

### 3.3.1 Basic process description

A schematic diagram of the CHP plant investigated (i.e. the CHP plant in Lienz in Austria) is shown in Figure 3.4, the main technical data of the plant are shown in Table 3.7, for more details see section 4.6. The plant supplies the town of Lienz with district heat. The electric capacity of the CHP plant is 1,100 $kW_{el}$. The CHP plant essentially consists of two biomass-fired boilers, an ORC process, a solar collector panel and an oil-fired peak load and stand-by boiler as well as a heat recovery and flue gas cleaning unit, consisting of a flue gas condensation plant combined with a wet ESP.

**Table 3.7:** Main technical data of the Austrian biomass CHP plant based on an ORC process

Explanations: data related to operation at nominal conditions

| Parameter | Value |
|---|---|
| Fuel energy input CHP | 6,900 $kW_{NCV}$ |
| Electric capacity CHP | 1,100 $kW_{el}$ |
| Useful heat capacity CHP | 4,900 $kW_{th}$ |
| Operation mode | heat controlled |

Forest and industrial wood chips, sawdust and bark (average water content between 40 and 55 wt.% w.b.) from the regional forestry and wood industries are utilised as biomass fuel. The fuel conversion unit is composed of the two biomass combustion plants, a hot water boiler with a nominal capacity of 7,000 $kW_{th}$ and a thermal oil boiler with a nominal capacity of 6,000 $kW_{th}$. The thermal oil boiler supplies the ORC process with a nominal net electric power of 1,100 $kW_{el}$. The heat recovery unit with a nominal capacity of 2,000 $kW_{th}$ increases the overall plant efficiency and covers a thermal oil economiser, located behind the thermal oil boiler, and a hot water economiser which recovers energy from the flue gases of both biomass-fired boilers. The solar collector panel is installed on the roof of the CHP plants and consists of a 630 m² collector surface and achieves a thermal power of up to 350 kW. Two oil-fired boiler with nominal capacities of 11,000 $kW_{th}$ and 7,000 $kW_{th}$ are installed for peak load coverage and as stand-by systems.

The biomass-fired thermal oil boiler, the thermal oil economiser and the air pre-heater are equipped with an automatic cleaning system based on pressurised air. This system has already proved 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 the boiler outlet. This aspect is of great relevance for a high availability and overall efficiency of the CHP plant.

The flue gas cleaning unit consists of two stages. In the first stage the coarse fly ash particles are precipitated in multi-cyclones which are placed downstream of each biomass-fired boiler. In the second stage, fine fly-ash and aerosol precipitation take place in a wet electrostatic precipitator integrated in a heat recovery and flue gas condensation unit.

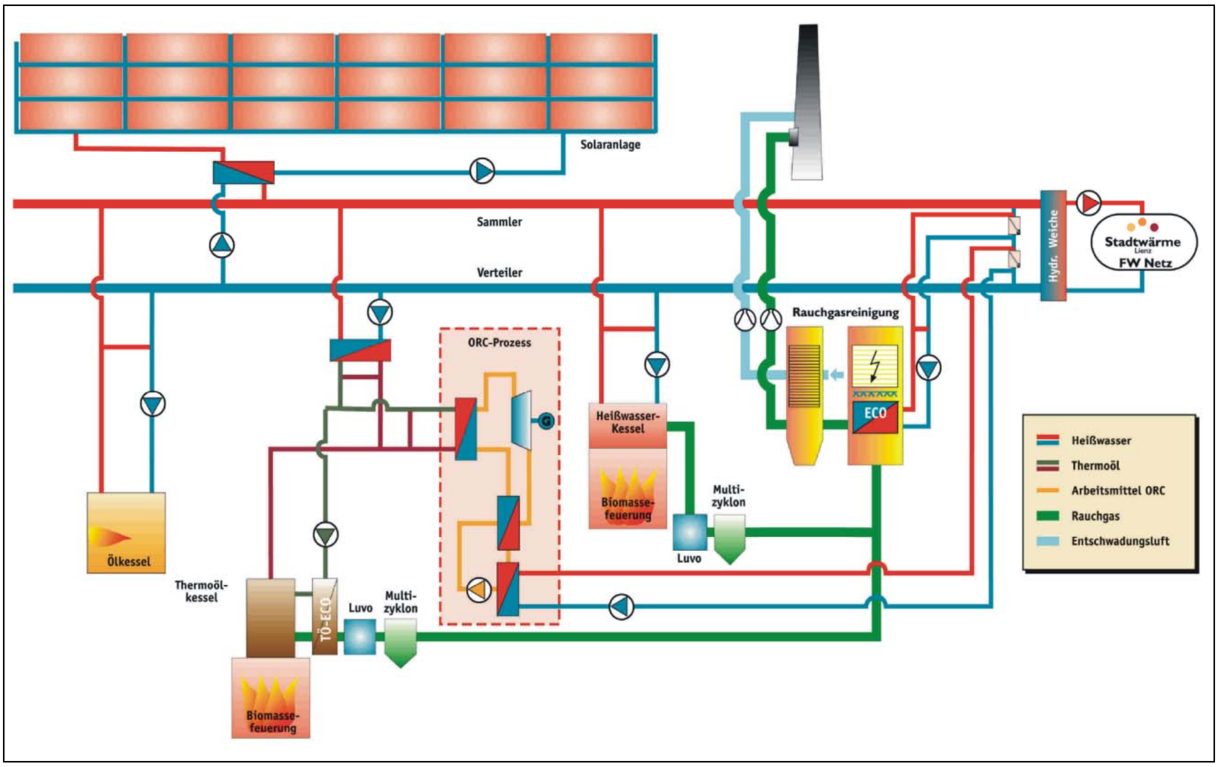


**Figure 3.4:** Schematic diagram of the overall biomass CHP plant based on an ORC process in Lienz (Austria)

Explanations: Arbeitsmittel…working medium; Biomassefeuerung...biomass furnace; ECO…economiser; Entschwadungsluft... air for avoidance of water vapour formation; FW Netz...district heating network; Heißwasser…hot water; Heißwasserkessel…hot water boiler; Hydr. Weiche…hydraulic gate; Luvo…air pre-heater; Multizyklon…multi-cyclone; Ölkessel…oil boiler; ORC-Prozess…Organic Rankine Cycle; Rauchgas…flue gas; Rauchgasreinigung…flue gas cleaning; Sammler…collector; Solaranlage…solar collector panel; Thermoöl…thermal oil; Thermoölkessel…thermal oil boiler; TÖ-ECO…thermal oil economiser; Verteiler…distributor; data source: Stadtwärme Lienz, Lienz, Austria

The main innovative part of the biomass CHP plant is the ORC process with a electric capacity of 1.1 MW and a nominal thermal capacity of 5.0 MW. The principle of electricity generation by means of an ORC process corresponds to the conventional Rankine process (see Figure 3.5). The substantial difference is that instead of water an organic working medium with favourable thermodynamic properties is used - hence the name Organic Rankine Cycle (ORC). The ORC process is connected with the thermal oil boiler via a thermal oil cycle. The ORC unit itself operates as a completely closed process utilising a silicon oil as organic working medium. This pressurised organic working medium is vaporised and slightly superheated by the thermal oil in the evaporator and then expanded in an axial turbine which is directly connected to an asynchronous generator. Subsequently, the expanded silicon oil passes through a regenerator (where in-cycle heat recuperation takes place) before it enters the condenser. The condensation of the working medium takes place at a temperature level which allows the heat recovered to be utilised as district heat (hot water feed temperature about 80 to 90°C). The liquid working medium then passes the feed pumps to again achieve the appropriate pressure level of the hot end of the cycle.

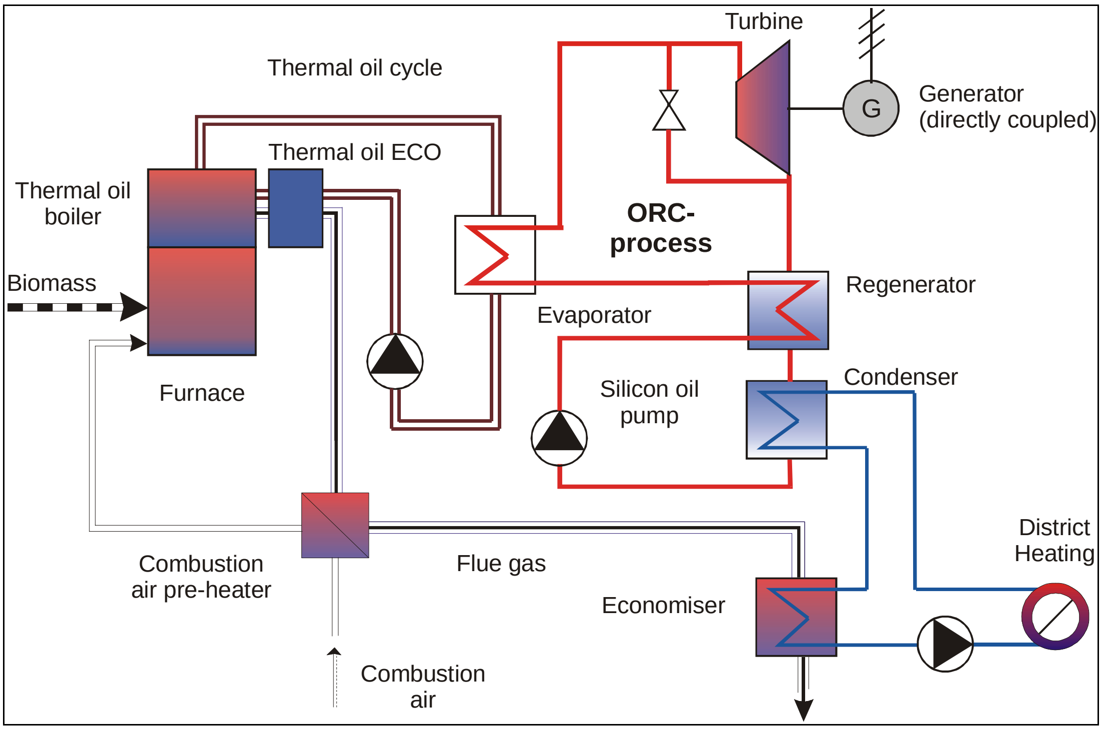


**Figure 3.5:** Working principle of the biomass-fired ORC process in Lienz

Explanations: source [2]

The design and integration of the ORC process in the entire plant took place with the objective to achieve a high capacity utilisation (large number of full load operating hours), a high overall electric efficiency and economic operation. A high capacity utilisation of the ORC in heat-controlled operation can be achieved by an appropriate dimensioning of the CHP system. The CHP unit should be able to operate the whole year in order to achieve at least 5,000 full load operating hours.

The annual heat and electricity output line as well as the energy supply of the different units installed for the Austrian biomass CHP plant based on an ORC process is shown in Figure 3.6.

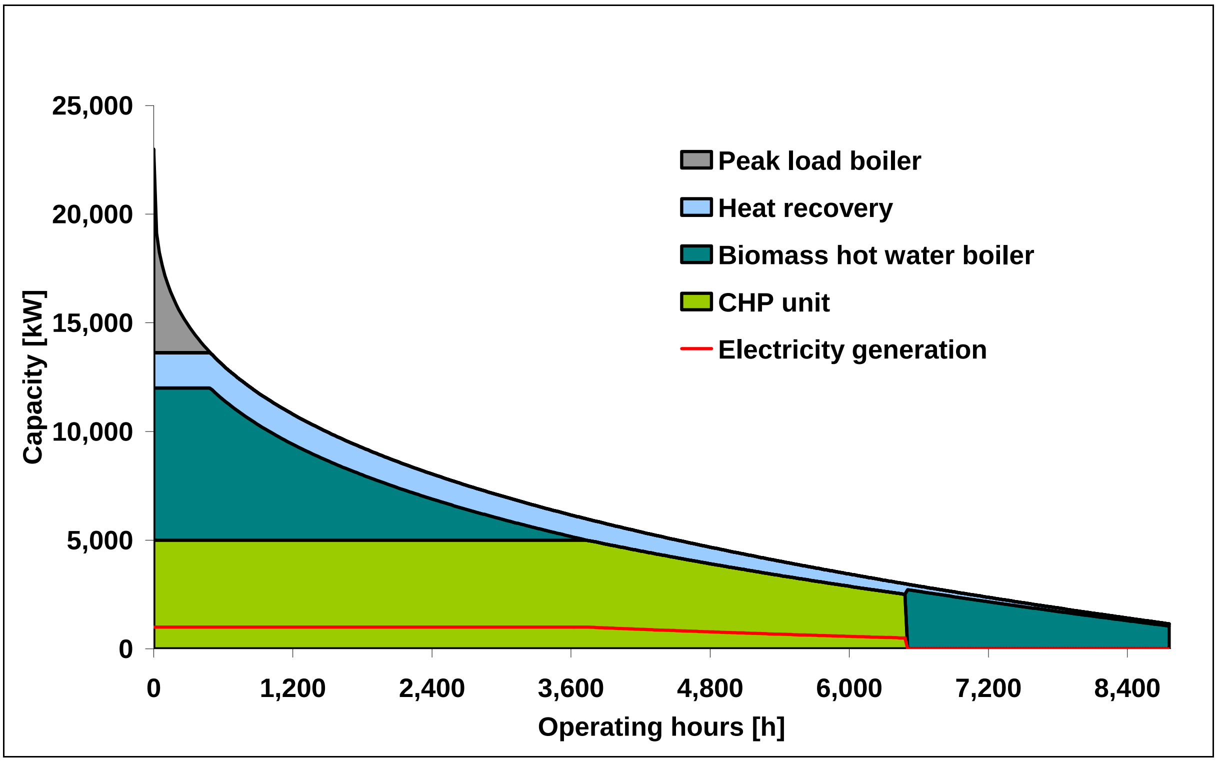


**Figure 3.6:** Annual heat and electricity output line for the Austrian biomass CHP plant based on an ORC process

### 3.3.2 Interface between the CHP technology and the combustion plant

The ORC process is connected with the thermal oil boiler via a thermal oil cycle. 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 condenser) 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 10 years if the nominal operating temperatures are kept (usually about 300 °C feed temperature).

### 3.3.3 Operating behaviour and efficiencies

The plant is operated fully heat controlled. 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 annual efficiencies of the biomass CHP plant investigated are shown in Table 3.8. Figure 3.7 contains an energy flow sheet of the ORC based biomass CHP plant at nominal load conditions.

**Table 3.8:** Efficiencies of the Austrian biomass CHP plant based on an ORC process

| Parameter | Value [%] |
|---|---|
| Annual total efficiency | 88.0 |
| Annual electric efficiency | 14.5 |
| Annual thermal efficiency | 73.5 |

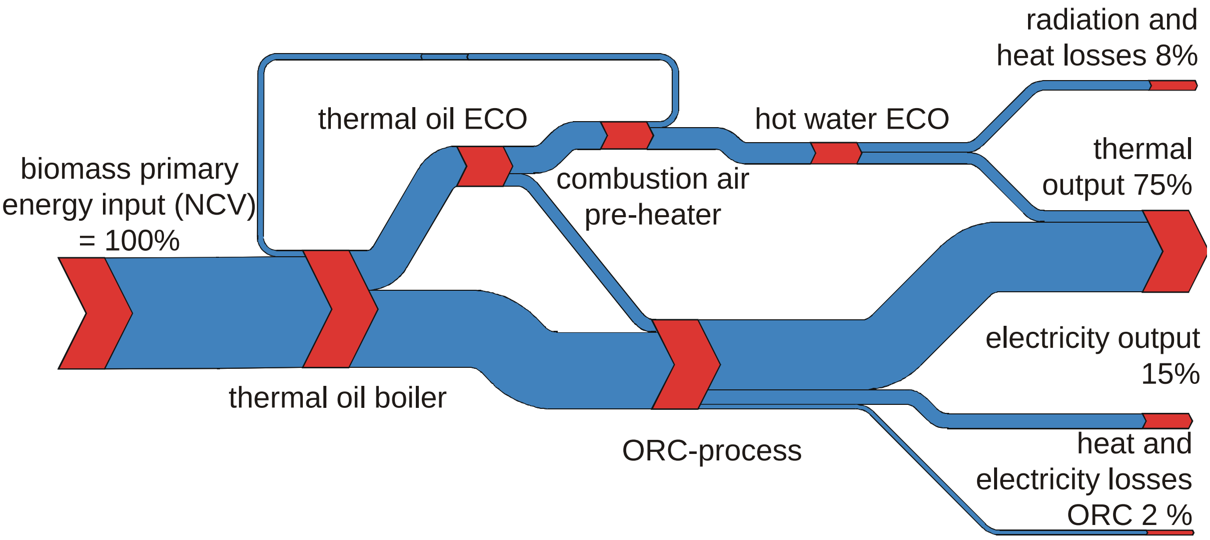


**Figure 3.7:** Energy flow sheet of the biomass CHP plant based on an ORC process at nominal capacity

Explanations: ECO…economiser; NCV…net calorific value

The ORC unit in the biomass CHP plant in Lienz is in successful operation since February 2002. Within the framework of the EU demonstration project a comprehensive monitoring programme has been performed during the first year. The data shown in Table 3.8 and Figure 3.7 are derived from this monitoring programme.

### 3.3.4 Control system

Due to strong fluctuations of the fuel quality and the heat demand in a district heating network, an optimised process control system of the CHP plant is of importance. The ORC process itself is controlled by an SPS, which ensures automatic start-up and shutdown procedures (without the necessary presence of an operator) as well as a smooth load control guided by the feed water temperature at the condenser outlet between 10 and 100% of nominal load. Due to this fully automatic operation 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 5,300 annual working hours.

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

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

The silicon oil used as a working medium in the ORC cycle is environmentally friendly (see section 3.3.7). Furthermore, due to the favourable thermodynamic properties of the silicon oil, there is no danger of droplet erosion on the turbine blades. As the working medium is flammable, the ORC process is equipped with a special detection system for organic compounds whereby a small amount of air over all the flanges is sucked in and subsequently analysed using a flame ionisation detector. Through this safety measure the ORC is monitored continuously for leaks.

### 3.3.5 Maintenance demand

Regarding the necessary maintenance, periodic weekly checks by the operator (some hours) as well as an annual routine examination of lasting 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 medium has the same lifetime as the ORC since it does not undergo any relevant ageing.

### 3.3.6 Special (technology related) operation costs

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

### 3.3.7 Ecological aspects

Measurements of emissions carried out at the biomass-fired CHP plant in Lienz showed that the prescribed limiting values according to Table 3.9 can be adhered to without problems both at nominal load and partial load operation.

**Table 3.9:** Emission limits to be met by the Austrian ORC based biomass CHP plant

Explanations: values in $mg/Nm^3_{dry,\ 13\ vol.\%\ O2}$; TOC…total organic carbon; data source [2]

| parameter | emission limit |
|---|---|
| CO | 100 |
| $NO_x$ ($NO_2$) | 200 |
| particulate emissions | 20 |
| TOC | 20 |

Based on an emission prediction performed for the biomass CHP plant, approximately 29,000 t/a of $CO_2$, 58 t/a of CO, 24 t/a of $SO_2$, 4.2 t/a of $NO_x$ and 1.4 t/a of dust can be prevented, mainly by the replacement of old oil-fired furnaces with district heat from biomass. Therefore, a clear improvement of the regional environmental situation is achieved.

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

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

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

### 3.3.8 State of development

The first biomass CHP plant based on an ORC cycle put in operation within the EU is situated at the STIA wood processing company in Admont (A). This plant has now been working for more than four years and has been running for around 35,000 operating hours [3; 4]. The second ORC process in combination with biomass combustion installed in Lienz in the framework of an EU demonstration project has reached more than 11,000 operating hours, which stresses the reliability and high availability of this technology [2].

Another plant based on an ORC process is located in Fussach in Austria, where electricity, heat and cold is produced. Further biomass CHP plants based on an ORC process are installed in Switzerland (2), Italy (2) and Germany (4). Moreover, 13 biomass CHP plants in total based on an ORC process are in the planning phase in Austria, Germany and Italy (in the capacity range between 200 and 1,500 $kW_{el}$).

### 3.3.9 Weak points

Die 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 automatic cleaning of the flue gas condenser section causes some problems. Therefore, an improved arrangement of the water nozzles is foreseen to overcome these problems.

The ORC unit did not show weak points, no relevant problems occurred.

### 3.3.10 Fuel characterisation and handling

Forest and industrial wood chips, sawdust and bark (average water content between 35 and 55 wt.% w.b.) from the regional forestry and wood industries are utilised as biomass fuels. The total annual biomass fuel consumption amounts to about 100,000 bulk $m^3$. The oil-fired peak load and stand-by boilers cover only approximately 4% of the entire thermal energy production. Concerning biomass storage, an open and a roofed area with a total storage capacity of 15,000 bulk $m^3$ is available (covering about 15% of the annual fuel supply).

The transport of the biomass fuel from the intermediate storage to the daily storage is done by wheel loaders. The daily storage is equipped with a sliding bar conveyor. The biomass fuel will be transported by hydraulic piston feeders directly to the furnace.

## 3.4 Case study 4: Biomass CHP plant based on a Stirling engine (Austria)

### 3.4.1 Basic process description

A schematic diagram of the CHP plant based on a Stirling engine process is shown in Figure 3.8, the main technical date of the CHP plant are shown in Table 3.10. For more details see section 3.4. The plant is currently in design stage, start-up is planned for winter 2004/2005. The plant should cover the base load of a district heating network. The mean load will be covered by an existing biomass hot water boiler (nominal capacity 2,500 $kW_{th}$) and for peak load and stand-by an oil burner (nominal capacity 800 $kW_{th}$) is installed. The electric capacity of the CHP plant will be 70 $kW_{el}$. The biomass district heating system (hot water boiler and oil boiler) is already existing and in operation since 1991. Due to a planned further expansion of the district heating network a second biomass fired boiler which will be connected with a CHP unit is foreseen.

**Table 3.10:** Main technical data of the Austrian biomass CHP plant based on a Stirling engine process

Explanations: data related operation at nominal conditions

| Parameter | Value |
|---|---|
| Fuel energy input CHP | 635 $kW_{NCV}$ |
| Electric capacity CHP | 70 $kW_{el}$ |
| Useful heat capacity CHP | 500 $kW_{th}$ |
| Stirling engine | 8 cylinder hermetically sealed |
| Working medium | helium |
| Mean pressure of the working medium | 4.5 MPa |

Basic components of the Stirling engine are the heated working cylinder, the cooled compression cylinder and a regenerator for temporary heat accumulation. The regenerator is a porous body with high heat capacity (e.g. steel wool). Heat absorption in combination with cooling of the engine causes changes in volume of the pressurised working medium. Due to the alternating expansion and compression thermal energy is transformed to mechanical energy by a piston. The more efficient the alternating heat exchange within the regenerator, the higher the difference between power and compression cylinder and further on the higher the efficiency of the Stirling engine.

In order to obtain a high overall electric efficiency of the CHP plant, the temperature in the hot heat exchanger should be as high as possible. Therefore, it is necessary to preheat the combustion air with the flue gas leaving the hot heat exchanger by means of an air pre-heater. Typically the temperature of the combustion air is raised to 500 °C – 600 °C, resulting in very high temperatures in the combustion chamber (about 1,300 °C).

The closed Stirling cycle makes it possible to use a working gas, which is better suited for heat transfer to and from the cycle than air. The use of helium or hydrogen is most efficient, but utilisation of these low molecular weight gases makes it difficult to design a piston rod seal, which keeps the working gas inside the cylinder and prevents the lubrication oil from entering the cylinder. Many solutions have been tested, but it is still a delicate component in the engine. An attractive possibility is to bypass the problem by designing the engine as a hermetically sealed unit with the generator incorporated in the pressurised crankcase, just like the electric motor in a hermetically sealed compressor for refrigeration. Only static seals are necessary and the only connections from the inside to the outside of the hermetically sealed crankcase are the cable connections between the generator and the grid. The Stirling engine used in this CHP plant is a hermetic eight cylinder Stirling engine, where Helium as working medium is used at a mean pressure of 4.5 MPa.

The cooler is connected to the district heating return (the temperature should be as low as possible). The return is pre-heated in the cooler and is then passed to the economiser, where it is heated to the necessary feed temperature.

The experience gained from two pilot plants already in operation showed, that an efficient dust precipitation can be achieved by the heater of the Stirling engine by ash vapour condensation. This heater is equipped with a specially developed pressurised air cleaning system. Behind the economiser, a cyclone precipitator is placed.

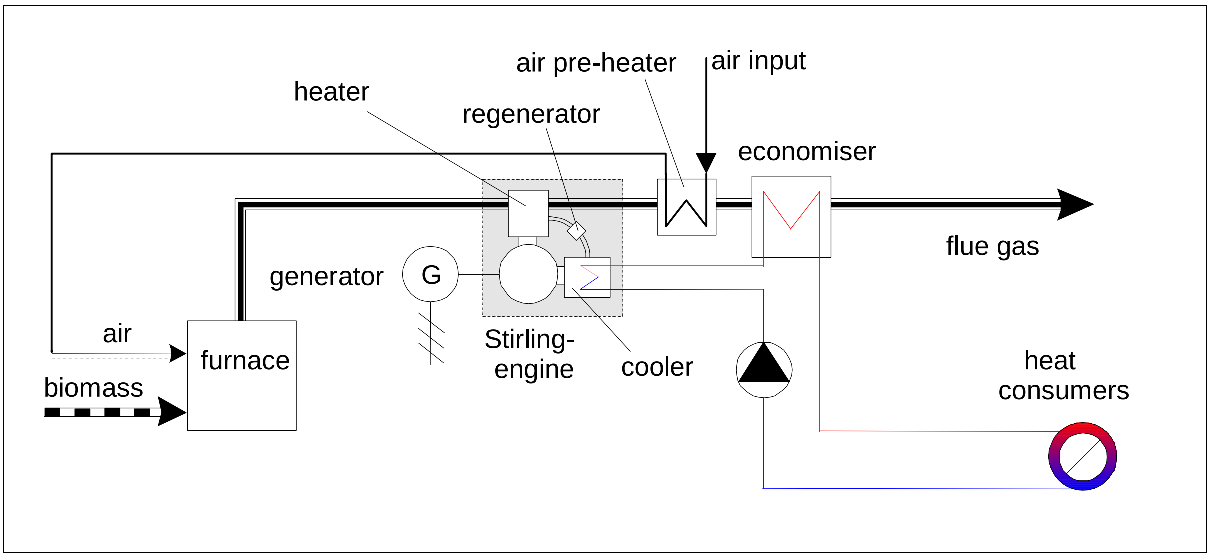


**Figure 3.8:** Schematic diagram of the biomass CHP plant based on a Stirling engine process (Austria)

Explanations: data source [5]

The biomass fuel used will be a mixture of forest wood chips, industrial wood chips and untreated wood waste with a water content between 25 and 30 wt.% (w.b.).

The annual heat and electricity output line as well as the energy supply of the different units installed for the Austrian biomass CHP plant based on a Stirling engine process is shown in Figure 3.9.

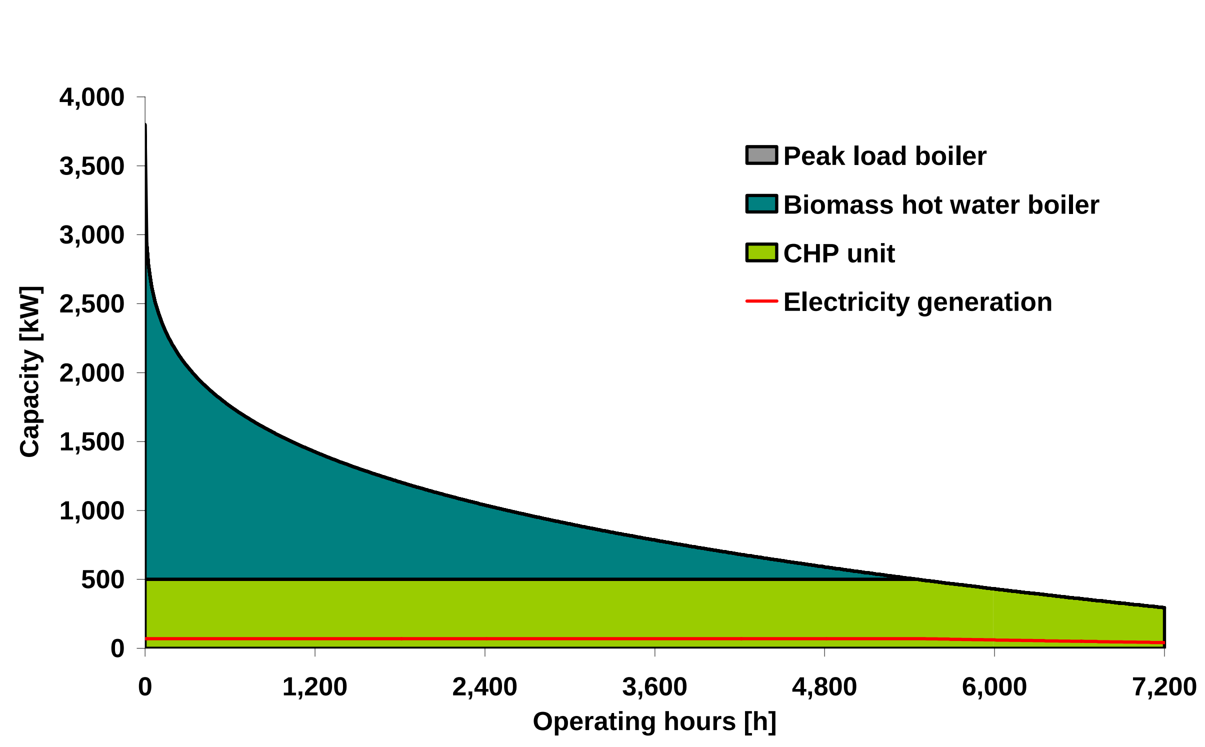


**Figure 3.9:** Annual heat and electricity output line for the Austrian biomass CHP plant based on a Stirling engine process

### 3.4.2 Interface between the CHP technology and the combustion plant

The advantage of the Stirling engine in comparison to internal combustion engines is that the heat is not supplied to the cycle by combustion of the fuel inside the cylinder, but transferred from the outside through a heat exchanger in the same way as in a steam boiler. Consequently, the combustion system for a Stirling engine can be based on proven biomass furnace technology.

In order to achieve a high electric efficiency, a high combustion temperature is necessary. Therefore, the combustion air is pre-heated to about 500 to 600 °C, which enables combustion temperatures of about 1,300 °C. Due to this high combustion temperature, a specially adapted combustion technology and material selection is necessary.

The Stirling cooler is connected to the return of the district heating network. The Stirling heater is directly inserted in the hot combustion chamber, the air pre-heater and the economiser are placed behind.

In case of malfunctions of the Stirling engine, the engine can be moved out of the combustion chamber and heat-only operation of the plant is also possible (important for security of heat supply).

### 3.4.3 Operating behaviour and efficiency

Start-up, shutdown and operation of the plant will be fully automatic. The plant will be operated heat controlled in order to achieve a high overall efficiency.

The efficiencies of the biomass CHP plant investigated are shown in Table 3.11.

**Table 3.11:** Annual efficiencies of the Austrian biomass CHP plant based on a Stirling engine

| **Parameter** | **Value [%]** |
|---|---|
| Annual total efficiency | 86.0 |
| Annual electric efficiency | 10.6 |
| Annual thermal efficiency | 75.4 |

The energy flow sheet of the biomass CHP plant based on a Stirling engine at nominal capacity is shown in Figure 3.10. Related to the primary energy input, about 11% of electricity and about 79% of heat are produced, which leads to a total efficiency of almost 90% at nominal load.

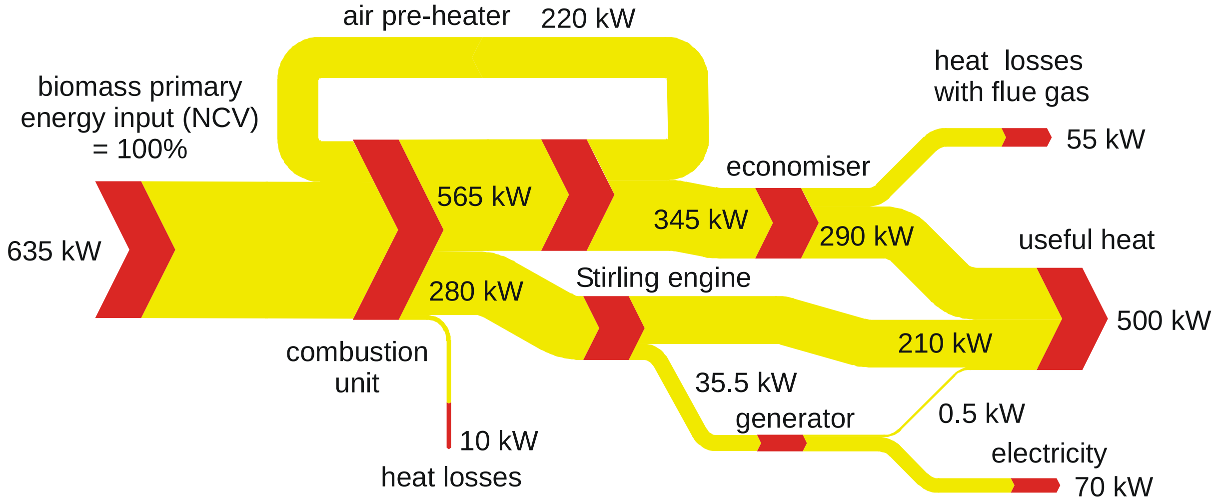


**Figure 3.10:** Energy flow sheet of the biomass CHP plant based on a Stirling engine at nominal capacity

Partial load operation of Stirling engines is not yet optimised (efficiency decrease). Therefore, a design for base load operation is essential.

Due to the dust loaded flue gas passing the Stirling heater, an automatic cleaning system is needed, which is based on pressurised air.

### 3.4.4 Control system

To keep the operating costs as low as possible, small-scale CHP plants have to be able to run in unattended operation for days / weeks. The Stirling engine system is therefore designed for fully automatic operation, which has already been proven to work well at a 35 and 70 $kW_{el}$ pilot plant. Start-up and shutdown procedures of the plant also take place automatically. If any engine failure is detected the combustion system is immediately shut down without operator intervention necessary.

The combustion plant is equipped with a special temperature control system by staged air and flue gas recirculation to ensure a stable and high combustion temperature. Security systems for the Stirling engine are also installed (emergency cooling in case of disconnection of the grid).

### 3.4.5 Maintenance demand

An automatic cleaning system especially developed for the Stirling engine heater has been improved stepwise during the test periods at the pilot plants described in [7]. According to the present state-of-the-art, manual cleaning of the hot heat exchanger is necessary after more than one month of operation (about 800 to 1,000 hours of operation). It is expected that further improvements of the automatic cleaning system will increase these intervals to 2,000 to 3,000 hours.

The 35 $kW_{el}$ Stirling engine pilot plant (see [7]) was disassembled for inspection after 5,000 operating hours. The results of this inspection showed that the major parts of the Stirling engine have only small or no wear. Only the design of one bearing and of the sealings of the piston and the piston rods has to be improved. These improvements as well as further developments planned within the first demonstration projects are expected to increase the service intervals further. The lifetime of the Stirling engine heater is not yet known but no corrosion or abrasion damage could be realised after 5,000 hours of operation. The lifetime of the engine itself is expected to be at least 100,000 hours.

### 3.4.6 Special (technology related) operation costs

As the Stirling engine cycle is a closed cycle, no special technology related operation costs are expected. The personnel demand for manual heat exchanger cleaning has, however, to be considered.

### 3.4.7 Ecological aspects

The expected emissions of the plant as well as the emission limits to be met are shown in Table 3.12. The expected emissions of the plant are based on measurements at the pilot plants already in operation [6; 7].

Table 3.12 shows the expected emissions to be clearly below the respective emission limits. For $SO_x$ no emission limit for small-scale biomass CHP plants exists in Austria. The Stirling engine heater effectively collects aerosols and therefore considerably reduces dust emissions in comparison to conventional small-scale biomass combustion plants.

The Stirling engine itself is a closed cycle, therefore no emissions occur.

Ashes can be utilised (a mixture of bottom ash and cyclone fly ash) as an additive in compost production or as a secondary raw material with fertilising and liming effects in forests or on agricultural soils. Therefore, no ash disposal is necessary.

Stirling engines achieve a considerable noise reduction compared to diesel engines. They do not need special noise insulations.

For the use of helium as working medium no special safety arrangements are required and therefore the use of helium can be regarded as harmless with respect to the environment.

**Table 3.12:** Plant emissions and emissions limits to be met (Austrian biomass CHP plant based on a Stirling engine)

Explanations: values in mg/Nm$^3$dry, 13 vol.% $O_2$; data source BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| parameter | plant emissions according to measurements at the pilot plant | emission limit according to national regulations |
|---|---|---|
| CO | 20 | 250 |
| TOC | 2 | 20 |
| $NO_x$ ($NO_2$) | 150 | 300 |
| $SO_x$ ($SO_2$) | 3 | - |
| particulate emissions | 40 | 100 |

### 3.4.8 State of development

A hermetic four cylinder Stirling engine for biomass fuels was developed and optimised in cooperation of the Technical University of Denmark, MAWERA Holzfeuerungsanlagen GesmbH, an Austrian biomass furnace and boiler manufacturer, and BIOS BIOENERGIESYSTEME GmbH, an Austrian development and engineering company. Based on the technology developed, a first 4 cylinder pilot plant was designed and erected in Austria. The nominal electric power output of this plant is 35 kW and the nominal thermal output amounts to approx. 220 kW. Currently, this plant has run for more than 7,000 hours. Furthermore, within the scope of an EU research project, a biomass CHP plant with a 75 $kW_{el}$ 8 cylinder Stirling engine was designed and put into operation [6; 7; 8]. This development is the first biomass CHP technology based on an 8 cylinder Stirling engine worldwide. This second pilot plant was put into operation at the end of 2003 and has already more than 1,500 operating hours achieved. Both pilot plants are installed in Austria and show a very promising performance.

The average availability of the pilot plants calculated amounted to more than 80%. The overall electric efficiency achieved was about 11% [7]. Further development and optimisation potential is given.

A first small series production of about 10 plants is planned for the years 2004/2005.

Figure 3.11 shows a picture of the 35 $kW_{el}$ Stirling engine pilot plant.

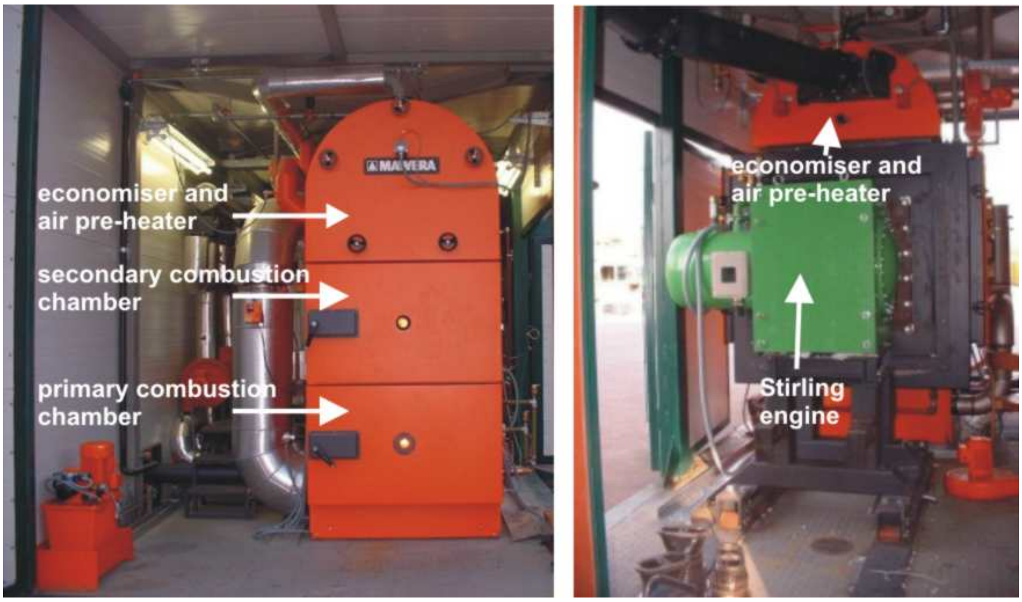


**Figure 3.11:** Pictures of the small-scale CHP pilot plant with a 35 $kW_{el}$ Stirling engine

Explanations: source [7]

### 3.4.9 Weak points

The problems concerning utilisation of biomass fuels in connection with a Stirling engine are concentrated on transferring the heat from the combustion of the fuel into the working gas. The temperature must be high in order to obtain an acceptable electric efficiency. The high temperatures needed in the combustion chamber can, however, cause ash slagging and fouling problems in biomass combustion systems and in the hot heat exchanger. The heat exchanger must therefore be designed in a way to minimise deposit formation and the combustion chamber has to be equipped with an efficient temperature control.

There are several problems / developments to be addressed in future, primarily regarding the achievement of an enhanced electric efficiency. In this context, major emphasis should be placed on improving the efficiencies of the hot heat exchanger, of the air pre-heater and of the entire combustion system. Furthermore, the optimisation of the pneumatic cleaning system to reduce ash deposition in the hot heat exchanger and thus to achieve a higher availability of the whole system is of great relevance. This work is continued in an international R&D project performed within the Austrian Bioenergy Centre in Graz.

### 3.4.10 Fuel and ash handling

The biomass fuel to be used in the CHP plant will be 50% forest wood chips (with a water content of about 30 wt.% (w.b.)) and 50% industrial wood chips and chemically untreated wood waste (with an average water content of about 25 wt.% (w.b.)).

The transport of the biomass fuel from the intermediate storage to the daily storage will be done by wheel loaders. The daily storage is equipped with a sliding bar conveyor. From there the biomass fuel will be transported by feeding screws directly into the furnace, which is designed as an underfeed stoker.

The bottom and the cyclone fly ash are collected, mixed and then utilised by the farmers who also supply the plant with the fuel. A closed cycle economy has been established by that approach.

# 4 Economic evaluations of the technologies investigated

## 4.1 Economic calculations according to the guideline VDI 2067

The guideline VDI 2067 [9] provided 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 4.1) with the investment costs. They are calculated for each unit of the process, taking the different utilisation periods into account.

**Equation 4.1:** $$CRF = \frac{(1+i)^n \cdot i}{(1+i)^n - 1}$$

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 produced (heat and electricity) according to Equation 4.2 for each process to be compared.

**Equation 4.2:** $$C_{spec.} = \frac{C_{tot}}{Q_{el} + Q_{th}}$$

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

Finally, the total income, calculated by taking the annual heat and electricity produced and the possible sales revenues for heat and electricity into consideration, can be compared with the total costs of energy generation. Following, minimum heat and electricity prices for an economic operation of the plant can be identified (see section 4.10).

## 4.3 General economic data

Utilisation periods and maintenance costs of the process units have been chosen according to usual depreciation periods for energy generation units and are the same for all plants compared (see Table 4.1). 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 (13 years in Austria, 10 years in Denmark), 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.

**Table 4.1:** Utilisation periods and maintenance costs for the different units of biomass CHP plants

Explanations: I...investment costs; 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] |
| **Construction** | | | | |
| Heating station, land | 25 | 1.0 | 10 | 1.0 |
| Fuel storage unit | 25 | 1.0 | 10 | 1.0 |
| Weighbridge | 25 | 1.0 | 10 | 1.0 |
| **Mechanical engineering** | | | | |
| Furnace and boiler | 15 | 2.0 | 10 | 2.0 |
| Flue gas cleaning | 15 | 2.0 | 10 | 2.0 |
| Ash container and conveyor | 15 | 2.0 | 10 | 2.0 |
| Heat recovery | 15 | 2.0 | 10 | 2.0 |
| Fuel conveyor | 15 | 2.0 | 10 | 2.0 |
| Electric installations | 15 | 2.0 | 10 | 2.0 |
| Hydraulic installations | 15 | 2.0 | 10 | 2.0 |
| Steelworks | 15 | 1.0 | 10 | 1.0 |
| CHP module | - | - | 10 | 2.0 |
| Vehicles | 8 | 3.0 | 8 | 3.0 |
| Planning | 15 | 0.0 | 10 | 0.0 |
| Other investment costs | 15 | 2.0 | 10 | 2.0 |

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

The technical data of the Danish biomass CHP plant based on a steam turbine process described in section 3.1 are shown in Table 4.2. The electric capacity of the plant is 4,700 $kW_{el}$, the nominal thermal capacity is 14,000 $kW_{th}$. The plant achieves about 5,500 annual full load operating hours, leading to a total annual electricity production of 25.9 GWh/a and a total annual heat production of 82.3 GWh/a. The useful heat sold to clients amounts to 74.0 GWh/a. The total fuel energy input amounts to 117.5 GWh/a.

As already mentioned in section 3.1.1, the existing old biomass heating plant, which acts as a stand-by and peak load system, has not been taken into account for the economic evaluation.

As shown in Table 4.3, the investment costs related to the CHP unit amounted to about 12.8 M€ or about 75% of the total investment costs. The specific investment costs amount to 2,717 €/$kW_{el}$. Investment funding has been granted in an amount of 21% of the total investment costs. Related to the investment costs for the CHP unit this amounts to a funding of about 2.6 M€. The specific investment costs could therefore be reduced to 2,158 €/$kW_{el}$.

**Table 4.2:** Technical data of the Danish biomass CHP plant based on a steam turbine process

Explanations: NCV...net calorific value; data source: Assens Fjernvarme, Denmark

| Parameter | Unit | Value |
|---|---|---|
| ***Combined heat and power plant (CHP)*** | | |
| Fuel energy input CHP (nominal conditions) | [$kW_{NCV}$] | 20,000 |
| Electric capacity CHP (nominal conditions) | [$kW_{el}$] | 4,700 |
| Useful heat capacity CHP (nominal conditions) | [$kW_{th}$] | 14,000 |
| Full load operating hours CHP | [h/a] | 5,500 |
| Annual electric efficiency | [%] | 22.0 |
| Annual total efficiency | [%] | 92.0 |
| Electrical flow index | - | 0.31 |
| Specific electricity consumption CHP (total) | [$kWh_{el}/MWh_{th}$] | 21.6 |
| Specific electricity consumption (heat related) | [$kWh_{el}/MWh_{th}$] | 17.3 |
| Total electricity consumption CHP | [$kWh_{el}/a$] | 2,339,092 |
| Electricity consumption heat related | [$kWh_{el}/a$] | 1,420,682 |
| Electricity consumption - CHP surplus | [$kWh_{el}/a$] | 918,410 |
| Electricity production | [$kWh_{el}/a$] | 25,850,000 |
| Heat production CHP | [$kWh_{th}/a$] | 82,250,000 |
| Total fuel energy input CHP | [$kWh_{NCV}/a$] | 117,500,000 |
| Fuel energy input heat related | [$kWh_{NCV}/a$] | 89,402,174 |
| Fuel energy input - CHP surplus | [$kWh_{NCV}/a$] | 28,097,826 |
| Distribution losses (network of pipes) | [%] | 10.0 |
| Useful heat (sold to clients) | [$kWh_{th}/a$] | 74,025,000 |

**Table 4.3:** Electricity related investment costs of the Danish biomass CHP plant based on a steam turbine process

Explanations: *…construction, land, weighbridge, fuel storage, credit costs ; data source: Assens Fjernvarme, Denmark

| Plant unit | Unit | Value |
|---|---|---|
| Furnace and boiler | [€] | 4,600,000 |
| Flue gas cleaning | [€] | 450,000 |
| Ash container and conveyor | [€] | 40,000 |
| Heat recovery | [€] | included |
| Fuel conveyor | [€] | 200,000 |
| Electric installations | [€] | 570,000 |
| Hydraulic installations | [€] | 20,000 |
| Steelworks | [€] | included |
| CHP module (incl. generator, grid connection, transformer) | [€] | 4,100,000 |
| Planning | [€] | 620,000 |
| Other investment costs* | [€] | 2,170,000 |
| **Investment costs CHP** | **[€]** | **12,770,000** |
| **Specific investment costs CHP** | **[€/$kW_{el}$]** | **2,717** |
| Funding | [%] | 21 |
| Funding | [€] | 2,625,411 |
| Specific investment costs CHP (with funding) | [€/$kW_{el}$] | 2,158 |

The calculation of the annual costs for electricity production as well as the specific electricity generation costs is shown in Table 4.4. The interest rate considered is comparatively low with 4.6% (compared to 6% for the plants located in Austria). The fuel price is an average price for the fuel mixture used, i.e. forest wood chips, industrial wood chips and sawdust with a water content between 5 and 55 wt.% (w.b.).

The specific additional heat generation costs of the CHP plant comprise the costs for the heat generation needed for the electricity production, apart from the fuel and capital costs, which are considered separately. Thus they include the heat generation costs caused by the consumption costs (excl. fuel), the operation costs and the other costs. They are based on practical experience of the plant operator.

**Table 4.4:** Electricity related annual costs of the Danish biomass CHP plant based on a steam turbine process

Explanations: NCV...net calorific value; I...investment costs; data source: Assens Fjernvarme, Denmark

| **Parameter** | **Unit** | **Value** |
|---|---|---|
| Interest rate | [%/a] | 4.6 |
| **Capital costs** | **[€/a]** | **1,621,802** |
| **Specific capital costs** | **[€/kWh$_{el}$]** | **0.0627** |
| Fuel price | [€/kWh$_{NCV}$] | 0.016 |
| Ash disposal costs | [€/a] | 23,913 |
| Fuel costs (incl. ash disposal) | [€/a] | 473,478 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.073 |
| Electricity costs | [€/a] | 67,044 |
| Specific additional heat generation costs CHP | [€/MWh$_{th}$] | 3.90 |
| Additional heat generation costs CHP | [€/a] | 100,815 |
| Share of general consumption costs | [(% of I$_{CHP}$)/a] | 0.9 |
| General consumption costs | [€/a] | 110,000 |
| **Consumption costs** | **[€/a]** | **751,337** |
| **Specific consumption costs** | **[€/kWh$_{el}$]** | **0.0291** |
| Hourly rate - personnel costs | [€/h] | 25.5 |
| Annual working hours CHP | [h/a] | 2,360 |
| Management CHP | [€/a] | 30,600 |
| Total personnel costs CHP | [€/a] | 90,780 |
| Maintenance costs | [€/a] | 161,275 |
| **Operation costs** | **[€/a]** | **252,055** |
| **Specific operation costs** | **[€/kWh$_{el}$]** | **0.0098** |
| Share of other costs | [(% of I$_{CHP}$)/a] | 1.1 |
| **Other costs** | **[€/a]** | **136,000** |
| **Specific other costs** | **[€/kWh$_{el}$]** | **0.0053** |
| **Total electricity generation costs** | **[€/a]** | **2,761,195** |
| **Specific electricity generation costs** | **[€/kWh$_{el}$]** | **0.1068** |
| **Specific electricity generation costs (incl. funding)** | **[€/kWh$_{el}$]** | **0.0939** |

The costs for a man-hour of work under Danish framework conditions are comparatively low. In addition, due to the fact that the plant can be operated unattended during evenings and nights, the annual working hours are comparatively low, leading to relative low personnel costs.

The capital costs (58.7%) and the consumption costs (27.2%) account together for almost 86% of the electricity generation costs. The operation costs account for about 9.1% and the other costs for about 4.9% of the electricity generation costs.

Table 4.5 shows the heat related investment costs of the plant. They amount to 4.25 M€ or about 25% of the total investment costs. As already mentioned above, the total plant has been funded with 21% of the total investment costs. Related to the heat production, this leads to a heat related investment subsidy of about 875,000 €, reducing the heat related investment costs to about 3.4 M€.

**Table 4.5:** Heat related investment costs of the Danish biomass CHP plant based on a steam turbine process

Explanations: *…cranes; data source: Assens Fjernvarme, Denmark

| **Plant unit** | **Unit** | **Value** |
|---|---|---|
| Heating station, land | [€] | 1,828,000 |
| Furnace and boiler | [€] | 300,000 |
| Flue gas cleaning | [€] | 60,000 |
| Ash container and conveyor | [€] | 80,000 |
| Heat recovery | [€] | included |
| Fuel conveyor | [€] | 600,000 |
| Electric installations | [€] | 100,000 |
| Hydraulic installations | [€] | 20,000 |
| Steelworks | [€] | included |
| Planning | [€] | 100,000 |
| Fuel storage unit | [€] | 600,000 |
| Weighbridge | [€] | 100,000 |
| Other investment costs* | [€] | 400,000 |
| Credit costs | [€] | 66,000 |
| Vehicles | [€] | included |
| **Investment costs (heat related)** | **[€]** | **4,254,000** |
| Funding | [%] | 20.6 |
| Funding | [€] | 874,589 |
| Investment costs (heat related, with funding) | [€] | 3,379,411 |

The calculation of the annual costs for heat production as well as the specific heat generation costs are shown in Table 4.6.

The consumption costs account for more than 76% of the electricity generation costs. The capital costs account for about 13.9%, the operation costs for about 7.9% and the other costs for about 1.9% of the electricity generation costs.

The specific heat generation costs ex plant amount to 0.0257 €/kWh$_{th}$ and can be reduced by approximately 2.9% to 0.0249 €/kWh$_{th}$, when the investment subsidy is taken into account.

**Table 4.6:** Heat related annual costs of the Danish biomass CHP plant based on a steam turbine process

Explanations: NCV...net calorific value; data source: Assens Fjernvarme, Denmark

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 4.6 |
| **Capital costs** | **[€/a]** | **293,482** |
| **Specific capital costs** | **[€/kWh$_{th}$]** | **0.0036** |
| Fuel price | [€/kWh$_{NCV}$] | 0.016 |
| Ash disposal costs | [€/a] | 76,087 |
| Fuel costs (incl. ash disposal) | [€/a] | 1,506,522 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.073 |
| Electricity costs | [€/a] | 103,710 |
| **Consumption costs** | **[€/a]** | **1,610,232** |
| **Specific consumption costs** | **[€/kWh$_{th}$]** | **0.0196** |
| Hourly rate - personnel costs | [€/h] | 26 |
| Annual working hours | [h/a] | 3,920 |
| Management | [€/a] | 13,114 |
| Personnel costs | [€/a] | 113,074 |
| Maintenance costs | [€/a] | 53,725 |
| **Operation costs** | **[€/a]** | **166,799** |
| **Specific operation costs** | **[€/kWh$_{th}$]** | **0.0020** |
| Share of other costs | [(% of $I_{th}$)/a] | 0.9 |
| **Other costs** | **[€/a]** | **40,000** |
| **Specific other costs** | **[€/kWh$_{th}$]** | **0.0005** |
| **Total heat generation costs** | **[€/a]** | **2,110,513** |
| **Specific heat generation costs** | **[€/kWh$_{th}$]** | **0.0257** |
| **Specific heat generation costs (incl. funding)** | **[€/kWh$_{th}$]** | **0.0249** |

Table 4.7 shows the total energy generation costs of the Danish biomass CHP plants based on a steam turbine process. They amount to 0.0451 €/kWh and can be reduced to 0.0414 €/kWh, taking the investment subsidy into account (- 8.1%). The total investment costs amount to about 17.0 M€. The annual energy generation costs amount to about 4.9 M€/a. The most important cost factors are the consumption costs, covering 48.5% of the total energy generation costs and the capital costs covering 39.3%. The operation costs and the other costs cover 8.6% and 3.6% of the total energy generation costs, respectively.

**Table 4.7:** Total energy generation costs of the Danish biomass CHP plant based on a steam turbine process

Explanations: data source: Assens Fjernvarme, Denmark

| Parameter | Unit | Value |
|---|---|---|
| Total investment costs | [€] | 17,024,000 |
| Total investment costs (incl. funding) | [€] | 13,524,000 |
| Capital costs | [€/a] | 1,915,285 |
| Specific capital costs | [€/kWh] | 0.0177 |
| Consumption costs | [€/a] | 2,361,569 |
| Specific consumption costs | [€/kWh] | 0.0218 |
| Operation costs | [€/a] | 418,854 |
| Specific operation costs | [€/kWh] | 0.0039 |
| Other costs | [€/a] | 176,000 |
| Specific other costs | [€/kWh] | 0.0016 |
| **Total energy generation costs** | **[€/a]** | **4,871,708** |
| **Specific energy generation costs** | **[€/kWh]** | **0.0451** |
| **Specific energy generation costs (incl. funding)** | **[€/kWh]** | **0.0414** |

## 4.5 Case study 2: 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 3.2 are shown in Table 4.8. The electric capacity of the plant amounts to 4,100 $kW_{el}$, the nominal thermal capacity is about 12,100 $kW_{th}$. About 6,000 annual full load operating hours can be achieved with the plant, leading to an annual electricity production of 24.6 GWh/a. The total annual heat production of the CHP plant amounts to about 80.6 GWh/a.

For mean and peak load coverage as well as a stand-by system a biomass hot water boiler will be installed. This boiler will produce in addition to the biomass CHP plant about 20.7 GWh of heat per year. The heat production of the whole plant will therefore amount to 101.3 GWh/a. Taking the distribution losses of the process heating network of about 5% into account, the useful heat sold to the clients will be about 96.3 GWh/a. This heat is utilised in drying chambers and in a belt dryer within the sawmill.

**Table 4.8:** Technical data of the Austrian biomass CHP plant based on a steam turbine process

Explanations: NCV...net calorific value; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| ***Combined heat and power plant (CHP)*** | | |
| Fuel energy input CHP (nominal conditions) | [$kW_{NCV}$] | 19,473 |
| Electric capacity CHP (nominal conditions) | [$kW_{el}$] | 4,100 |
| Useful heat capacity CHP (nominal conditions) | [$kW_{th}$] | 12,063 |
| Full load operating hours CHP | [h/a] | 6,000 |
| Annual electric efficiency | [%] | 19.4 |
| Annual total efficiency | [%] | 83.0 |
| Electrical flow index | - | 0.31 |
| Specific electricity consumption CHP (total) | [$kWh_{el}/MWh_{th}$] | 30.0 |
| Specific electricity consumption (heat related) | [$kWh_{el}/MWh_{th}$] | 13.0 |
| Total electricity consumption CHP | [$kWh_{el}$/a] | 3,157,423 |
| Electricity consumption heat related | [$kWh_{el}$/a] | 1,048,416 |
| Electricity consumption - CHP surplus | [$kWh_{el}$/a] | 2,109,006 |
| Electricity production | [$kWh_{el}$/a] | 24,600,000 |
| Heat production CHP | [$kWh_{th}$/a] | 80,647,423 |
| Total fuel energy input CHP | [$kWh_{NCV}$/a] | 126,804,124 |
| Fuel energy input heat related | [$kWh_{NCV}$/a] | 97,165,569 |
| Fuel energy input - CHP surplus | [$kWh_{NCV}$/a] | 29,638,554 |
| ***Biomass hot water boiler (HWB)*** | | |
| Fuel energy input HWB | [$kWh_{NCV}$/a] | 25,850,000 |
| Nominal boiler capacity HWB | [kW] | 8,000 |
| Heat production HWB | [kWh/a] | 20,680,000 |
| Specific electricity consumption HWB | [$kWh_{el}/MWh_{th}$] | 13.0 |
| Electricity consumption HWB | [kWh/a] | 268,840 |
| ***Whole plant (CHP, hot water boiler)*** | | |
| Fuel energy input | [$kWh_{NCV}$/a] | 152,654,124 |
| Total electricity production | [$kWh_{el}$/a] | 24,600,000 |
| Total heat production | [$kWh_{th}$/a] | 101,327,423 |
| Distribution losses (network of pipes) | [%] | 5.0 |
| Useful heat (sold to clients) | [$kWh_{th}$/a] | 96,261,052 |

The investment costs related to the electricity production amount to about 10.2 M€ or about 54.2% of the total investment costs (see Table 4.9). This leads to specific electricity related investment costs of 2,485 €/$kWh_{el}$. Investment subsidies are not granted within Austrian framework conditions for electricity related parts of biomass CHP plants (due to the increased feed-in tariffs for such plants).

**Table 4.9:** Electricity related investment costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: *…construction, land; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Plant unit | Unit | Value |
|---|---|---|
| Furnace and boiler | [€] | 4,002,900 |
| Flue gas cleaning | [€] | 426,800 |
| Ash container and conveyor | [€] | 64,900 |
| Heat recovery | [€] | 426,800 |
| Fuel conveyor | [€] | 173,800 |
| Electrics | [€] | 343,200 |
| Hydraulic installations | [€] | 523,600 |
| Steelworks | [€] | 70,400 |
| CHP module (incl. generator, grid connection, transformer) | [€] | 2,000,000 |
| Planning | [€] | 926,000 |
| Other investment costs* | [€] | 1,230,000 |
| **Investment costs CHP** | **[€]** | **10,188,400** |
| **Specific investment costs CHP** | **[€/kW$_{el}$]** | **2,485** |
| Funding | [%] | - |
| Funding | [€] | - |
| Specific investment costs CHP (with funding) | [€/kW$_{el}$] | 2,485 |

Table 4.10 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 6%, based on realistic Austrian framework conditions. The fuel price is an average price for the fuel mixture used, i.e. about 50% bark and about 50% wood chips and sawdust with a water content of about 50 wt.% (w.b) (see section 3.2.10) and includes the ash disposal costs.

The costs for man-hours of work are comparatively high (35 €/h), which is due to the fact, that steam boiler operators are required. In addition, a significantly higher number of staff is foreseen than for the Danish plant, which is partly due to the fact that the fuel transport is performed by wheel loaders.

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 factor are the capital costs, covering about 52.0% of the electricity generation costs. The consumption costs cover about 25.3%, and the operation costs about 18.9% of the electricity generation costs. The other costs are with 3.8% of the electricity generation costs of minor importance.

**Table 4.10:** Electricity related annual costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: NCV...net calorific value; I...investment costs; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 6.0 |
| **Capital costs** | **[€/a]** | **1,384,277** |
| **Specific capital costs** | **[€/kWh$_{el}$]** | **0.0563** |
| Fuel price | [€/kWh$_{NCV}$] | 0.011 |
| Ash disposal costs | [€/a] | included |
| Fuel costs (incl. ash disposal) | [€/a] | 326,024 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.080 |
| Electricity costs | [€/a] | 168,720 |
| Specific additional heat generation costs CHP | [€/MWh$_{th}$] | 3.90 |
| Additional heat generation costs CHP | [€/a] | 95,940 |
| Share of general consumption costs | [(% of I$_{CHP}$)/a] | 0.8 |
| General consumption costs | [€/a] | 81,507 |
| **Consumption costs** | **[€/a]** | **672,192** |
| **Specific consumption costs** | **[€/kWh$_{el}$]** | **0.0273** |
| Hourly rate - personnel costs | [€/h] | 35 |
| Annual working hours CHP | [h/a] | 7,884 |
| Management CHP | [€/a] | 42,000 |
| Total personnel costs CHP | [€/a] | 317,940 |
| Maintenance costs | [€/a] | 185,248 |
| **Operation costs** | **[€/a]** | **503,188** |
| **Specific operation costs** | **[€/kWh$_{el}$]** | **0.0205** |
| Share of other costs | [(% of I$_{CHP}$)/a] | 1.0 |
| **Other costs** | **[€/a]** | **101,884** |
| **Specific other costs** | **[€/kWh$_{el}$]** | **0.0041** |
| **Total electricity generation costs** | **[€/a]** | **2,661,541** |
| **Specific electricity generation costs** | **[€/kWh$_{el}$]** | **0.1082** |
| **Specific electricity generation costs (incl. funding)** | **[€/kWh$_{el}$]** | **0.1082** |

The heat related investment costs of the plant amount to about 8.6 M€ (see Table 4.11). Investment subsidies can be granted for the heat related part of the plant in an amount of up to 30%, if the plant is operated heat controlled. Costs for land, vehicles and other investments cannot be funded. This leads to an investment funding of about 2.45 M€ or 28.4% of the total heat related investment costs.

The calculation of the annual and the specific heat generation costs is shown in Table 4.12. According to this, the consumption costs account for almost 55% of the heat generation costs, followed by the capital costs covering 32% of the heat generation costs. The operation costs cover about 11% and the other costs about 2.3% of the heat generation costs.

The specific heat generation costs ex plant amount to 0.0262 €/kWh$_{th}$. Taking the investment subsidy into account, they can be reduced by 9.1% to 0.0239 €/kWh$_{th}$.

**Table 4.11:** Heat related investment costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: *…crane; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Plant unit | Unit | Value |
|---|---|---|
| Heating station, land | [€] | 1,577,000 |
| Furnace and boiler | [€] | 2,545,750 |
| Flue gas cleaning | [€] | 747,150 |
| Ash container and conveyor | [€] | 162,350 |
| Heat recovery | [€] | 90,950 |
| Fuel conveyor | [€] | 520,200 |
| Electric installations | [€] | 1,018,300 |
| Hydraulic installations | [€] | 711,450 |
| Steelworks | [€] | 387,600 |
| Planning | [€] | 564,253 |
| Fuel storage unit | [€] | included |
| Other investment costs* | [€] | 300,000 |
| **Investment costs (heat related)** | **[€]** | **8,625,003** |
| Funding | [%] | 28.4 |
| Funding | [€] | 2,452,501 |
| Investment costs (heat related, with funding) | [€] | 6,172,502 |

**Table 4.12:** Heat related annual costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: NCV...net calorific value; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 6.0 |
| **Capital costs** | **[€/a]** | **849,045** |
| **Specific capital costs** | **[€/kWh$_{th}$]** | **0.0084** |
| Fuel price | [€/kWh$_{NCV}$] | 0.011 |
| Ash disposal costs | [€/a] | included |
| Fuel costs (incl. ash disposal) | [€/a] | 1,353,171 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.080 |
| Electricity costs | [€/a] | 105,381 |
| **Consumption costs** | **[€/a]** | **1,458,552** |
| **Specific consumption costs** | **[€/kWh$_{th}$]** | **0.0144** |
| Hourly rate - personnel costs | [€/h] | 30 |
| Annual working hours | [h/a] | 4,380 |
| Management | [€/a] | 18,000 |
| Personnel costs | [€/a] | 149,400 |
| Maintenance costs | [€/a] | 141,569 |
| **Operation costs** | **[€/a]** | **290,969** |
| **Specific operation costs** | **[€/kWh$_{th}$]** | **0.0029** |
| Share of other costs | [(% of I$_{th}$)/a] | 0.7 |
| **Other costs** | **[€/a]** | **60,375** |
| **Specific other costs** | **[€/kWh$_{th}$]** | **0.0006** |
| **Total heat generation costs** | **[€/a]** | **2,658,941** |
| **Specific heat generation costs** | **[€/kWh$_{th}$]** | **0.0262** |
| **Specific heat generation costs (incl. funding)** | **[€/kWh$_{th}$]** | **0.0239** |

**Table 4.13:** Total energy generation costs of the Austrian biomass CHP plant based on a steam turbine process

Explanations: data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Total investment costs | [€] | 18,813,403 |
| Total investment costs (incl. funding) | [€] | 16,360,902 |
| Capital costs | [€/a] | 2,233,322 |
| Specific capital costs | [€/kWh] | 0.0177 |
| Consumption costs | [€/a] | 2,130,744 |
| Specific consumption costs | [€/kWh] | 0.0169 |
| Operation costs | [€/a] | 794,157 |
| Specific operation costs | [€/kWh] | 0.0063 |
| Other costs | [€/a] | 162,259 |
| Specific other costs | [€/kWh] | 0.0013 |
| **Total energy generation costs** | **[€/a]** | **5,320,482** |
| **Specific energy generation costs** | **[€/kWh]** | **0.0423** |
| **Specific energy generation costs (incl. funding)** | **[€/kWh]** | **0.0403** |

The total energy generation costs of the Austrian biomass CHP plant based on a steam turbine process are shown in Table 4.13. The total investment costs of the plant amount to about 18.8 M€. The annual energy generation costs amount to about 5.3 M€/a, the specific energy generation costs to 0.0423 €/kWh. They can be reduced to 0.0403 €/kWh, taking the investment subsidy into consideration (- 4.5%). The most important cost factors are the capital costs and the consumption costs, each covering about 41% of the energy generation costs. The operation costs cover about 15% and the other costs about 3% of the energy generation costs.

## 4.6 Case study 3: Biomass CHP plant based on an ORC process (Austria)

Table 4.14 shows the technical data of the biomass CHP plant based on an ORC process located in Austria. The plant has already been described in section 3.3. About 5,000 annual full load operating hours can be achieved with the plant. Based on a electric capacity of 1,100 $kW_{el}$, this leads to an annual electricity production of about 5.5 GWh/a. The heat production of the CHP plant amounts to about 27.9 GWh/a.

A hot water boiler has been installed covering the middle load range of the plant. Moreover, for peak load coverage and as a stand-by system two oil boilers have been installed. The heat produced from these boilers amounts to about 34.3 GWh/a, 31.8 GWh/a from the hot water boiler and about 2.5 GWh/a from the peak load boilers. The total heat production of the plant therefore amounts to about 62.2 GWh/a. The distribution losses of the district heating network are about 13%, which leads to a useful heat sold to the clients of about 54.1 GWh/a. This heat is utilised as district heat.

ORC based biomass CHP plants are innovative applications which are especially suitable for small-scale systems with a nominal electric capacity below 1.5 MW. They still show comparatively high investment costs, because no serial production has yet been achieved, but are very cheap concerning operation costs, because no steam boiler operators are needed and very low maintenance is required.

**Table 4.14:** Technical data of the Austrian biomass CHP plant based on an ORC process

Explanations: NCV...net calorific value; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| ***Combined heat and power plant (CHP)*** | | |
| Fuel energy input CHP (nominal conditions) | [$kW_{NCV}$] | 6,897 |
| Electric capacity CHP (nominal conditions) | [$kW_{el}$] | 1,100 |
| Useful heat capacity CHP (nominal conditions) | [$kW_{th}$] | 4,969 |
| Full load operating hours CHP | [h/a] | 5,000 |
| Annual electric efficiency | [%] | 14.5 |
| Annual total efficiency | [%] | 88.0 |
| Electrical flow index | - | 0.20 |
| Specific electricity consumption CHP (total) | [$kWh_{el}/MWh_{th}$] | 27.0 |
| Specific electricity consumption (heat related) | [$kWh_{el}/MWh_{th}$] | 13.0 |
| Total electricity consumption CHP | [$kWh_{el}/a$] | 901,241 |
| Electricity consumption heat related | [$kWh_{el}/a$] | 362,431 |
| Electricity consumption - CHP surplus | [$kWh_{el}/a$] | 538,810 |
| Electricity production | [$kWh_{el}/a$] | 5,500,000 |
| Heat production CHP | [$kWh_{th}/a$] | 27,879,310 |
| Total fuel energy input CHP | [$kWh_{NCV}/a$] | 37,931,034 |
| Fuel energy input heat related | [$kWh_{NCV}/a$] | 31,681,034 |
| Fuel energy input - CHP surplus | [$kWh_{NCV}/a$] | 6,250,000 |
| ***Biomass hot water boiler (HWB)*** | | |
| Fuel energy input HWB | [$kWh_{NCV}/a$] | 36,164,106 |
| Nominal boiler capacity HWB | [kW] | 7,000 |
| Heat production HWB | [kWh/a] | 31,824,413 |
| Specific electricity consumption HWB | [$kWh_{el}/MWh_{th}$] | 13.0 |
| Electricity consumption HWB | [kWh/a] | 413,717 |
| ***Peak load boiler (PLB)*** | | |
| Nominal boiler capacity PLB | [kW] | 18,000 |
| Heat production PLB | [$kWh_{th}/a$] | 2,487,655 |
| ***Whole plant (CHP, hot water boiler and peak load boiler)*** | | |
| Fuel energy input | [$kWh_{NCV}/a$] | 74,095,141 |
| Total electricity production | [$kWh_{el}/a$] | 5,500,000 |
| Total heat production | [$kWh_{th}/a$] | 62,191,379 |
| Distribution losses (network of pipes) | [%] | 13.0 |
| Useful heat (sold to clients) | [$kWh_{th}/a$] | 54,106,500 |

The electricity related investment costs are shown in Table 4.15. They amount to about 3.0 M€ and cover about 33% of the total investment costs. The specific investment costs amount to 2,704 €/$kW_{el}$. Investment subsidies are not granted within Austrian framework conditions for electricity related parts of biomass CHP plants (due to the increased feed-in tariffs for such plants).

**Table 4.15:** Electricity related investment costs of the Austrian biomass CHP plant based on an ORC process

Explanations: *…building, land; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Plant unit | Unit | Value |
|---|---|---|
| Furnace and boiler | [€] | 695,000 |
| Flue gas cleaning | [€] | 35,000 |
| Ash container and conveyor | [€] | included |
| Heat recovery | [€] | included |
| Fuel conveyor | [€] | included |
| Electric installations | [€] | 175,000 |
| Hydraulic installations | [€] | 98,000 |
| Steelworks | [€] | included |
| CHP module (incl. generator, grid connection, transformer) | [€] | 1,335,000 |
| Planning | [€] | 270,000 |
| Other investment costs* | [€] | 366,000 |
| **Investment costs CHP** | **[€]** | **2,974,000** |
| **Specific investment costs CHP** | **[€/$kW_{el}$]** | **2,704** |
| Funding | [%] | - |
| Funding | [€] | - |
| Specific investment costs CHP (with funding) | [€/$kW_{el}$] | 2,704 |

The calculation of the annual and specific electricity generation costs is shown in Table 4.16. The interest rate chosen with 6% p.a. is based on realistic Austrian framework conditions. The fuel price of 0.015 €/kWh is an average price for the fuel mixture used (see section 3.3.10) and includes the ash disposal costs.

The costs for man-hours of work are lower (30 €/h) compared to the steam turbine process described in section 3.2, because no steam boiler operators are needed to operate the plant. 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.

As the electricity related part of the CHP plant is not eligible under Austrian framework conditions, no reduction of the specific electricity generation costs by funding is possible.

The most important cost factor are the capital costs covering about 58.9% of the electricity generation costs, followed by the consumption costs covering about 24.6%. The operation costs cover 12.2% and the other costs cover 4.3% of the electricity generation costs.

**Table 4.16:** Electricity related annual costs of the Austrian biomass CHP plant based on an ORC process

Explanations: NCV...net calorific value; I...investment costs; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 6.0 |
| **Capital costs** | **[€/a]** | **404,071** |
| **Specific capital costs** | **[€/kWh$_{el}$]** | **0.0735** |
| Fuel price | [€/kWh$_{NCV}$] | 0.015 |
| Ash disposal costs | [€/a] | included |
| Fuel costs (incl. ash disposal) | [€/a] | 93,750 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.080 |
| Electricity costs | [€/a] | 43,105 |
| Specific additional heat generation costs CHP | [€/MWh$_{th}$] | 4.70 |
| Additional heat generation costs CHP | [€/a] | 25,850 |
| Share of general consumption costs | [(% of $I_{CHP}$)/a] | 0.2 |
| General consumption costs | [€/a] | 5,948 |
| **Consumption costs** | **[€/a]** | **168,653** |
| **Specific consumption costs** | **[€/kWh$_{el}$]** | **0.0307** |
| Hourly rate - personnel costs | [€/h] | 30 |
| Annual working hours CHP | [h/a] | 800 |
| Management CHP | [€/a] | 5,918 |
| Total personnel costs CHP | [€/a] | 29,918 |
| Maintenance costs | [€/a] | 54,080 |
| **Operation costs** | **[€/a]** | **83,998** |
| **Specific operation costs** | **[€/kWh$_{el}$]** | **0.0153** |
| Share of other costs | [(% of $I_{CHP}$)/a] | 1.0 |
| **Other costs** | **[€/a]** | **29,740** |
| **Specific other costs** | **[€/kWh$_{el}$]** | **0.0054** |
| **Total electricity generation costs** | **[€/a]** | **686,463** |
| **Specific electricity generation costs** | **[€/kWh$_{el}$]** | **0.1248** |
| **Specific electricity generation costs (incl. funding)** | **[€/kWh$_{el}$]** | **0.1248** |

Table 4.17 shows the heat related investment costs of the plant, amounting to almost 6.0 M€. For heat controlled CHP plants an investment subsidy can be granted for the heat related part of the plant of up to 30% (except the costs for land of about 593,000 €, for vehicles of about 213,000 € and other costs of about 139,000 €). This leads to an investment subsidy of about 1.5 M€ or 25.3% of the total heat related investment costs, reducing the heat related investment costs to about 4.5 M€.

**Table 4.17:** Heat related investment costs of the Austrian biomass CHP plant based on an ORC process

Explanations: *…crane; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Plant unit | Unit | Value |
|---|---|---|
| Heating station, land | [€] | 2,163,223 |
| Furnace and boiler | [€] | 2,697,817 |
| Flue gas cleaning | [€] | included |
| Ash container and conveyor | [€] | included |
| Heat recovery | [€] | included |
| Fuel conveyor | [€] | included |
| Electric installations | [€] | 381,770 |
| Hydraulic installations | [€] | included |
| Steelworks | [€] | included |
| Planning | [€] | 391,598 |
| Fuel storage unit | [€] | included |
| Other investment costs* | [€] | 138,758 |
| Vehicles | [€] | 212,685 |
| **Investment costs (heat related)** | **[€]** | **5,985,850** |
| Funding | [%] | 25.3 |
| Funding | [€] | 1,512,517 |
| Investment costs (heat related, with funding) | [€] | 4,473,333 |

Table 4.18 shows the calculation of the annual and specific heat generation costs. It can be seen, that the most important cost factors are the consumption costs covering more than 55% of the heat generation costs and the capital costs covering almost 30%. The operation costs cover almost 13% and the other costs about 2.2% of the heat generation costs.

The specific heat generation costs of 0.0313 €/kWh$_{th}$ can be reduced by approximately 7.5% to 0.0290 €/kWh$_{th}$ by taking the investment subsidy into account.

Table 4.19 shows the total investment costs for the Austrian biomass CHP plant based on an ORC process to be about 9.0 M€ and the annual energy generation costs to be about 2.6 M€/a. The specific energy generation costs amount to 0.0389 €/kWh. They can be decreased by about 5.5% to 0.0368 €/kWh, when the investment subsidy is taken into consideration. The most important cost factors are the consumption costs covering more than 47% of the energy generation costs followed by the capital costs covering about 37%. The operation costs cover about 13% and the other costs about 2.7% of the energy generation costs.

**Table 4.18:** Heat related annual costs of the Austrian biomass CHP plant based on an ORC process

Explanations: NCV…net calorific value; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 6.0 |
| **Capital costs** | **[€/a]** | **575,161** |
| **Specific capital costs** | **[€/kWh$_{th}$]** | **0.0092** |
| Fuel price | [€/kWh$_{NCV}$] | 0.015 |
| Ash disposal costs | [€/a] | included |
| Fuel costs (incl. ash disposal) | [€/a] | 1,017,677 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.080 |
| Electricity costs | [€/a] | 62,092 |
| **Consumption costs** | **[€/a]** | **1,079,769** |
| **Specific consumption costs** | **[€/kWh$_{th}$]** | **0.0174** |
| Hourly rate - personnel costs | [€/h] | 30 |
| Annual working hours | [h/a] | 4,456 |
| Management | [€/a] | 24,082 |
| Personnel costs | [€/a] | 157,762 |
| Maintenance costs | [€/a] | 92,380 |
| **Operation costs** | **[€/a]** | **250,141** |
| **Specific operation costs** | **[€/kWh$_{th}$]** | **0.0040** |
| Share of other costs | [(% of $I_{th}$)/a] | 0.7 |
| **Other costs** | **[€/a]** | **41,901** |
| **Specific other costs** | **[€/kWh$_{th}$]** | **0.0007** |
| **Total heat generation costs** | **[€/a]** | **1,946,973** |
| **Specific heat generation costs** | **[€/kWh$_{th}$]** | **0.0313** |
| **Specific heat generation costs (incl. funding)** | **[€/kWh$_{th}$]** | **0.0290** |

**Table 4.19:** Total energy generation costs of the Austrian biomass CHP plant based on an ORC process

Explanations: data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Total investment costs | [€] | 8,959,850 |
| Total investment costs (incl. funding) | [€] | 7,447,333 |
| Capital costs | [€/a] | 979,233 |
| Specific capital costs | [€/kWh] | 0.0145 |
| Consumption costs | [€/a] | 1,248,422 |
| Specific consumption costs | [€/kWh] | 0.0184 |
| Operation costs | [€/a] | 334,140 |
| Specific operation costs | [€/kWh] | 0.0049 |
| Other costs | [€/a] | 71,641 |
| Specific other costs | [€/kWh] | 0.0011 |
| **Total energy generation costs** | **[€/a]** | **2,633,435** |
| **Specific energy generation costs** | **[€/kWh]** | **0.0389** |
| **Specific energy generation costs (incl. funding)** | **[€/kWh]** | **0.0368** |

## 4.7 Case study 4: Biomass CHP plant based on a Stirling engine (Austria)

The technical data of the Austrian biomass CHP plant based on a Stirling engine, which has already been described in section 3.4, are shown in Table 4.20. The Stirling engine has a electric capacity of 70 $kW_{el}$. The annual full load operating hours of approximately 5,400 h p.a. lead to an annual electricity production of about 376 MWh/a. The annual heat production of the CHP plant amounts to about 2.7 GWh/a.

**Table 4.20:** Technical data of the Austrian biomass CHP plant based on a Stirling engine

Explanations: NCV...net calorific value; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| ***Combined heat and power plant (CHP)*** | | |
| Fuel energy input CHP (nominal conditions) | [$kW_{NCV}$] | 635 |
| Electric capacity CHP (nominal conditions) | [$kW_{el}$] | 70 |
| Useful heat capacity CHP (nominal conditions) | [$kW_{th}$] | 500 |
| Full load operating hours CHP | [h/a] | 5,367 |
| Annual electric efficiency | [%] | 10.6 |
| Annual total efficiency | [%] | 86.0 |
| Electrical flow index | - | 0.14 |
| Specific electricity consumption CHP (total) | [$kWh_{el}/MWh_{th}$] | 20.0 |
| Specific electricity consumption (heat related) | [$kWh_{el}/MWh_{th}$] | 13.0 |
| Total electricity consumption CHP | [$kWh_{el}$/a] | 60,961 |
| Electricity consumption heat related | [$kWh_{el}$/a] | 34,741 |
| Electricity consumption - CHP surplus | [$kWh_{el}$/a] | 26,220 |
| Electricity production | [$kWh_{el}$/a] | 375,690 |
| Heat production CHP | [$kWh_{th}$/a] | 2,672,361 |
| Total fuel energy input CHP | [$kWh_{NCV}$/a] | 3,544,245 |
| Fuel energy input heat related | [$kWh_{NCV}$/a] | 3,107,396 |
| Fuel energy input - CHP surplus | [$kWh_{NCV}$/a] | 436,849 |
| ***Biomass hot water boiler (HWB)*** | | |
| Fuel energy input HWB | [$kWh_{NCV}$/a] | 4,594,929 |
| Nominal boiler capacity HWB | [kW] | 2,500 |
| Heat production HWB | [kWh/a] | 3,951,639 |
| Specific electricity consumption HWB | [$kWh_{el}/MWh_{th}$] | 13.0 |
| Electricity consumption HWB | [kWh/a] | 51,371 |
| ***Peak load boiler (PLB)*** | | |
| Nominal boiler capacity PLB | [kW] | 800 |
| Heat production PLB | [$kWh_{th}$/a] | 276,000 |
| ***Whole plant (CHP, hot water boiler and peak load boiler)*** | | |
| Fuel energy input | [$kWh_{NCV}$/a] | 8,139,174 |
| Total electricity production | [$kWh_{el}$/a] | 375,690 |
| Total heat production | [$kWh_{th}$/a] | 6,900,000 |
| Distribution losses (network of pipes) | [%] | 23.2 |
| Useful heat (sold to clients) | [$kWh_{th}$/a] | 5,299,200 |

A biomass hot water boiler is installed to cover the middle load range of the plant and produces about 4.0 GWh/a. The peak load oil boiler installed produces about 276 MWh of heat per year. This results in a total annual heat production of about 6.9 GWh/a. The distribution losses are comparatively high with 23.2%, leading to an annual useful heat sold to the clients of about 5.3 GWh/a. The whole heat produced is utilised as district heat.

The economic data derived for this plant are data taken from a demonstration project which will cover the first biomass CHP plant based on a 8 cylinder Stirling engine for commercial operation. Following, the investment costs are high due to the fact that no serial production is yet achieved, which is essential for the future development of this micro-CHP technology. Regarding operation, Stirling engine based CHP plants can be operated fully automatic, which keeps the demand for personnel low.

The electricity related investment costs shown in Table 4.21 amount to about 245,000 € and account for about 11% of the total investment costs. The specific investment costs amount to about 3,500 €/kW$_{el}$.

Usually no funding for CHP related investments is granted in Austria due to the increased feed-in tariffs for green electricity. For this plant a special funding of 100,000 € was granted due to the fact that it is the first demonstration unit of this kind. This is equal to an investment subsidy of about 41% of the total electricity related investment costs, reducing the specific investment costs to about 2,070 €/kW$_{el}$.

**Table 4.21:** Electricity related investment costs of the Austrian biomass CHP plant based on a Stirling engine

Explanations: data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| **Plant unit** | **Unit** | **Value** |
|---|---|---|
| Furnace and boiler | [€] | 32,000 |
| Flue gas cleaning | [€] | included |
| Ash container and conveyor | [€] | included |
| Heat recovery | [€] | 7,500 |
| Fuel conveyor | [€] | included |
| Electric installations | [€] | 7,500 |
| Hydraulic installations | [€] | 5,000 |
| Steelworks | [€] | included |
| CHP module (incl. generator, grid connection, transformer) | [€] | 140,000 |
| Planning | [€] | 18,200 |
| Other investment costs* | [€] | 35,000 |
| **Investment costs CHP** | **[€]** | **245,200** |
| **Specific investment costs CHP** | **[€/kW$_{el}$]** | **3,503** |
| Funding | [%] | 41 |
| Funding | [€] | 100,000 |
| Specific investment costs CHP (with funding) | [€/kW$_{el}$] | 2,074 |

Table 4.22 shows the calculation of the annual and specific electricity generation costs. The interest rate chosen is based on realistic Austrian framework conditions. The fuel price is an average price for the fuel mixture used (see section 3.4.10) and includes the ash disposal costs.

The costs for man-hours of work are comparatively low (25 €/h), which is realistic for plants of this kind and size, as no steam boiler operators and no permanent staff is required. The annual working hours are low as unattended operation is possible and the work to be done is confined to ongoing maintenance and supervision of the plant mainly.

As this biomass CHP plant is embedded in a bigger utility and the plant is comparatively small, no management costs have been taken into account for this plant.

The main cost factor are the capital costs, accounting for 58.4% of the electricity generation costs. The consumption costs and operation costs are in about the same range, covering each about 19% of the electricity generation costs. The other costs account for about 3% of the electricity generation costs.

The specific electricity generation costs of 0.1418 €/kWh$_{el}$ can be reduced by more than 25% to 0.1057 €/kWh$_{el}$ by taking the special investment subsidy granted for this plant into account.

**Table 4.22:** Electricity related annual costs of the Austrian biomass CHP plant based on a Stirling engine

Explanations: NCV...net calorific value; I...investment costs; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 6.0 |
| **Capital costs** | **[€/a]** | **33,315** |
| **Specific capital costs** | **[€/kWh$_{el}$]** | **0.0887** |
| Fuel price | [€/kWh$_{NCV}$] | 0.013 |
| Ash disposal costs | [€/a] | included |
| Fuel costs (incl. ash disposal) | [€/a] | 5,679 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.130 |
| Electricity costs | [€/a] | 3,396 |
| Specific additional heat generation costs CHP | [€/MWh$_{th}$] | 3.73 |
| Additional heat generation costs CHP | [€/a] | 1,401 |
| Share of general consumption costs | [(% of I$_{CHP}$)/a] | 0.3 |
| General consumption costs | [€/a] | 736 |
| **Consumption costs** | **[€/a]** | **11,211** |
| **Specific consumption costs** | **[€/kWh$_{el}$]** | **0.0298** |
| Hourly rate - personnel costs | [€/h] | 25 |
| Annual working hours CHP | [h/a] | 100 |
| Management CHP | [€/a] | 0 |
| Total personnel costs CHP | [€/a] | 2,500 |
| Maintenance costs | [€/a] | 4,540 |
| **Operation costs** | **[€/a]** | **7,040** |
| **Specific operation costs** | **[€/kWh$_{el}$]** | **0.0187** |
| Share of other costs | [(% of I$_{CHP}$)/a] | 0.7 |
| **Other costs** | **[€/a]** | **1,716** |
| **Specific other costs** | **[€/kWh$_{el}$]** | **0.0046** |
| **Total electricity generation costs** | **[€/a]** | **53,283** |
| **Specific electricity generation costs** | **[€/kWh$_{el}$]** | **0.1418** |
| **Specific electricity generation costs (incl. funding)** | **[€/kWh$_{el}$]** | **0.1057** |

The heat related investment costs amount to about 1.9 M€ (see Table 4.23). As the biomass hot water boiler of this plant is an existing unit, which has been funded with 50% of the investment costs when it has been built (early 90´s), this higher percentage has been taken into account (different from the newly erected Austrian plants investigated in the previous sections where heat related funding is limited to 30% of the total heat related investment costs). This results in a total funding of about 968,000 €, which reduces the heat related investment costs to about 968,000 €.

**Table 4.23:** Heat related investment costs of the Austrian biomass CHP plant based on a Stirling engine

Explanations: data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Plant unit | Unit | Value |
|---|---|---|
| Heating station, land | [€] | 440,000 |
| Furnace and boiler | [€] | 1,308,000 |
| Flue gas cleaning | [€] | included |
| Ash container and conveyor | [€] | 17,000 |
| Heat recovery | [€] | 22,500 |
| Fuel conveyor | [€] | 30,000 |
| Electric installations | [€] | 7,500 |
| Hydraulic installations | [€] | 20,000 |
| Steelworks | [€] | included |
| Planning | [€] | 41,210 |
| Fuel storage unit | [€] | included |
| Other investment costs* | [€] | 50,000 |
| Vehicles | [€] | included |
| **Investment costs (heat related)** | **[€]** | **1,936,210** |
| Funding | [%] | 50.0 |
| Funding | [€] | 968,105 |
| Investment costs (heat related, with funding) | [€] | 968,105 |

The calculation of the annual and specific heat generation costs is shown in Table 4.24. It can be seen, that the capital costs are comparatively high, covering more than 53% of the heat generation costs. The consumption costs are also of great relevance, covering almost 32% of the heat generation costs. The operation costs and the other costs are of minor importance for the heat generation costs, covering 11.3% and 3.8%, respectively.

The investment subsidy granted for the plant leads to a decrease of the specific heat generation costs from 0.0512 €/kWh$_{th}$ to 0.0375 €/kWh$_{th}$ (- 26.7%).

The total energy generation costs of the Austrian biomass CHP plant based on a Stirling engine are shown in Table 4.25. The total investment costs of the plant amount to about 2.2 M€ and the annual energy generation costs to about 406,000 €/a. The specific energy generation costs amount to 0.0558 €/kWh, which can be decreased to 0.0410 €/kWh (- 26.5%), taking the investment subsidies granted into account. The most important cost factor for the energy generation costs are the capital costs, accounting for almost 55% of the costs. The consumption costs account for slightly more than 30% of the energy generation costs. The operation costs are with 11.5% and the other costs with 3.8% of the energy generation costs of minor importance.

**Table 4.24:** Heat related annual costs of the Austrian biomass CHP plant based on a Stirling engine

Explanations: NCV...net calorific value; data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Interest rate | [%/a] | 6.0 |
| **Capital costs** | **[€/a]** | **188,474** |
| **Specific capital costs** | **[€/kWh$_{th}$]** | **0.0273** |
| Fuel price | [€/kWh$_{NCV}$] | 0.013 |
| Ash disposal costs | [€/a] | included |
| Fuel costs (incl. ash disposal) | [€/a] | 100,130 |
| Electricity price (own needs) | [€/kWh$_{el}$] | 0.130 |
| Electricity costs | [€/a] | 11,152 |
| **Consumption costs** | **[€/a]** | **111,282** |
| **Specific consumption costs** | **[€/kWh$_{th}$]** | **0.0161** |
| Hourly rate - personnel costs | [€/h] | 25 |
| Annual working hours | [h/a] | 250 |
| Management | [€/a] | 0 |
| Personnel costs | [€/a] | 6,250 |
| Maintenance costs | [€/a] | 33,500 |
| **Operation costs** | **[€/a]** | **39,750** |
| **Specific operation costs** | **[€/kWh$_{th}$]** | **0.0058** |
| Share of other costs | [(% of $I_{th}$)/a] | 0.7 |
| **Other costs** | **[€/a]** | **13,553** |
| **Specific other costs** | **[€/kWh$_{th}$]** | **0.0020** |
| **Total heat generation costs** | **[€/a]** | **353,059** |
| **Specific heat generation costs** | **[€/kWh$_{th}$]** | **0.0512** |
| **Specific heat generation costs (incl. funding)** | **[€/kWh$_{th}$]** | **0.0375** |

**Table 4.25:** Total energy generation costs of the Austrian biomass CHP plant based on a Stirling engine

Explanations: data source: BIOS BIOENERGIESYSTEME GmbH, Graz, Austria

| Parameter | Unit | Value |
|---|---|---|
| Total investment costs | [€] | 2,181,410 |
| Total investment costs (incl. funding) | [€] | 1,113,305 |
| Capital costs | [€/a] | 221,788 |
| Specific capital costs | [€/kWh] | 0.0305 |
| Consumption costs | [€/a] | 122,493 |
| Specific consumption costs | [€/kWh] | 0.0168 |
| Operation costs | [€/a] | 46,790 |
| Specific operation costs | [€/kWh] | 0.0064 |
| Other costs | [€/a] | 15,270 |
| Specific other costs | [€/kWh] | 0.0021 |
| **Total energy generation costs** | **[€/a]** | **406,342** |
| **Specific energy generation costs** | **[€/kWh]** | **0.0558** |
| **Specific energy generation costs (incl. funding)** | **[€/kWh]** | **0.0410** |

## 4.8 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 4.26. The electric capacity of the CHP plants ranges from 70 to 4,700 $kW_{el}$, covering the most relevant capacity range for decentralised biomass CHP plants. The thermal capacities of the CHP units range from 500 to 14,000 $kW_{th}$. The annual total efficiencies of the CHP plants investigated vary between 83% and 92%, the annual electric efficiencies increase with increasing electric capacities from 10.6% to 22.0%.

**Table 4.26:** Technical data of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; NCV…net calorific value

| Parameter | Unit | STE-A | ORC-A | ST-A | ST-DK |
|---|---|---|---|---|---|
| ***Combined heat and power plant (CHP)*** | | | | | |
| Fuel energy input CHP (nominal conditions) | [$kW_{NCV}$] | 635 | 6,897 | 19,473 | 20,000 |
| Electric capacity CHP (nominal conditions) | [$kW_{el}$] | 70 | 1,100 | 4,100 | 4,700 |
| Useful heat capacity CHP (nominal conditions) | [$kW_{th}$] | 500 | 4,969 | 12,063 | 14,000 |
| Full load operating hours CHP | [h/a] | 5,367 | 5,000 | 6,000 | 5,500 |
| Annual electric efficiency | [%] | 10.6 | 14.5 | 19.4 | 22.0 |
| Annual total efficiency | [%] | 86.0 | 88.0 | 83.0 | 92.0 |
| Electrical flow index | - | 0.14 | 0.20 | 0.31 | 0.31 |
| Specific electricity consumption CHP (total) | [$kWh_{el}/MWh_{th}$] | 20.0 | 27.0 | 30.0 | 21.6 |
| Specific electricity consumption (heat related) | [$kWh_{el}/MWh_{th}$] | 13.0 | 13.0 | 13.0 | 17.3 |
| Total electricity consumption CHP | [$kWh_{el}$/a] | 60,961 | 901,241 | 3,157,423 | 2,339,092 |
| Electricity consumption heat related | [$kWh_{el}$/a] | 34,741 | 362,431 | 1,048,416 | 1,420,682 |
| Electricity consumption - CHP surplus | [$kWh_{el}$/a] | 26,220 | 538,810 | 2,109,006 | 918,410 |
| Electricity production | [$kWh_{el}$/a] | 375,690 | 5,500,000 | 24,600,000 | 25,850,000 |
| Heat production CHP | [$kWh_{th}$/a] | 2,672,361 | 27,879,310 | 80,647,423 | 82,250,000 |
| Total fuel energy input CHP | [$kWh_{NCV}$/a] | 3,544,245 | 37,931,034 | 126,804,124 | 117,500,000 |
| Fuel energy input heat related | [$kWh_{NCV}$/a] | 3,107,396 | 31,681,034 | 97,165,569 | 89,402,174 |
| Fuel energy input - CHP surplus | [$kWh_{NCV}$/a] | 436,849 | 6,250,000 | 29,638,554 | 28,097,826 |
| ***Biomass hot water boiler (HWB)*** | | | | | |
| Fuel energy input HWB | [$kWh_{NCV}$/a] | 4,594,929 | 36,164,106 | 25,850,000 | - |
| Nominal boiler capacity HWB | [kW] | 2,500 | 7,000 | 8,000 | - |
| Heat production HWB | [kWh/a] | 3,951,639 | 31,824,413 | 20,680,000 | - |
| Specific electricity consumption HWB | [$kWh_{el}/MWh_{th}$] | 13.0 | 13.0 | 13.0 | - |
| Electricity consumption HWB | [kWh/a] | 51,371 | 413,717 | 268,840 | - |
| ***Peak load boiler (PLB)*** | | | | | |
| Nominal boiler capacity PLB | [kW] | 800 | 18,000 | - | - |
| Heat production PLB | [$kWh_{th}$/a] | 276,000 | 2,487,655 | - | - |
| ***Whole plant (CHP, hot water boiler and peak load boiler)*** | | | | | |
| Fuel energy input | [$kWh_{NCV}$/a] | 8,139,174 | 74,095,141 | 152,654,124 | 117,500,000 |
| Total electricity production | [$kWh_{el}$/a] | 375,690 | 5,500,000 | 24,600,000 | 25,850,000 |
| Total heat production | [$kWh_{th}$/a] | 6,900,000 | 62,191,379 | 101,327,423 | 82,250,000 |
| Distribution losses (network of pipes) | [%] | 23.2 | 13.0 | 5.0 | 10.0 |
| Useful heat (sold to clients) | [$kWh_{th}$/a] | 5,299,200 | 54,106,500 | 96,261,052 | 74,025,000 |

The biomass CHP unit covers the base load in all system. Mean and peak thermal load are covered by a second biomass hot water boiler or a combination of a biomass hot water boiler and an oil-fired boiler. For the Danish CHP plant the hot water boiler has not been considered in Table 4.26, because it is an old system which is already paid off. Taking all these boilers and the heat distribution into consideration, between 5.3 and 96.3 GWh/a of heat are produced by the plants investigated. The annual electricity production of the biomass CHP plants investigated varies between 376 $MWh_{el}$/a and almost 26 $GWh_{el}$/a. The annual full load operation hours of the CHP units vary between 5,000 and 6,000 hours per year. The specific electricity consumption of the CHP plants varies between 20 and 30 $kWh_{el}/MWh_{th}$ leading to an electricity consumption (auxiliary energy) between 9.0 and 16.4 % of the overall electricity production.

Figure 4.1 and Figure 4.2 show the absolute and relative investment costs of the biomass CHP plants investigated. The highest investment costs with almost 19 M€ are shown by the Austrian plant based on a steam turbine process (ST-A). The biomass CHP plant based on a Stirling engine shows the lowest investment costs with 2.2 M€ (STE-A). As the plants compared have different electricity and heat capacities, 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 maximum investment subsidy granted for the heat related part of the plant (except land, vehicles and other costs) amounts to 30%, if the plant is operated heat controlled. For the Stirling engine based biomass CHP plant, however, a special funding of 100,000 € was granted due to the fact that it is the first demonstration unit of this kind. Related to the total investment costs, this leads to investment subsidies between 13.0% and 49.0% for the Austrian plants investigated. In Denmark, investment subsidies are granted for the whole plant, therefore both electricity and heat related funding are shown in the figures, which amounts to about 20.6% of the total investment costs for the case studies investigated.

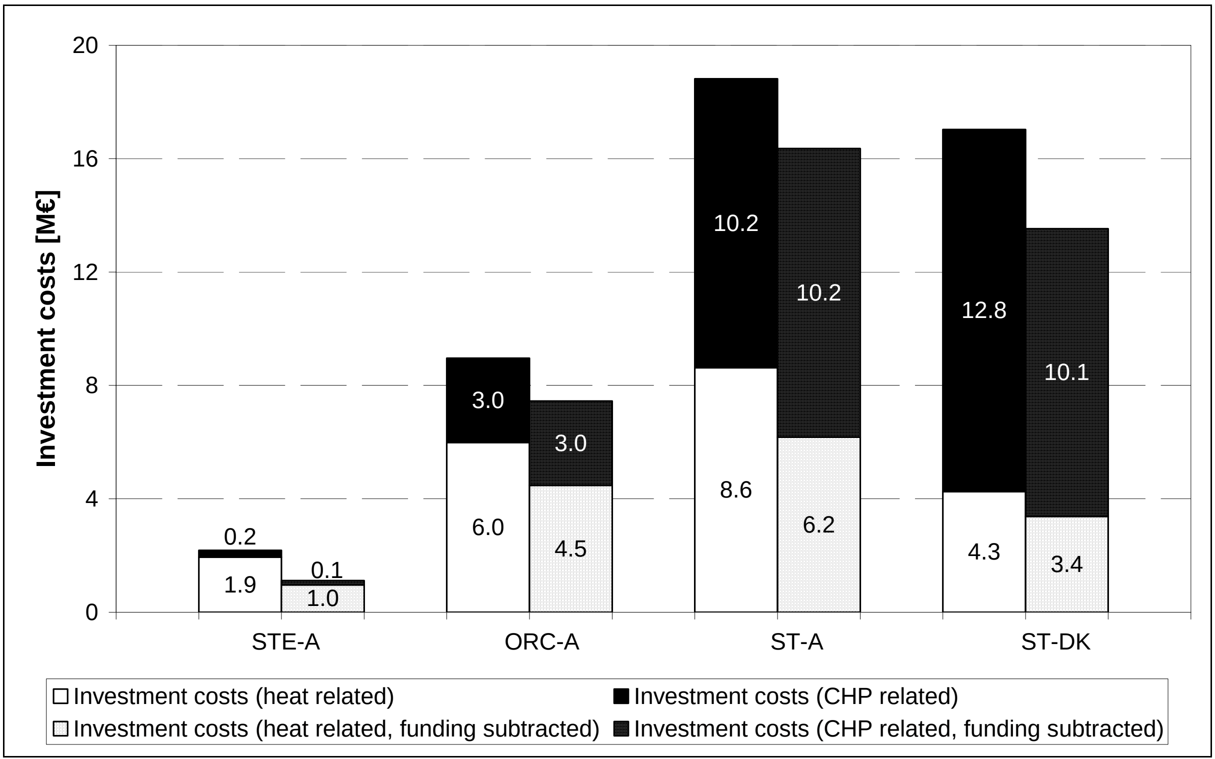


**Figure 4.1:** Investment costs of the biomass CHP plants investigated (absolute)

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark

The biomass CHP plants based on steam turbine processes from Austria and Denmark have similar electric capacities and show therefore similar total investment costs. However, the composition of the investment costs is different. In the Austrian case, the heat related investment costs cover about 46% and the electricity related investment costs about 54% of the total investment costs. In the Danish case, the ratio of heat to electricity related investment costs is about 25% to 75%. This is mainly caused by the fact, that the mean and peak load coverage by a biomass hot water boiler and for oil-fired boilers has been taken into consideration for the Austrian plants investigated but not for the Danish plant. Following, the heat related investment costs of the Austrian plants (steam turbine, Stirling engine and ORC process) comprise also the investment costs for the hot water and for peak load boilers.

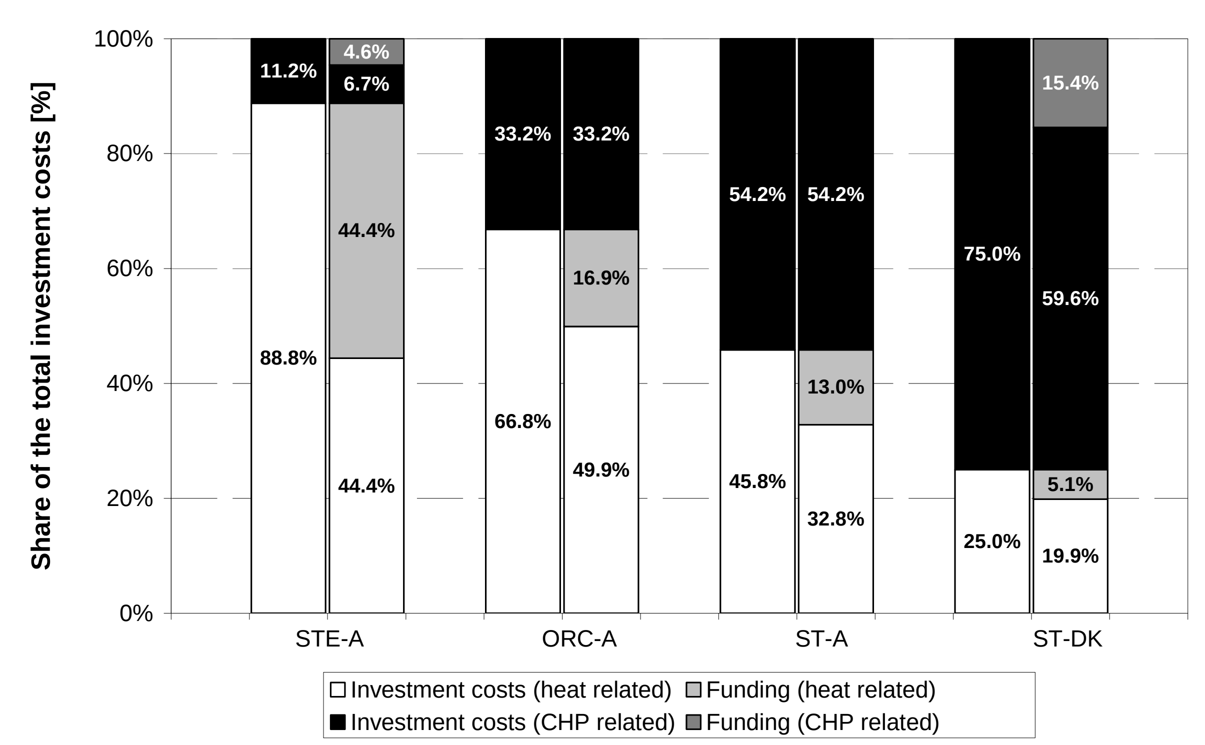


**Figure 4.2:** Investment costs of the biomass CHP plants investigated (relative)

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark

The specific CHP related investment costs of the biomass CHP plants investigated are shown in Figure 4.3. The highest specific investment costs occur for the Stirling engine process. This is mainly due to the small electric capacity of the Stirling engine and its novelty. However, the special investment subsidy granted for this plant (see above) reduces the specific investment costs significantly. In addition, a first small series production of Stirling engines is planned to be launched in 2004, and it is expected that the manufacturing costs will considerably drop, as soon as the first two or three small series will have been built. 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 steam turbine process under Danish 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 can be reduced to a level below the one for the Austrian steam turbine based plant.

The specific CHP related investment costs of the ORC process are located between the Stirling engine and the steam turbine process, which is also due to the medium position concerning the electric capacity. A cost reduction can also be expected, as soon as a small serial production (higher number of units of a certain size) can be achieved.

Moreover, for both the Stirling engine as well as the ORC process a certain cost reduction potential exists due to the development potential concerning the electric efficiency achievable. It can be expected, that overall electric efficiencies of up to 20% will be possible in the future.

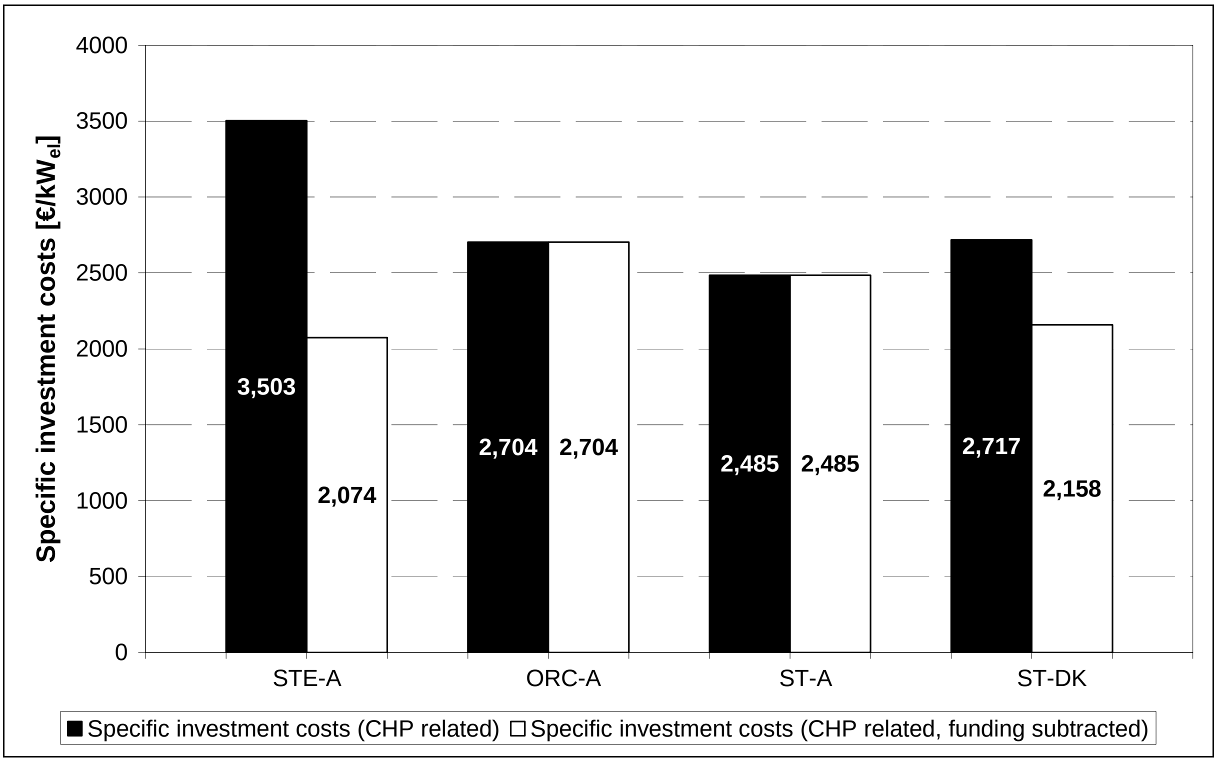


**Figure 4.3:** Specific CHP related investment costs of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; 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 4.3, Table 4.9, Table 4.15 and Table 4.21)

The specific heat related investment costs of the biomass CHP plants investigated are shown in Figure 4.4. The Austrian plants investigated include also the biomass hot water boilers installed to cover the middle load range. The oil-fired peak load boilers in case of the ORC and Stirling engine process have not been taken into account for the calculation of the specific heat related investment costs. The investment costs of the existing biomass hot water boiler for the Danish plant has also not been taken into account as this unit is already paid off. Therefore the heat related investment of the Austrian and Danish plants are not directly comparable.

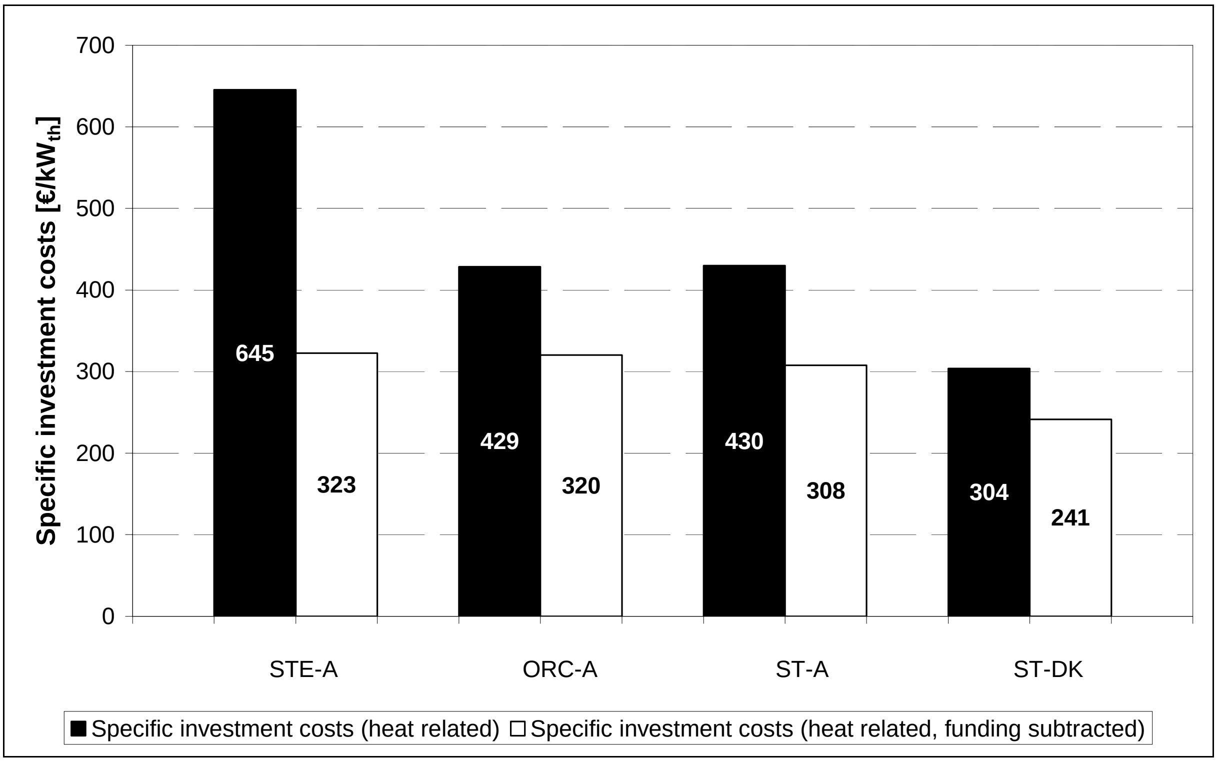


**Figure 4.4:** Specific heat related investment costs of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; 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 4.5, Table 4.11, Table 4.17 and Table 4.23); specific investment costs are based on useful thermal power related to biomass (without oil-fired peak load boiler)

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 4.5) can most probably only be achieved by a reduction of the CHP related investment costs.

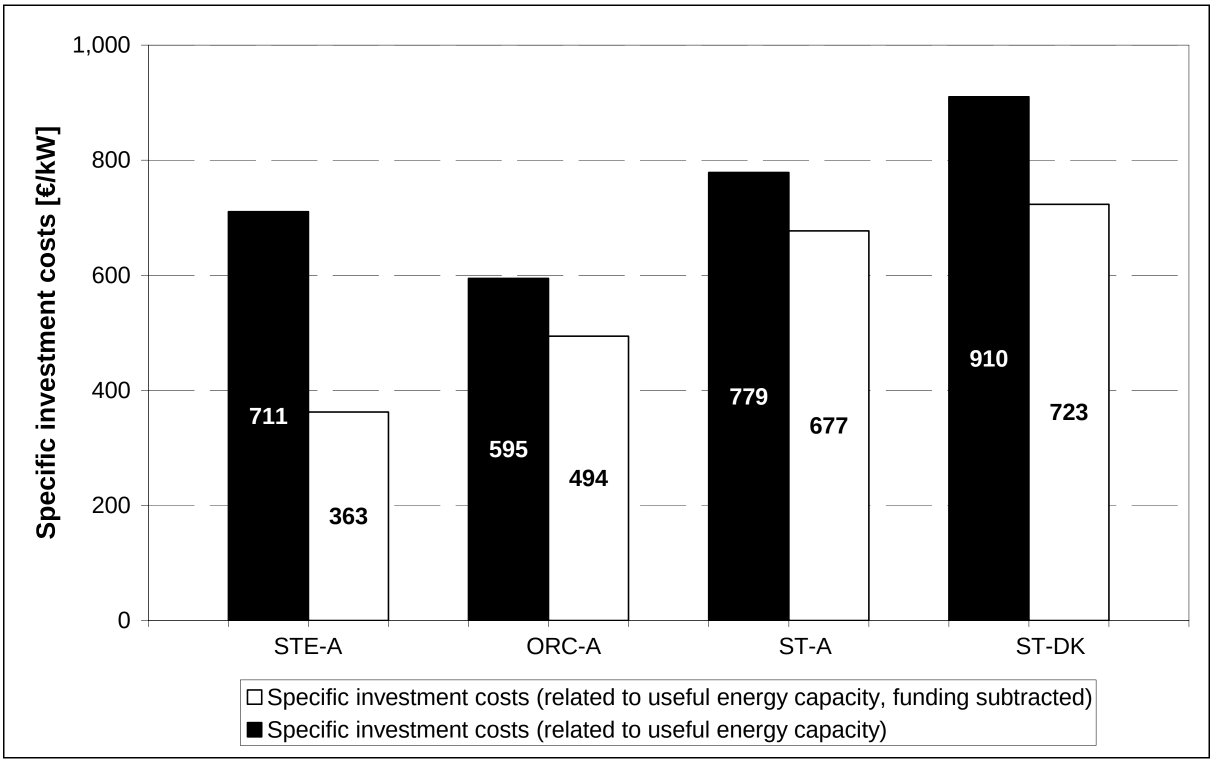


**Figure 4.5:** Specific total investment costs related to the useful energy capacity of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the specific investment costs shown are related to the total investment costs (additional investment costs of a CHP unit in comparison to a heat-only unit with the same nominal thermal capacity and the investment costs of the heat-only plant itself without consideration of the network of pipes for heat distribution, see also Table 4.25); specific investment costs are based on useful thermal and electric power related to biomass (without oil-fired peak load boiler)

The specific heat generation costs of the biomass CHP plants investigated are shown in Figure 4.6. They decrease with increasing plant capacities from 0.0512 €/kWh$_{th}$ for the Stirling engine process to 0.0256 €/kWh$_{th}$ for the Danish steam turbine process. Taking the funding into account, the specific heat generation costs decrease from 0.0375 €/kWh$_{th}$ for the Stirling engine process to 0.0202 €/kWh$_{th}$ for the Austrian steam turbine process.

The heat generation costs calculated are heat generation costs ex plant without heat distribution costs. Average costs of the heat distribution for district heating plants amount to about one third of the total heat generation costs. The heat distribution costs for process heating in the wood industry are very low due to the small network of pipes necessary.

Average price ranges for district heat in Austria for heat consumers amount to between 0.044 and 0.062 €/kWh. The district heat price level in Denmark is slightly lower. Process heat in Austria costs between 0.018 and 0.033 €/kWh, depending on the fuel price and the quality of the heat (temperature level, hot water or steam).

The specific heat generation costs of the Stirling engine process are dominated by the specific capital costs, when the funding is not taken into account. The specific heat generation costs of the other processes shown in Figure 4.6 are dominated by the consumption costs, which comprise mainly the fuel costs, but also the electricity (auxiliary energy) costs. The operation costs (personnel costs, maintenance costs) and other costs (insurance, administration) are of minor importance.

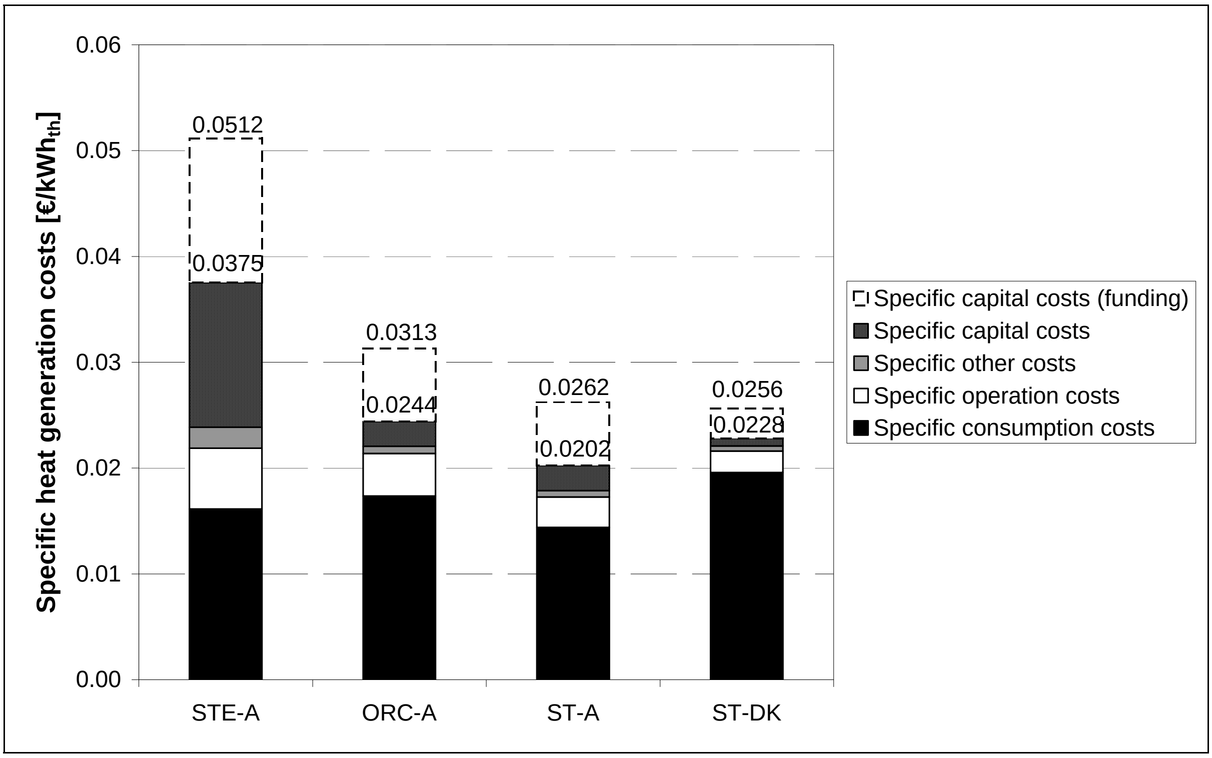


**Figure 4.6:** Specific heat generation costs of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; 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 4.8 shows the specific electricity generation costs of the biomass CHP plants investigated. A detailed overview of the Austrian feed-in tariffs for electricity from solid biomass is given in Figure 4.7. The Austrian feed-in tariffs depend both on the electric capacity of the CHP plant and on the biomass fuel used. Taking these framework conditions into consideration, the feed-in tariff for green electricity in Austria varies in a broad range between 6.63 and 16.0 €Cent/kWh$_{el}$. If fuel mixtures are used, a proportional feed-in tariff based on the proportional fuel energy input is applied. The Austrian biomass CHP plants based on a Stirling and on an ORC process are in a capacity range below 2 MW$_{el}$. The Stirling engine based CHP plant uses about 50% forest wood chips and about 50% by-products from sawmills. Therefore, a feed-in tariff of 14.4 €Cent/kWh$_{el}$ applies. The Austrian biomass CHP plant based on an ORC process uses about 10% forest wood chips and about 50% by-products from sawmills. The feed-in tariff valid in this case amounts to 13.12 €Cent/kWh$_{el}$. The Austria steam turbine based biomass CHP plant is the capacity range between 2 and 5 MW$_{el}$ and uses 100% by-products from sawmills. Therefore, a feed-in tariff of 12.0 €Cent/kWh$_{el}$ applies. The Danish plant obtains an average feed-in tariff for the electricity produced of 8.53 €Cent/kWh$_{el}$.

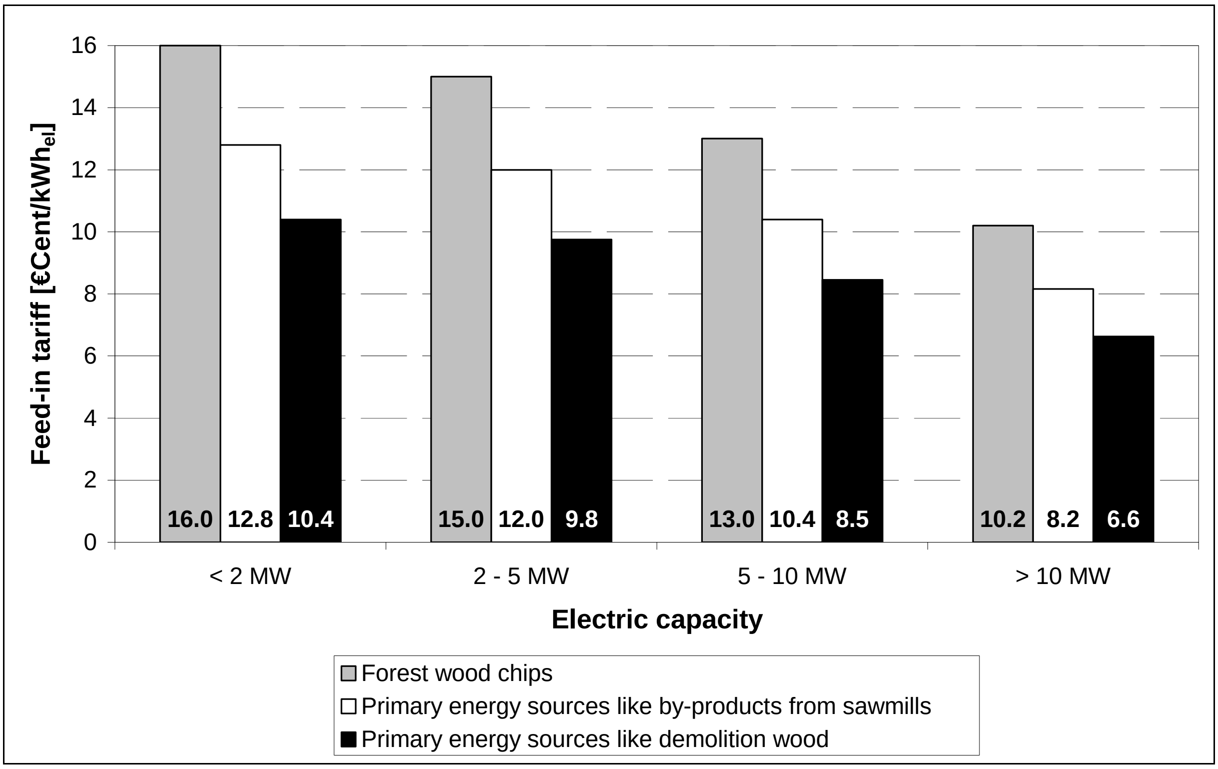


**Figure 4.7:** Feed-in tariffs in Austria for electricity from solid biomass

Explanations: data source [10]

The specific electricity generation costs range between 0.1418 and 0.1068 €/kWh$_{el}$, whereas the Stirling engine process shows the highest, and the Danish steam turbine process shows the lowest.

The main cost categories are the specific capital costs, covering between 52% and 63% of the specific electricity generation costs. The specific consumption costs are in a similar range for all processes compared and cover between 21% and 27% of the specific electricity generation costs. The specific other costs are of minor relevance.

The specific operation costs are in the Danish case comparatively low. On the one hand, this is caused by the comparatively low hourly rate for personnel of 25.5 €/h. In addition, comparatively low annual working hours are needed, because the plant is operated unattended during evenings and nights.

The investment subsidy granted for the electricity related part of the Danish plant reduces the specific capital costs by about 0.013 €/kWh$_{el}$ and therefore also the specific electricity generation costs by this amount. The special subsidy granted for the Austrian Stirling engine process reduces the specific electricity generation costs from 0.1418 to 0.1057 €/kWh$_{el}$.

The feed-in tariffs valid for the Austrian plants are above the respective electricity generation costs calculated. This is also the case for the Stirling engine process (if funding is not considered), which is important, as usually no investment subsidy can be gained in Austria for the electricity related part of the plant. The electricity generation costs of the Danish CHP plant are higher than the respective feed-in tariff, which is only partly compensated by the funding. This comparison shows, that the feed-in tariffs valid in Austria at present are adequate in order to support and increase the number of biomass CHP plants.

The main cost reduction potential is given by the reduction of the investment costs by small serial production (production of standardised CHP modules for certain size ranges). In addition, a further increase of the electric efficiency especially for the ORC process and the Stirling engine could contribute to a cost reduction in the future.

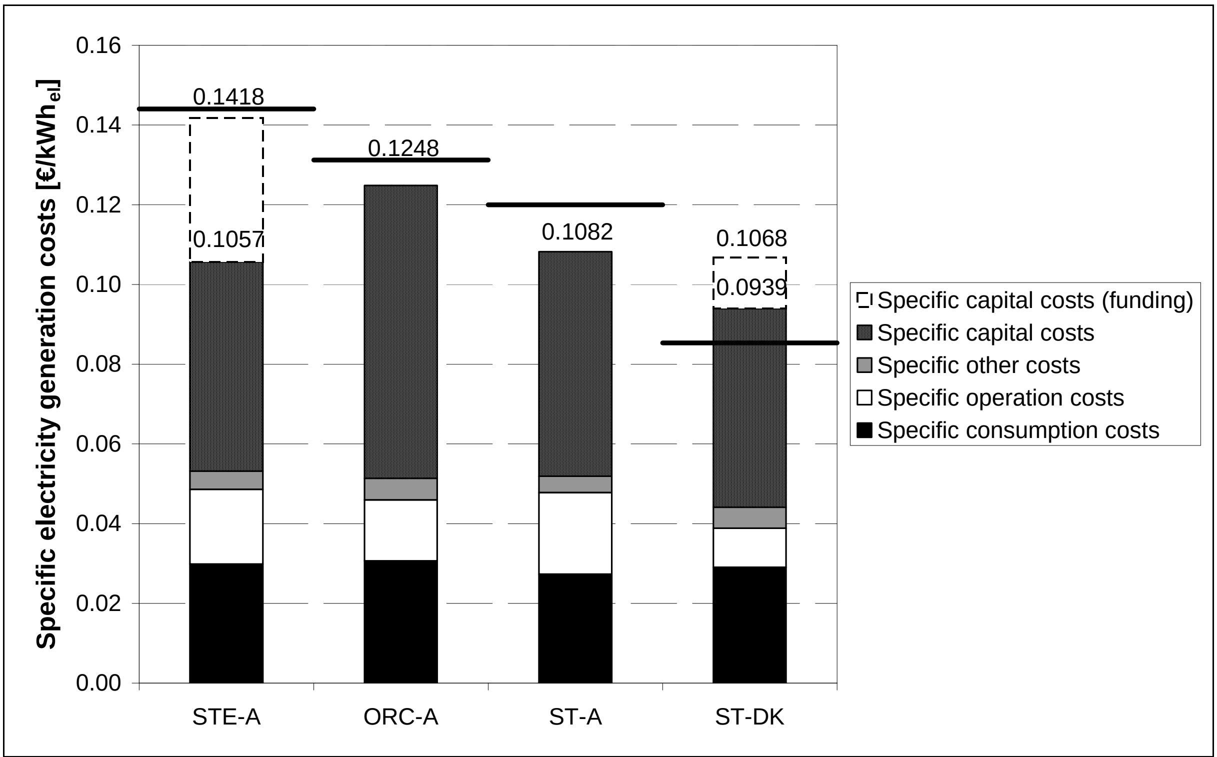


**Figure 4.8:** Specific electricity generation costs of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; feed-in tariff for STE-A based on utilisation of 50% forest wood chips and 50% by-products from sawmills; feed-in tariff for ORC-A based on utilisation of 10% forest wood chips and 90% by-products from sawmills; feed-in tariff for ST-A based on utilisation of 100% by-products from sawmills

The specific total energy generation costs of the biomass CHP plants investigated are shown in Figure 4.9. They vary between 0.0389 and 0.0558 €/kWh (without taking funding into account) and between 0.0368 and 0.0414 €/kWh, when the investment subsidies granted are taken into account. The biomass CHP plant based on a Stirling engine shows the highest and the plant based on an ORC process shows the lowest specific energy generation costs.

A main difference between the Austrian and the Danish plants is the fact, that in the Danish case only the CHP unit has been considered for the economic calculation. The biomass hot water boiler of the Danish plant has not been taken into account, as this unit is an old existing unit and has already been paid off. In the Austrian cases the whole plants including the CHP units for the base load, the hot water boilers for the middle load range and the peak load boilers (for the ORC and the Stirling engine process) have been considered. Depending on the dimensioning, the hot water and the peak load boilers act also as a stand-by system.

The main cost categories of the total energy generation costs are the capital costs and the consumption costs. The capital costs can be reduced by investment subsidies. The consumption costs are dominated by the fuel costs. Operation costs and other costs are of minor relevance.

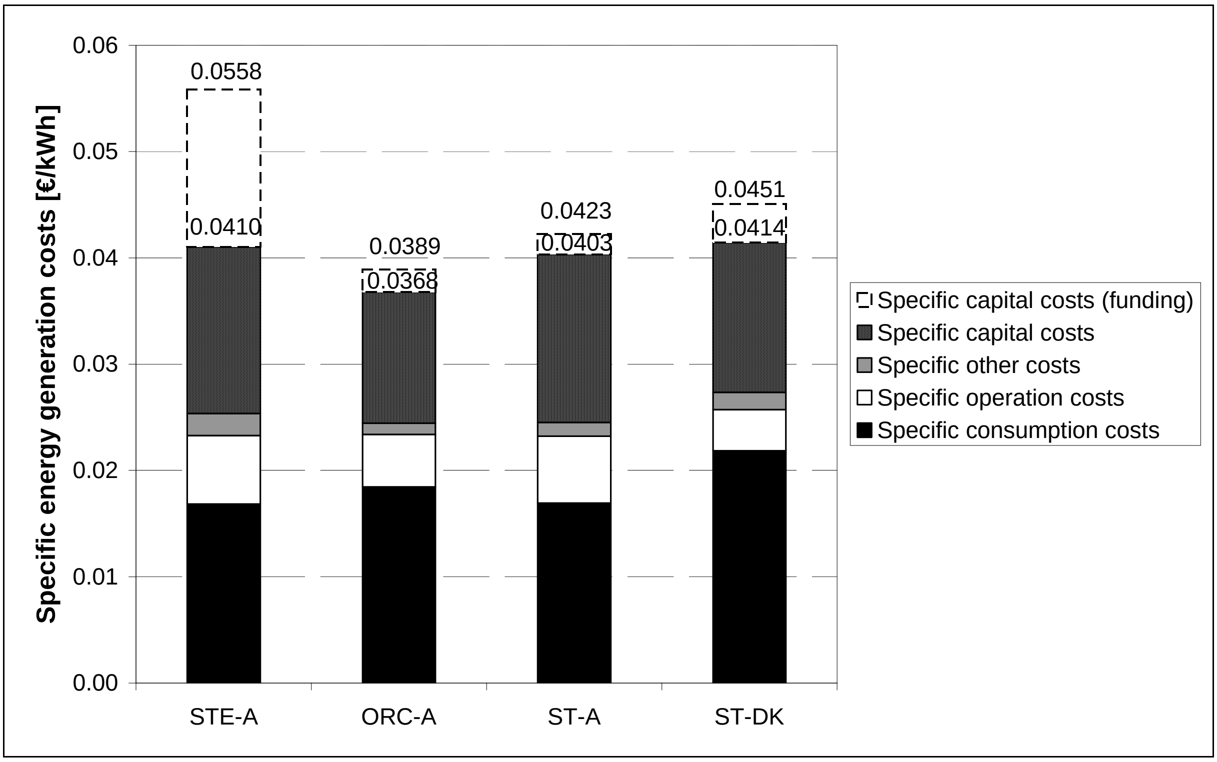


**Figure 4.9:** Specific energy generation costs of the biomass CHP plants investigated

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark

## 4.9 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, as the investment costs (especially for the Stirling engine and the ORC process) are expected to be able to be reduced by serial production, 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.

All calculations of heat and energy generation costs have been performed without consideration of the heat distribution costs. The heat distribution costs usually cover about one third of the total heat price for district heat supply and is almost negligible for process heat supply within an industry. Also the price ranges for heat generation costs identified in this section are calculated ex plant (without heat distribution).

### 4.9.1 Influence of the investment costs

The influence of the investment costs on the specific heat generation costs in comparison to achievable heat prices is shown in Figure 4.10. The achievable heat prices show the possible range according to Austrian conditions. The lower price range is valid for process heat and the upper price range for district heat.

It can be seen, that the specific heat generation costs are, without consideration of investment subsidies, within the range of achievable heat prices (except the Austrian Stirling engine process). Taking the investment subsidies into account, even the heat generation costs of the Stirling engine process are within this range.

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. A variation of the investment costs by ± 10% would lead to a variation of the specific heat generation costs between ± 1.4% and ± 6.7%.

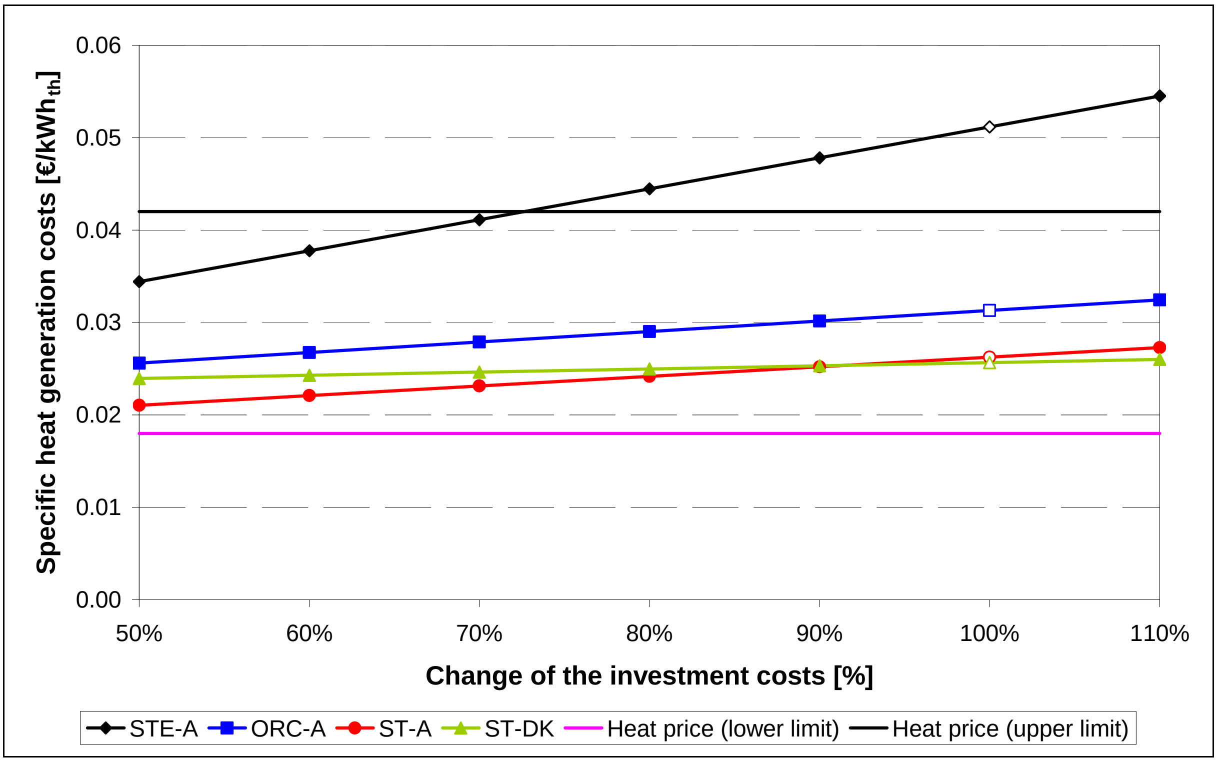


**Figure 4.10:** Influence of the change of the investment costs on the specific heat generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; all heat prices have been calculated without consideration of the heat related investment funding achieved for the projects; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; heat distribution costs not considered (heat price ex plant)

The influence of the investment costs on the specific electricity generation costs in comparison to the respective feed-in tariffs is shown in Figure 4.11.

The results show that the electricity generation costs of all Austrian processes compared are below the respective feed-in tariffs. Only the Danish plant shows higher electricity generation costs than the Danish feed-in tariff granted.

Especially the CHP related investment costs of the Stirling engine and the ORC process show a reduction potential due to small serial production, which should be achievable in the near future. Therefore, a decrease of the electricity generation costs and consequently a more economic operation of biomass CHP plants based on Stirling engine and ORC processes can be expected in the near future.

A variation of the investment costs by ± 10% would lead to a variation of the specific electricity generation costs between ± 6.3% and ± 7.6%.

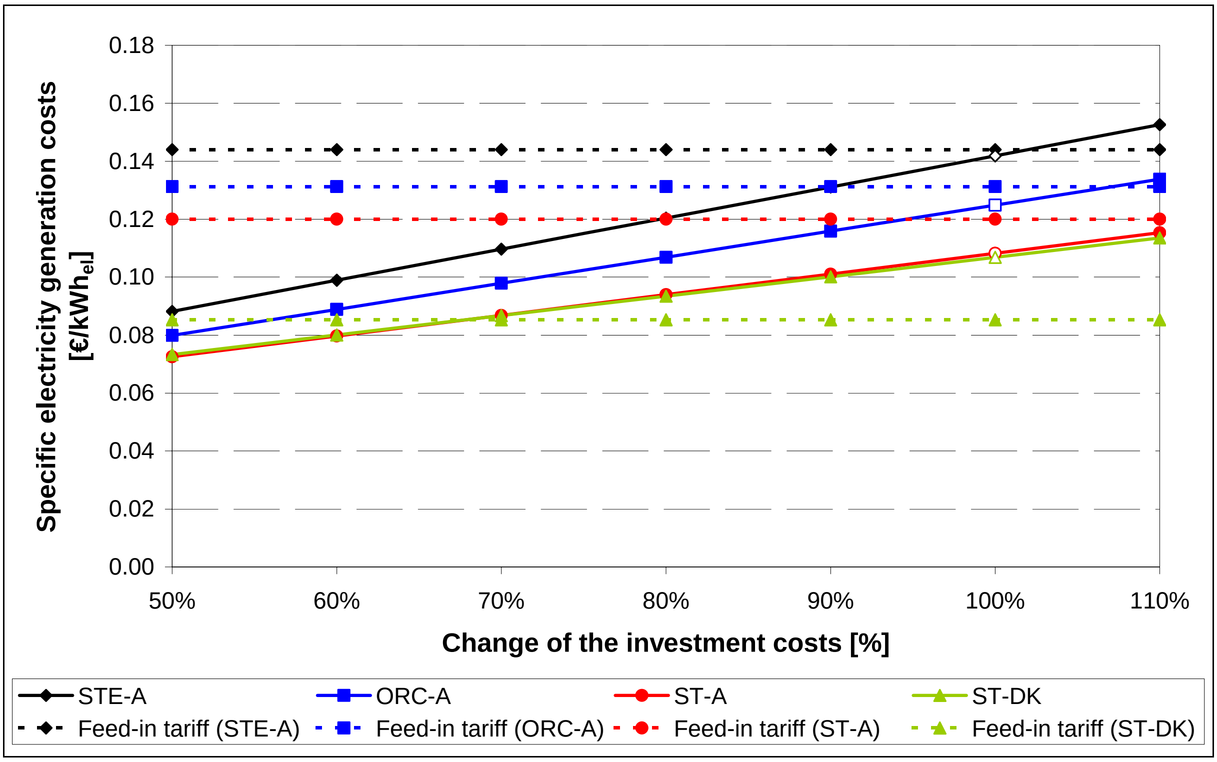


**Figure 4.11:** Influence of the change of the investment costs on the specific electricity generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; all electricity prices have been calculated without consideration of the electricity related investment funding achieved for the projects; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding

The influence of the variation of the investment costs on the specific energy generation costs is shown in Figure 4.12. The main cost reduction potential is expected to be given by the reduction of the investment costs for ORC processes and Stirling engines due to serial production of such units in the near future. It is not expected, that the heat related investment costs can be reduced due to well proven state-of-the-art combustion technologies already applied but investment funding could be a relevant point for the reduction of heat related investment costs (up to 30% possible in Austria at present).

A variation of the investment costs by ± 10% would lead to a variation of the specific energy generation costs between ± 4.2% and ± 6.8%.

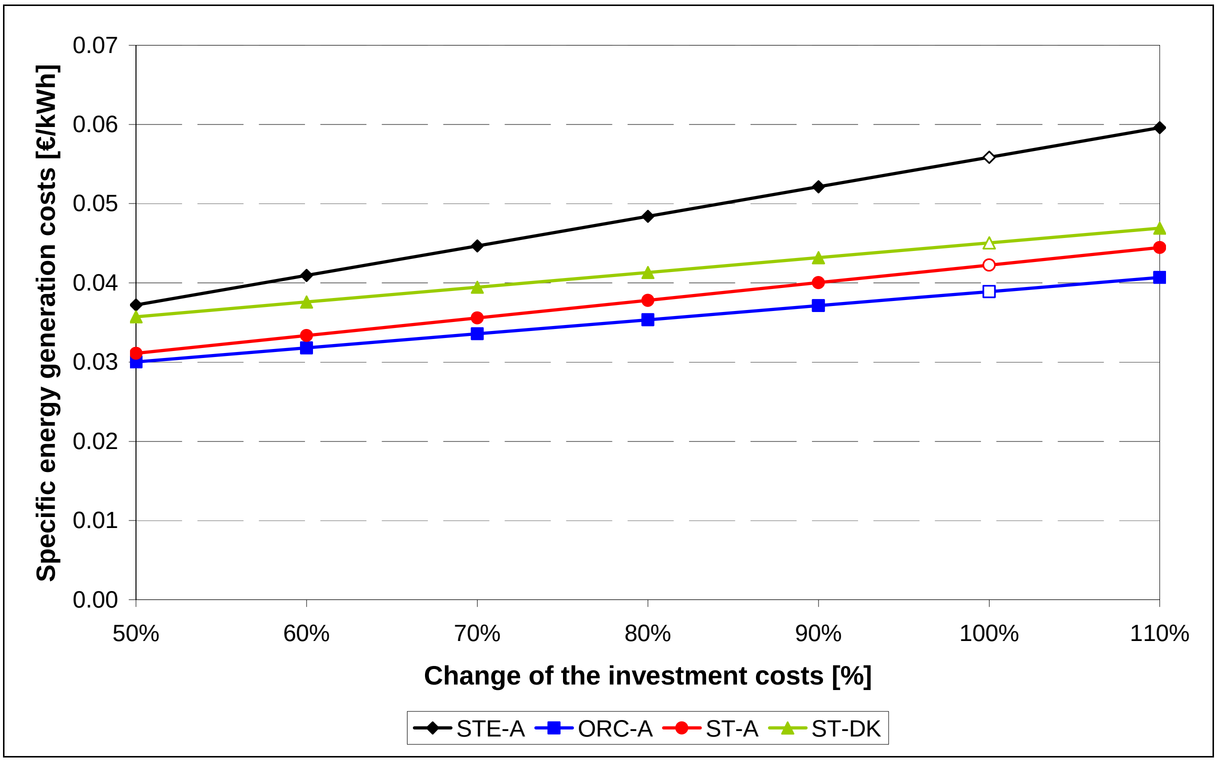


**Figure 4.12:** Influence of the change of the investment costs on the specific energy generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; all energy prices have been calculated without consideration of the investment funding achieved for the projects; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; heat distribution costs not considered (heat price ex plant)

### 4.9.2 Influence of the fuel price

The influence of the fuel price on the specific heat generation costs in comparison to heat prices, which are achievable, is shown in Figure 4.13. The upper range of the heat price range indicated relates to district heat, the lower range to process heat (according to Austrian constraints). Typical price ranges of different biomass fuels in Austria are shown in Table 4.27. The use of these different biomass fuel fractions for the plants investigated and their influence on the economy will be discussed in the following section.

Without consideration of investment funding, the heat generation costs of the Stirling engine process are for the base case above the upper limit of the achievable heat price. For the other case studies the economy of heat production mainly depends on the fuel costs.

Bark is the cheapest fuel, mainly used by sawmills and wood manufacturing industries internally. Sawdust, industrial wood chips and forest wood chips are the main fuels utilised in biomass district heating plants. These fuels usually enable an economic operation of district heat plants, if a certain investment subsidy is granted. The use of pellets in biomass CHP plants in Austria would only be economically meaningful, if cheap industrial pellets with a price of around 0.016 to 0.020 €/kWh would be available. The utilisation of high quality pellets for the residential sector with prices of up to 0.040 €/kWh will not be suitable at all.

**Table 4.27:** Price ranges of different biomass fuels in Austria

Explanations: delivered; source: http://www.proholz.at/, own inquries

| Fuel | Price range [€/kWh$_{NCV}$] |
|---|---|
| Bark | 0.005 – 0.008 |
| Industrial wood chips | 0.009 – 0.013 |
| Sawdust | 0.008 – 0.011 |
| Forest wood chips | 0.015 – 0.019 |
| Pellets | 0.025 – 0.040 |

A variation of the fuel price by ± 10% leads to a variation of the specific heat generation costs between ± 2.8% and ± 6.8%.

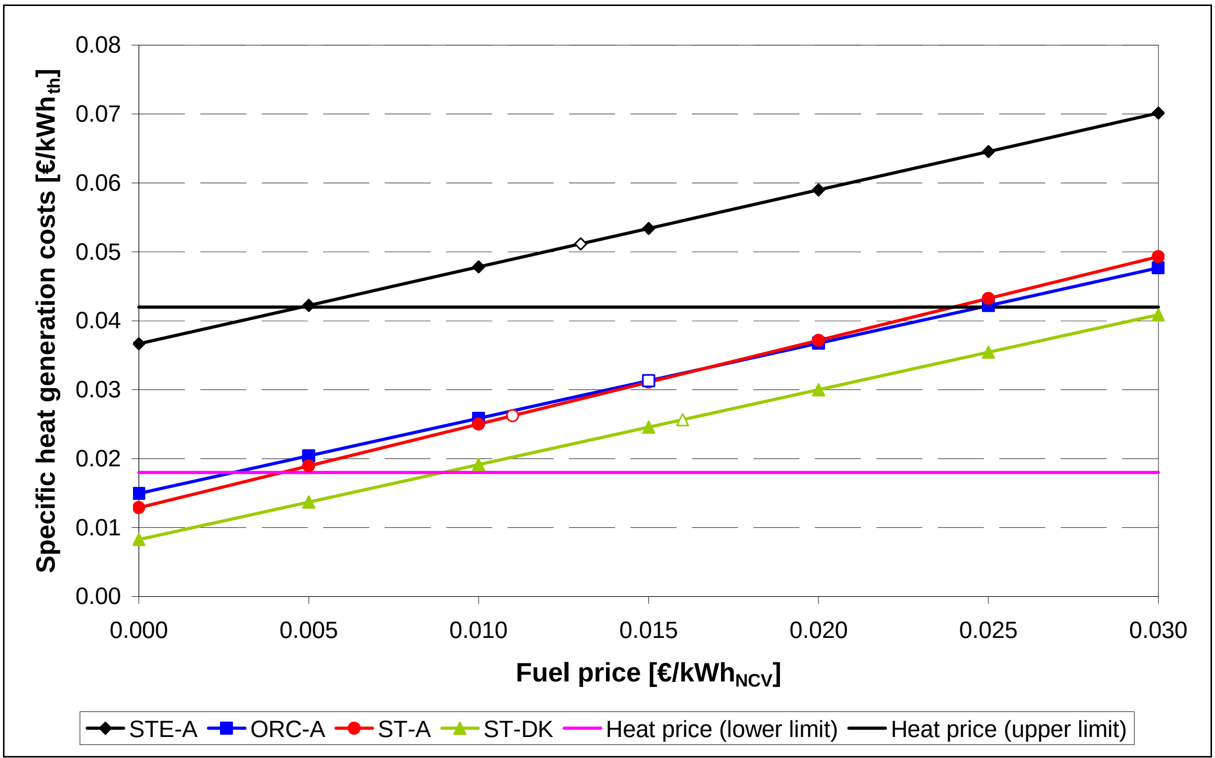


**Figure 4.13:** Influence of the fuel price on the specific heat generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; all heat prices have been calculated without consideration of the heat related investment funding achieved for the projects; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; heat distribution costs not considered (heat price ex plant)

The electricity generation costs of all Austrian processes compared are for the base case scenarios below the respective feed-in tariff. Only the Danish plant shows higher electricity generation costs than the feed-in tariff granted.

Regarding the influence of the fuel price on the specific electricity generation costs, two different sensitivity analyses have been performed. For the basic sensitivity analysis the fuel price has been varied, which influences both the heat and the electricity generation costs. However, due to the fact, that the heat price which can be achieved by a biomass CHP plant is usually fixed, the additional costs caused by a more expensive fuel should rather be charged to the electricity generation costs than to the heat and electricity generation costs. Hence, sensitivity analyses, where the heat generation costs have been kept constant and the variation of the fuel costs has been charged only to the electricity generation costs, have also been performed. The influence of the fuel price on the specific electricity generation costs according to this different approaches as well as a comparison with the respective feed-in tariffs is shown in Figure 4.14 and Figure 4.15.

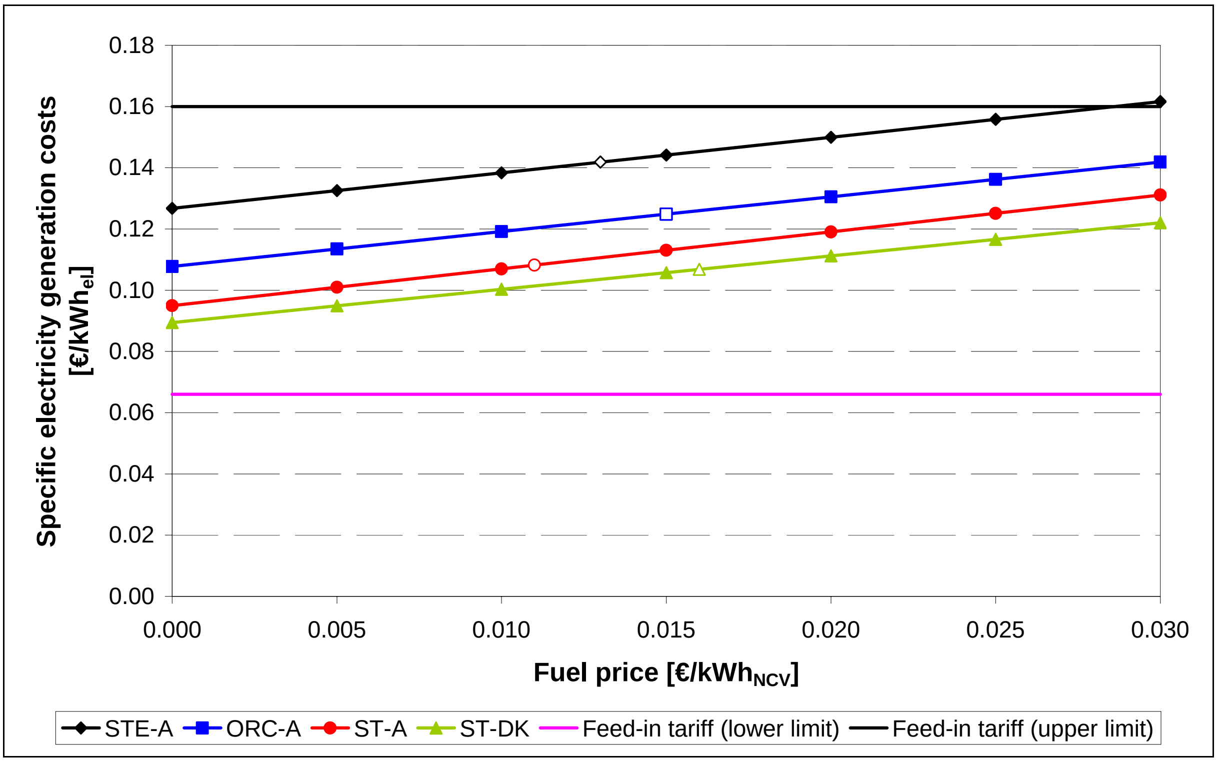


**Figure 4.14:** Influence of the fuel price on the specific electricity generation costs (increase of the heat price considered)

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; calculations based on the assumption, that an increasing fuels price increases the heat price as well; lower and upper limit for the feed-in tariff according to Austrian constraints (see Figure 4.7)

The influence of the fuel price on the electricity generation costs is much stronger, when the variation of the fuel costs is completely charged to the electricity generation costs. Only a small increase of the fuel price leads to strongly increasing electricity generation costs, which makes the use of more expensive biomass fuel fractions only possible, if the feed-in tariff also depends on the biomass fuel used (like in Austria, see Figure 4.7). This fuel flexibility given by different feed-in tariffs for different biomass fuels considerably increases the flexibility of fuel selection, which is relevant for a secured long-term operation of a biomass CHP plant.

A variation of the fuel price by ± 10% leads to a variation of the specific electricity generation costs between ± 1.1% and ± 1.6%, if an increase of the heat price is also considered. Charging the fuel price variation only to the electricity generation costs, a variation of the fuel price by ± 10% leads to a variation of the electricity generation costs between ± 6.3% and ± 19.9%.

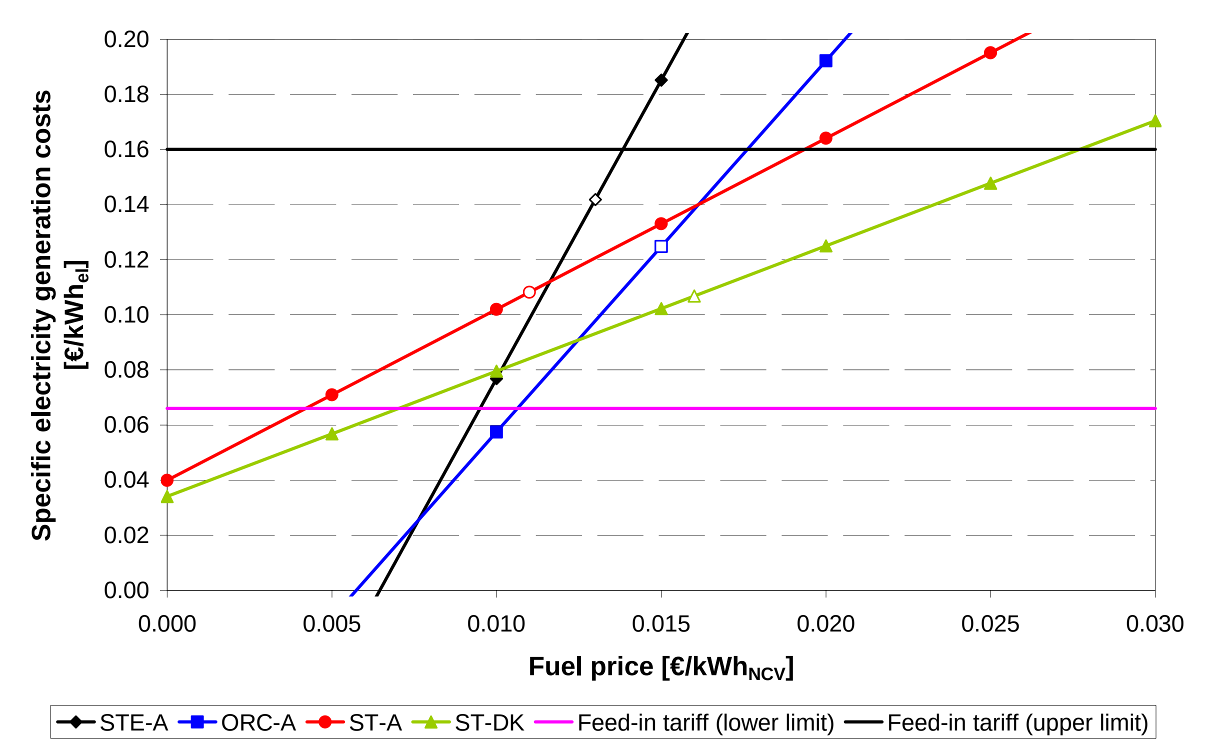


**Figure 4.15:** Influence of the fuel price on the specific electricity generation costs (increase of the heat price not considered)

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; calculations based on the assumption, that an increasing fuels price increases only the electricity generation costs (constant heat price); lower and upper limit for the feed-in tariff according to Austrian constraints (see Figure 4.7)

Figure 4.16 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 ± 2.6% and ± 4.2%.

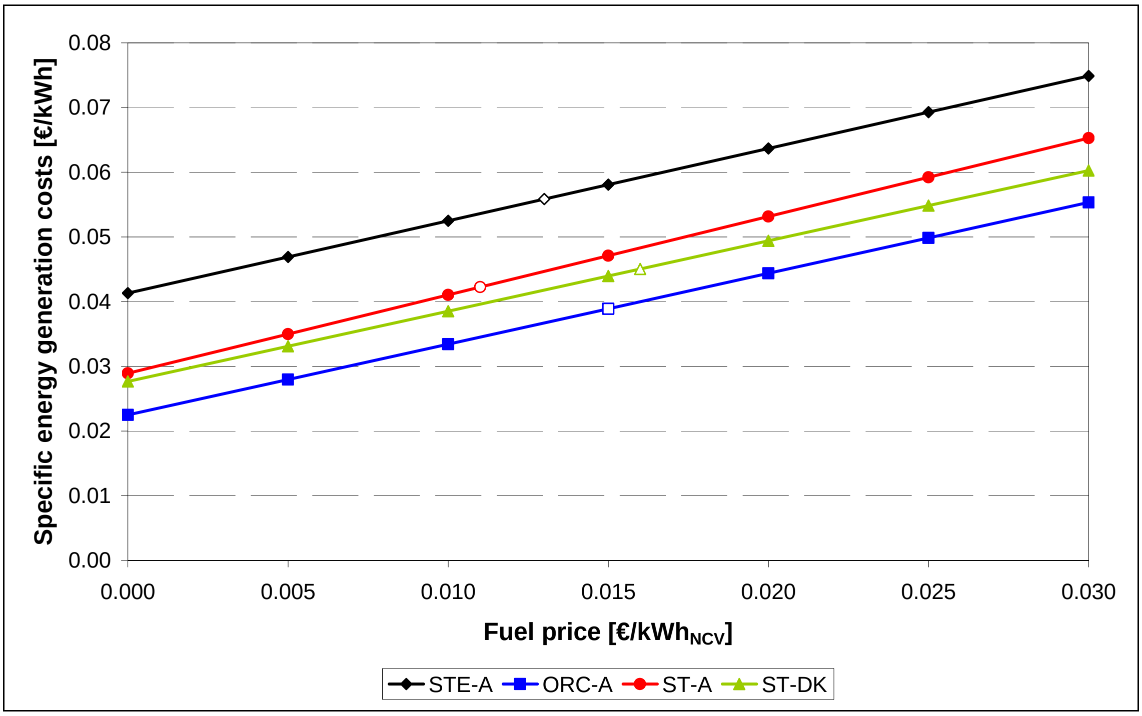


**Figure 4.16:** Influence of the fuel price on the specific energy generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; heat distribution costs not considered (heat price ex plant)

### 4.9.3 Influence of the annual full load operating hours of the CHP unit

In the following sensitivity analyses only the annual full load operating hours of the CHP unit have been varied. This means, that the annual full load operating hours of used biomass hot water boilers and peak load boilers and therefore the heat production from these units remained constant.

The influence of the annual full load operating hours on the specific heat generation costs is shown in Figure 4.17.

As obvious, the influence of the annual full load operating hours on the specific heat generation costs of the Danish steam turbine process is strong, which is due to the fact, that the existing old biomass heating plant has not been considered in the economic calculation. In contrast, a relevant part of the heat produced from the Austrian biomass CHP plant based on a Stirling engine process is produced from a hot water boiler. Therefore, the influence of the annual full load operating hours of the CHP plant on the specific heat generation costs is lower, because the annual full load operating hours of the biomass hot water boiler have not been varied (same annual heat production).

Moreover, Figure 4.17 shows, that the specific heat generation costs of the Austrian ORC and steam turbine process as well as of the Danish steam turbine process are within the achievable range of heat prices. It can also be seen, that the specific heat generation costs show a strong increase below about 3,000 annual full load operating hours. Following, to achieve a high plant utilisation, a proper dimensioning and a heat controlled operation of biomass CHP plants is recommended (from an ecologic as well as an economic point of view).

A reduction of the CHP related annual full load operating hours by 10% leads to an increase of the specific heat generation costs between 2.2% and 3.9%. An increase of the annual full load operating hours leads to a decrease of the specific heat generation costs between 2.0% and 3.4%.

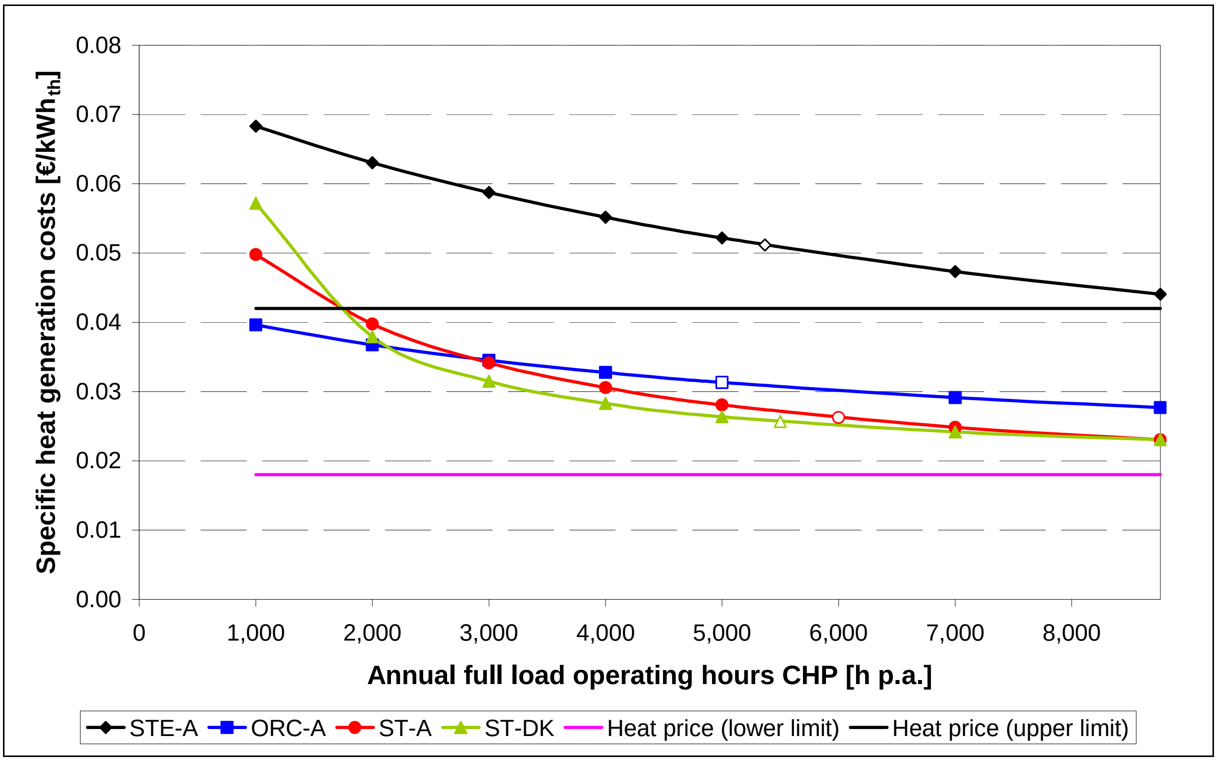


**Figure 4.17:** Influence of the annual full load operating hours on the specific heat generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; heat distribution costs not considered (heat price ex plant)

The influence of the annual full load operating hours of the CHP plant on the specific electricity generation costs and a comparison with the feed-in tariffs is shown in Figure 4.18. The specific electricity generation costs of the Danish steam turbine process are above the respective feed-in tariff. However, by an increase of the annual full load operating hours the process could become economic. The increase of the specific electricity generation costs below about 4,000 annual full load operating hours is substantial and must in any case be avoided. As a recommendation, a biomass CHP plant should achieve at least 5,000 full load operating hours. A correct dimensioning in dependence of the heat demand (annual utilisation line) is very important in this context.

A reduction of the annual full load operating hours of the CHP plant by 10% leads to an increase of the specific electricity generation costs between 8.5% and 8.9%. An increase of the annual full load operating hours leads to a decrease of the specific electricity generation costs between 6.9% and 7.3%.

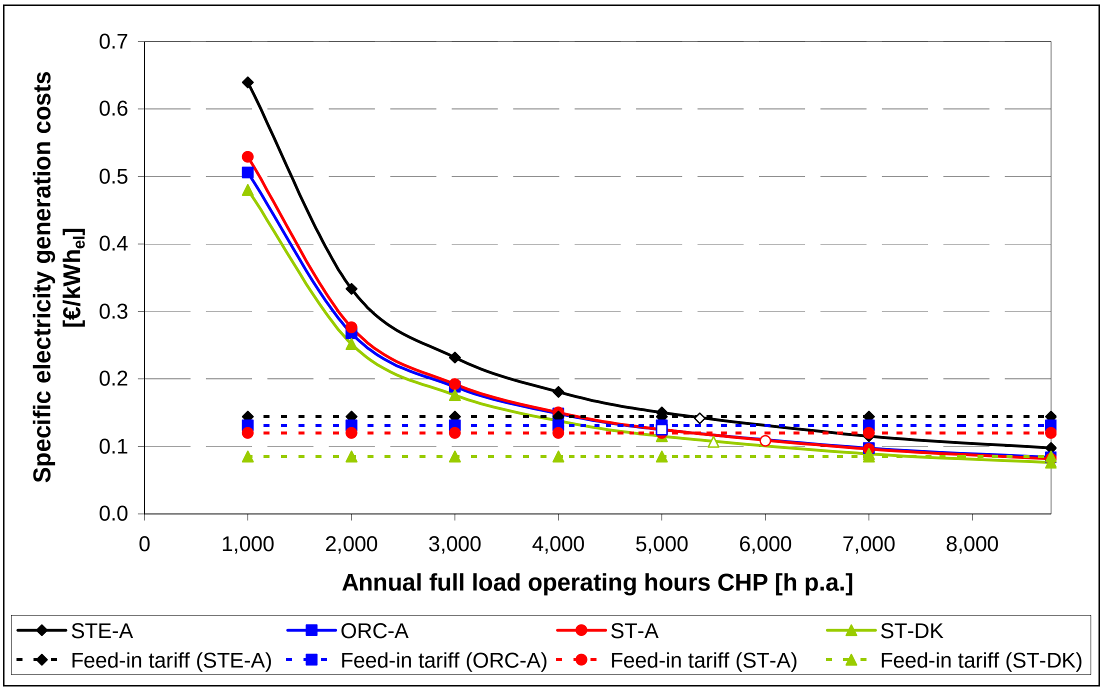


**Figure 4.18:** Influence of the annual full load operating hours on the specific electricity generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding

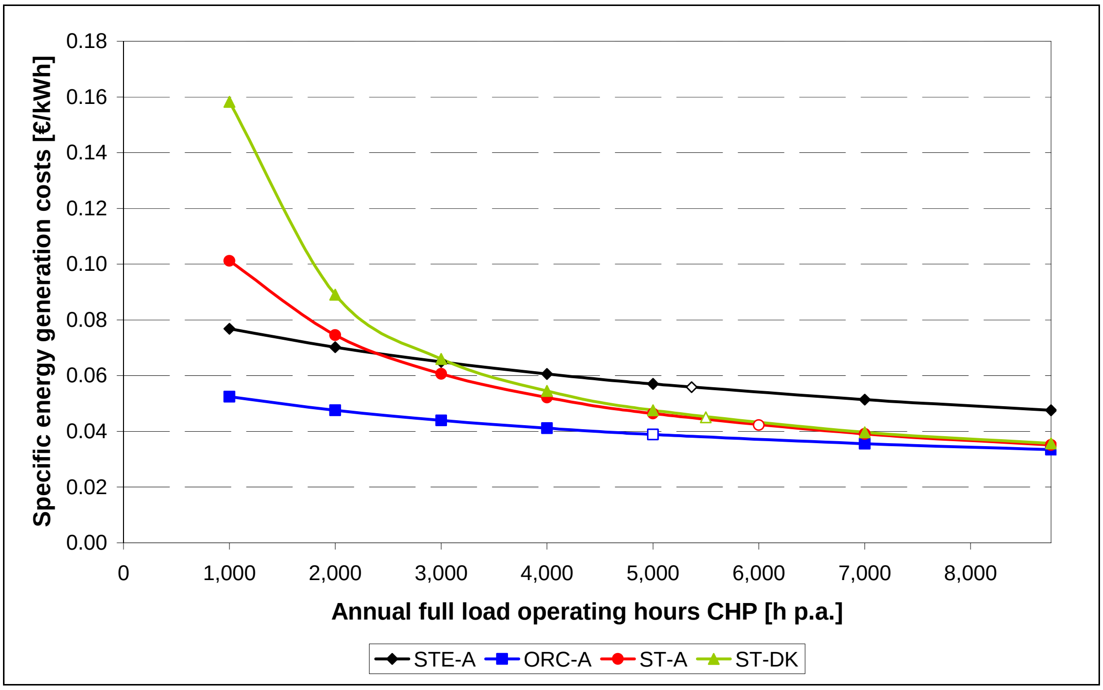


**Figure 4.19:** Influence of the annual full load operating hours on the specific energy generation costs

Explanations: STE...Stirling engine process; ORC...Organic Rankine Cycle process; ST...steam turbine process; A...Austria; DK...Denmark; the empty dots indicate the base cases; calculations performed according to chapter 4; heat controlled operation of the plants given for all cases; all case studies calculated without consideration of investment funding; heat distribution costs not considered (heat price ex plant)

Figure 4.19 shows the influence of the annual full load operating hours of the CHP plant on the specific energy generation costs of the plants investigated.

The specific energy generation costs are also strongly influenced by decreasing annual full load operating hours of the CHP unit, which stresses again the importance of a correct dimensioning of biomass CHP plants adapted to the heat demand of the process or district heating network.

A reduction of the annual full load operating hours of the CHP plant by 10% leads to an increase of the specific energy generation costs between 2.7% and 6.2%. An increase of the annual full load operating hours leads to a decrease of the specific electricity generation costs between 2.4% and 5.1%.

## 4.10 Profitability of the processes for different national framework conditions

Different national framework conditions lead to different economics of the processes investigated. In this context, especially the price for the heat and the feed-in tariffs for the electricity are of great relevance. In this section, the influence of the heat prices and the feed-in tariffs on the specific income of the respective processes is discussed.

The diagrams used allow to evaluate the economics of the processes for different national framework conditions regarding heat price, feed-in tariff and investment costs / subsidies. In addition, the minimum heat price for an economic operation at a given feed-in tariff or, the other way round, a minimum feed-in tariff at a given heat price can be identified for a certain investment / subsidy.

Figure 4.20 shows the interrelation between the heat price, the electricity price, a change concerning the investment costs and the income for the Austrian Stirling engine process. The energy generation costs amount to 0.0558 €/kWh for the base case calculated. By a variation of the investment costs between 10 and 50% (cost reduction or funding), the specific energy generation can be reduced to between 0.0521 to 0.0372 €/kWh.

For the given feed-in tariff for the Austrian plant of 0.144 €/$kWh_{el}$ (use of 50% forest wood chips and 50% by-products from sawmills) a heat price ex plant of at least 0.051 €/$kWh_{th}$ must be achieved to reach a specific income above the specific costs without investment subsidy. 30% investment costs reduction for instance reduces the necessary heat price for an economic operation to about 0.040 €/$kWh_{th}$.

Taking an average heat price ex plant of 0.036 €/$kWh_{th}$ (mean value from the average price range for district heat between 0.044 and 0.062 €/$kWh_{th}$; reduced by 31.5% for the heat distribution costs) for an Austrian biomass district heating plant and a feed-in tariff of 0.144 €/$kWh_{el}$ into account, an investment subsidy of about 40% in comparison to the base case would be needed for an economic operation of the plant.

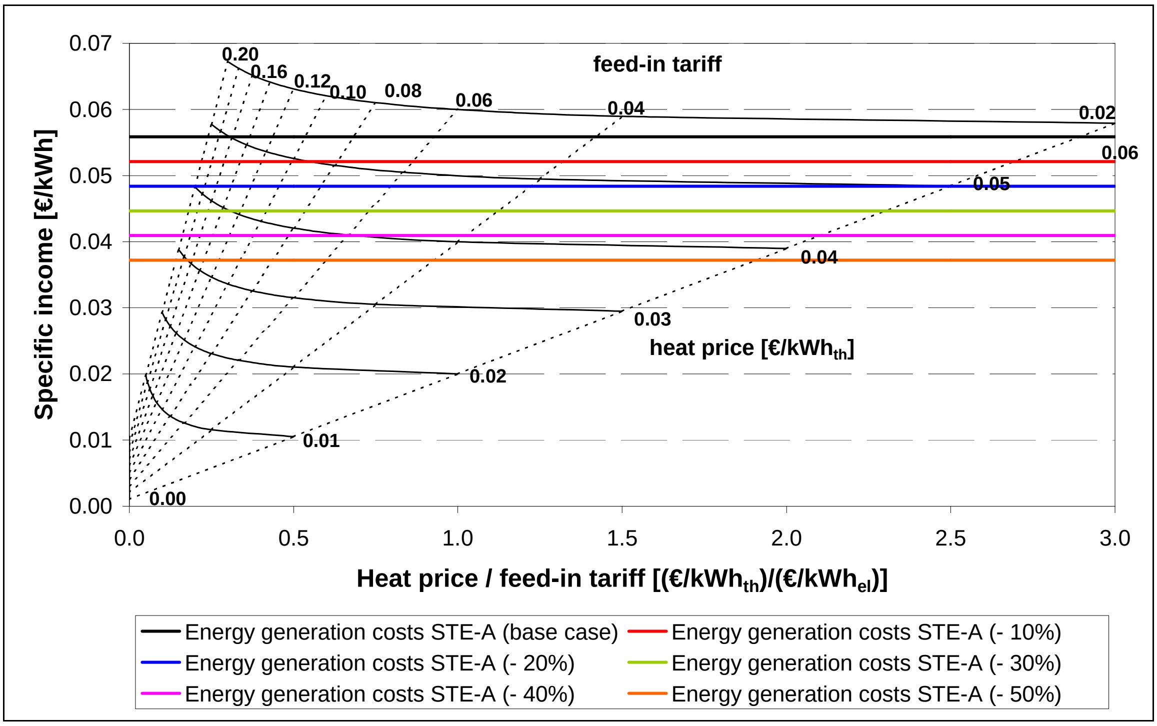


**Figure 4.20:** Specific income of the Austrian Stirling engine process (STE-A) versus the prices for heat and electricity sold as well as the influence of investment costs/subsidies

Explanations: diagram valid for an annual heat production of about 6.9 GWh/a and an annual electricity production of about 0.38 GWh/a; heat price ex plant

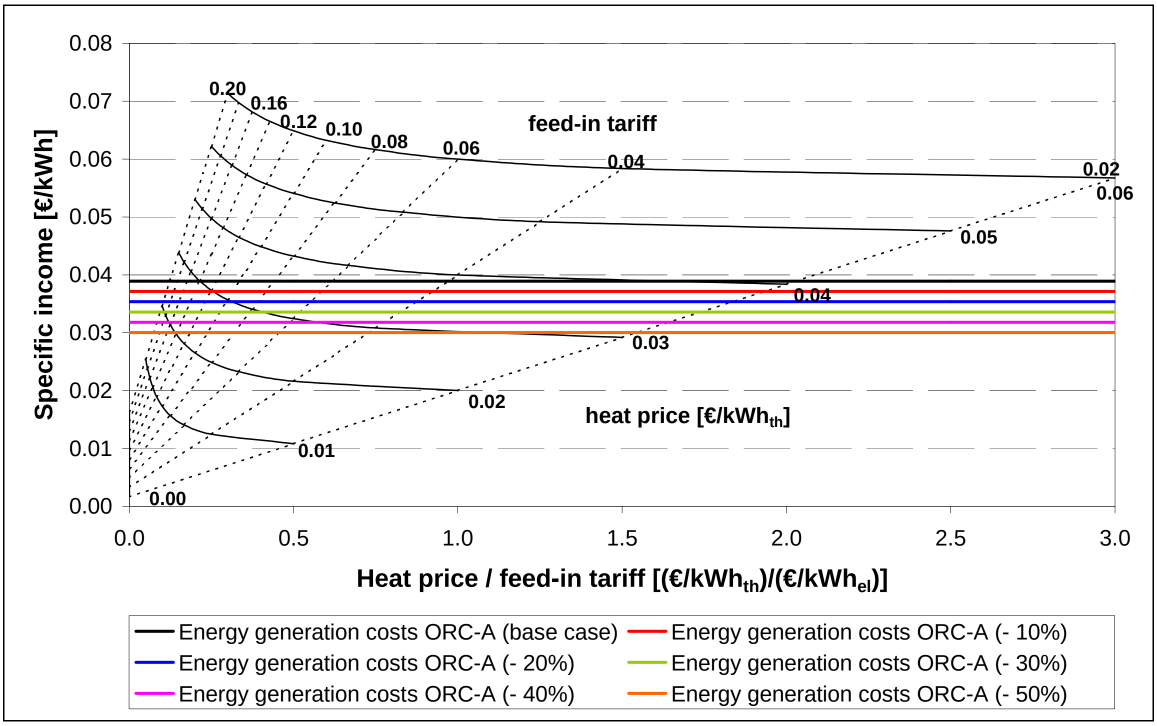


**Figure 4.21:** Specific income of the Austrian ORC process (ORC-A) versus the prices for heat and electricity sold as well as the influence of investment costs/subsidies

Explanations: diagram valid for an annual heat production of about 62.2 GWh/a and an annual electricity production of about 5.5 GWh/a; heat price ex plant

The influence of the heat price and the feed-in tariff on the specific income of the Austrian ORC process is shown in Figure 4.21. The energy generation costs without consideration of investment subsidies amount to 0.0389 €/kWh.

The feed-in tariff for this Austrian plant amounts to 0.1312 €/kWh$_{el}$ (use of 10% forest wood chips and 90% by-products from sawmills). The heat price ex plant needed under these framework conditions to reach a specific income above the specific costs must at least be 0.031 €/kWh$_{th}$.

The situation for the Austrian steam turbine process is similar (see Figure 4.22). However, with the difference, that process heat is produced. The specific energy generation costs amount to 0.0423 €/kWh (without consideration of investment subsidies).

The feed-in tariff for this Austrian plant amounts to 0.120 €/kWh$_{el}$ (use of 100% by-products from sawmills). The heat price ex plant needed under these framework conditions to reach a specific income above the specific costs must at least be 0.023 €/kWh$_{th}$.

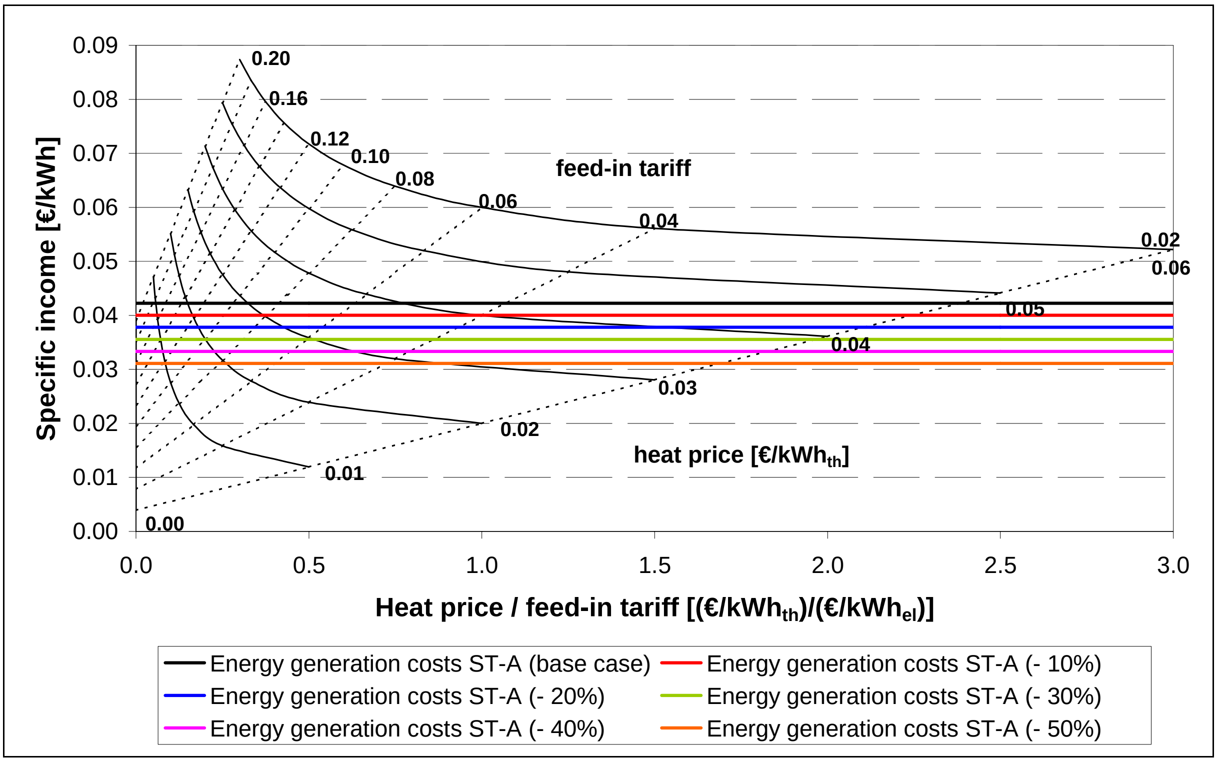


**Figure 4.22:** Specific income of the Austrian steam turbine process (ST-A) versus the prices for heat and electricity sold as well as the influence of investment costs/subsidies

Explanations: diagram valid for an annual heat production of about 101.3 GWh/a and an annual electricity production of about 24.6 GWh/a; heat price ex plant

The interaction between heat price, feed-in tariff and specific income for the Danish steam turbine process is shown in Figure 4.23. The energy generation costs amount to 0.0451 €/kWh (without consideration of the investment subsidies).

The average feed-in tariff achieved for the Danish plant amounts to 0.0853 €/kWh$_{el}$. The heat price ex plant needed for an economic operation amounts to about 0.032 €/kWh$_{th}$. A cost reduction or investment funding reduces the necessary heat price as shown in Figure 4.23.

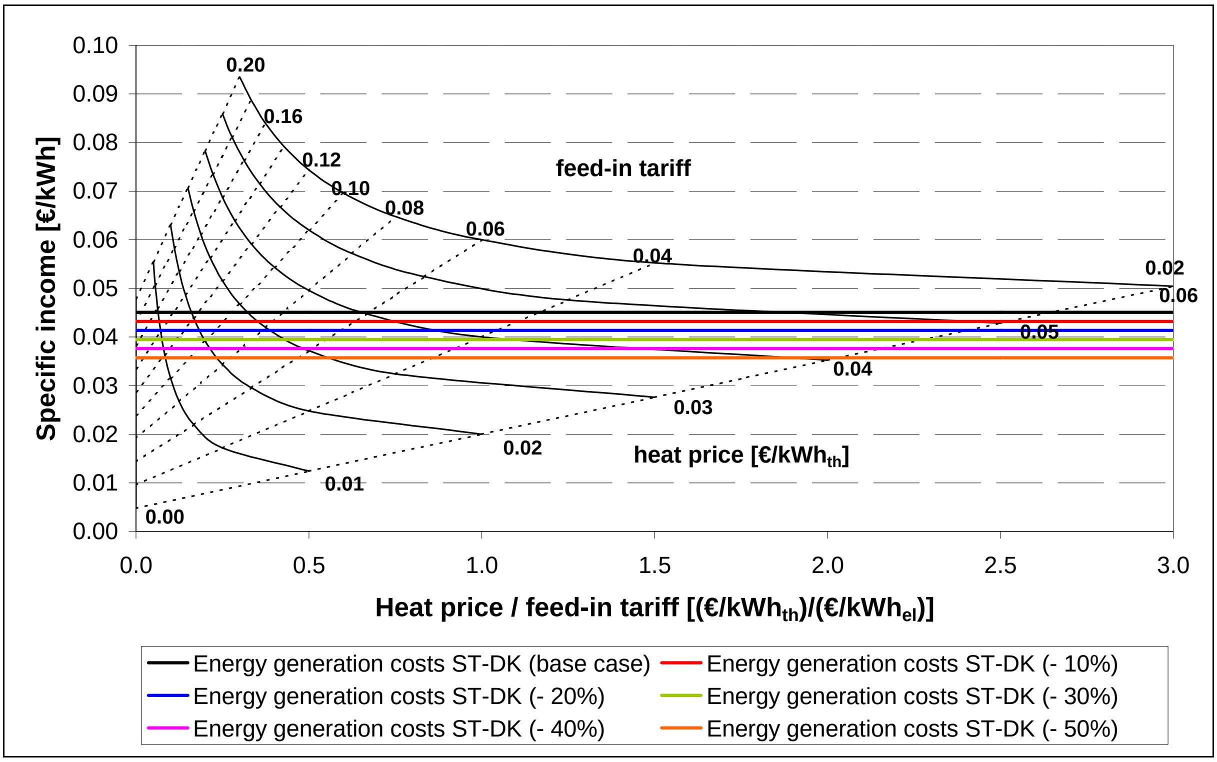


**Figure 4.23:** Specific income of the Danish steam turbine process (ST-DK) versus the prices for heat and electricity sold as well as the influence of investment costs/subsidies

Explanations: diagram valid for an annual heat production of about 101.3 GWh/a and an annual electricity production of about 24.6 GWh/a; heat price ex plant

# 5 Summary, conclusions and recommendations

Within this study, four case studies of biomass CHP plants have been investigated. Case study 1 is a biomass CHP plant based on a steam turbine process with an electric capacity of 4.7 $MW_{el}$. The plant is located in Assens in Denmark and supplies district heat. Case study 2 is also a biomass CHP plant based on a steam turbine process. This plant will be located in Austria and designed for process heat supply. The electric capacity of the plant will be 4.1 MW. Case study 3 is a biomass CHP plants based on an ORC process with an electric capacity of 1.1 $MW_{el}$, which is located in Lienz in Austria and provides district heat. Finally, case study 4, which will also be located in Austria, is a biomass CHP plant based on a Stirling engine process. The electric capacity of the plant will be 70 kW, the plant provides district heat.

Both the steam turbine process as well as the ORC process have already achieved market introduction and are well proven technologies for decentralised biomass CHP plants in the meantime. Stirling engines have not reached market introduction yet, however, several pilot plants already in operation show, that this technology is a promising technology for the small-scale biomass CHP sector in the near future. A first small series production of Stirling engines for biomass CHP plants is planned to be launched in the years 2004/2005.

All processes investigated are controlled by computer based systems, making fully automatic operation possible, which is an important factor to reduce personnel and therefore the energy generation costs. All plants are operated in heat controlled mode.

The plants investigated show no negative ecological impacts. The liquid emissions can easyly be controlled, e.g. by an appropriate waste water treatment. Solid emissions (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). The noise emissions are acceptable and can be controlled by appropriate noise insulations. The gaseous emissions are below the respective emission limits for all plants investigated, therefore also from this point of few no negative ecological impacts must be expected. Moreover, decentralised biomass CHP plants have the great advantage, that they can be operated in a heat controlled way which results in high overall efficiencies (usually above 80%) and which leads to substantial $CO_2$ emission reductions.

The overall annual efficiencies of the plants investigated vary between 83 and 92%. The annual electric efficiencies achieved are between 10.6 and 22.0%. The electricity produced in biomass CHP plants is a valuable second product, but heat utilisation is absolutely necessary and of great relevance for an ecologic and economic operation.

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. In addition, at least 4,000 annual full load operating hours must be achieved from a biomass CHP plant for an economic operation of the plant. 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 3,500 €/$kW_{el}$ for the Stirling engine process, to about 2,700 €/$kW_{el}$ for the ORC process, to about 2,600 €/$kW_{el}$ for the Danish and to about 2,500 €/$kW_{el}$ for the Austrian steam turbine process. The electricity generation costs vary between 0.1068 €/$kWh_{el}$ (Danish steam turbine process) and 0.1418 €/$kWh_{el}$ (Stirling engine process). The specific heat generation costs vary between 0.0256 €/$kWh_{th}$ (Danish steam turbine process) and 0.0512 €/$kWh_{th}$ (Stirling engine process). Most important influencing variables for the electricity generation costs are the investment costs (first priority) and the fuel costs (second priority). For the heat generation costs, the most important influencing variables are the fuel costs (first priority) and the investment costs (second priority). 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. In this context it is important to consider the cost reduction potential for the Stirling engine, the ORC process and the steam turbine process, which is given by a reduction of the investment costs due to enforced market introduction and serial production (production of standardised modules for certain size ranges). In addition, a certain cost reduction potential also exists due to the development potential concerning an increase of the electric efficiencies of the Stirling engine and the ORC process.

Average price ranges for district heat in Austria for heat consumers amount to 0.044 to 0.062 €/$kWh_{th}$. The district heat price level in Denmark is slightly lower. Process heat in Austria costs between 0.018 and 0.033 €/$kWh_{th}$, depending on the fuel price and the quality of the heat (temperature level, hot water or steam). The average costs of the heat distribution for district heating plants amount to about one third of the total heat generation costs. The heat distribution costs for process heating in the wood industry are very low (almost negligible) due to the small network of pipes necessary. Following, heat generation prices ex CHP plant of 0.030 to 0.042 €/$kWh_{th}$ for district heat and slightly below the range for process heat mentioned above have to be achieved.

The Austrian feed-in tariffs depend both on the electric capacity of the CHP plant and on the biomass fuel used. Taking these framework conditions into consideration, the feed-in tariff for green electricity in Austria varies in a broad range between 6.63 and 16.0 €Cent/$kWh_{el}$. If fuel mixtures are used, a proportional feed-in tariff based on the proportional fuel energy input is applied. In Denmark no standard increased feed-in tariffs are available for decentralised CHP plants based on biomass combustion, which are built after the year 2002. Existing CHP plants built before 2002, however, receive an increased feed-in tariff, consisting of different components. Biomass CHP plants receive a market based price. The average payment according to this price is about 4.9 €Cent/$kWh_{el}$. In addition, a subsidy is granted for electric power generation from straw, wood chips or other solid biomass fuels, which amounts to 2.3 €Cent/$kWh_{el}$. Finally, the $CO_2$ tax of 1.3 €Cent/$kWh_{el}$ is refunded which results in a total increased feed-in tariff for electricity from biomass in Denmark of about 8.5 €Cent/$kWh_{el}$. This tariff is independent from the plant size and the fuel used.

Taking the Austrian framework conditions regarding average heat prices ex plant into consideration, the feed-in tariffs valid are adequate for an economic operation and increased market introduction of biomass CHP plants and also consider different feed-in tariffs for different fuel types, which is of special relevance concerning fuel flexibility and enforced utilisation of fuel potentials not yet exploited (e.g. forest wood chips).

Under the current framework conditions in Austria the erection and operation of decentralised biomass CHP plants is economically meaningful and possible. However, the heat related investment subsidies and the increased feed-in tariffs currently available 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.

Therefore, the support of decentralised biomass CHP plants is very important. An appropriate approach already successfully implemented in Austria, Germany and Italy seems to be the support by increased feed-in tariffs, which are secured for at least 10 years from start-up of the plant in combination with investment subsidies for the heat related part of the plants. These subsidies can then be gradually reduced in dependence of market introduction and market penetration (as soon as small serial productions are achieved).

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