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Cogeneration (CHP) TechnologyPortrait

*Institute for Thermal Turbomachinery
and Machine Dynamics*



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I. Technology Profile

The Technology Profile is designed to give an overview of the different possibilities for production and utilization of electricity and heat through combined heat and power (CHP, cogeneration).

Besides technologies that are ready for the market, like e.g. gas turbine cogeneration, you will also find an overview of technologies in the stage of development or in the testing phase.

The Technology Profile is further designed to help people interested in CHP find the type of cogeneration plant suitable for their needs.

1 What is cogeneration (CHP)?

CHP plants provide the consumer with the two most important types of energy, namely with electrical power and heat. The heat obtained during power generation is used for supplying heating water, steam or drying heat. By utilizing this waste heat, losses can be kept low and therefore consumption of primary energy can be reduced. The following figure explains this connection using the example of a gas and steam turbine plant.

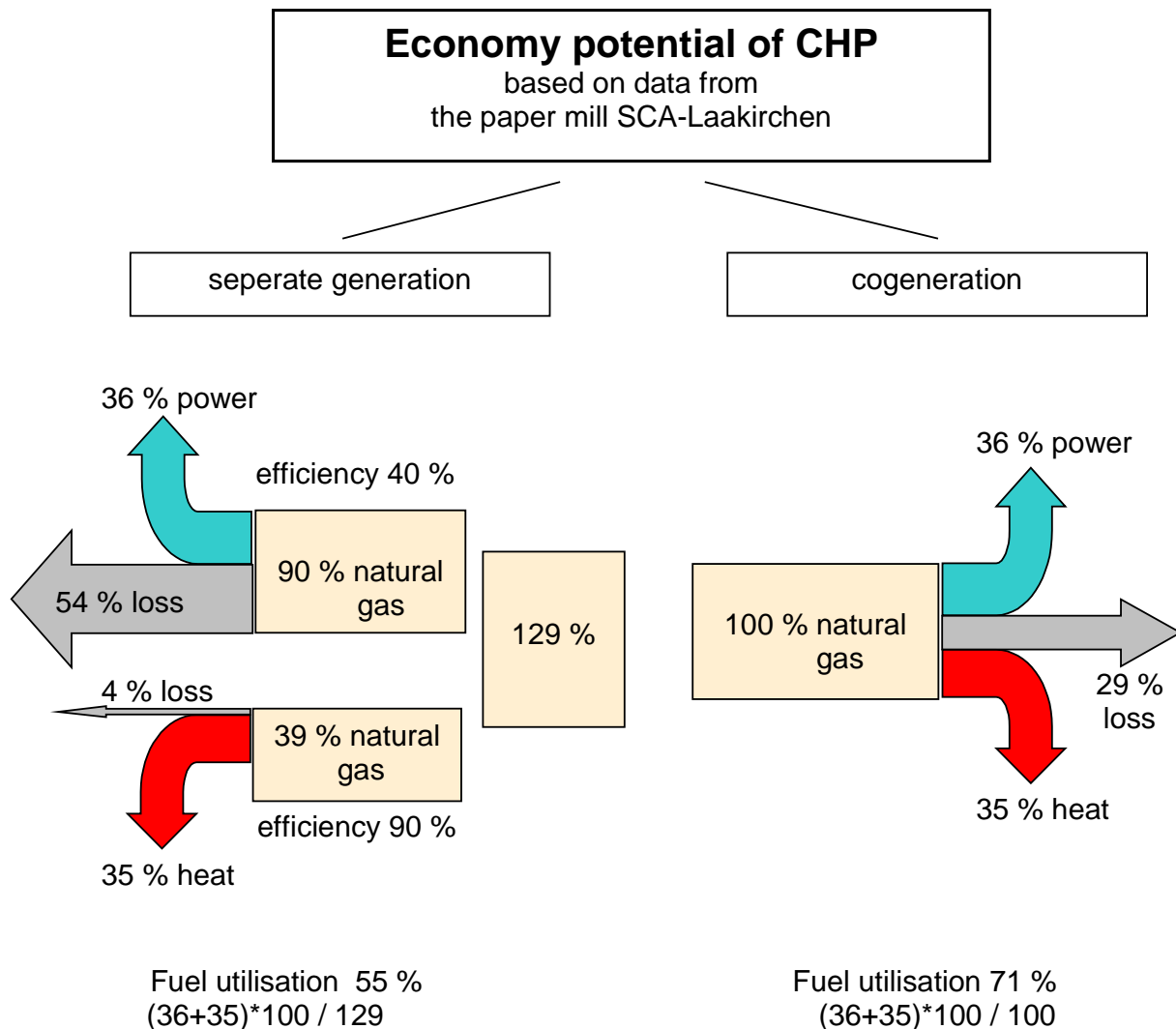


Figure 1: Economy potential of CHP (source OKA)

Comments on figure 1:

This figure is based on a comparison of fuel consumption for the production of heat and power with and without cogeneration.

Using e.g. a gas and steam turbine cycle during which waste heat is utilized, primary energy input – at the same level of heat and power production - is significantly lower than in separate generation of heat and power. The above example shows that the fuel

utilization of a CHP plant amounts to 71 % whereas it only amounts to 55% in separate generation. This leads to a sustainable use of primary energy which results in a reduction of emissions of pollutants to the environment.

Design options:

CHP plants can basically be designed in the following ways

- heat-oriented design and operation mode
- power-oriented design and operation mode
- cost-oriented design and operation mode

Heat-oriented design and operation mode:

In the heat-operated application of a CHP plant the heat requirements are determined and the whole plant is aligned with them. The surplus power produced will be injected into the public power network.

Power-oriented design and operation mode:

In the power-operated application of a CHP plant the focus is on the power requirements. The utilized heat will vary depending on the power production.

Cost-oriented design and operation mode:

The lowest operating costs of a CHP plant are achieved using the cost operated design and operation mode. The annual total costs (investment costs and running costs) are calculated for different design variants, later the design with the lowest total costs will be implemented. Possible surplus or underproduction of power and heat can be evened out with the help of the public power and heat network.

Yet it is of great importance that the plant is run at full load. Therefore most plants are dimensioned to cover the basic load.

To cover peak heat demand usually a peak boiler providing the necessary heat is used. Another possibility is to cover the demand by connecting to the public network.

Incidental peak loads regarding power requirements can then for example be covered by the public power network.

The extra costs resulting from this have to be taken into account in the evaluation of economic efficiency.

Another possibility would be to use the plant only for peak load coverage. As peak loads are particularly expensive, this possibility represents a good option to the above mentioned designs and operation modes.

CHP plants are of great significance to power and heat generating enterprises (higher output) because of the primary energy savings and other reasons which will be dealt with later in more detail. They do also offer attractive options for providing smaller outputs of power and heat like they are needed in industrial companies, laundries, housing estates etc. In the following particularly the decentralized application of CHP will be discussed in more detail while the special needs of public energy supply companies will not be described any further.

2 Different concepts of CHP plants

There are various concepts allowing a process to be carried out on the basis of cogeneration.

The most important types of plants are outlined in figure 2.

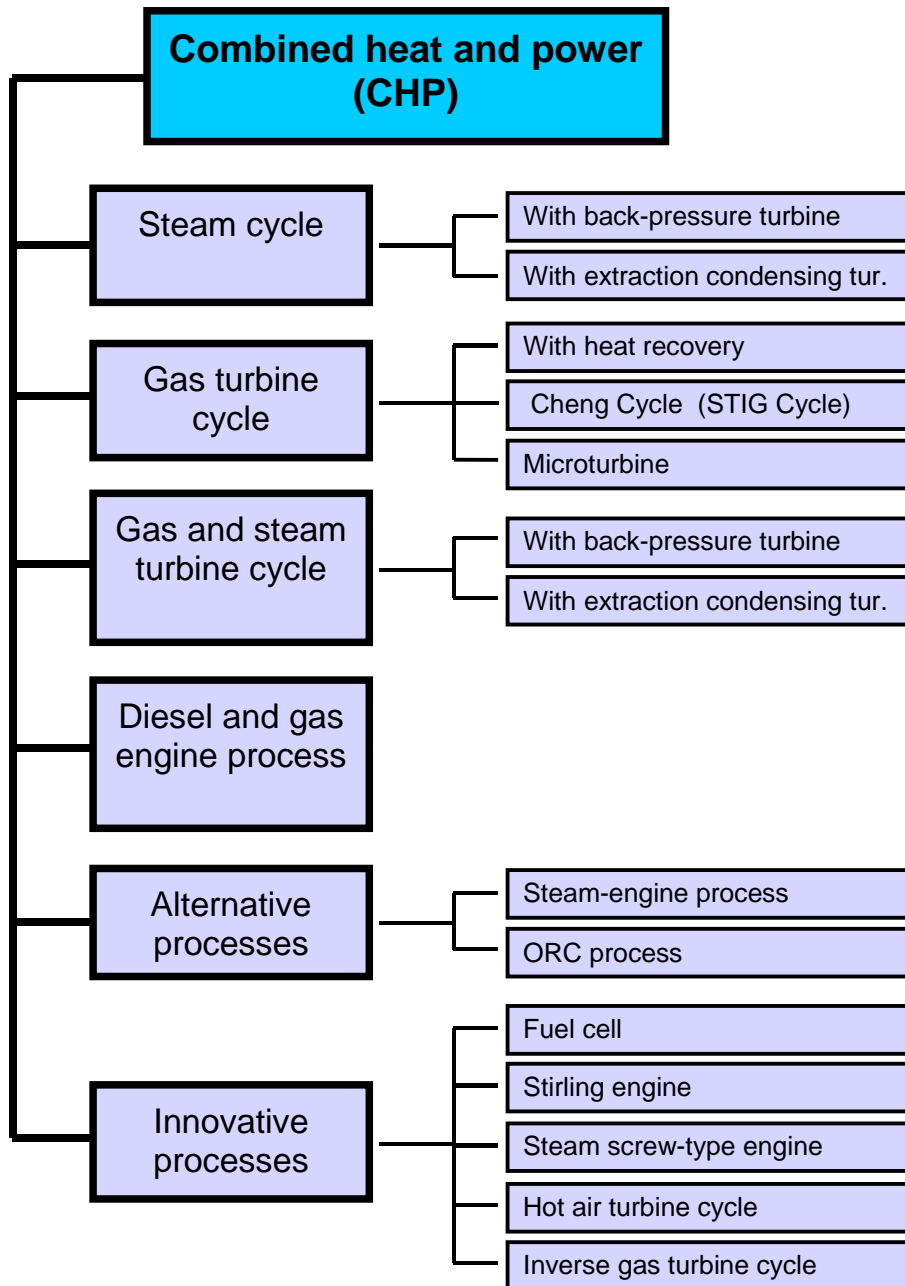


Figure 2: CHP concepts

The microturbine process, the fuel cell as well as the gas and diesel engine process are typical exponents for decentralized plants that can be run as block heat and power plants. A block heat and power plant is a CHP plant which is completely installed, delivered and run as a “block”.

Design options for a block CHP plant:

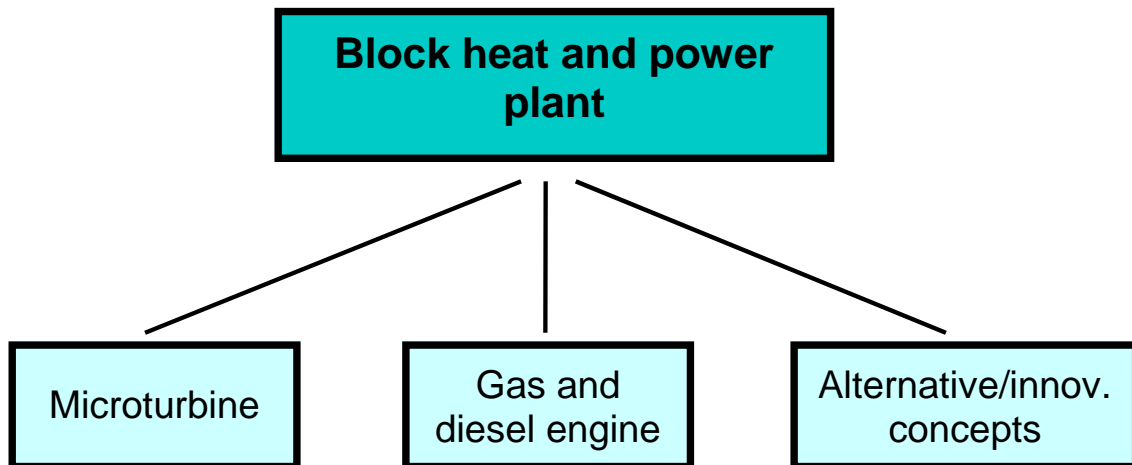


Figure 3: Block heat and power plant processes

2.1 CHP with steam turbine cycle

Basic principle:

- Conversion of mechanical energy (turbine) into electrical energy with the help of a generator.
- Utilization of the heat energy of the steam discharging from the turbine to provide heat.

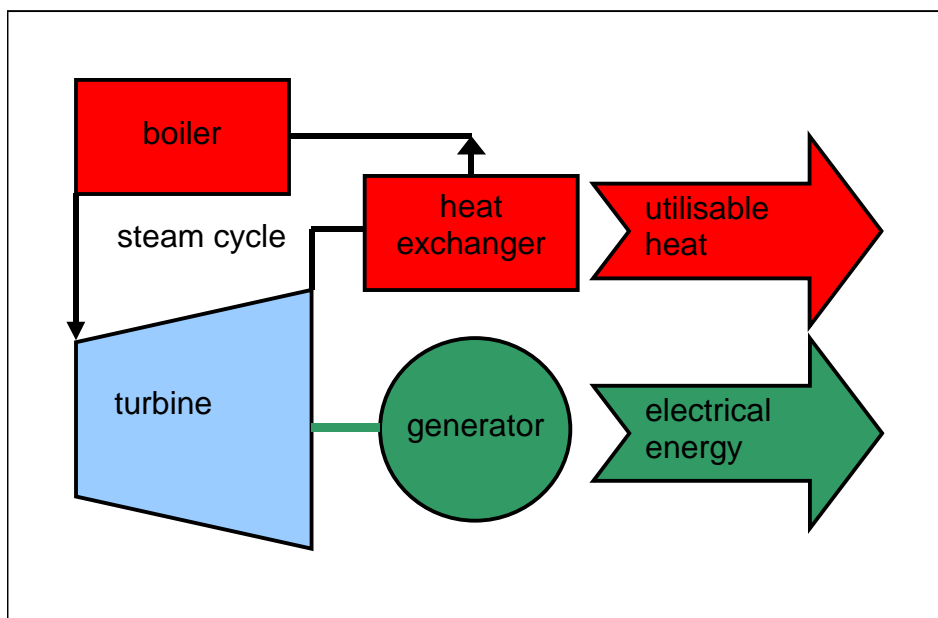


Figure 4: Principle of CHP with steam turbine cycle

The basis for this type of CHP is the steam turbine cycle which is explained in more detail in the following.

Steam turbine cycle:

The main elements of a steam turbine cycle are: the boiler with super-heater, the turbine, the condenser and the feed water pump.

The water is vaporized in the boiler and later brought to the desired temperature in the super-heater. This live steam then is flowing through the turbine which drives the generator to generate power. In the condenser the steam discharging from the turbine condenses and is brought to process pressure with the help of the feed water pump. Afterwards the steam is fed into a boiler whereby the cycle is closed.

As a cooling medium in the condenser usually river water or surrounding air will be used, and the released condensation heat remains unused.

To use this waste heat there are a series of different configurations allowing the usage of any incidental heat. It is crucial though that for using waste heat a higher pressure and temperature level is required.

The following figure shows a section through a steam turbine for high output which consists of a high pressure-, a medium pressure- and a low pressure section . In this kind of machines about 70 % of live steam from the low pressure sections is passed on to the condenser, the remaining 30 % are used for preheating feed water and afterwards are fed to the steam cycle.

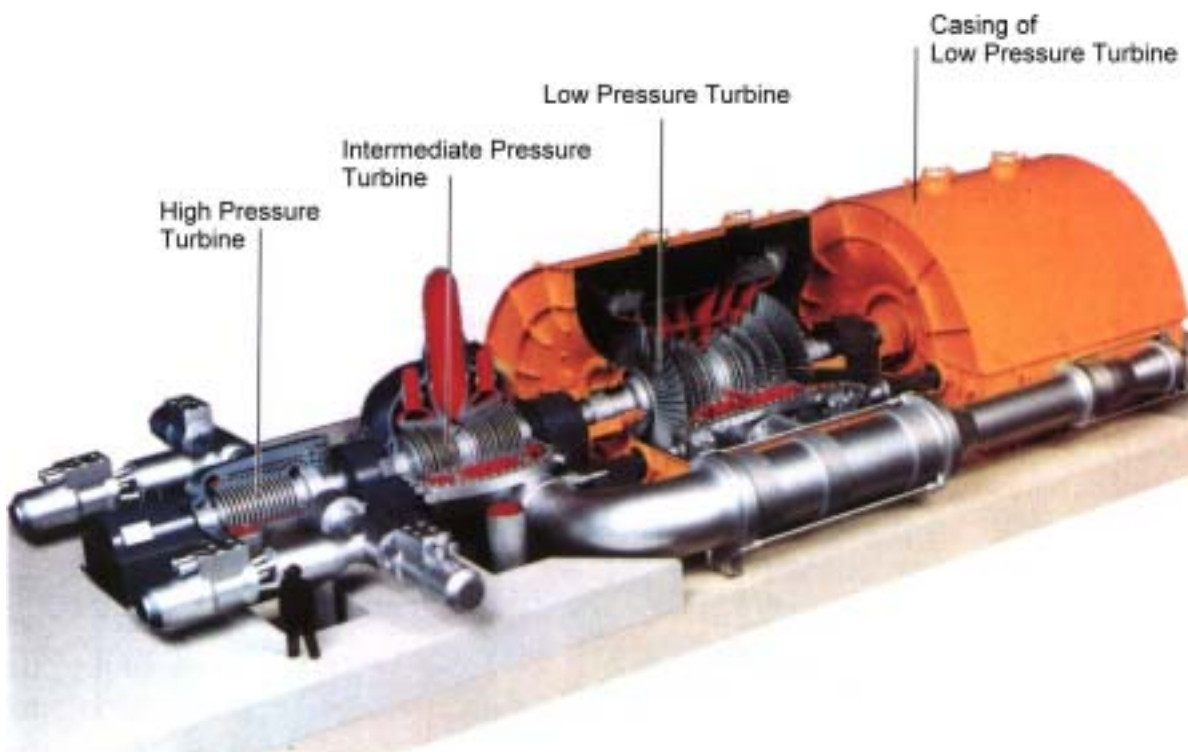


Figure 5: Section through a steam turbine

The following figure shows the rotor of a steam turbine with an output of 8 MW_{el}.
Source: Peter Brotherhood Ltd



Figure 6: Rotor of a steam turbine with 8 MW_{el}

In figure 7 a plant with a condensation steam turbine is depicted. The plant has an electrical output of 10MW.



Figure 7: A condensation steam turbine with 10 MW_{el}

There are two main types of CHP plants based on steam cycle:

- Steam cycle with a back pressure turbine
- Steam cycle with an extraction condensing turbine

For lower heat output steam is extracted by tapping the steam turbine and therefore the technical design is simpler compared to an extraction condensing turbine. Yet pressure and temperature during the tapping process can only be kept when run in full load.

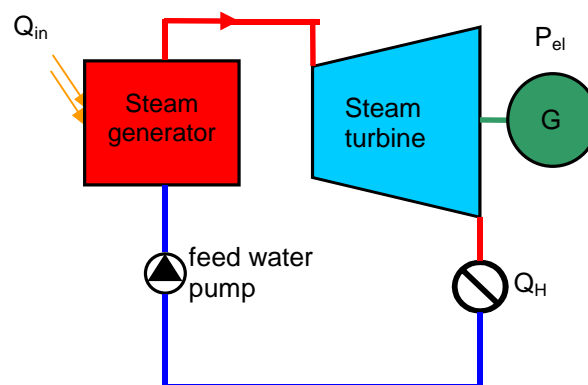
2.1.1 CHP with steam cycle and back pressure turbine

Functionality:

In a turbine (back pressure turbine) the hot steam produced in the boiler is expanded down to back pressure which results from the desired temperature of the process heat. Thus it is performing mechanical work for the generator. The generator transforms mechanical energy into electrical energy. Heat exchangers outside the turbine can be used to pass the remaining heat quantity of the steam to another medium (e.g. water) with the help of condensation. This heat quantity can now be utilized in different ways. Later the condensed steam is fed to the steam generator again with the help of water preparation through a feed water pump. Thus the cycle starts again. Valves on the turbine are used for control.

This design is mostly used when a more or less constant amount of heat is required.

Set-up of a simple steam cycle with back pressure turbine :



P_{el}	electrical output	—	feed water
Q_H	heat consumer	—	steam
Q_{in}	heat input	—	shaft
G	generator		

Figure 8: Steam cycle with back pressure turbine

Application

- Industry and power supply enterprises (electricity, district heating), (outputs of $\sim 0,5-30 \text{ MW}_{el}$ and more)
- When a constant amount of heat is required (because of little possibilities of control)
- Very often there are various steam turbines arranged on a line in order to allow using one or more turbines according to the requirements.

2.1.2 CHP with steam cycle and extraction condensing turbine

Functionality:

The functionality is similar to that of a cycle with back pressure turbine with the difference that here the extraction steam for heat generation is not taken from the rear part but from the middle part of the turbine. This has the advantage that heat and power generation can be adjusted to the different requirements.

With the help of valves the extraction pressure can be adjusted right at the extraction point so that the required steam conditions for heat generation can also be kept when run at part load. This is the advantage over the topping steam turbine where the conditions vary according to the load point.

To meet the demands of high heat requirements all steam for heat generation can be taken from the extraction point. For low heat requirements this type of turbine can be used like a conventional condensing turbine. Various other operational modes are possible due to valve control.

Set-up of a simple steam cycle with an extraction condensing turbine:

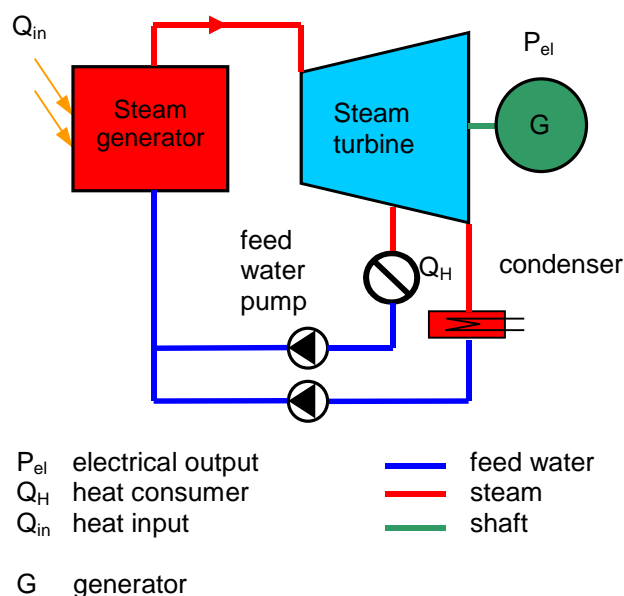


Figure 9: Steam cycle with extraction condensing turbine

Application

- medium to higher output (~0,5-10 MW_{el} and more)
- variable heat and power requirements

2.1.3 General information on CHP with steam turbine cycle**Possible fuels**

- coal
- petroleum
- biomass, garbage
- basically every fuel is possible that can be burnt in a boiler

Advantages

- basically every fuel can be used
- well-established technology
- size of plants is not limited

Disadvantages

- low electrical plant efficiency
- bad part load performance
- expensive operation

In table 1 some data from a plant within a certain range of performance is outlined.

Plant size ~ 1 MW _{el}	Unit	Value
Specific investment costs (with back pressure turbine)	[EUR/kW _{el}]	~ 1.500
Specific maintenance costs	[EUR/kWh _{el}]	~ 0,007
Electrical efficiency _{el}	[%]	10 - 20
Overall efficiency	[%]	70 - 85
Emissions (NOx) – coal fired	[mg/Nm ³]	~ 450 - 600

Table 1: Data of a back pressure steam plant

Best operational mode:

Power or heat operated.

Very often various steam turbines are arranged on one line so that one or more machines can be used according to power demands. Therefore it is possible to run the turbines close to the optimal operating point.

Steam conditions:

Decentralized CHP plants of low to medium output (output ~1 - 10 MW)

Steam pressure: 30 - 70 bar

Live steam temperature: ~ 400 – 500 °C

Control:

Control of the steam turbine can be reached through the following two possibilities:

- Through a throttle valve in front of the turbine which controls steam pressure of the flow leading from the steam line to the individual turbines as well as their output.
- Through nozzle group control in the individual turbine, which allows individual nozzles before the first blade wheel (control wheel) to be switched in or off. Thus the mass flow rate of the other stages as well as the output can be regulated.

Maintenance:

- Inspection of the turbines and the steam pipelines for irregularities once a week
- Every 5 years a more extensive one-week revision should be conducted
- Regular inspection of steam conditions

Ecological aspects:

During the vaporization process of water the salts contained in the water remain in the boiler. In order to avoid high salinity (scale build-up!) water is continuously desalinated (1-5 % of the circulated feed water).

In addition it is necessary to discharge the mud resulting from material abrasion and the remaining salts in the water (manually or automatically).

When discharging sewages into a stream or into the sewerage system, the corresponding legal regulations have to be complied with.

Weak points:

a) Thermodynamics:

High electrical efficiency can only be achieved through high live steam pressure and temperature (170 bar, 600°C) at given condensation conditions. Since this requires expensive high temperature material, CHP plants of low and medium output are designed for lower live steam conditions.

b) Operation:

The operation of a steam plant is relatively expensive because according to the Austrian laws for steam boiler operation there always has to be a steam guard present.

c) Biomass utilization:

Live steam temperature in biomass plants is limited because of the increased danger of corrosion due to alkali metals, sulphur and chlorine contained in the fuel.

Variations in the water content of biomass can lead to changes in temperature and mass flow of the steam. In order to prevent this, it has to be taken into account in the control system.

Stage of development/outlook:

Industrial steam turbines are well-established and therefore used in big quantities all over the world.

Trends are definitely going towards higher temperatures resulting in increased output . Therefore the development of high temperature proof material is of great importance.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	ready for the market ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	low ²⁾

¹⁾ Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

²⁾ 1 year...high, 2 years...medium, 3 years...low

2.2 CHP with gas turbine cycle

Basic principle:

- Conversion of mechanical energy (turbine) into electrical energy with the help of the generator.
- Utilization of gases escaping from the turbine for heat supply.

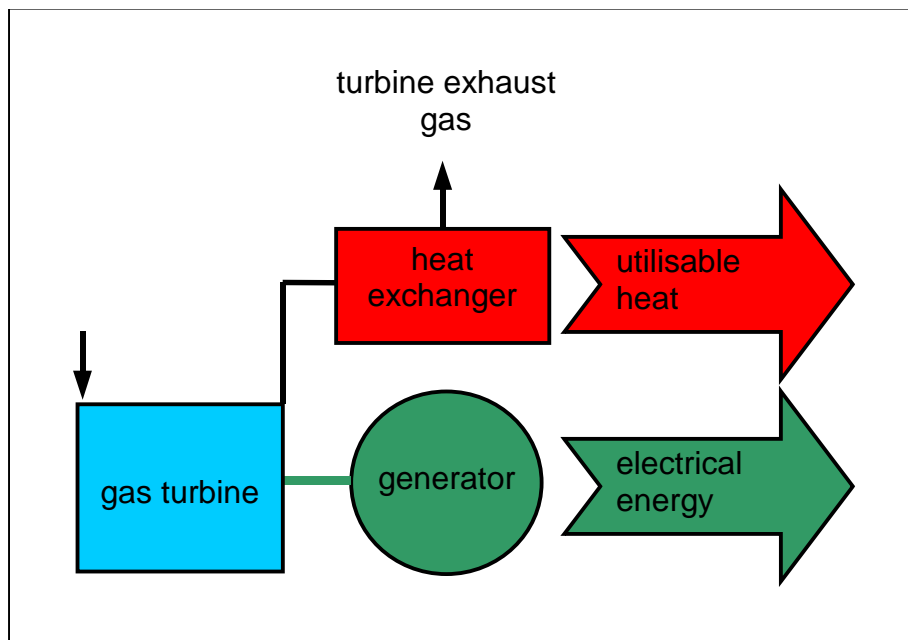


Figure 10: Basic principle of CHP with gas turbine cycle

The basis for this type of CHP is the gas turbine cycle which is explained in more detail in the following.

Gas turbine cycle:

The main elements of the gas turbine cycle are: the compressor, the combustion chamber and the turbine.

Surrounding air is sucked in and compressed in a compressor. Subsequently it is fed into the combustion chamber where a combustion reaction takes place when fuel (gas, oil...) is added. The exhaust gas resulting from the combustion is expanded in the turbine. The turbine drives the compressor as well as the generator responsible for power generation. The exhaust gas leaves the turbine with a temperature of about 400-600°C and in the simple gas turbine cycle escapes into open air without any further utilization.

For further utilization of this heat a heat exchanger transferring heat energy to another medium (mostly water) is required. For this process there are various set-ups described in more detail in the following.

The following figure shows a gas turbine from Siemens (Siemens V64.3) for higher output.

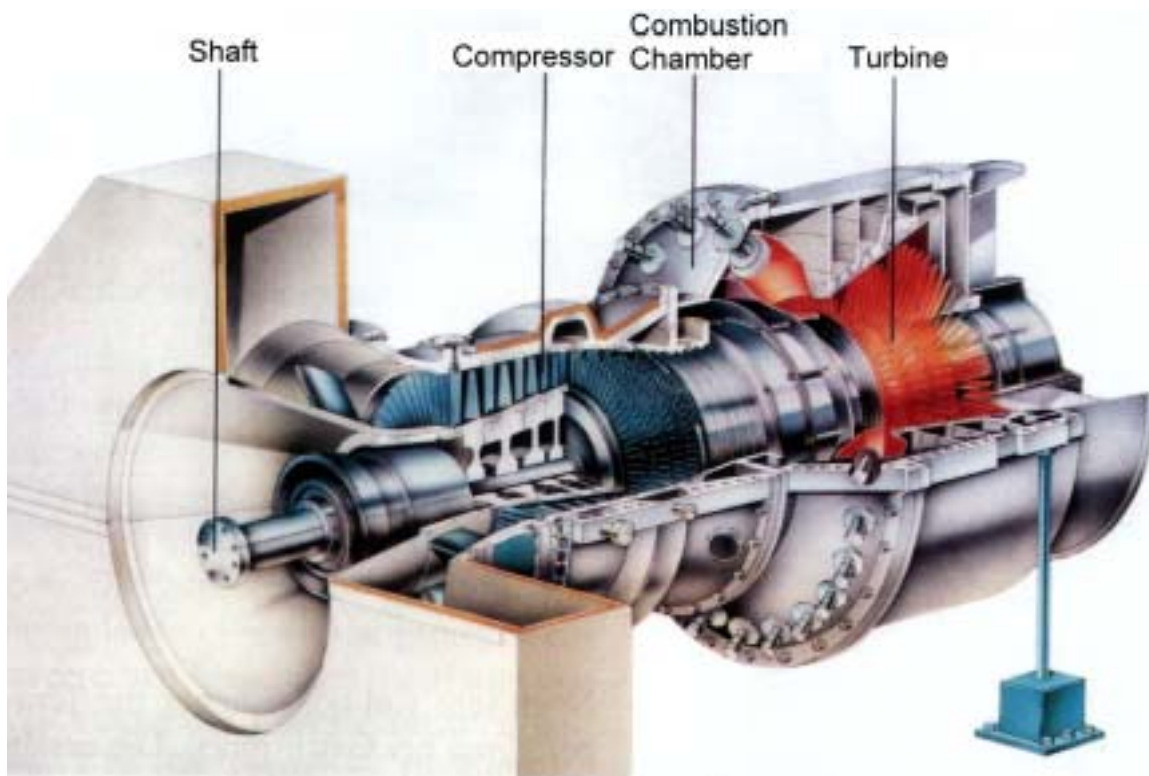


Figure 11: Section through a gas turbine of higher output

2.2.1 Gas turbine cycle with heat recovery

Functionality:

In this process the heat content of the turbine exhaust gases is entirely used for supplying heat. This heat is then available for heating purposes, drying processes or other processes requiring heat (e.g. absorption refrigerating machines).

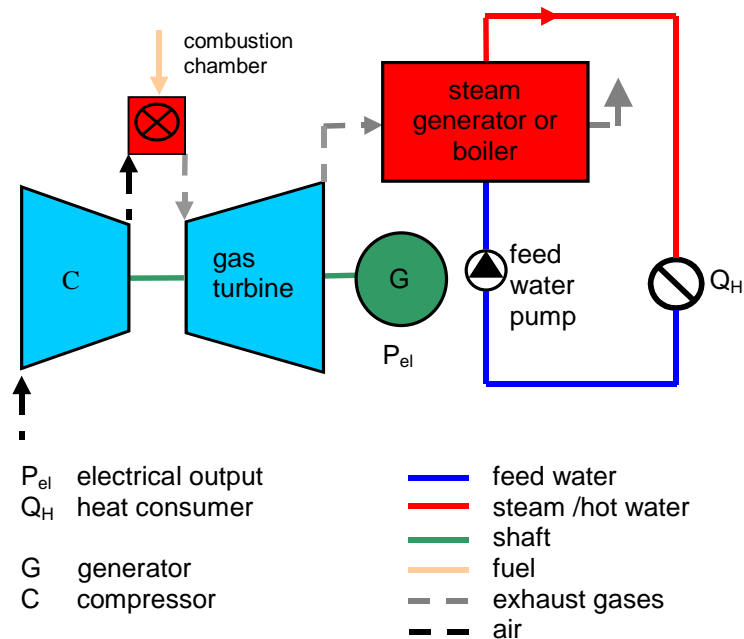
Set-up of a gas turbine cycle with heat recovery:

Figure 12: Gas turbine cycle with heat recovery

Application	
<ul style="list-style-type: none"> for generation of electrical output and heat from $\sim 30 \text{ kW}_{el}$ when a relatively constant amount of heat is required 	
Possible fuels	
<ul style="list-style-type: none"> gas petroleum gasification of coal ... 	

In table 2 some data from a plant within a certain range of performance is outlined.

Plant size $\sim 20 \text{ MW}_{el}$	Unit	Value
Specific investment costs	[EUR/ kW_{el}]	~ 1.200
Specific maintenance costs	[EUR/ kWh_{el}]	$\sim 0,007$
Electrical efficiency $_{el}$	[%]	25 - 35
Overall efficiency	[%]	70 - 92
Emissions (NOx)	[mg/ Nm^3]	~ 25

Table 2: Data of a gas turbine plant with heat recovery

Best operational mode:

Power or heat operated.

Picture of a gas turbine:

The picture shows a gas turbine type FP-16-G with an electrical output of about 1,6 MW.
Source: FP Turbomachinery



Figure 13: Gas turbine FP-16-G

Operating state:

Gas turbines of medium and higher output (~20 MW_{el} and more)

Peak temperature: ~1200 °C

Control:

Control of the gas turbine is mostly achieved through the amount of fuel injected into the combustion chamber of the turbine. To cover increased heat requirements there is an auxiliary firing equipment in the waste heat boiler.

Stage of development/ outlook:

CHP plants with gas turbines are well-established and therefore used in big quantities all over the world.

Trends are definitely going towards higher temperatures and pressures resulting in increased output and efficiency.

Some important parameters regarding stage of development and outlook are summed up in the following table

Stage of development/ outlook	Status
Present stage of development	ready for the market ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	low ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.2.2 Cheng-Cycle (Steam Injected Gas Turbine, STIG)

Functionality:

The so-called Cheng-Cycle (STIG-Cycle) offers another variant of the gas turbine cycle with utilization of waste heat. The generated steam is partly fed into the combustion chamber and the turbine. Thus output and electrical efficiency are significantly increased. It also allows an adjustment to the heat requirements of the plant so there can be more or less steam fed into the gas turbine according to the requirements.

Set-up of a Cheng-Cycle:

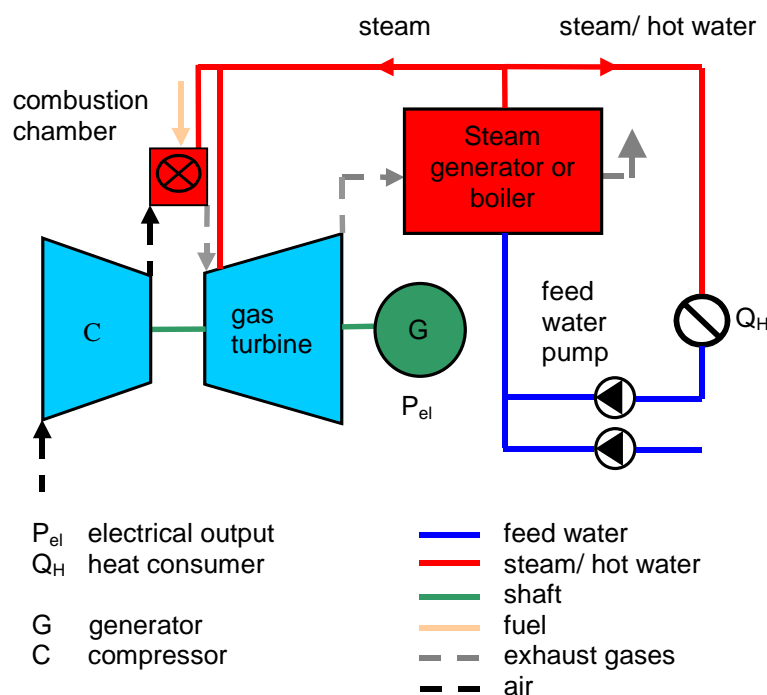


Figure 14: Set-up of a Cheng-Cycle

Application
<ul style="list-style-type: none"> • variable power and heat requirements • for higher output (~ 20 MW_{el} and more)
Possible fuels
<ul style="list-style-type: none"> • gas • petroleum • gasification of coal
Advantages
<ul style="list-style-type: none"> • released heat can be varied • increase in gas turbine output and electrical efficiency
Disadvantages
<ul style="list-style-type: none"> • Processing of steam fed into the gas turbine is expensive

In table 3 some data from a plant within a certain range of performance is outlined.

Plant size ~ 20 MW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 1.300
Specific maintenance costs	[EUR/kWh _{el}]	~ 0,007 – 0,011
Electrical efficiency _{el}	[%]	~ 40
Overall efficiency	[%]	~ 70 - 85
Emissions (NOx)	[mg/Nm ³]	~ 25

Table 3: Data of a Cheng-Cycle

Best operational mode:

Power or heat operated.

Operating state:

Gas turbines of medium and higher output (~20 MW_{el} and more)

Peak temperature: ~1100 °C

Control:

Control of the electrical output is achieved through fuel supply into the combustion chamber of the gas turbine and through variation of the amount of steam injected into the turbine.

Control of the released heat is achieved through variation of the amount of steam injected into the turbine.

Stage of development/ outlook:

CHP plants with Cheng-Cycle are well-established and therefore used in big quantities all over the world.

Trends are definitely going towards higher temperatures and pressures resulting in increased electrical output and efficiency.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	Status
Present stage of development	ready for the market ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	medium ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.2.3 Microturbine

So-called microturbines offer an interesting possibility for the realization of lower output (~30-300 kW and less).

Functionality:

In contrast to a gas turbine cycle with heat recovery, block construction is possible because of the compactness of the plant. Therefore this microturbine plant can also be seen as a block heat and power plant. Yet electrical efficiency of the plant is relatively low (~15-25%) because of its small size.

In order to achieve good electrical efficiency despite low peak temperatures usually a heat exchanger (recuperator) is used for preheating combustion air with the help of hot turbine exhaust gas. Another heat exchanger is used for obtaining process heat. If the first heat exchanger can be switched off the released process heat can be increased at the expense of electrical efficiency if required. This enables a very good adjustment to variable heat requirements.

Set-up of a microturbine:

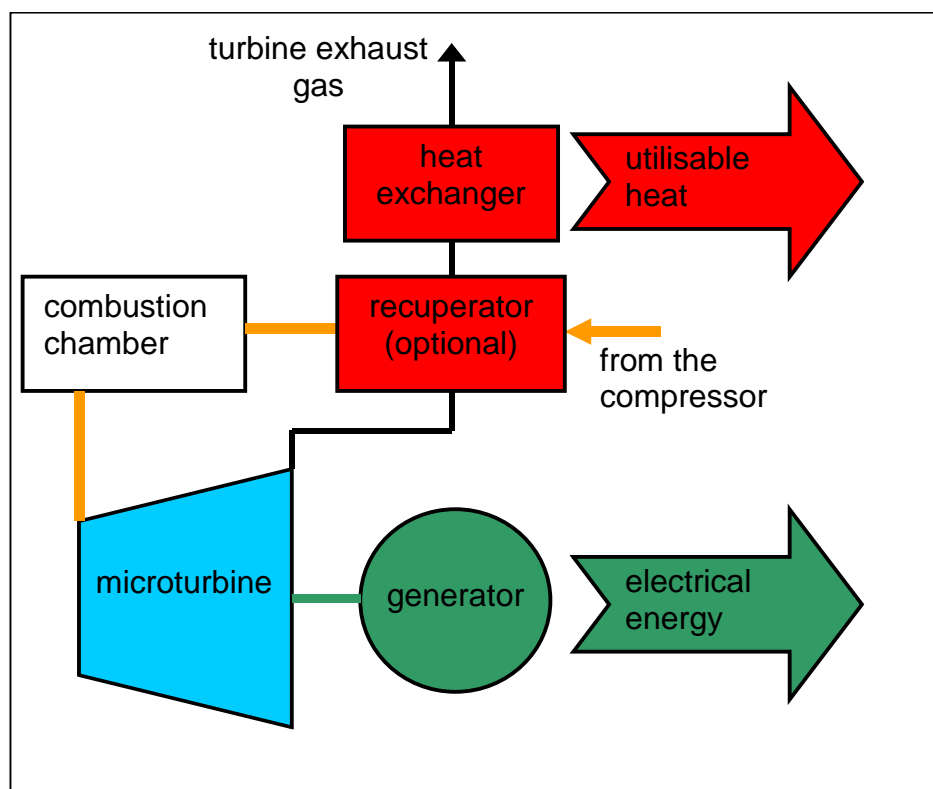


Figure 15: Diagram of a microturbine

Besides block heat and power plants equipped with gas or diesel engines, recently also microturbines are gaining importance as another variant of a block CHP plant. If, however, high waste heat temperatures are required the microturbine represents the better solution.

Figure 16 shows the temperature level at which heat is available for different concepts. A high temperature level is usually put down to worse electrical efficiency. Therefore bigger heat quantity, that has to be taken in account in the design, is obtained in the gas turbine if electrical efficiency of the gas turbine and the internal combustion engine are equal.

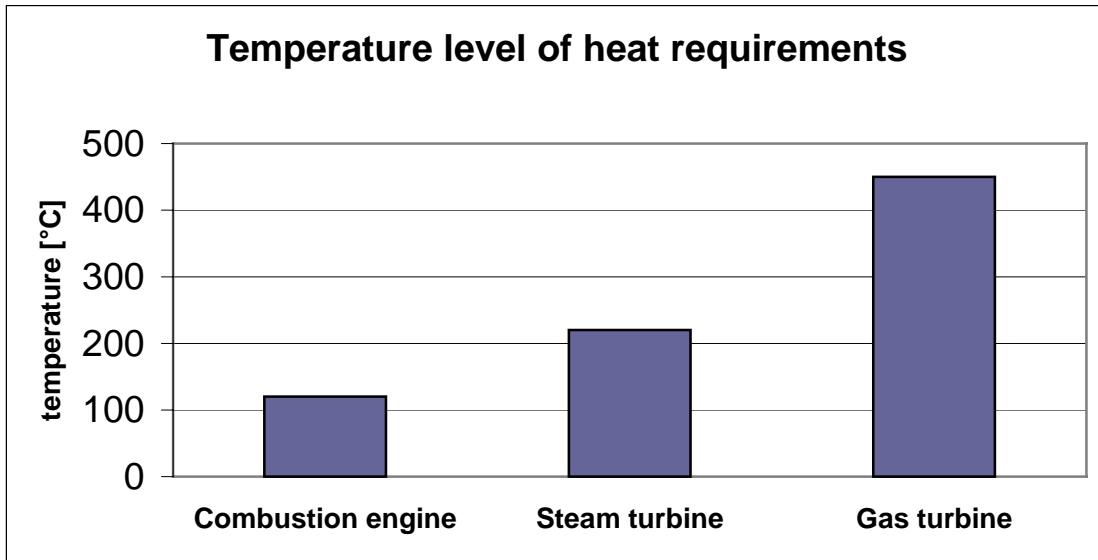


Figure 16: Temperature level of heat available for different CHP plants

Application of microturbines

- steam generation in small boiler plants
- high temperature water networks over 100°C
- drying plants
- hospitals
- laundries
- local heat networks
-

Possible fuels for microturbines

- natural gas
- fuel oil
- liquid gas
- sewage gas
- firedamp
- petroleum associated gas
- ...

Advantages
<ul style="list-style-type: none"> • compact design • low maintenance costs at maintenance intervals of at least 8000 hours of operation • easy installation Because of compact design and low plant weight it is possible to keep a small plant area. • adjustment of heat and power requirements is possible • quiet because there are no low frequency noise emissions
Disadvantages
<ul style="list-style-type: none"> • full market maturity of the technology is not yet achieved

In table 4 some data from a plant within a certain range of performance is outlined.

Plant size 30-75 kW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	650 – 1.100
Specific maintenance costs	[EUR/kWh _{el}]	0,005 – 0,007
Electrical efficiency _{el}	[%]	15 - 25
Overall efficiency	[%]	70 - 90
Emissions (NO _x) ¹⁾	[mg/Nm ³]	20

¹⁾ based on 15% O₂ in exhaust gas

Table 4: Data of a microturbine

Best operational mode:

Power or heat operated.

Picture of a microturbine:

The picture shows a microturbine type FP-CS-30 with a heat output of about 69 kW.
Source: FP Turbomachinery



Figure 17: Microturbine FP-CS-30

Operating state:

For microturbines of low output (~55 kW_{el}):

Exhaust gas temperature: ~600 °C

Pressure ratio: 3 - 5

Rotational speed: 105.000 rpm

Control:

Control of the gas turbine is usually achieved through fuel supply.

Maintenance:

(Source Capston)

Part	Action	Maintenance interval
Air filter and fuel filter	replace	8.000 hrs.
Turbine exhaust gas thermocouple	replace	16.000 hrs.
Ignition	replace	16.000 hrs.
Fuel injection	replace	16.000 hrs.

Stage of development:

The breakthrough of the microturbine has not yet been achieved in Austria. However in the USA they are often used and have therefore already reached high technological maturity.

Because of their easy handling and high overall efficiency they will soon win recognition in Austria too and will offer an alternative possibility to block heat and power plants with internal combustion engines.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/outlook	Status
Present stage of development	Demonstration stage to market maturity ¹⁾
Short term cost reduction potential	high ²⁾
Short term development potential	medium ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.2.4 General information on the gas turbine cycle

Ecological aspects:

When using natural gas in gas turbines very low emission values can be obtained. The NO_x content amounts to 25 ppm, the CO content can be further reduced with the help of a downstream catalyst.

Weak points:

Thermodynamics:

High efficiency of gas turbines can be achieved through high turbine inlet temperatures of up to 1300 °C. This process requires expensive material and complex technologies for blade cooling. Therefore gas turbines of highest efficiency are very maintenance intensive.

2.3 CHP with combined steam-and-gas cycle

Basic principle:

- Mechanical energy (gas turbine and steam turbine) is converted into electrical energy with the help of a generator.
- Hot gases escaping from the gas turbine are used for generating steam for the steam turbine.
- Heat energy of the steam escaping from the turbine is used for providing heat.

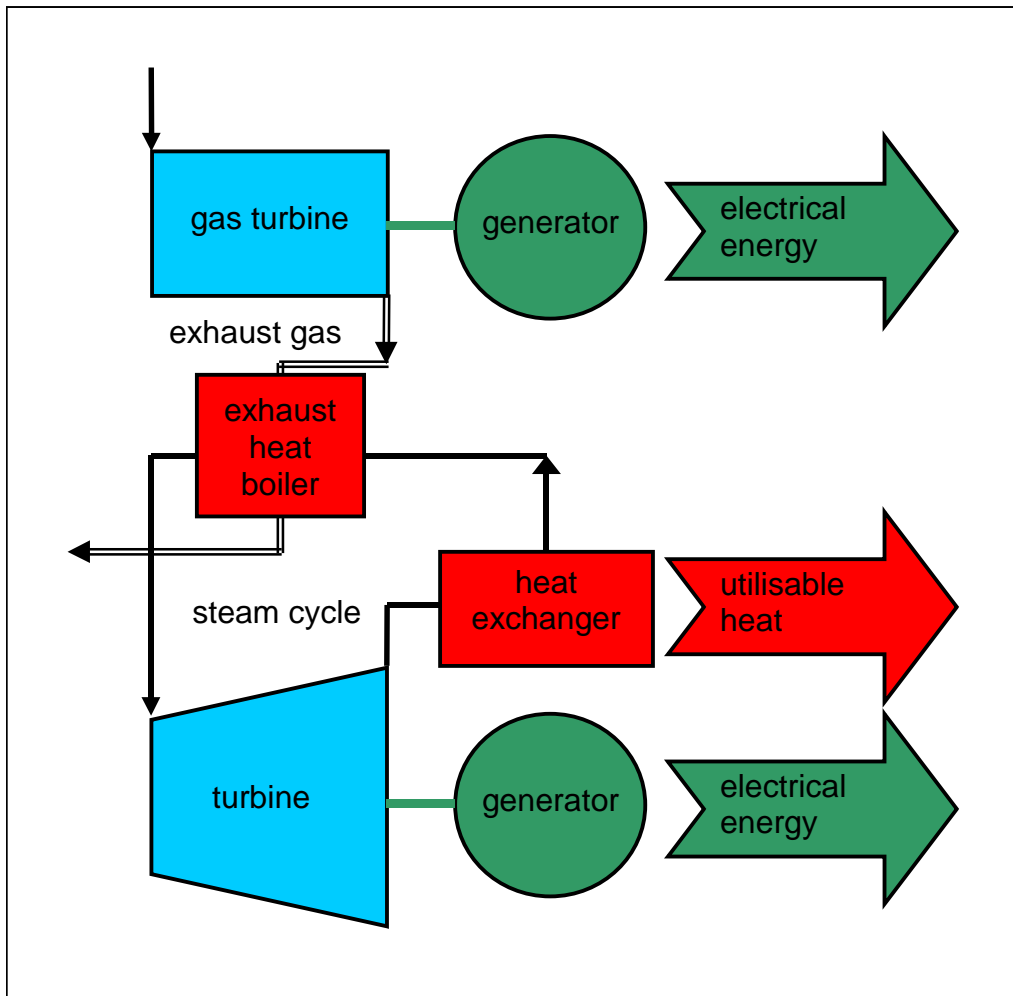


Figure 18: Principle of CHP with combined steam and gas cycle

The following figure (Source: GEW Köln AG) shows a simplified section through a combined steam and gas plant with its most important components:

1. Air filter at the compressor inlet
2. Gas turbine
3. Generator
4. Waste heat boiler
5. Steam turbine
6. Condenser

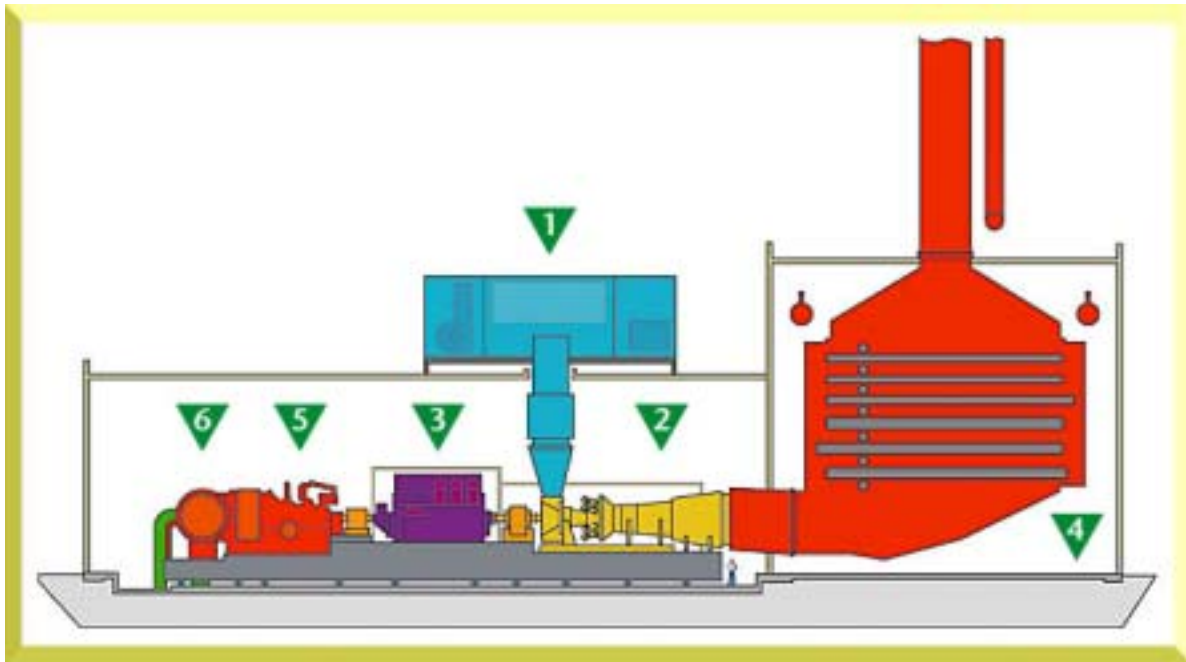


Figure 19: Section through a combined steam and gas plant

The steam turbine cycle can again be carried out in backpressure operation or in extraction condenser operation.

These two types are explained in more detail in the following.

2.3.1 Combined steam and gas turbine cycle with back pressure turbine

Functionality:

The combined steam and gas cycle is a combination of the steam turbine cycle and the gas turbine cycle. Exhaust gases from the gas turbine are used for generating high pressure steam which is later expanded in a steam turbine. Electrical output is reached by the gas turbine as well as the steam turbine. The steam escaping from the steam turbine can further be used for providing heat.

Set-up of a combined cycle with back pressure turbine:

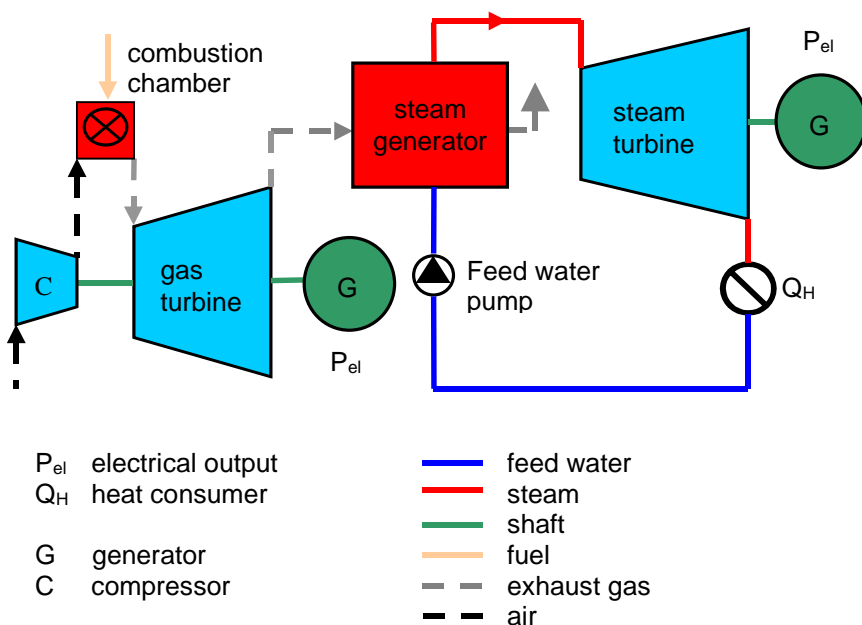


Figure 20: Combined steam and gas cycle with back pressure turbine

Application

- for power and heat requirements of higher output (> 10 MW electrical)
- if a constant process heat is required (e.g. paper mill)
- if high electrical efficiency is required

2.3.2 Combined steam and gas cycle with extraction condensing turbine

Functionality:

The functionality is based on the same principle as the combined steam and gas cycle with back pressure turbine, but with the difference that here extraction steam for heat generation is not taken from the end of the turbine but from the middle part. This has the advantage that heat as well as power generation can be better adjusted to the different requirements.

Set-up of a combined CHP plant with extraction condensing turbine:

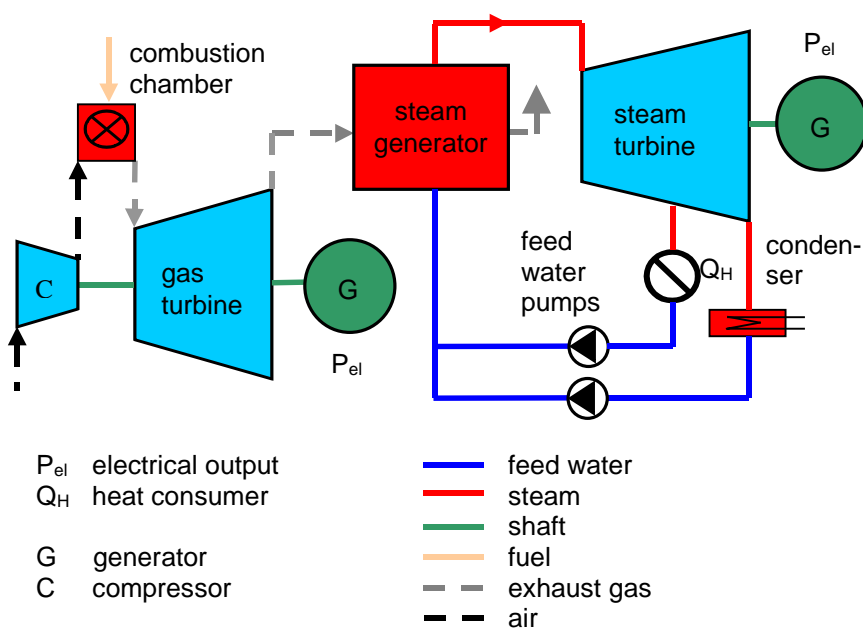


Figure 21: Combined steam and gas cycle with extraction condensing turbine

Application

- for heat and power requirements of higher output ($> 10 \text{ MW}_{el}$)
- different requirements concerning heat and power requirements
- if high electrical efficiency is required

2.3.3 General information on the combined steam and gas cycle

Possible fuels
<ul style="list-style-type: none"> • gas • petroleum • fuels obtained through gasification of biomass or coal
Advantages
<ul style="list-style-type: none"> • high electrical efficiency • sophisticated technology
Disadvantages
<ul style="list-style-type: none"> • expensive operation • only suitable for higher output (electrical)

In table 5 some data from a plant within a certain range of performance is outlined.

Plant size ~40 MW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	800
Specific maintenance costs	[EUR/kWh _{el}]	0,007 – 0,011
Electrical efficiency _{el}	[%]	up to 50 (55)
Overall efficiency	[%]	up to 85 (90)
Emissions (NOx) – gas turbine	[mg/Nm ³]	~ 25

Table 5: Data of a combined steam and gas cycle

Best operational mode:

Power or heat operated.

Operating state:

Decentralized CHP plants of medium output:

- gas turbine:
 - peak temperature: ~1150 °C
 - pressure: ~ 12 bar
- steam turbine cycle (often also run as a double-pressure cycle):
 - steam pressure: ~50 bar
 - live steam temperature: ~ 400 °C

Control:

Control of the gas turbine is usually achieved through fuel supply.

Control of the steam turbine is on the one hand reached through the steam condition in the heat recovery steam generator which depends on the output of the gas turbine.

On the other hand the steam turbine can be controlled as follows:

- Through a throttle valve in front of the turbine controlling steam pressure and output
- Through nozzle group control in the individual turbine, which allows individual nozzles in front of the first blade wheel to be switched in or off. Thus the mass flow rate as well as the output of the turbine can be regulated.

Maintenance :

Gas turbine cycle:

- Inspection of the fuel piping, the turbine casing, etc. once a week

Steam cycle:

- Inspection of the steam piping once a week
- Regular inspection of the steam conditions
- Every 5 years a more extensive one-week revision should be conducted

Ecological aspects:

Gas turbine cycle:

When using natural gas in gas turbines very low emission values can be achieved. The NO_x content amounts to 25 ppm, the CO content can be further reduced with the help of a downstream catalyst.

Steam cycle:

During the vaporization process of water the salts contained in the water remain in the boiler. In order to avoid high salinity (scale build-up!) water is continuously desalinated (1-5 % of the circulated feed water).

In addition it is necessary to discharge the mud resulting from material abrasion and the remaining salts in the water (manually or automatically).

When discharging sewages into a stream or into the sewerage system, the corresponding legal regulations have to be complied with.

Weak points:

Thermodynamics:

The greatest losses occur in the heat recovery steam generator because of the great temperature differences between the cooling curve of the exhaust gas and the heating curve of the steam including vaporization. Therefore often double pressure as well as triple pressure cycles are used in order to achieve a better adjustment of the steam curve to the exhaust gas curve.

Costs:

The operation of combined steam and gas plants is very expensive. Yet they show remarkably high electrical efficiency. In CHP they are usually used if a high amount of power is required.

Stage of development/outlook:

CHP plants with combined steam and gas cycles use a well-established technology and therefore used in big quantities all over the world.

Trends are going towards gas turbines with high exhaust temperatures in order to have the possibility to connect a downstream steam cycle with high efficiency.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	ready for the market ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	low ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.4 Block CHP plants with diesel and gas engines

Diesel and gas engines are often used as block heat and power plants (also see CHP concepts).

Definition of a block heat and power plant: A block heat and power plant is a CHP plant which is completely installed, delivered and run as a “block”.

Basic principle:

- Mechanical energy (gas and diesel engine) is converted into electrical energy with the help of a generator.
- Hot exhaust gases are used for providing heat.

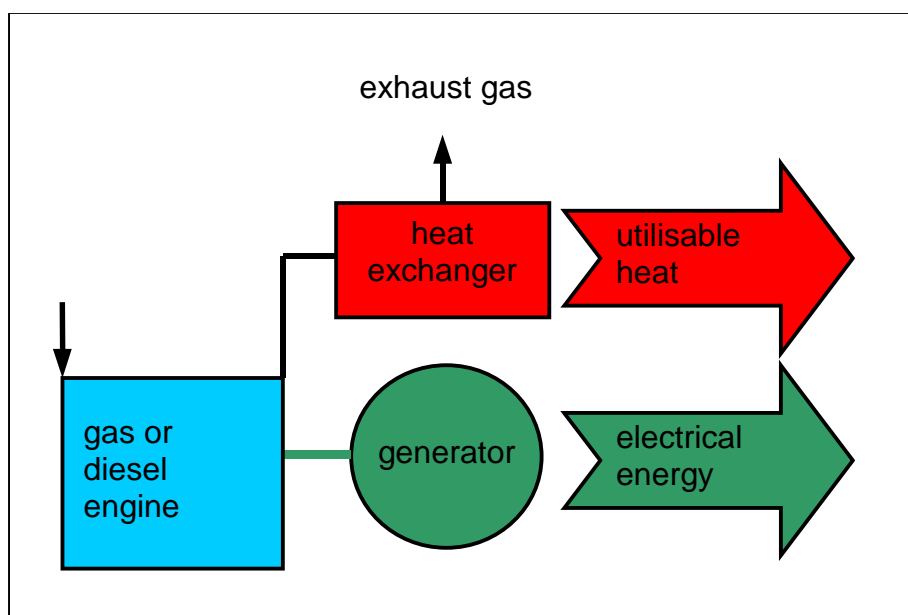


Figure 22: Basic principle of a block heat and power plant

Functionality:

The generator is converting mechanical work produced at the engine shaft into electrical energy. The heat resulting from combustion during power generation is used for process heat supply or heating purposes. Exhaust gases and engine cooling water function as heat sources.

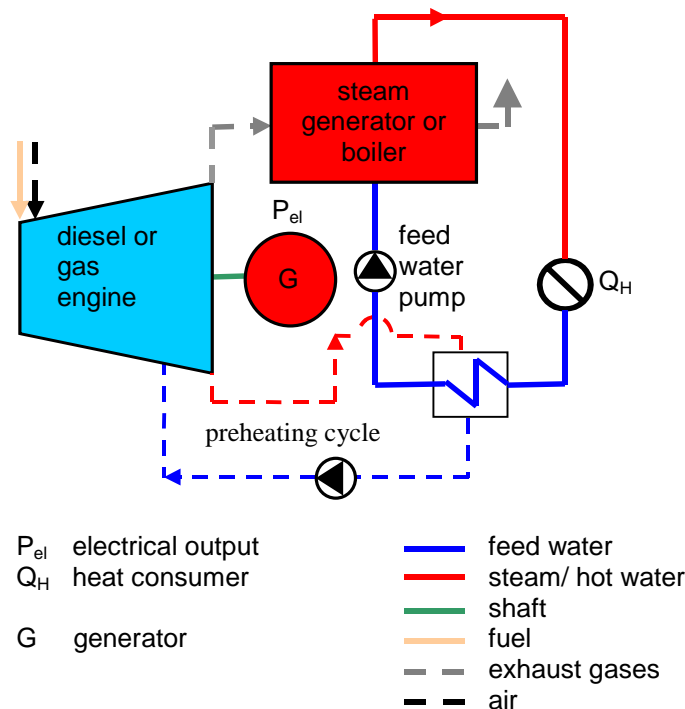
Set-up of a block CHP plant:

Figure 23: Diesel and gas engine block CHP plants

General information on block CHP plants with diesel and gas engines:**Application**

- For decentralized power and heat supply of lower to medium output (from ~15 kW_{el} upwards)
- Examples: housing estates, industry (drying processes), hospitals, sewage plants (utilization of sewage gas)

Possible fuels

- gas
- biogas (sewage gas, landfill gas)
- diesel
- gas from biomass gasification, methanol, rape oil
- gasification products

Advantages

- Power and heat are generated right at the spot where they are needed and thus big transmission losses like they occur in district heating networks can be prevented.
- Overall efficiency of such block heat and power plants amounts to 85% and more referring to the end user. Thus its efficiency is up to 10% higher than in conventional district heating plants.
- Reduction of primary energy consumption with the help of high efficiency
 - through waste heat utilization of exhaust gases
 - through waste heat utilization of engine cooling and therefore
- Reduction of environmental pollution through waste heat and harmful substances.
- Modular design is possible
 - Adjustment to variable power requirements is possible
 - Maintenance work on one of the modules is possible while the other modules are at work.
- Low maintenance expenditure
- Many providers available

Disadvantages

- High temperature heat supply is not possible (temperature level of waste heat is too low)

In table 6 some data from a plant within a certain range of performance is outlined.

Plant size 30-75 kW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	1.250 – 1.800
Specific maintenance costs	[EUR/kWh _{el}]	0,2 – 0,3
Electrical efficiency η_{el}	[%]	28 - 31
Thermal efficiency η_{th}	[%]	52 - 57
Overall efficiency	[%]	80 - 88
Emissions (NOx) ¹⁾	[mg/Nm ³]	100 - 250

¹⁾ based on 5% O₂ in exhaust gas

Table 6: Data of a block heat and power plant

High efficiency is reached at normal flow temperatures of up to about 90°C. In the water flow temperatures of about 120°C can be reached by using hot-cooled engines.

Best operational mode:

Power or heat operated.

Design:

Usually various modules, each consisting of a gas or diesel engine, a generator and a heat exchanger, are connected in parallel. According to the requirements one or more modules can be operated so that the individual units can be run near full load in a favorable efficiency range. Another advantage is that maintenance work and repairs at multi-module plants can be carried out easier.

Figure 24 shows an example of modular concept.

Source: Jenbacher



Figure 24: Block CHP plant with modular construction

Another extension possibility for a block heat and power plant is to use a combination with an absorption refrigerating machine which uses waste heat of the exhaust gas for generating cold. This combination is particularly favourable if besides heat there is also cold required, e.g. for air conditioning.

Control:

Control can be achieved through the fuel supply.

Maintenance :

Maintenance intervals amount to 2000 hours.

Ecological aspects:

The exhaust gas resulting from combustion is cleaned in a catalyst. Exhaust gas emissions are usually below the permitted. Incidental amounts of waste oil have to be disposed of separately.

Stage of development:

Block heat and power plants with gas and diesel engines are very well-established and therefore used in big quantities all over the world.

In the future, operator convenience of the plants is to be increased so that an automatic control of plant conditions is transmitted to plant administrators via internet. This allows them to react quicker to possible malfunctions.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	ready for the market ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	low ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.5 CHP with alternative processes

Alternative processes are sophisticated enough to be put in practice but are not yet implemented in great numbers.

The following figure shows different options for CHP with alternative processes.

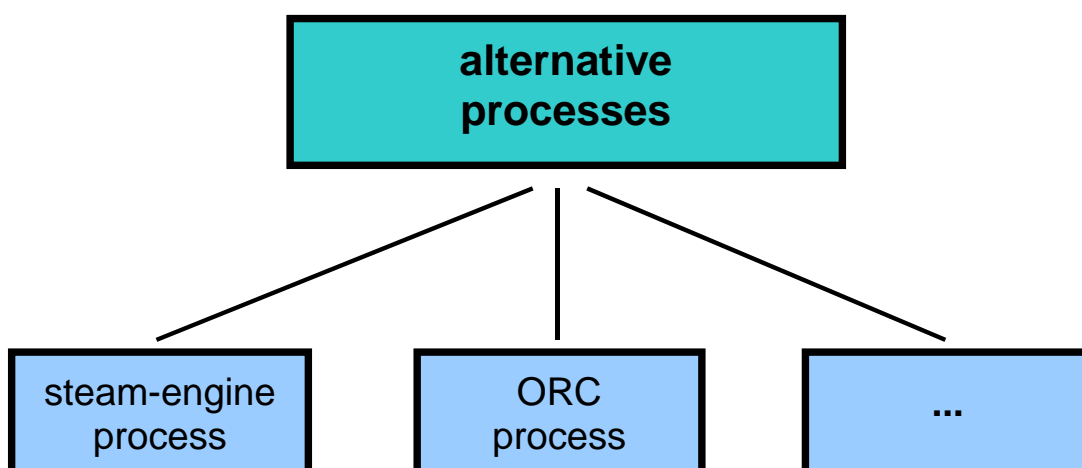


Figure 25: CHP with alternative processes

In the following the steam-engine process and the ORC process are explained in more detail.

2.5.1 Steam-engine process

Functionality:

Exhaust gas resulting from combustion is passing through a boiler in which steam is generated. The steam is then flowing into the steam-engine where by expansion it is performing mechanical work which is later converted into electrical energy in the generator. Now the steam is passed into the condenser where incidental condensation heat can be used as district or process heat. The water is brought to operating pressure by a feed water pump and is then fed to the boiler, thus closing the cycle. Therefore the process corresponds to a steam turbine cycle in which the turbine is replaced by a steam-engine. However, compared to the steam turbine cycle the steam-engine can produce power from 20 kW_{el} which allows a decentralized application for lower output.

Set-up of a CHP plant with steam engine:

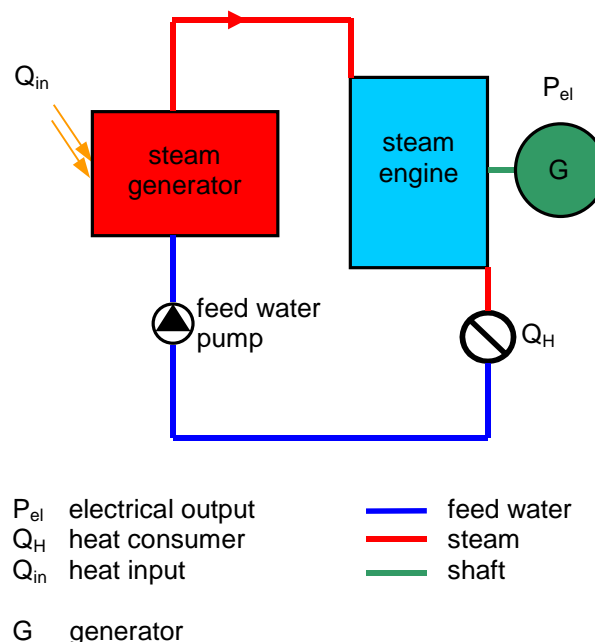


Figure 26: Diagram of a CHP plant with steam-engine

Principle of a steam-engine:

The steam enters the cylinder (figure a) until the inlet process is stopped by control pistons. The steam expands and is performing work at the piston (figure b). Since thus the volume is increased, pressure is continuously reduced. When the piston has reached its dead center it moves to the right again which causes the control piston to unblock the outlet valve and the steam is leaving the cylinder again (figure c). Thus the process is restarted.

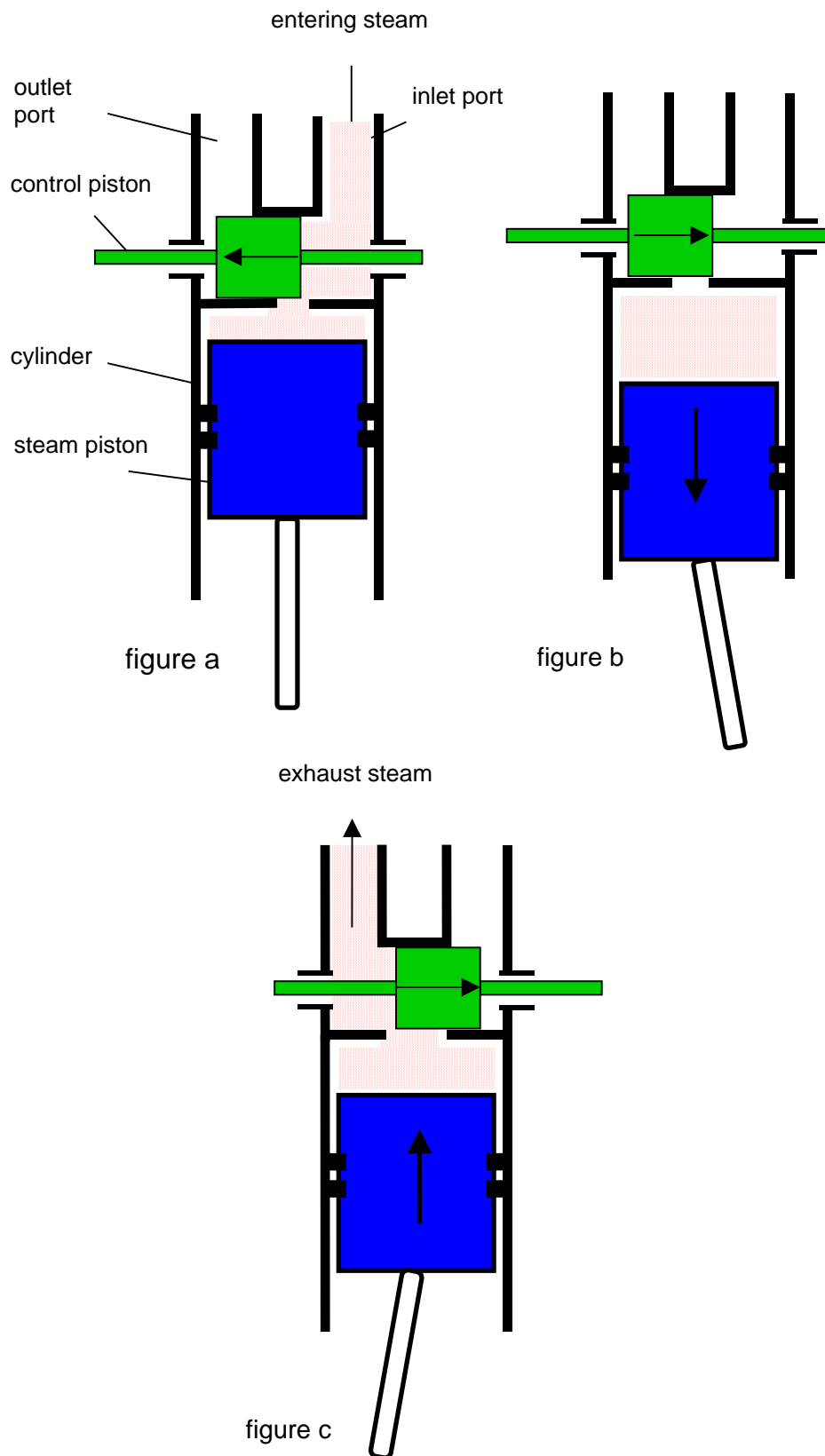


Figure 27: Principle of a steam engine

General information on CHP with steam engine

Application
<ul style="list-style-type: none"> • For decentralized power and heat supply of lower to medium output (from ~20 kW_{el} to ~2000 kW_{el}) • Examples: housing estates, industry (drying processes), hospitals
Possible fuels
<ul style="list-style-type: none"> • coal • petroleum • biomass, garbage • basically every fuel is possible
Advantages
<ul style="list-style-type: none"> • very good part-load performance • technology maturity
Disadvantages
<ul style="list-style-type: none"> • low electrical plant efficiency • requires much maintenance work • noise intensive (acoustic insulation!!)

In table 7 some data from a plant within a certain range of performance is outlined.

Plant size ~500 kW _{el} (biomass-fired)	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 1.500
Specific maintenance costs	[EUR/kWh _{el}]	0,007 – 0,011
Electrical efficiency _{el}	[%]	6 – 20
Overall efficiency	[%]	~ 80 – 90
Emissions (NOx)	-	depending on fuel ¹⁾

¹⁾ at the scale of gas engines (ca. 50-500 mg/Nm³, according to output)

Table 7: Data of a steam-engine process

Best operational mode:

Power or heat operated.

Design:

The steam engine can consist of one to six working cylinders. Each cylinder has its own control piston; thus the engine consists of two shafts, one regulator shaft and one working shaft. In the following important correlations concerning the steam engine are described.

Control:

The amount of entering steam can be controlled through the control piston stroke. The stroke of the control piston is adjusted at the regulator shaft with the help of an eccentric with a centrifugal governor. The regulator shaft can be separated so that it is possible to run individual cylinders with different steam inlet and outlet conditions in multi-piston engines.

Steam condition:

The steam engine can work with saturated steam as well as with superheated steam. If, however, superheated steam is used, the same engine can produce up to 60% more electrical output. The reason for this is the utilization of the higher enthalpy drop of superheated steam compared to the one of saturated steam.

Inlet pressures of the steam can range between 6 and 60 bar.

Steam quantities range from 0,2 to 20 t/h according to requirements.

Feed water treatment:

Compared to the steam turbine the steam engine is less sensitive to soiling. This makes simpler feed water treatment plants possible (costs !!).

Operating performance:

When run at part load the produced amount of steam decreases at unchanging temperature and pressure. The released mechanical energy and thus also the electrical energy decreases. It is important though that the greatest possible efficiency of the plant is not reached at the highest electrical output but slightly below it. This is an advantage of the steam engine if it is run at part load. After all, electrical part load efficiency amounts to 90% of the highest possible electrical efficiency when run at half load.

Maintenance :

- daily check on cylinder oil (takes about half an hour)
- condensate samples at sporadic intervals to check oil content (takes about half an hour)
- After about 8000 hours: - Oil change in the crank case of the engine
- components of the steam engine have to be checked
- Replacement of piston and seal rings according to their condition
- Replacement of the piston every 3 - 5 years
- Regular check on the filter equipment

It can basically be assumed that a steam-engine reaches a service life of more than 200.000 operating hours if maintenance is sufficient and proper.

Ecological aspects:

The oil obtained in the steam-engine can either be burnt in the firing equipment or has to be disposed of separately.

During the vaporization process of water the salts contained in the water remain in the boiler. In order to avoid high salinity (scale build-up!) water is continuously desalinated (1-5 % of the circulated feed water).

In addition it is necessary to discharge the mud resulting from material abrasion and the remaining salts in the water (manually or automatically).

When discharging sewages into a stream or into the sewerage system, the corresponding legal regulations have to be complied with.

Weak points:

Because of the high noise level (up to 95 dBA) an application of this technology is not possible without corresponding noise suppression measures in residential buildings etc.

Stage of development:

Since service life of such a plant highly depends on the maintenance work carried out by the staff, attempts are made to reduce these works to a minimum in the future.

An important approach for achieving this is the development of piston materials that do not need lubrication. This would on the one hand improve operator convenience and on the other hand service life could generally be increased. Besides that, lubricant waste and thus also environmental impact could be reduced.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	ready for the market ¹⁾
Short term cost reduction potential	low ²⁾
Short term development potential	medium ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.5.2 CHP on the basis of an ORC process (Organic Rankine Cycle) with biomass

Difference compared to the steam turbine cycle:

The difference compared to the steam turbine cycle is that instead of water an organic working fluid (hydrocarbons like isopentane, iso-octane, toluene or silicone fluid) is used. Since this working fluid vaporizes at lower temperatures than water, the process can better be adjusted to a fuel like biomass with its low combustion temperatures.

In order to delay the ageing process of the working fluid, the permitted temperatures close to the wall may not be exceeded. Therefore an intermediate thermo oil cycle allowing better temperature control is necessary.

The thermo oil cycle further allows depressurized operating at high temperatures and thus does not require a steam guard.

Functionality:

The exhaust gas resulting from the combustion process in the biomass boiler supplies heat to the thermo oil cycle. Later the heat is fed to an organic working fluid which therefore vaporizes. The vaporized fluid is expanded in a turbine and the obtained mechanical work is passed to a generator where it is converted into electrical energy. The expanded fluid then enters a condenser where the discharged heat is available at a temperature level which allows the operating of a hot-water network for district or process heat supply. Later the condensate is brought to operating pressure by the pump and is fed to the evaporator again.

In order to increase electrical output, the working fluid escaping from the turbine can be passed through a recuperator (not included in the figure) before it enters the condenser.

Set-up of an ORC plant:

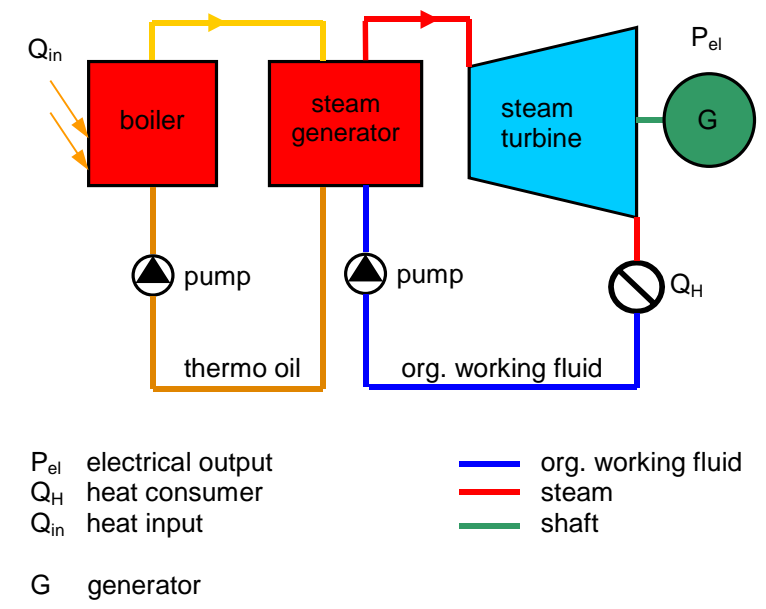


Figure 28: Set-up of an ORC process

Application

- For decentralized power and heat supply of medium output (~300 kW_{el} and more)
- Examples: timber industry, industry (drying processes), housing estates

Possible fuels

- biomass
- basically every fuel is possible

Advantages
<ul style="list-style-type: none"> • very good part-load performance • technology maturity
Disadvantages
<ul style="list-style-type: none"> • intermediate thermo oil cycle necessary (costs !) • little experiences with ORC plants with biomass firing • relatively high investment costs

In table 8 some data from a plant within a certain range of performance is outlined.

Plant size ~500 kW _{el} (biomass-fired)	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 2.300
Silicon oil	[EUR/l]	~ 22
Specific maintenance costs	[EUR/kWh _{el}]	0,007
Electrical efficiency _{el}	[%]	10 – 20
Overall efficiency	[%]	up to 85
Emissions (NO _x)	[mg/Nm ³]	Depending on fuel ~ 250-400

Table 8: Data of an ORC process

Best operational mode:

Power or heat operated.

Design:

ORC plants are offered as complete modules. The electrical output of an ORC module ranges between 200 and 1500 kW_{el}. Higher plant output can be achieved by a parallel operation of modules.

The main part of heat supply is realized in the combustion chamber; but exhaust gas heat can further be utilized by releasing the heat in an economizer. The recovered heat can be used additionally for district and process heat, thus increasing overall efficiency of the plant. Besides that, exhaust gas utilization in the economizer allows a lower operating temperature of the condenser because the necessary heat for reaching the required final temperature for process heat is supplied by the economizer. Thus the electrical efficiency of the plant can be improved.

Usually silicone fluid is used as an organic working fluid in a closed cycle because it is neither toxic nor a greenhouse gas.

Picture of an ORC plant:

Figure 29 shows an ORC plant like it was used for the timber industry in Admont



Figure 29: ORC plant in Admont (Source Bios Bioenergiesysteme)

Control:

Control of the ORC process can be reached through the heat supply in the boiler.

Operating state:

Evaporating pressure of the working fluid: 10 bar

Exhaust gas temperature from the boiler: 300 °C

Maintenance :

ORC plants basically require little maintenance work. Maintenance works amount to about 4 hours a week.

The working fluid (usually silicone fluid) has to be replaced after about 20 years.

Ecological aspects:

The frequently used silicone fluid doesn't have any ozone-depleting potential, it is easily combustible but not explosive. Because of the low flash point (34°C) leakage losses of the working fluid have to be widely avoided.

Because of the high service life of the fluid (up to 20 years) no replacement is required.

Conditions for an efficient operating on biomass basis:

- High amount of annual full-load operating hours (> 4000 h)
 - achievable through proper plant design
- High possible efficiency
 - achievable through heat-oriented design
- Utilization of cheap fuel assortments
 - e. g. sawing by-products, production waste

Weak points:

The low process temperature resulting from biomass utilization and limited upwards by the thermal stability of the working fluid and the thermo oil only allows relatively low efficiency.

Stage of development:

In the field of geothermics there are already many ORC plants used. Therefore the process represents a proven technology.

In 1999 Austria's first biomass-fired ORC plant was put in operation by the timber industry in Admont (Styria). Further plants are being planned.

Some important parameters regarding stage of development and outlook are summed up in the following table. (Source: Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien)

Stage of development/ outlook	status
Present stage of development	demonstration stage ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	low ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.6 Innovative processes

Innovative processes are processes that are not yet mature enough to be put into practice. Most of these processes are still in their developing stage. The following figure shows different options for CHP with innovative processes.

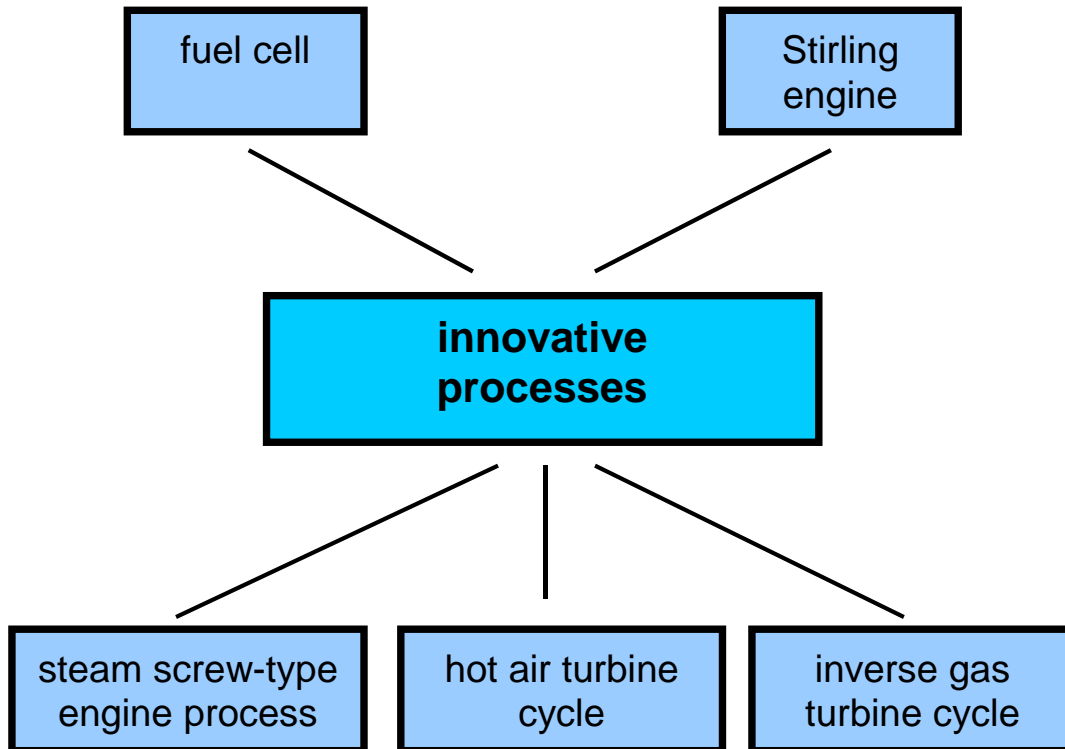


Figure 30: CHP with innovative processes

These technologies are mostly in their developing stage or are not tested enough yet. In the following, CHP with fuel cell technology, with Stirling engine, with inverse gas turbine cycle, with hot air turbine cycle and with steam screw-type engines are explained in more detail.

2.6.1 CHP with fuel cell technology

The fuel cell is one option for decentralized power and heat generation with very high efficiency and very low emissions.

Functionality:

The functionality of the fuel cell corresponds to the inversion of the water electrolysis. During water electrolysis water is split into hydrogen and oxygen by applying voltage to two electrodes.

If the reaction is run backwards and the electrodes are surrounded by hydrogen (or hydrogen rich gas) and oxygen (or air) the highly exothermic detonating gas reaction (combining hydrogen and oxygen into water) causes measurable direct voltage and release of heat. In order to continuously keep the process running, a consistent process gas supply has to be ensured.

Classic pollutants like CO und NO_x are not produced.

Set-up of a fuel cell:

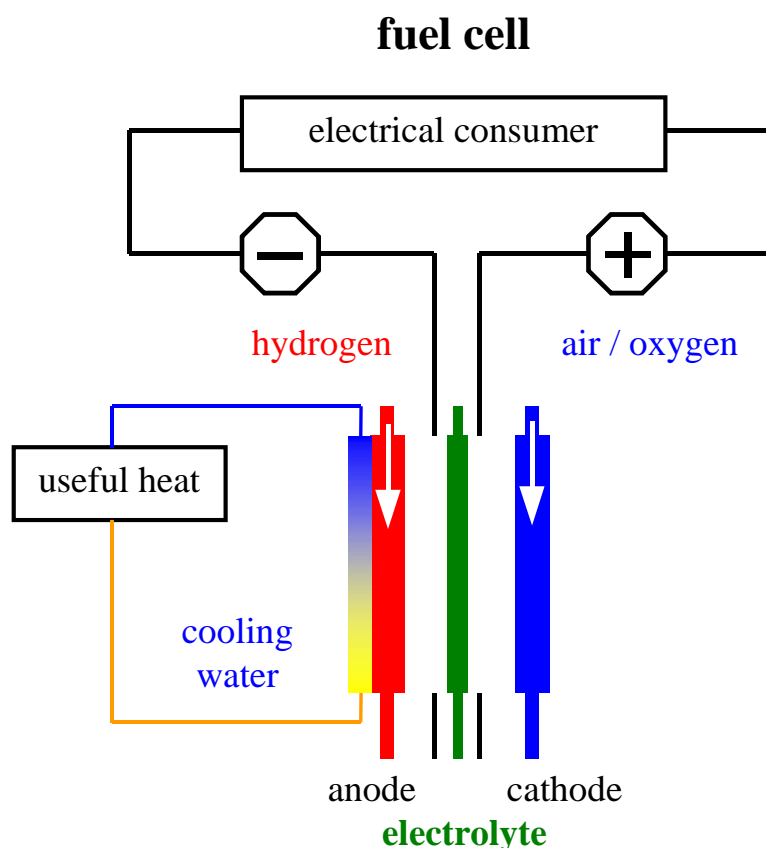


Figure 31: Principle of a fuel cell

Application
<ul style="list-style-type: none"> The application of the fuel cell in decentralized CHP supply corresponds to the application of combustion engines in block heat and power plants. Fuel cells are covering the basic load while oil or gas boilers are responsible for the temporally limited peak load.
Required fuels
<ul style="list-style-type: none"> hydrogen oxygen / air electrolyte
Advantages
<ul style="list-style-type: none"> Extremely low emissions without any secondary measures Another advantage is that the limits of the theoretically ideal Carnot process do not apply to this process. Thus fuel cells have a very big potential for generating power and heat with high efficiency. Efficiency of this process is almost independent of the unit size High part load performance Simple modular set-up Low maintenance effort Little noise
Disadvantages
<ul style="list-style-type: none"> Very high acquisition costs (block CHP plant about 4000 US-\$/kW, Source Fa. ONSI). Technology not yet mature Another problem - which is not that serious though- is start-up time of the plants which still amounts to a couple of hours from a cold state .

In table 9 some data from a plant within a certain range of performance is outlined.

Plant size ~100 kW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 3.000
Specific maintenance costs	[EUR/kWh _{el}]	low
Electrical efficiency _{el}	[%]	25 - 40
Overall efficiency	[%]	up to 90
Emissions (NOx) ¹⁾	[mg/Nm ³]	~ 5

¹⁾ based on 5% O₂ in exhaust gas

Table 9: Data of a fuel cell plant

Best operational mode:

Power or heat operated.

Design/Application:

Operating temperatures in table 10 show that the SOFC type is more suitable for generating high temperature heat whereas the PEM type can also be used for low temperature heat supply (preheating temperature ~90 °C).

In the future fuel cell systems allowing flexible operating between 100% power and 100% heat are to be used. This makes the installation of a peak boiler unnecessary.

Type	Operating temperature	Electrolyte
PEM (Polymer Electrolyte Membrane)	~ 80-100 °C	solid
PAFC (Phosphoric Acid Fuel Cell)	~ 200°C	aqueous
MCFC (Molten Carbonate Fuel Cell)	~ 650°C	liquid
SOFC (Solid Oxide Fuel Cell)	~ 1000°C	solid

Table 10: Types of fuel cells

Picture of a fuel cell plant:

The fuel cell plant shown on the picture has an electrical output of about 250 kW. This type of plant is also called „direct fuel cell power plant“.



Source: Fuel cell 2000

Figure 32: Fuel cell plant (Energy Research Corporation) with an electrical output of 250 kW

Maintenance :

Maintenance details are not yet available since most of the plants are still in their pilot stage.

Ecological aspects:

Since hydrogen and partly pure oxygen are used, tightness of the pipelines has to be ensured because of possible fire hazard. Basically these two components do not have environmental impact.

Low emissions are another crucial advantage.

Working with highly acidic electrolytes requires acid-resistant material preventing leakage.

Another important aspect are the seals which should prevent any possible leakage of acid.

Stage of development:

At present fuel cells are still in their pilot stage. The high investment costs are the main reason preventing the breakthrough of this technology.

Starting from the USA R&D activities have also been intensified in Europe. The three leading enterprises (Sulzer Hexis AG, HGC, and Vaillant) are announcing commercial small batch series for the years 2002/2003.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	pilot stage to demonstration stage ¹⁾
Short term cost reduction potential	medium to high ²⁾
Short term development potential	medium ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

Ongoing projects:

(Source Austria Ferngas Gesellschaft m.b.H., EVA)

PAFC
<ul style="list-style-type: none"> • Test runs with 200 plants of 50 KW up to 11 MW • More than 2 billion operating hours • Reliable concept
MCFC / SOFC
<ul style="list-style-type: none"> • Some pilot plants are being tested (up to 2 MW) • Material problems • Highest development potential
PEM
<ul style="list-style-type: none"> • First stationary pilot plants • Particularly suitable for mobile application • Significant cost reduction potential

Table 11: Fuel cell projects

2.6.2 Stirling engine process

Functionality:

Exhaust gas resulting from a combustion process enters a boiler-heat exchanger and releases heat to the active gas in the engine. Possible working fluids are air, nitrogen, helium or hydrogen. Residual heat of the exhaust gas can be used for supplying heat with the help of an additional heat exchanger. Cooling in the cooler-heat exchanger happens with the help of the return pipe of the heat supply network. Thus the heat discharged in the engine can be further utilized (heating purposes, ...).

The operating mode of the Stirling engine is explained in more detail in the following.

Set-up of a CHP plant with Stirling engine:

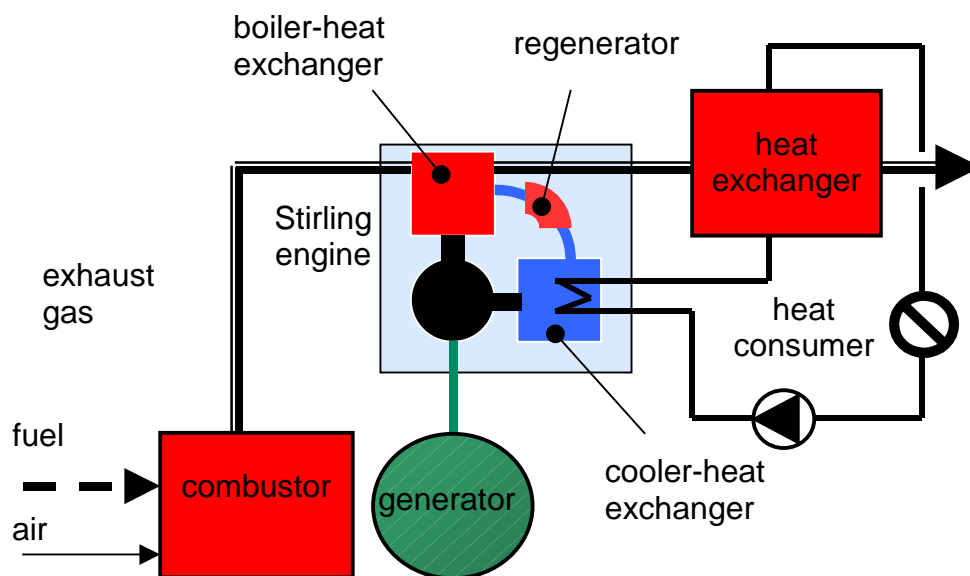


Figure 33: Set-up of a CHP plant with Stirling engine

Operating mode of the Stirling engine:

In the Stirling engine the working fluid is moving in a closed system between two cylinders. In the working cylinder heat for the work output is supplied whereas in the compression cylinder heat is discharged in order to reduce compression work. When the working fluid is moved from the working cylinder to the compression cylinder the residual heat is stored in the regenerator. When the compressed fluid is moved back to the working cylinder this stored heat can be utilized again.

Basically one work cycle consists of the following individual phases:

1-2: Isochoric heating phase:

Because of the downward movement of the compression piston the gas is isochorically pushed into the working cylinder passing the regenerator. The piston of the working cylinder is then moving to the right. At the same time the heat stored in the regenerator

(see isochoric cooling phase) is discharged to the working fluid. Because of the heating in the working cylinder temperature and pressure are rising. The active gas is passed from the cold to the hot cylinder.

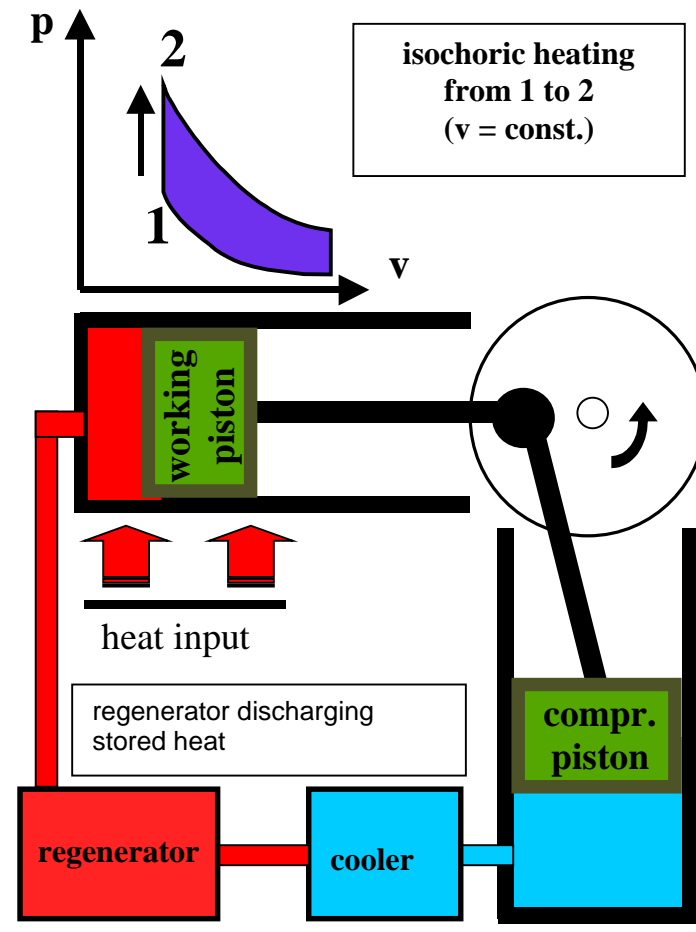


Figure 34: Functionality of a Stirling engine: Isochoric compression

2-3: Isothermic expansion phase:

Because of the additional heat input the working fluid expands and is pushing the working piston to the right. Mechanical output is transmitted to the piston rod. The compression piston is moving upwards with slight time shift.

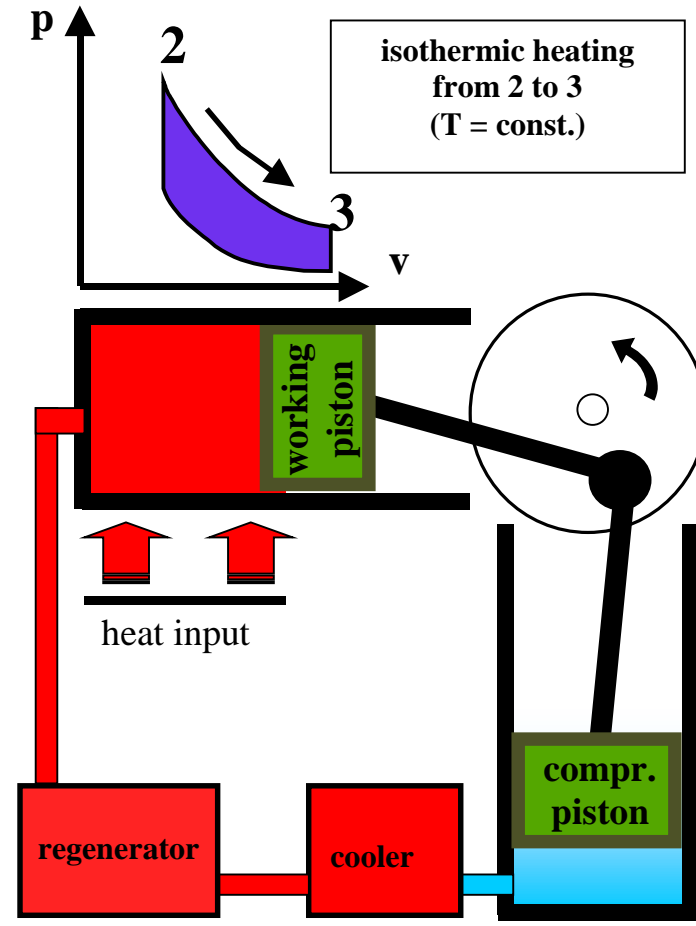


Figure 35: Functionality of a Stirling engine: Isothermic expansion

3-4: Isochoric cooling phase:

After reaching its lower dead center the working piston moves to the left and thus isochorically pushes the working fluid first through the regenerator which is taking up heat and then through the cooler before it enters the compression cylinder which is moving upwards.

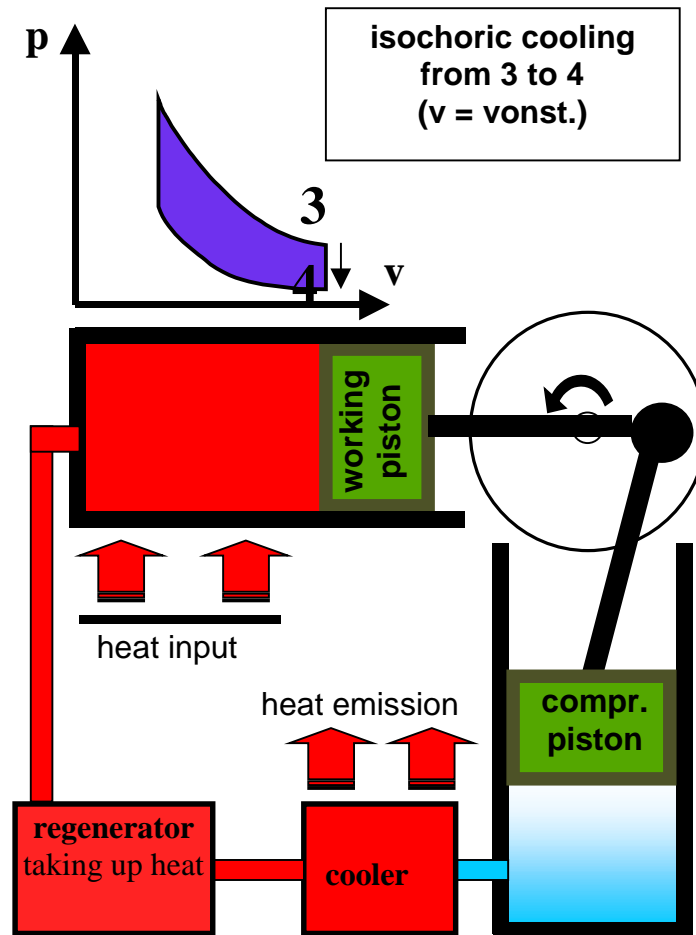


Figure 36: Functionality of a Sterling engine: Isochoric cooling phase

4-1: Isothermic compression (without picture) :

The working fluid is cooled in the compression cylinder, its volume decreases, the compression piston moves down. The working piston moves to the left and is thus compressing the working fluid.

When the working piston has reached its upper dead center the cycle starts again.

Application
<ul style="list-style-type: none"> • For decentralized power and heat supply of low output (10 - 45 kW_{el})
Possible fuels
<ul style="list-style-type: none"> • coal • petroleum • biomass • basically every fuel is possible
Advantages
<ul style="list-style-type: none"> • low in maintenance • low in noise
Disadvantages
<ul style="list-style-type: none"> • Boiler-heat exchanger is problematic because of the high temperature • Sealing difficulties • Poor part load performance • Small plant size (only up to ~ 50 kW_{el} [in the future up to 150 kW_{el}] possible)

In table 12 some data from a plant within a certain range of performance is outlined.

Plant size 10 - 40 kW _{el} (biomass-fired)	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 2.400
Specific maintenance costs	[EUR/kWh _{el}]	~ 0,004 – 0,011
Electrical efficiency _{el}	[%]	21 - 28
Overall efficiency	[%]	63 - 86
Emissions (NOx)	[mg/Nm ³]	~ 10-15

Table 12: Data of a Stirling engine process

Best operational mode:

Heat operated

Design:

There are two important designs differing in the arrangement of the pistons.

- -Type: the pistons are at a 90° angle to each other
- -Type: The two pistons (working and compression piston) are arranged one above the other in the same cylinder. The necessary phase shift of the two pistons is reached with the help of a special linkage.

Picture of a Stirling engine:

The following picture shows a Stirling engine with an easy functioning 90°-V2-machine with a shaft power between 3 kW and 10 kW.



Figure 37: Stirling engine (Source: zsw)

Control:

Control of the Stirling engine is achieved through adjustment of the temperature in the boiler-heat exchanger.

Operating state:

Operating pressure: between 33 bar and 150 bar

Exhaust gas temperature at the boiler-heat exchanger: between 600 °C and 1400 °C

Maintenance :

Maintenance intervals range between 5.000 and 7.000 operating hours.

After 25.000 operating hours a more thorough revision should be carried out.

Ecological aspects:

Stirling engines have noise emission levels that are 90% more favourable than those of comparable diesel engines.

The used fluids air and helium do not have environmental impact. The usage of hydrogen requires special precautions.

Weak points:

The temperature can not be increased arbitrarily due to the properties of the material of the boiler-heat exchanger.

Another problem is the sealing of the pressurized exhaust chamber (space between the two pistons).

Stage of development:

Stirling engines are gaining more and more importance in their application as block heat and power plants. The basis for this is an intensive advancement of the aggregates.

Output can be significantly improved by increasing the working pressure and reducing the mass of the moved parts.

CHP plants with Stirling engines are close to market maturity.

Intensive research is amongst others done at the research institute Joanneum Research in Graz. Mainly tests with a biomass firing equipment are being carried out there.

Some important parameters regarding stage of development and outlook are summed up in the following table. (Source: Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien)

Stage of development/outlook	Stage
Present stage of development	pilot stage ¹⁾
Short term cost reduction potential	Medium ²⁾
Short term development potential	high ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.6.3 Inverse gas turbine cycle

Functionality:

In the conventional gas turbine cycle air is compressed, fuel is fed and burnt, and exhaust gas is then expanded from high pressure to ambient pressure in the turbine.

In the inverse gas turbine cycle atmospheric combustion takes place, exhaust gas is expanded from ambient pressure to a pressure below atmosphere in the turbine and is later compressed to ambient pressure again in a compressor. The advantage of this cycle lies in atmospheric combustion which avoids expensive and difficult fuel supply to the pressure vessel if biomass is used.

The heat contained in the exhaust gas after passing the turbine is used for generating steam or hot water and is thus available for other heat consumers. At the same time cooling of the exhaust gas reduces compression work. The exhaust gas is heated during compression and this heat can further be used for preheating air before it enters the combustion chamber (not in the picture).

In order to increase electrical output and efficiency it is possible to produce steam with the help of turbine exhaust gas. This steam is then fed into the turbine again, which of course happens on the expense of heat output.

As another option a combined steam and gas cycle with a downstream steam turbine cycle which leads to increased electrical output and efficiency has been examined.

Set-up of a CHP plant with inverse gas turbine cycle:

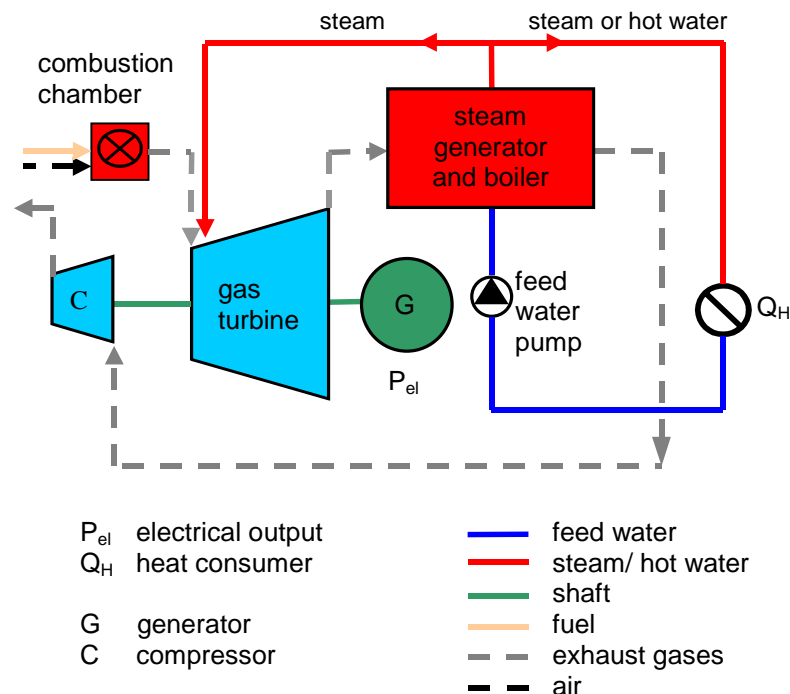


Figure 38: Inverse gas turbine cycle with heat recovery

Application
<ul style="list-style-type: none"> For the production of electrical output and heat with biomass starting from about 1 MW_{el}
Possible fuels
<ul style="list-style-type: none"> Intended for biomass
Advantages
<ul style="list-style-type: none"> Good electrical efficiency No overpressure Standard components can be used Also moist biomass can be used
Disadvantages
<ul style="list-style-type: none"> Technology not yet mature Plant complexity High specific investment costs because turbo machines are very large due to vacuum operation Cleaning of exhaust gas with the help of a cyclone before entering the gas turbine is necessary

In table 13 some data from a plant within a certain range of performance is outlined.

Plant size ~500 - 1500 kW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 3.600
Specific maintenance costs	[EUR/kWh _{el}]	Unknown
Electrical efficiency _{el}	[%]	up to 22
Overall efficiency	[%]	up to 75
Emissions (NO _x)	-	no data available yet

Table 13: Data of an inverse gas turbine cycle

Best operational mode:

Power or heat operated.

Operating state:

Medium output (~1 MW_{el} and higher)

Turbine inlet temperature: 600 – 800°C

Low pressure: 0,30 bar – 0,39 bar

Control:

Because of possible steam injection into the turbine a shift between heat and power output is possible.

Another possibility is to vary the amount of fuel burnt in the combustion chamber.

Maintenance :

There is no data available yet. However, if standard components are used there should not be any major problems.

Ecological aspects:

Since this process is intended to be run with biomass there are also low emissions associated with biomass combustion. Biomass is CO₂ neutral and is thus not contributing to the greenhouse effect.

Stage of development:

The concept of CHP with inverse gas turbine cycle was developed at the Institute for Thermal Turbomachinery and Machine Dynamics of the Graz University of Technology. In a study supported by the Province of Styria the costs of such a plant and the possibilities for the construction of a pilot plant have been elaborated.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	concept stage ¹⁾
Short term cost reduction potential	low ²⁾
Short term development potential	low ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.6.4 Hot air turbine cycle (indirect gas turbine cycle)

Functionality:

In the conventional gas turbine cycle the exhaust gas is expanded in the turbine. In the indirect gas turbine cycle instead of exhaust gas air is expanded in the turbine and the heat is transmitted from the exhaust gas to the process air in a heat exchanger.

Any type of fuel can be atmospherically burnt in a boiler. In a high temperature heat exchanger the exhaust gas gives off heat to the compressed process air. The heated working air flows into the turbine and performs mechanical work. The escaping expanded air is passed to an air preheater preheating combustion air. The residual heat contained in the exhaust gas after passing the preheater can be used for generating steam or hot water and is thus available to other heat consumers.

Another possibility is steam injection into the turbine. In this process part of the generated steam is injected into the power turbine in order to increase electrical output and reduce heat output.

Set-up of CHP plant with indirect gas turbine cycle:

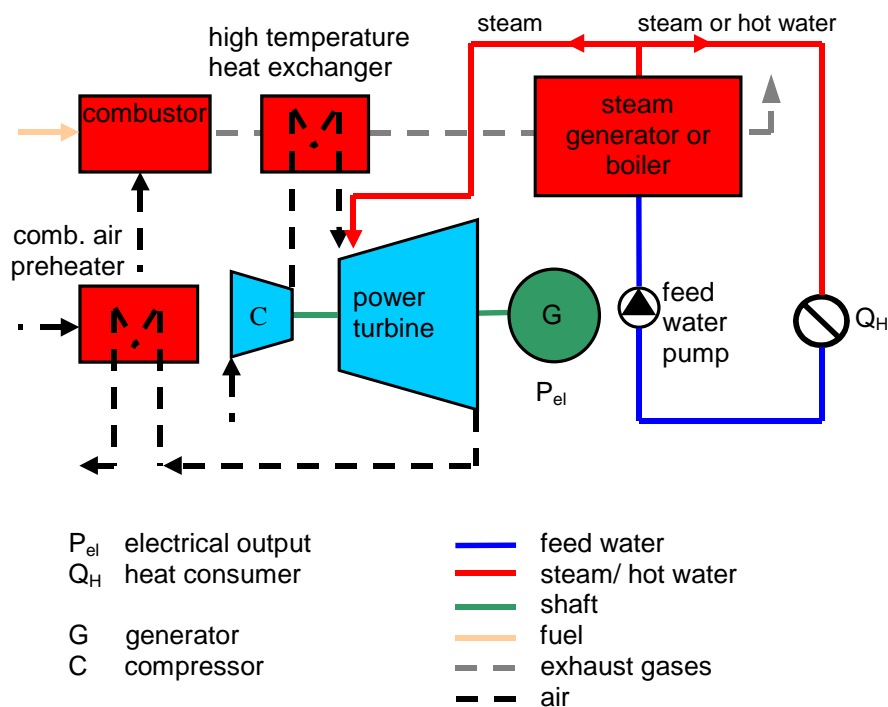


Figure 39: CHP plant with hot air turbine cycle

Application
<ul style="list-style-type: none"> For the production of electrical output and heat starting from 400 kW_{el}
Possible fuels
<ul style="list-style-type: none"> biomass coal petroleum basically every fuel can be used
Advantages
<ul style="list-style-type: none"> plants with high electrical output are possible high electrical plant efficiency can be achieved through steam injection
Disadvantages
<ul style="list-style-type: none"> Technology is not yet mature Plant complexity High thermal stresses in the heat exchanger Expensive heat exchanger

In table 14 some data from a plant within a certain range of performance is outlined.

Plant size ~250 – 500 kW _{el}	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~3.900
Specific maintenance costs	[EUR/kWh _{el}]	unknown
Electrical efficiency _{el}	[%]	up to 30 (with steam injection !)
Overall efficiency	[%]	~ 80
Emissions (NOx)	[mg/Nm ³]	depending on fuel ¹⁾

¹⁾ at a scale of about 200-500 mg/Nm³, according to output

Table 14: Data of an indirect gas turbine cycle

Best operational mode:

Power operated

Operating state:

Medium output (~1 MW_{el} and higher)

Turbine inlet temperature: ~ 800 – 1000 °C

Turbine inlet pressure: ~ 10 bar

Control:

Because of possible steam injection into the turbine the electrical output can be increased while the released useful heat is reduced.

Control can also be achieved through variation of the amount of fuel burnt in the firing equipment. Yet it is important that the permitted temperature limits of the heat exchangers are not exceeded.

Maintenance :

The parts of the heat exchangers where the exhaust gas passes through have to be continuously cleaned which is mostly done automatically.

Besides that, the highly thermally stressed parts have to be regularly checked for stress cracks.

More detailed data about maintenance activities have to be gained through pilot plants.

Ecological aspects:

The ecological impact is mostly dependent on the type of fuel which is used.

Stage of development/ outlook:

Presently a test plant at the Free University of Brussels is run with biomass as a fuel. In order to avoid the problems caused by the varying moisture content of the biomass, it is only used as a basic fuel. The desired final temperature is achieved through an auxiliary gas firing equipment.

Some important parameters regarding stage of development and outlook are summed up in the following table.

Stage of development/ outlook	status
Present stage of development	demonstration stage ¹⁾
Short term cost reduction potential	low ²⁾
Short term development potential	low ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

2.6.5 Steam screw-type engine process

Functionality:

The steam screw-type engine process is different from the conventional steam turbine cycle or the steam engine process because a screw-type engine is used for steam expansion. The exhaust gas resulting from combustion produces steam inside the boiler. The steam enters the steam screw-type engine, where it is expanded. Because of that the steam performs mechanical work, which is converted into power by the generator. In the subsequent condenser the obtained condensation heat is used for district or process heat supply. With the help of a feed water pump the water is then brought to operating pressure and is fed into the boiler, thus closing the cycle.

Set-up of a CHP plant with steam screw-type engine:

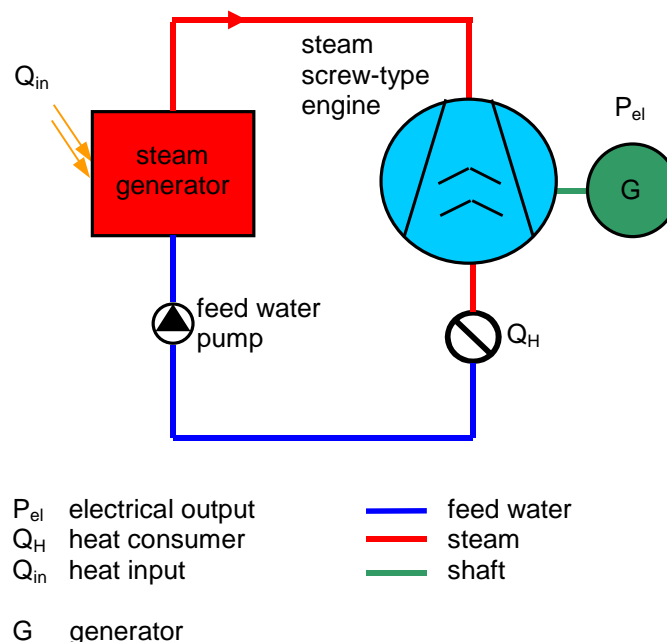


Figure 40: Diagram of a CHP plant with steam screw-type engine

Principle of a steam screw-type engine:

A screw-type engine consists of two interlocking spiral rotors. The working space between the two spiral rotors is changing periodically.

The intake is open. The steam enters the working space, the intake is closing because of the continuous rotor movement, and the steam begins to expand.

The two rotors are driven by this expansion process. This mechanical work is later converted into power by the generator.

General information on the steam screw-type engine

Application
<ul style="list-style-type: none"> For decentralized power and heat supply of lower to medium output (~20 kW_{el} - ~2000 kW_{el})
Possible fuels
<ul style="list-style-type: none"> biomass petroleum coal basically every fuel is possible
Advantages
<ul style="list-style-type: none"> good part load performance wet steam can be used low maintenance expenditure
Disadvantages
<ul style="list-style-type: none"> little operational experience limited steam pressure

In table 15 some data from a plant within a certain range of performance is outlined.

Plant size ~500 – 700 kW _{el} (biomass-fired)	Unit	Value
Specific investment costs	[EUR/kW _{el}]	~ 1.600
Specific maintenance costs	[EUR/kWh _{el}]	0,004 – 0,007
Electrical efficiency _{el}	[%]	10 – 15 (20)
Overall efficiency	[%]	up to 90
Emissions (NOx)	-	depending on fuel ¹⁾

¹⁾ at the scale of gas engines (ca. 50-500 mg/Nm³, according to output)

Table 15: Data of a steam screw-type engine process

Best operational mode:

Power or heat operated.

Design:

There are two types of steam screw-type engines: the wet-running and the dry-running engines.

In the wet-running engines oil is injected into the working space for lubrication purposes. Later this oil has to be filtered out of the cycle again.

The dry-running engines achieve a contactless movement because of a special synchromesh gear and therefore no lubrication is necessary. Yet the leakage between the screws and the engine casing is bigger than the one of the lubricated engine and thus also leakage loss is higher.

Picture of a steam screw-type engine:

The following figure shows the prototype plant for a steam screw-type engine process at the University of Dortmund.

The plant has an electrical output of about 250 kW.

Source: UNI Dortmund



Figure 41: Prototype plant for a steam screw-type engine at the University of Dortmund

Control:

Control can be achieved by throttling the steam entering the working space. Thus pressure and released electrical output are reduced.

Steam conditions:

The steam screw-type engine can be operated with superheated steam and saturated steam as well as with wet steam.

Maintenance :

Steam screw-type engines are very low in maintenance. The oil in the oil-lubricated design has to be checked regularly in order to avoid possible damage.

Maintenance expenditure amounts to about 3 hours per week.

After about 5 years a more extensive revision should be conducted.

Ecological aspects:

The oil from the wet operated steam screw-type engine can be burnt in the firing equipment or has to be disposed of separately.

During the vaporization process of water the salts contained in the water remain in the boiler. In order to avoid high salinity (scale build-up!) water is continuously desalinated (1-5 % of the circulated feed water).

In addition it is necessary to discharge the mud resulting from material abrasion and the remaining salts in the water (manually or automatically).

When discharging sewages into a stream or into the sewerage system, the corresponding legal regulations have to be complied with.

Further information:

- Compared to the steam engine, the foundation required for the steam screw-type engine does not have to be that strong because the vibrations caused by the rotatory movements are not as strong as the ones caused by the translatory movements.
- Since steam screw-type engines with 90 dBA are pretty noisy, sufficient acoustic insulation is required when used in residential areas.

Weak points:

Because of the high noise emissions (up to 90 dBA) an application of this technology in apartment houses etc. is not possible without corresponding noise insulation measures.

Stage of development:

Today screw-type engines are mostly used as compressors. When they are run as engines, a well-proven technology is also used.

Trends are definitely going towards dry running engines because oil problems can be avoided and thus maintenance expenditure is reduced.

Some important parameters regarding stage of development and outlook are summed up in the following table. (Source: UNI Dortmund)

Stage of development/ outlook	status
Present stage of development	demonstration stage ¹⁾
Short term cost reduction potential	medium ²⁾
Short term development potential	medium ²⁾

1) Stages of development: concept stage, laboratory stage, pilot stage, demonstration stage, market maturity

2) 1 year...high, 2 years...medium, 3 years...low

3 Which type of fuel can be used for each process?

CHP plants can be operated with lots of different fuels, but not every fuel can be used for each process. Therefore an overview of the various possible fuels and their application in CHP is presented in the following.

3.1 Gas

When operated with the low-emission fuel natural gas, block heat and power plants contribute to the reduction of environmental impact because there are hardly any pollutant-producing elements to be found in natural gas. Therefore the exhaust gases produced during combustion of natural gas in block heat and power plants are almost free of sulphur dioxide, dust, heavy metal and halogen compounds. Besides that, the low carbon natural gas contributes the least to the greenhouse effect compared to other fossil fuels. At the same energy content about 40-50% less CO₂ is produced during the combustion of natural gas than during the combustion of coal. About 25 % less CO₂ is produced than during the combustion of fuel oil.

The following figure shows options for the utilization of gas in CHP.

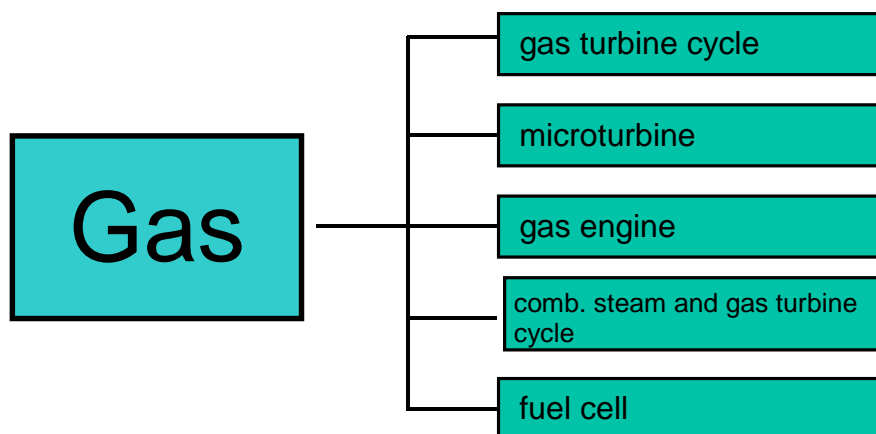


Figure 42: Options for the application of gas

3.2 Biomass

Decentralized thermal utilization of biomass is gaining more and more importance in Austria. The reason for this is on the one hand the decentralized production of biomass and on the other hand the high transportation costs compared to the fossil fuels because of the low energy density of biomass.

An EU target even aims at tripling the application of biomass until the year 2010. The following figure shows examples for the application of biomass in CHP.

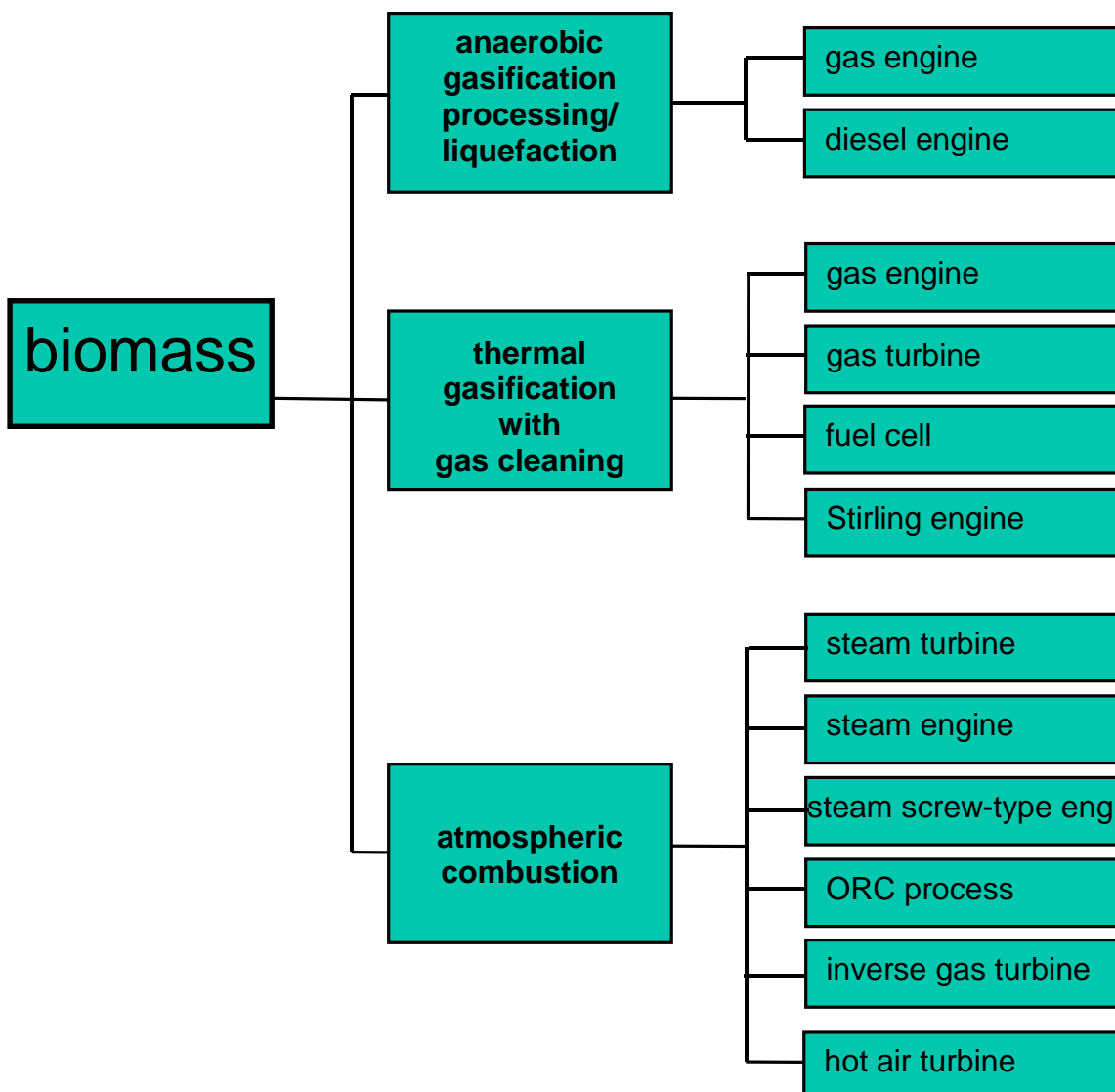


Figure 43: Options for the application of biomass

3.3 Coal, petroleum products

These fuels can basically be used in all plants in which a boiler has to be fired. However petroleum products can also be used in processes without boilers, e.g. in the diesel engine process or the gas turbine cycle.

The following figure shows examples for the application of coal and petroleum in CHP.

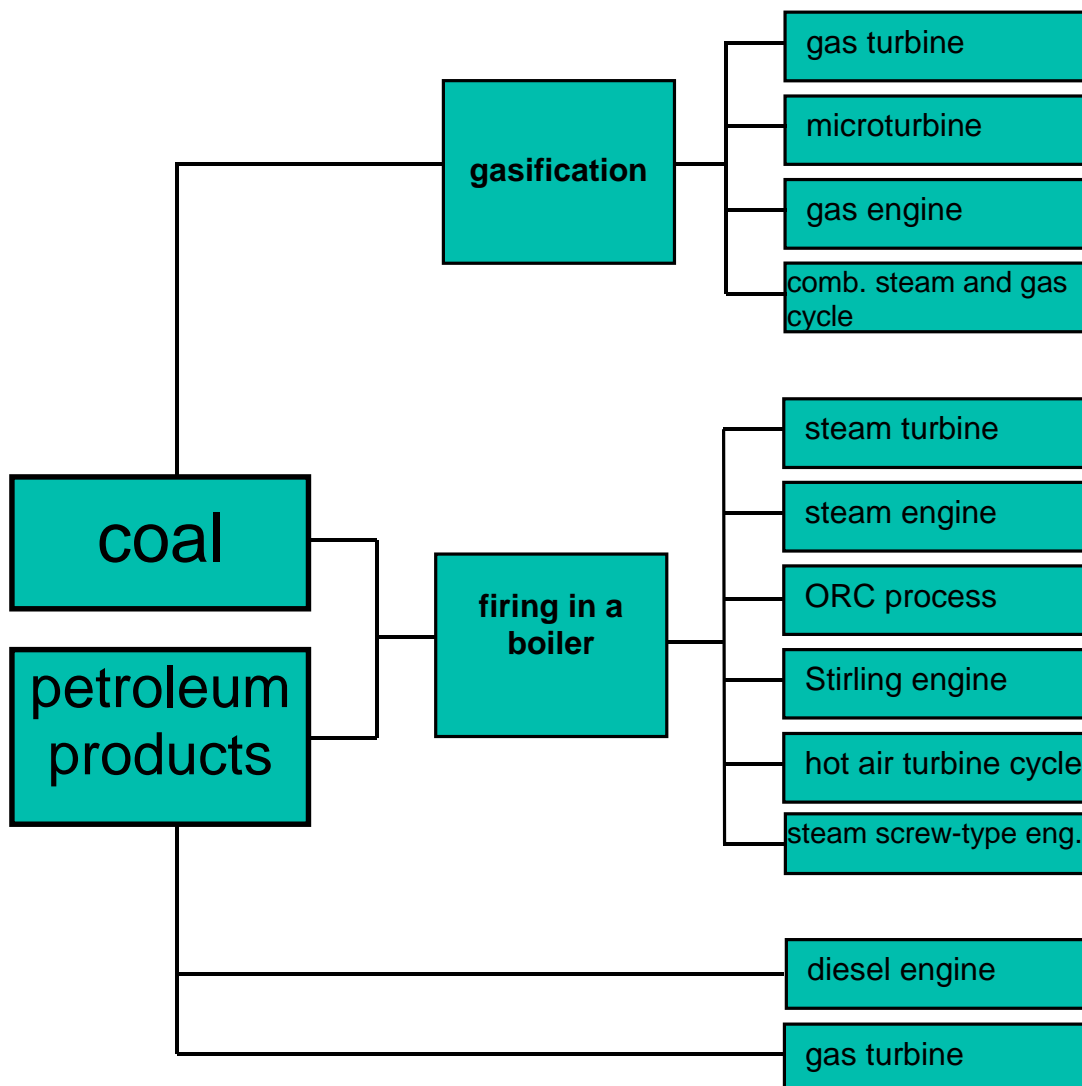


Figure 44: Options for the application of coal and petroleum products in CHP

4 Economic aspects:

CHP plants basically have a higher capital expenditure than heat or power plants. Yet they require less primary energy. Economic efficiency of the CHP plant is reached if energy cost reduction balances additional investment costs within an acceptable time.

The price level of fuel and electricity are of vital importance for energy cost reduction. Therefore the expected energy price development has to be taken into account in the calculations.

It also has to be noted that amortization time is not really informative regarding economic efficiency of the plant. It is only relevant for risk estimation.

In order to determine economic efficiency of the plant usually either the net present value method, the terminal value method, the actual cash value method or the annuity method are used. In addition to the static calculation methods also dynamic efficiency calculations which are taking price alterations into account, are used for long-term comparisons. In the following the receipts are compared with the incidental costs.

The receipts of a CHP plant consist of the following:

Receipts
<ul style="list-style-type: none">• Electricity tariff and demand rate (service supply costs)• Heating tariff when supplied by district heating network or own heat generation costs via a boiler• Feeding of surplus power into the public network• Avoided power outage costs through emergency power supply

The annual costs of a CHP plant consist of the following:

Costs
<ul style="list-style-type: none">• Capital costs• Consumption costs• Operating costs

In the following the different types of costs are explained in more detail.

Capital costs:

In order to determine the capital costs, the investment costs of the individual plant components have to be calculated.

This type of costs is heavily influenced by the underlying interest rate and the depreciation time.

If the CHP plant only covers the base load (e.g. block CHP plants), also the investment costs for the peak boiler have to be taken into account.

Costs originate from:

- Required modules
- Electrical equipment
- Adjustment of the heating system
- System control
- Building, foundation,...
- Fuel supply
- Additional costs through planning, approval,...
- Commissioning
- ...

Consumption costs:

Consumption costs are the costs for fuel and auxiliary power – mostly electrical energy – for pumps or the like.

If the CHP plant only covers the base load (e.g. block CHP plants), also the fuel and the auxiliary power for the peak boiler have to be taken into account.

Operating costs:

This type of costs consists of the maintenance costs, the service costs and the personnel costs required for operating the plant.

Besides that, also reserve power costs can incur, e.g. insurances for larger plants.

Maintenance costs are difficult to calculate and are thus usually calculated percentally from the investment costs.

Using the costs and the receipts, the annual surplus can be calculated.

With the help of these surpluses the amortization time of the plant can be determined and thus it is also shown if an investment should be done.

When financing such plants, it has to be noted that it is possible to receive financial support. Thus investment costs can be reduced and the plant can be depreciated sooner.

The following link offers an overview of different possibilities for financial support.:

<http://www.energytech.at/foerderung/index.html>

5 References

5.1 Basics (in German)

- **Thermische Turbomaschinen**
Vorlesungsskriptum für das Fach Thermische Turbomaschinen an der TU-Graz
3. Auflage, Graz
Nähere Information:
Herbert Jericha , Em.Univ.-Prof. DI Dr.techn. , e-mail: jericha@ttm.tu-graz.ac.at
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[http://www.energytech.at/\(en\)/kwk/results.html?id=1153](http://www.energytech.at/(en)/kwk/results.html?id=1153)
- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
Potentiale, Einsatzgebiete, technische und wirtschaftliche Bewertung
Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.
Online Bezugsmöglichkeit: <http://bios-bioenergy.at/bios/bios.shtml>
nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1128](http://www.energytech.at/(en)/kwk/results.html?id=1128)
- **Wärmetechnik I**
Vorlesungsskriptum für das Fach Wärmetechnik an der TU-Graz
Lehrveranstaltung 307.001
Nähere Informationen:
Reetz Beate; O.Univ.-Prof. DI Dr.techn. ;e-mail: reetz@iwt.tu-graz.ac.at
[http://www.energytech.at/\(en\)/kwk/results.html?id=1154](http://www.energytech.at/(en)/kwk/results.html?id=1154)
- **Untelagen ZSW** (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg)
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- **Untelagen Energiewerkstatt, Deutschland (Hersteller)**
Kontakt:
e-mail: steinborn@bhkw-info.de
Internet: www.energiewerkstatt.de
- **Praxis Kraft-Wärme-Kopplung**
umfangreiches Buch zum Thema KWK (3500 Seiten)
nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1146](http://www.energytech.at/(en)/kwk/results.html?id=1146)

5.2 Concepts of CHP plants

Steam Turbine Process (in German):

- **Thermische Turbomaschinen**
Vorlesungsskriptum für das Fach Thermische Turbomaschinen an der TU-Graz
3. Auflage, Graz
Nähere Information:
Herbert Jericha , Em.Univ.-Prof. DI Dr.techn. , e-mail: jericha@ttm.tu-graz.ac.at
Wolfgang Sanz, Ao.Univ.-Prof. DI Dr. techn., e-mail: sanz@ttm.tu-graz.ac.at
[http://www.energytech.at/\(en\)/kwk/results.html?id=1153](http://www.energytech.at/(en)/kwk/results.html?id=1153)
- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
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(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1128](http://www.energytech.at/(en)/kwk/results.html?id=1128))
- **Wärmetechnik I**
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Reetz Beate; O.Univ.-Prof. DI Dr.techn. ;e-mail: reetz@iwt.tu-graz.ac.at
[http://www.energytech.at/\(en\)/kwk/results.html?id=1154](http://www.energytech.at/(en)/kwk/results.html?id=1154)
- **Praxis Kraft-Wärme-Kopplung**
umfangreiches Buch zum Thema KWK (3500 Seiten)
nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1146](http://www.energytech.at/(en)/kwk/results.html?id=1146)

Gas Turbine Process (in German):

- **Thermische Turbomaschinen**
Vorlesungsskriptum für das Fach Thermische Turbomaschinen an der TU-Graz
3. Auflage, Graz
Nähere Information:
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[http://www.energytech.at/\(en\)/kwk/results.html?id=1153](http://www.energytech.at/(en)/kwk/results.html?id=1153)
- **Thermische Turbomaschinen I, 3.Auflage 1982**
Autor: W.Traupel
Verlag: Springer
- **Thermische Turbomaschinen II, 3.Auflage 1982**
Autor: W.Traupel
Verlag: Springer
- **Zeitschrift Ful (Siemens)**
Artikel: Brennstoffzellen, Die Effizienz-Weltmeister: Brennstoffzelle mit Gasturbine
Ausgabe: Heft 1/2000
Online verfügbar unter: <http://www.siemens.com/Ful/de/zeitschrift/aktuell/index.html>

- **Wärmetechnik I**
Vorlesungsskriptum für das Fach Wärmetechnik an der TU-Graz
Lehrveranstaltung 307.001
Nähere Informationen:
Reetz Beate; O.Univ.-Prof. DI Dr.techn. ;e-mail: reetz@iwt.tu-graz.ac.at
[http://www.energytech.at/\(en\)/kwk/results.html?id=1154](http://www.energytech.at/(en)/kwk/results.html?id=1154)
- **Praxis Kraft-Wärme-Kopplung**
umfangreiches Buch zum Thema KWK (3500 Seiten)
nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1146](http://www.energytech.at/(en)/kwk/results.html?id=1146)

Gas Turbine Process (in English):

- **Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications**
Publication by Arthur D. Little
More information: [http://www.energytech.at/\(en\)/kwk/results.html?id=1118](http://www.energytech.at/(en)/kwk/results.html?id=1118)

Microturbine (in German):

- **Zeitschrift Ful (Siemens)**
Artikel: Brennstoffzellen, Die Effizienz-Weltmeister: Brennstoffzelle mit Gasturbine
Ausgabe: Heft 1/2000
Online verfügbar unter: <http://www.siemens.com/Ful/de/zeitschrift/aktuell/index.html>
- **Unterlagen von G.Simader (EVA)**
Kontakt: simader@eva.ac.at
- **Mikroturbine, Neue Chancen der KWK im Leistungsbereich 30-200 kW_{el}**
Publikation, DI Reinhard Ihle, VDI, Krefeld

Microturbine (in English):

- **Descriptive literature by Bowman, manufacturer**
contact: sales@bowmanpower.co.uk
- **Descriptive literature by Capstone, manufacturer**
Website: <http://www.capstoneturbine.com>
- **Descriptive literature by Allied Signal Power Systems, manufacturer**
Website: <http://www.alliedsignal.com>
- **Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications**
Publication by Arthur D. Little
More information: [http://www.energytech.at/\(en\)/kwk/results.html?id=1118](http://www.energytech.at/(en)/kwk/results.html?id=1118)

Block CHP Plants (in German):

- **Jenbacher AG**
Maßnahmen zur Schadstoffreduzierung bei der Nutzung von Biogas in Gasmotoren
Skript, ATV Seminar, Essen 08./09. Februar 1999
Kontakt: Martin Schneider,e-mail: m.schneider@jenbacher.com ,
Tel.: +43 / 5244 / 600-2507
(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1148](http://www.energytech.at/(en)/kwk/results.html?id=1148))

- **Jenbacher AG**
Kraft-Wärme-Kältekopplung mit Gasmotoren
10. Deutsche Euroforum-Branchentage, 19.-22. Oktober 1998, Bonn
Kontakt: Martin Schneider, e-mail: m.schneider@jenbacher.com ,
Tel.: +43 / 5244 / 600-2507
(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1141](http://www.energytech.at/(en)/kwk/results.html?id=1141))
- **Untelagen ZSW** (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg)
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- **Untelagen BHKW Infozentrum**
Kontakt: Dipl.-Ing. (FH) Friedhelm Steinborne, e-mail: steinborn@bhkw-info.de
- **Untelagen Energiewerkstatt, Deutschland (Hersteller)**
Kontakt: e-mail: steinborn@bhkw-info.de
Internet: www.energiewerkstatt.de
- **Wärmetechnik I**
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[http://www.energytech.at/\(en\)/kwk/results.html?id=1154](http://www.energytech.at/(en)/kwk/results.html?id=1154)
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nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1146](http://www.energytech.at/(en)/kwk/results.html?id=1146)

Steam engine (in German):

- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
Potentiale, Einsatzgebiete, technische und wirtschaftliche Bewertung
Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.
Online Bezugsmöglichkeit: <http://bios-bioenergy.at/bios/bios.shtml>
(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1128](http://www.energytech.at/(en)/kwk/results.html?id=1128))

ORC Process (in German):

- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
Potentiale, Einsatzgebiete, technische und wirtschaftliche Bewertung
Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.
Online Bezugsmöglichkeit: <http://bios-bioenergy.at/bios/bios.shtml>
(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1128](http://www.energytech.at/(en)/kwk/results.html?id=1128))

Fuel Cell (in German):

- **Brennstoffzellen-Systeme – Energietechnik der Zukunft?**
Publikation: Günter Simader, e-mail: simader@eva.ac.at
- **Zeitschrift Ful (Siemens)**
Artikel: Brennstoffzellen, Die Effizienz-Weltmeister: Brennstoffzelle mit Gasturbine
Ausgabe: Heft 1/2000
Online verfügbar unter: <http://www.siemens.com/Ful/de/zeitschrift/aktuell/index.html>

- **Untelagen ZSW** (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg)
Kontakt: Dipl.-Ing. (FH) Friedhelm Steinborne, e-mail: steinborn@bhkw-info.de
- **Untelagen BHKW Infozentrum**
Kontakt: Dipl.-Ing. (FH) Friedhelm Steinborne, e-mail: steinborn@bhkw-info.de
- **Brennstoffzelle, eine Option für die Zukunft**
Vortrag von Martin Pokojski, Berliner Kraft- und Licht (Bewag)- AG
2. EUROFORUM-Branchentage „KWK“
Download: <http://www.eva.ac.at/publ/pdf/fuelcell.pdf>
- **Das Brennstoffzellen BHKW PC25-A: Ein Erfahrungsbericht**
Vortrag von Thomas Heissenberger, Austria Ferngas Gesellschaft m.b.H.
2. EUROFORUM-Branchentage „KWK“
- **Praxis Kraft-Wärme-Kopplung**
umfangreiches Buch zum Thema KWK (3500 Seiten)
nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1146](http://www.energytech.at/(en)/kwk/results.html?id=1146)

Fuel Cell (in English):

- **Opportunities for Micropower and Fuel Cell/Gas Turbine Hybrid Systems in Industrial Applications**
Publication by Arthur D. Little
More information: [http://www.energytech.at/\(en\)/kwk/results.html?id=1118](http://www.energytech.at/(en)/kwk/results.html?id=1118)

Stirling engine (in German):

- **Forschungsunterlagen der Fa. SOLO Kleinmotoren GmbH**
Kontakt: Dipl.-Ing. Andreas Baumüller
e-mail: andres.baumueller@solo-germany.com
Tel.: +49 / 7031 301-0
- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
Potentiale, Einsatzgebiete, technische und wirtschaftliche Bewertung
Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.
Online Bezugsmöglichkeit: <http://bios-bioenergy.at/bios/bios.shtml>

Steam screw-type engine (in German):

- **Forschungsunterlagen: UNI Dortmund (Fluidenergiemaschinen)**
Kontakt: Prof. Kauder e-mail: kauder@fem.mb.uni-dortmund.de
Dr. Claus Fost e-mail: fost@fem.mb.uni-dortmund.de
- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
Potentiale, Einsatzgebiete, technische und wirtschaftliche Bewertung
Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.
Online Bezugsmöglichkeit: <http://bios-bioenergy.at/bios/bios.shtml>
(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1128](http://www.energytech.at/(en)/kwk/results.html?id=1128))
- **Schraubenmaschinen**
Tagung Dortmund, 30. September und 1. Oktober 1998 ; VDI Bericht 1391
(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1149](http://www.energytech.at/(en)/kwk/results.html?id=1149))

Inverse gas turbine cycle (in English):

- **Research reports of TU-Graz**

Institute for Thermal Turbomachinery and Machine Dynamics

Contact:

Wolfgang Sanz, Ao.Univ.-Prof. DI Dr. techn., e-mail: sanz@ttm.tu-graz.ac.at

Hot air turbine cycle (in German):

- **Thermische Turbomaschinen**

Vorlesungsskriptum für das Fach Thermische Turbomaschinen an der TU-Graz
3. Auflage, Graz

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[http://www.energytech.at/\(en\)/kwk/results.html?id=1153](http://www.energytech.at/(en)/kwk/results.html?id=1153)

- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**

Potentiale, Einsatzgebiete, technische und wirtschaftliche Bewertung

Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.

Online Bezugsmöglichkeit: <http://bios-bioenergy.at/bios/bios.shtml>

(nähere Informationen: [http://www.energytech.at/\(en\)/kwk/results.html?id=1128](http://www.energytech.at/(en)/kwk/results.html?id=1128))

5.3 Economic Aspects (in German):

- **Unterlagen zsw** (Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg)
Kontakt:
Dipl.-Ing. (FH) Friedhelm Steinborne, e-mail: steinborn@bhkw-info.de
- **Untelagen BHKW Infozentrum**
Kontakt:
Dipl.-Ing. (FH) Friedhelm Steinborne, e-mail: steinborn@bhkw-info.de
- **Dezentrale Biomasse-Kraft-Wärme-Kopplungstechnologien**
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Autoren: Ingwald Obernberger, Alfred Hammerschmid, unter Mitarbeit der E.V.A.
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Reetz Beate; O.Univ.-Prof. DI Dr.techn. ;e-mail: reetz@iwt.tu-graz.ac.at
[http://www.energytech.at/\(de\)/kwk/results.html?id=1154](http://www.energytech.at/(de)/kwk/results.html?id=1154)
- **Thermische Turbomaschinen**
Vorlesungsskriptum für das Fach Thermische Turbomaschinen an der TU-Graz
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- **Untelagen Energiewerkstatt, Deutschland (Hersteller)**
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- **Jenbacher AG**
Kraft-Wärme-Kältekopplung mit Gasmotoren
10. Deutsche Euroforum-Branchentage, 19.-22. Oktober 1998, Bonn
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(nähere Informationen: [http://www.energytech.at/\(de\)/kwk/results.html?id=1141](http://www.energytech.at/(de)/kwk/results.html?id=1141))
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umfangreiches Buch zum Thema KWK (3500 Seiten)
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