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 table shows different options for CHP with innovative processes.

Table 20: CHP with innovative processes

Innovative processes
Fuel cell
Stirling engine
Inverse gas turbin cycle
Hot air turbine cycle
Steam screw-type engine

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.

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>> 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. It is a very promising technology especially for small cogeneration units.

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.

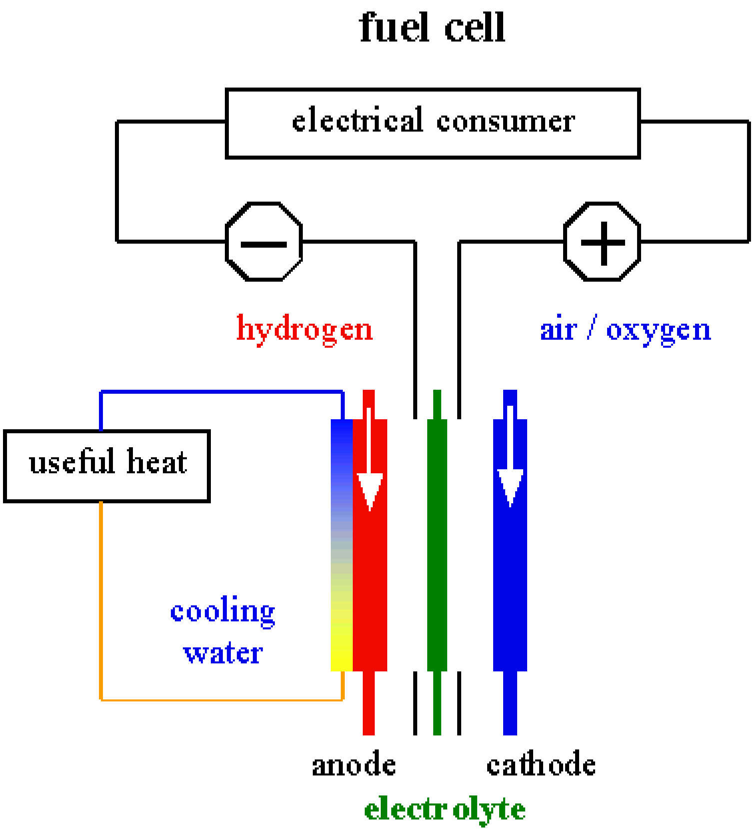
If the reaction is run backwards and the electrodes are surrounded by hydrogen (or hydrogen rich gas) and oxygen (or air) the highly exothermic detonating gas reaction (combining hydrogen and oxygen into water) causes measurable direct voltage and release of heat. In order to continuously keep the process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

Classic pollutants like CO und NOx are not produced.

The theoretical no-load voltage at room temperature is 1.23 V. To achieve higher voltages and power densities units are arranged in series to form fuel cell stacks.

Set-up of a fuel cell

Figure 27: Principle of a fuel cell



Fuels

Although fuel cells convert hydrogen and oxygen to power, they must also be capable to use standard fuels, mainly fossil fuels. But in the last years also technologies for the production of hydrogen are investigated more and more.

By reforming gases with a high hydrogen content are produced from fossil fuels and fed to the anode. At the cathode mostly air is used. The requirements on the hydrogen content depend on the type of fuel cell (see below). In general the efforts for the reforming process decrease with increasing operational temperature of the fuel cell.

Reforming technologies are:

- steam reforming
- partial oxidation
- auto-thermal reforming

The most widely used process is the steam reforming, working at high temperatures with natural gas and steam. The efficiencies of the reforming are 70 % to 85 % for natural gas.

During the reforming process also carbon monoxide CO is produced in a considerable amount so that a follow-on CO conversion must be performed, where CO and H20 are transferred to H2 and CO2.

Types of fuel cells

Fuel cells are mainly divided according to their operational temperature:

Low-temperature fuel cells (operational temperature 80 – 220 °C)	
AFC	Alkaline Fuel Cell
PEFC	Polymer Electrolyte Fuel Cell
PAFC	Phosphoric Acid Fuel Cell

DMFC	Direct Methanol Fuel Cell

Hochtemperatur-Brennstoffzellen (Arbeitstemperatur 600 – 1000 °C)

MCFC	Molten Carbonate Fuel Cell
SOFC	Solide Oxid Fuel Cell

The AFC works with pure hydrogen and has already achieved a high stage of development. But they have only minor importance for decentralized power generation.

The PEFC works with natural gas or methanol. It is a promising technology for decentralized power generation. At the moment installations up to 250 kW electrical output for industrial applications and micro fuel cells up to 5 kW electrical output for residential applications are tested.

The PAFC is the most mature technology for stationary applications in the range of few kW up to several MW. The disadvantage of this type is that longer outage periods can damage the fuel cell. Despite of its maturity a large market penetration is not expected in Europe.

DMFC fuel cells are not commercially available as cogeneration units.

The MCFC works at high temperatures and can thus internally reform most fuel gases like methane or biogas. It is a very promising technology for higher outputs and for block cogeneration units.

The SOFC works at 1000 °C and offers some advantages despite its high demands on the material. It can be used in micro fuel cells for single and multi-family houses as well as in block cogeneration units up to 1 MW. The combination of SOFC with gas turbines is also investigated.

Application

- 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. Besides, micro fuel cells (starting at 1 kW electric power) are promoted to supply residential homes with electric power and heat.

Required fuels

- hydrogen/hydrogen-rich gas from the reforming of fossil fuels
- oxygen / air
- electrolyte

Advantages

- 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

- Very high acquisition costs (block CHP plant about 3000 US-$/kW, Source ONSI).
- Technology not yet mature
- Higher output (> 1 MW electric power) is difficult to realize
- 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 21 some data for plants of two different sizes outlined.

Table 21: Data of fuel cell plants

PAFC PC-25 200 kWel	Unit	Value
Specific investment costs	[€/kWel]	~ 3.000
Specific maintenance costs	[€/kWhel]	low
Electrical efficiency [etha]el	[%]	35 - 40
Overall efficiency	[%]	up to 90
Emissions (NOx) 1)	[mg/Nm³]	~ 5
1) based on 15% O2 in exhaust gas		

SOFC (Sulzer Hexis) 1 kWel	Unit	Value
Specific investment costs	[€/kWel]	~ 3.500
Specific maintenance costs	[€/kWhel]	low
Electrical efficiency [etha]el	[%]	25
Overall efficiency	[%]	up to 90
Emissions (NOx) 1)	[mg/Nm³]	~ 5
1) based on 15% O2 in exhaust gas		

Best operational mode

Power or heat operated.

Design/Application

The high-temperature fuel cells MCFC and SOFC provide heat at a high temperature level, which makes many applications for industry possible. The heat of the low-temperature fuel cells is mostly used for heating purposes.

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.

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".

Figure 28: Fuel cell plant (Energy Research Corporation) with an electrical output of 250 kW (Source: Fuel Cell 2000)

Maintenance

Maintenance details are not yet available since most of the plants are still in their pilot stage. But fuel cells are said to be low-maintenance.

Ecological aspects

One decisive advantage of fuel cells is their low emission of pollutants. The NOx and CO emissions are by one order of magnitude smaller than from a block cogeneration unit based on a piston engine or a micro-turbine.

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, research programs of the European Commission support the development of fuel cells. 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.

Table 23: Stage of development/ outlook

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

Table 24: Fuel cell projects (Source: EVA)

PAFC
■ Test runs with 200 plants of 50 KW up to 11 MW ■ More than 2 billion operating hours ■ Reliable concept
MCFC / SOFC
■ Some pilot plants are being tested (from 1 kW up to 2 MW) ■ Material problems ■ Highest development potential
PEM
■ First stationary pilot plants ■ Particularly suitable for mobile application ■ Significant cost reduction potential

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>> Stirling engine process

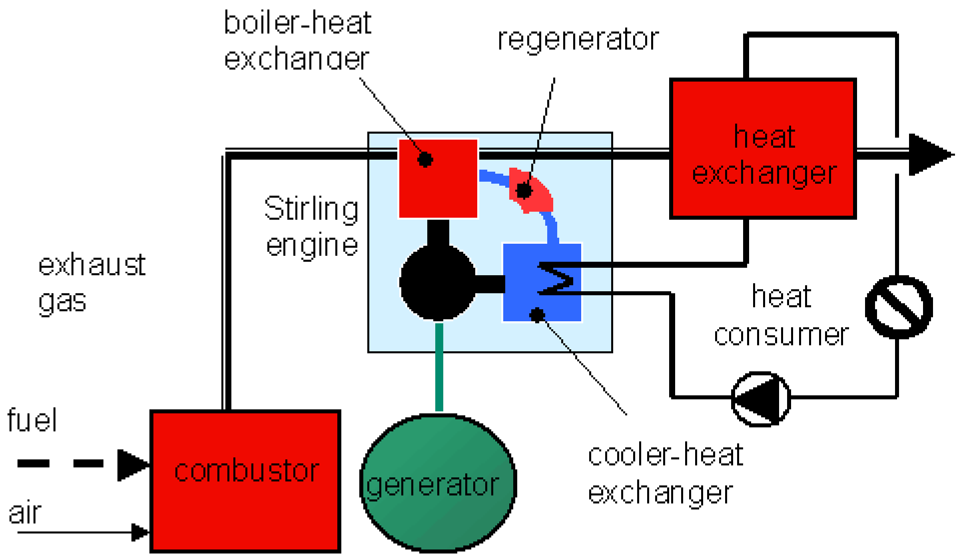
Functionality

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 29: Set-up of a CHP plant with Stirling engine



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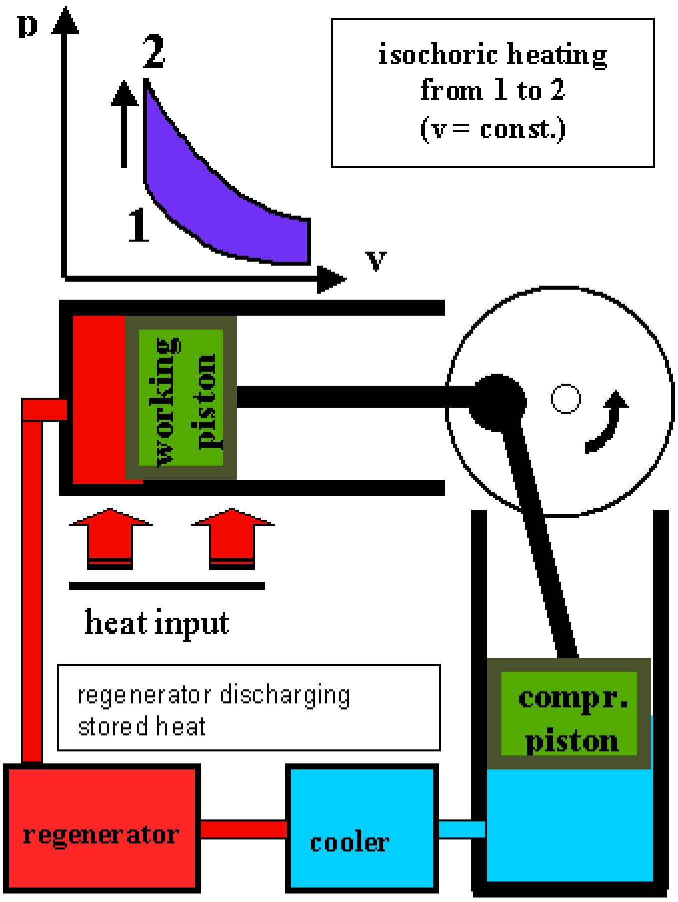
>> Operating mode of the Stirling engine

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:

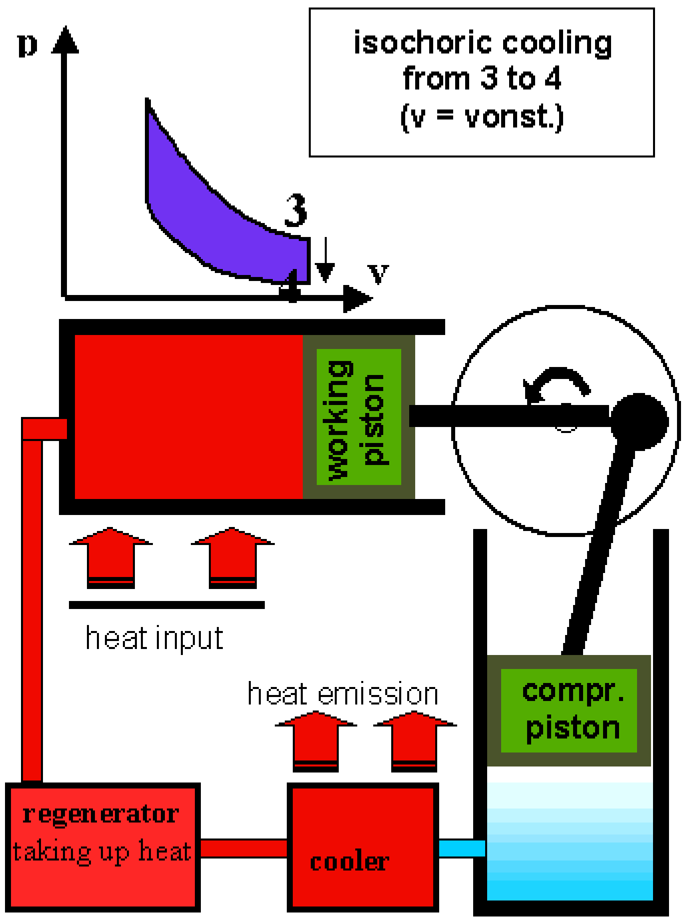
1-2: Isochoric heating phase
Because of the downward movement of the compression piston the gas is isochorically pushed into the working cylinder passing the regenerator. The piston of the working cylinder is then moving to the right. At the same time the heat stored in the regenerator (see isochoric 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 30: Functionality of a Stirling engine: Isochoric compression



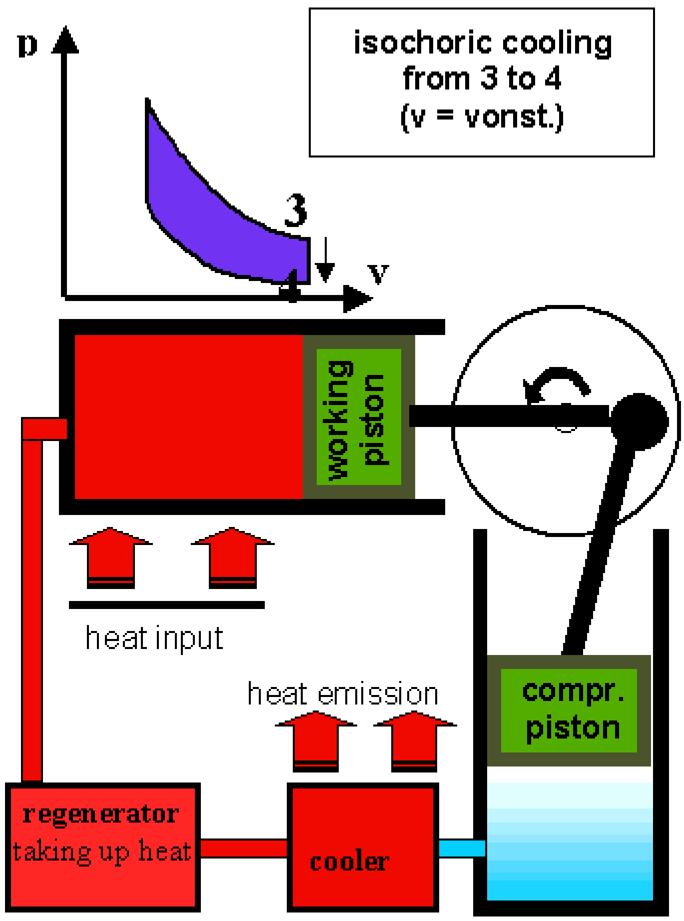
2-3: Isothermic expansion phase
Because of the additional heat input the working fluid expands and is pushing the working piston to the right. Mechanical output is transmitted to the piston rod. The compression piston is moving upwards with slight time shift.

Figure 31: 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 32: 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

- For decentralized power and heat supply of low output (10 - 45 kWel)

Possible fuels

- coal
- petroleum
- biomass
- basically every fuel is possible

Advantages

- low in maintenance
- low in noise

Disadvantages

- Boiler-heat exchanger is problematic because of the high temperature
- Sealing difficulties
- Poor part load performance
- Small plant size (only up to ~ 50 kWel [in the future up to 150 kWel] possible)

In table 25 some data from a plant within a certain range of performance is outlined.

Table 25: Data of a Stirling engine process

Plant size 10 - 40 kWel	Unit	Value
Specific investment costs	[EUR/kWel]	~ 2.400
Specific maintenance costs	[EUR/kWhel]	~ 0,004 - 0,011
Electrical efficiency [etha]el	[%]	21 - 28
Overall efficiency	[%]	63 - 86
Emissions (NOx)	[mg/Nm^3]	~ 10-15

Best operational mode

Heat operated

Design

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

- alpha-Type: the pistons are at a 90° angle to each other
- beta-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 33: 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 favorable 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).

Table 26: Entwicklungsstand / Aussichten

Stage of development / outlook	status
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	

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>> 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.

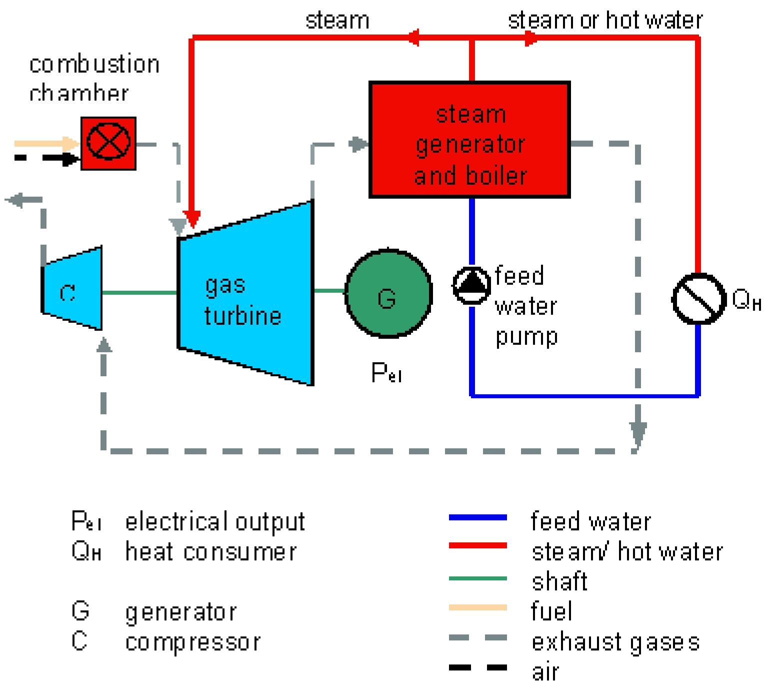
The heat contained in the exhaust gas after passing the turbine is used for generating steam or hot water and is thus available for other heat consumers. At the same time cooling of the exhaust gas reduces compression work. The exhaust gas is heated during compression and this heat can further be used 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 34: Inverse gas turbine cycle with heat recovery



Application

- For the production of electrical output and heat with biomass starting from about 1 MWel

Possible fuels

- Intended for biomass

Advantages

- Good electrical efficiency
- No overpressure
- Standard components can be used
- Also moist biomass can be used

Disadvantages

- 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 27 some data from a plant within a certain range of performance is outlined.

Table 27: Data of an inverse gas turbine cycle

Plant size 10 - 40 kWel	Unit	Value
Specific investment costs	[EUR/kWel]	~ 3.600
Specific maintenance costs	[EUR/kWhel]	unknown
Electrical efficiency [etha]el	[%]	up to 22
Overall efficiency	[%]	up to 75

Emissions (NOx)	-	no data available yet

Best operational mode

Power or heat operated

Operating state

- Medium output (~1 MWel 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 CO_2 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.

Table 28: Stage of development / outlook

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	

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>> Hot air turbine cycle (indirect gas turbine cycle)

Functionality

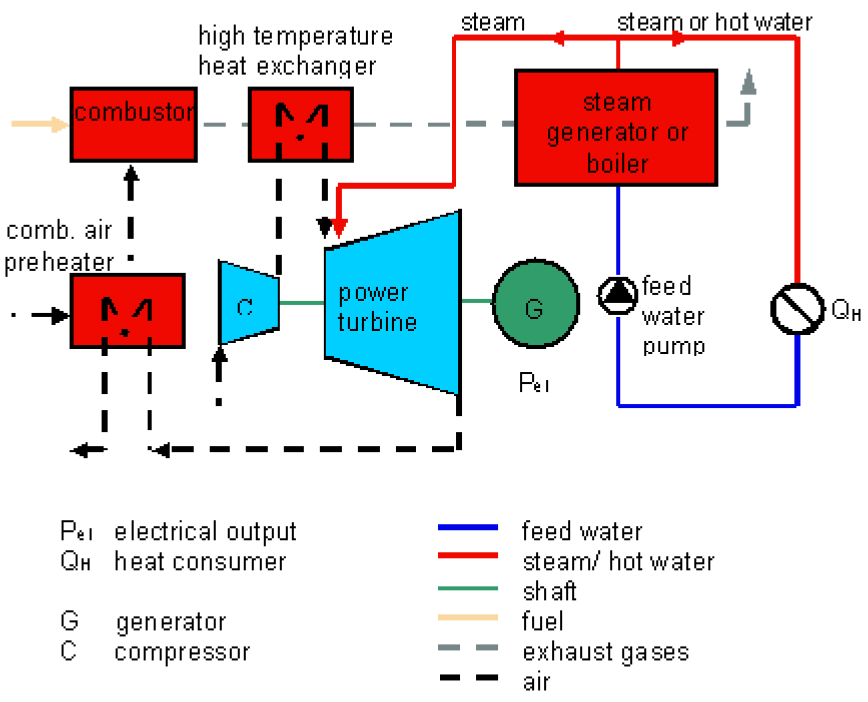
In the conventional gas turbine cycle the exhaust gas is expanded in the turbine. In the indirect gas turbine cycle instead of exhaust gas air is expanded in the turbine and the heat is transmitted from the exhaust gas to the process air in a heat exchanger.

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 35: CHP plant with hot air turbine cycle



Application

- For the production of electrical output and heat starting from 400 kWel

Possible fuels

- biomass
- coal
- petroleum
- basically every fuel can be used

Advantages

- plants with high electrical output are possible
- high electrical plant efficiency can be achieved through steam injection

Disadvantages

- Technology is not yet mature
- Plant complexity
- High thermal stresses in the heat exchanger
- Expensive heat exchanger

In table 29 some data from a plant within a certain range of performance is outlined.

Table 29: Data of an indirect gas turbine cycle

Plant size 10 - 40 kWel	Unit	Value
Specific investment costs	[EUR/kWel]	~ 3.900
Specific maintenance costs	[EUR/kWhel]	unknown
Electrical efficiency [etha]el	[%]	up to 30 (with steam injection !)
Overall efficiency	[%]	~ 80
Emissions (NOx)	[mg/Nm³]	depending on fuel 1)
1) at a scale of about 200-500 mg/Nm³, according to output		

Best operational mode

Power operated

Operating state

- Medium output (~1 MWel 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.

Table 30: Stage of development / outlook

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	

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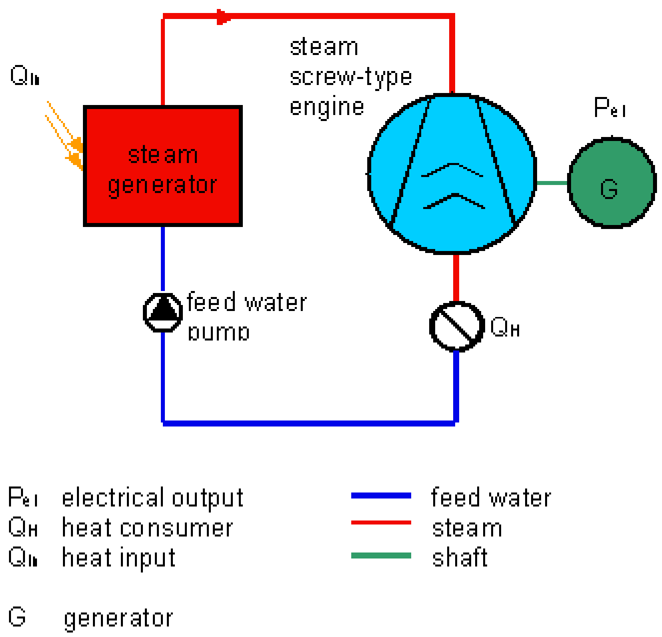
>> Steam screw-type engine process

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



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>> 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.

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>> General information on the steam screw-type engine

Application

- For decentralized power and heat supply of lower to medium output (~20 kWel - ~2000 kWel)

Possible fuels

- biomass
- petroleum
- coal
- basically every fuel is possible

Advantages

- good part load performance
- wet steam can be used
- low maintenance expenditure

Disadvantages

- little operational experience
- limited steam pressure

In table 31 some data from a plant within a certain range of performance is outlined.

Table 31: Data of a steam screw-type engine process

Plant size ~500 - 700 kWel (biomass-fired)	Unit	Value
Specific investment costs	[EUR/kWel]	~ 1.600
Specific maintenance costs	[EUR/kWhel]	0,004 - 0,007
Electrical efficiency [etha]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)		

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.

Figure 37: Prototype plant for a steam screw-type engine at the University of Dortmund (Source: UNI 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).

Table 32: Stage of development / outlook

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	