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Power-Generating Heating Systems

Opportunities for improving energy efficiency

Contents

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1 Better environmental protection through more efficient energy use

Energy consumption worldwide is rising sharply, putting a strain on resources while increasing emissions harmful to the climate and the environment. Against this backdrop, ecologically sustainable alternatives are becoming more and more important. These alternatives include in particular

- a more efficient use of energy sources,
- new, environmentally friendly and energy-saving technologies,
- new forms of energy generation and distribution, and
- the use of renewable sources of energy.

Increased energy efficiency has a very prominent role to play as it can help to meet the climate protection targets agreed under the Kyoto Protocol. Improved energy efficiency should be combined with a greater use of renewable energy sources. However, the use of renewables alone cannot ensure compliance with national energy conservation and environmental protection targets because renewables such as wind and solar energy are not always available, and there are natural limits to the quantities of resources like wood that can be grown.

When it comes to improving energy efficiency, power generation at the point of use, i.e. in the home, is an important alternative. Not only with fuel cells which are widely regarded as the technology of tomorrow. Point-of-use power generation is already possible today using appliances that operate according to the CHP (Combined Heat and Power) principle. Apart from power they also generate heat for space heating and domestic hot water production. This makes them much more efficient than appliances generating power and heat separately.

Aside from the systems already available, there are new power-generating heating systems about to be introduced to the market. In terms of reliability, efficiency and availability, they meet the high demands and expectations associated with their use in single and two-family homes. It therefore makes sense to consider this option for new homes, but also to design piping systems such that this technology can easily be retrofitted to existing systems.

This brochure provides an up-to-date overview of the state of the art, the features and the benefits of power-generating heating systems. It explains the different operating principles and describes designs already on the market or still undergoing development or field testing. On of the chapters looks at the technical, economic and energy requirements for these systems. Key aspects to be considered for the installation and tie-in of this technology into new and existing space heating, hot water and power systems are also described.

Top: Home-made power and heat (picture courtesy of Senertec)
Bottom: Senertec Dachs HKTA

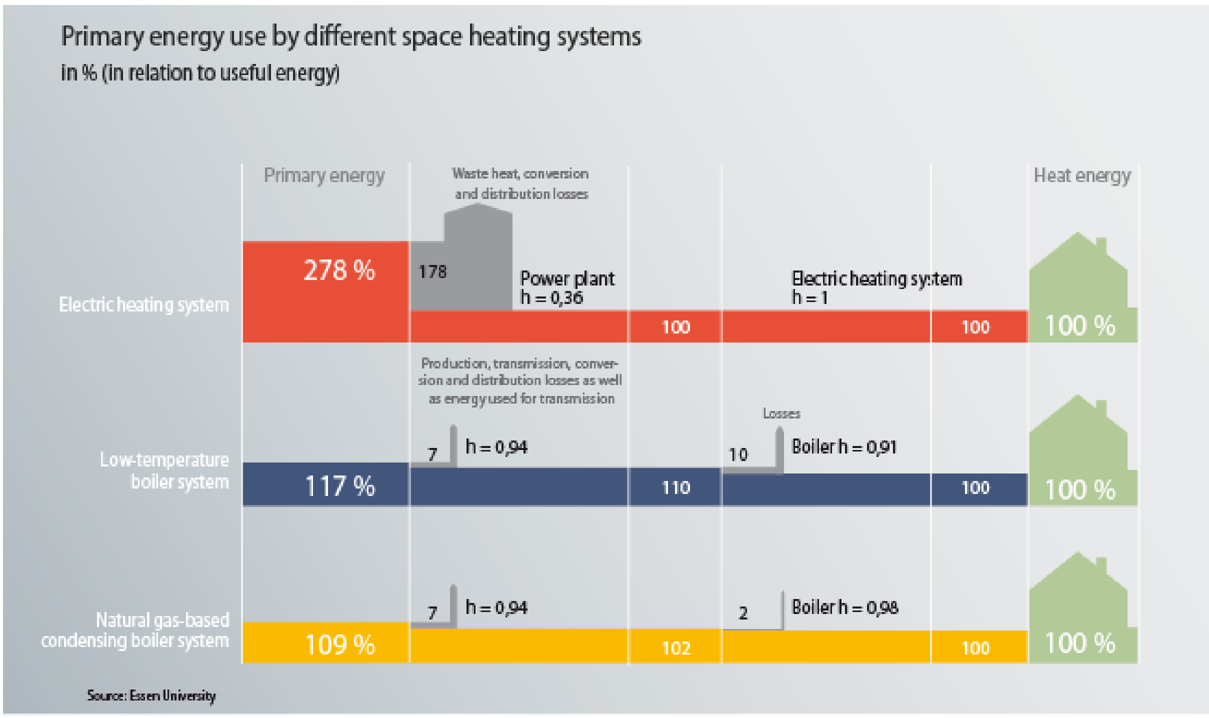
2 What are power-generating heating systems?

According to a survey conducted by the Jülich research centre in 2003, space heating and hot water production accounts for more than one third of all primary energy consumption in Germany. In private households, almost 90 % of the final energy is used for producing heat and domestic hot water. So this sector offers a huge potential for cutting energy consumption and reducing the CO_2 footprint.

A lot has already been achieved in recent years. Improved thermal insulation and more efficient heating systems have significantly reduced the space heating demand of buildings. Among other things, these developments have been brought about by new legal requirements (Renewable Energy Act, Order for the Implementation of the Environmental Protection Act, Energy Conservation Ordinance) and various support programmes. Today, almost half of the 650,000 or so space heating systems installed in Germany every year use energy-saving natural gas-fired condensing boilers.

So in the domestic space heating market, energy-efficient and environmentally friendly technology is already widely used. For electricity, the situation is very different. Electricity is drawn from the public grid. In central power plants (not fitted with recuperators for recovering waste heat) and during power transmission, about two thirds of the input energy is lost.

Primary energy can be used much more efficiently if heat and power are generated directly at the place of use. For these on-site systems it is important to focus on the recovery of the waste heat produced during the power generation process.



Primary energy use and conversion losses for space heating systems based on different generation processes

2.1 Cogeneration: Fuel-efficient and environmentally friendly

Natural gas-based cogeneration systems relying on gas engine-driven small-scale CHP units or gas turbines have long been one of the most efficient ways of saving energy. These systems have overall efficiencies of as much as 90 %, resulting in significant energy savings and reductions of polluting CO_2 emissions. Cogeneration has seen significant technical advances over the past few years. Today there are several thousand CHP systems in Germany with electrical capacities ranging from a few kilowatts to more than a hundred megawatts. Small units with electrical capacities of up to 10 kilowatts (kW_e) are referred to as micro-CHP units. They can be used very effectively where both electrical and thermal energy is needed at the same time and where they are operated in a baseload regime clocking up more than 4,000 load hours per year.

There are several manufacturers offering dedicated micro CHP units (which are the building's only source of heat). During periods of low heat demand, the heat is stored, which prevents the unit from short-cycling (i.e. having to make too many starts and stops). Larger quantities of heat (e.g. for a shower) can be taken from storage as and when needed.

EC Power XRGI 13-G-TO

WhisperGen

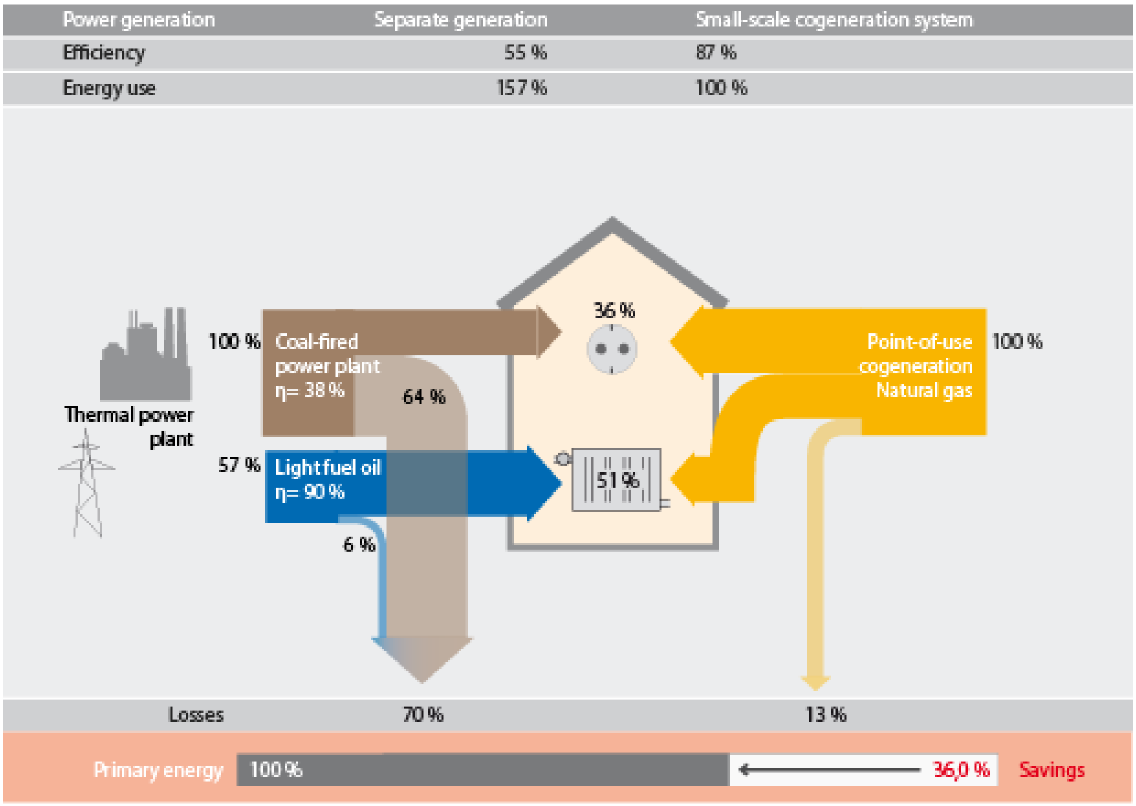
2.2 Heat and power generation in homes

Power-generating heating systems have an even lower output range (1 to 3 kW_e) but the operating principle is very similar. They can meet up to 100 % of a home's heating demand. Unlike conventional space heating systems, they also produce electricity, thereby reducing the amount of electricity drawn from the grid and reducing overall energy costs.

Combining the two processes allows the primary energy to be used much more efficiently. To obtain the same amount of heat and electricity as conventional systems (where heat is produced in the home and electricity is drawn from the public grid), combined systems require up to 36 % less primary energy.

Overall efficiency

Despite their efficient energy use, power-generating heating systems appear to have lower overall efficiencies than condensing appliances when one only looks at the numbers, which may lead to a misjudgement. For a direct comparison, it is important to remember that power-generating heating units produce both **heat and power**, which means their overall efficiency rating is for both processes. Condensing appliances only generate heat for space heating and domestic hot water. So their efficiency rating applies only to the heating process. Any comparison of the two systems therefore also has to take account of the power drawn from the public grid.



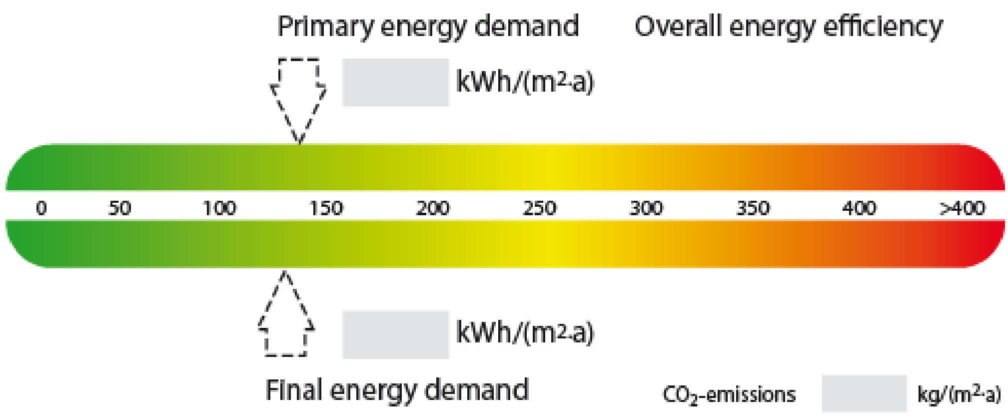
Comparison of primary energy consumption by central and point-of-use power and heat-generating systems

Energy conservation requirements met easily

The German Energy Conservation Ordinance (EnEV) specifies a maximum annual primary energy demand for all new buildings. Ways of ensuring compliance include installing energy-efficient heating systems, thermal insulation or a combination of both. Hence, according to the Ordinance, buildings using cogeneration systems for heat and power generation are given a far lower annual primary energy demand rating.

According to Section 3 (3), of the Energy Conservation Ordinance, new buildings using CHP units for at least 70 % of their space heat are even exempt from the requirements set forth in the Ordinance, which means that additional measures (special thermal insulation etc.) do not have to be taken.

Energy demand



Energy passport
From 2008, even existing buildings will require an energy "passport" as set forth in the Energy Conservation Ordinance. This passport describes the energetic quality of the building. In future, highly energy-efficient homes rented or sold on the market will carry an energy premium.
As with new buildings, homes retrofitted with a power-generating heating system will be assigned a better primary energy factor to indicate that their annual primary energy demand is lower. So power-generating heating systems help secure a higher energy efficiency rating than conventional heating systems, and hence a better score for a building's energy passport.

New contracting opportunities

Power-generating heating systems offer new opportunities for contracting models.

In the energy industry, contracting is a service concept that includes energy system design, financing, construction and operation. The service can e.g. be provided by energy utilities, which means that the utility will finance and operate a power-generating heating system installed inside the customer's home. A number of energy utilities are already offering contract models for various highly efficient energy systems including condensing boiler systems for single and two-family homes.

In rented accommodation, it is usually the tenant who has a contract with the local utility for electricity (incl. meter reading and billing services) while heat (incl. meter reading and billing services) is provided under a contract with the landlord. This situation makes contracting a very interesting option for power-generating heating systems. In many cases (depending on the terms of the rental agreement), the tenant's approval may be required.

3 Operating principle of power-generating heating systems

Power-generating heating systems burn primary energy to generate both heat and mechanical energy. This mechanical energy is used to drive a generator that produces electricity. Three different technologies are available:

- internal and external combustion engines (Otto and Stirling engines, etc.)
- steam expansion engines
- fuel cells

Systems driven by combustion engines have a shaft connecting the power generator with the engine. Steam expansion engines have a piston, which is driven by the expanding steam to turn the generator, or which is part of the generator. Fuel cells are electromechanical devices that convert the energy of the fuel released by the conversion process directly into electrical and thermal energy. They therefore do not require a generator.

Combustion engines are currently the state of the art for most applications. In the higher output range, steam expansion is the technology of choice. Efforts are underway to make this technology usable also for lower outputs. Fuel cells are a future possibility which, if developed further, may expand the range of technologies available for power-generating heating systems in a few years time.

3.1 Otto engine

Operating principle: The Otto engine is an internal combustion engine in which fuel is mixed with air drawn into the cylinder for spark ignition. The combustion gas is generated by an explosion under controlled conditions, increasing the pressure to drive a piston. The linear motion of the piston is converted into the rotary motion of a shaft that turns the generator. In power-generating heating systems, most of the waste heat produced by the engine is recovered in heat exchangers for use as space heat or for heating domestic water.

Development status: Otto engine-based cogeneration systems are widely used in the higher output range (electrical capacities of up to several MW_e). Also available on the market are micro-CHP units rated at around 5 kW_e for use in multi-family homes, large single-family homes with high a energy demand, hotels, commercial buildings, etc. Manufacturers include PowerPlus Technologies ("Ecopower"), Senertec ("Dachs") and EC Power.

The same technology can also be used for power-generating heating systems. In Japan, Honda has teamed up with a gas supply company to successfully launch an Otto engine-based system generating 1 kW of electrical energy and 3.25 kW of thermal energy. At the end of 2006, some 30,000 of these units were already in use. They are installed outside the building, usually in combination with a peak-load boiler and a hot-water storage tank. In Japan, it is not permitted to feed power into the public grid.

Source: PowerPlus Technologies

Outside Japan, the units were first introduced in the US in late 2006. In Europe and particularly Germany, they will require some modification for indoor installation and for feeding excess electricity into the grid. Honda is currently looking at the options for introducing these units on the German and European markets.

Assessment: Otto engine-based power-generating heating systems benefit from a thoroughly developed technology that has been around for more than 100 years. They also have a relatively high electrical efficiency (approx. 25 %) and a very high overall efficiency (approx. 89 to 90 %). Drawbacks include the high maintenance cost (regular oil changes) and possibly also higher emissions when compared with other power-generating heating systems, which are due the internal combustion process. Vibration and noise emissions can be mitigated by appropriate attenuation measures and an acoustic enclosure.

3.2 Stirling engine

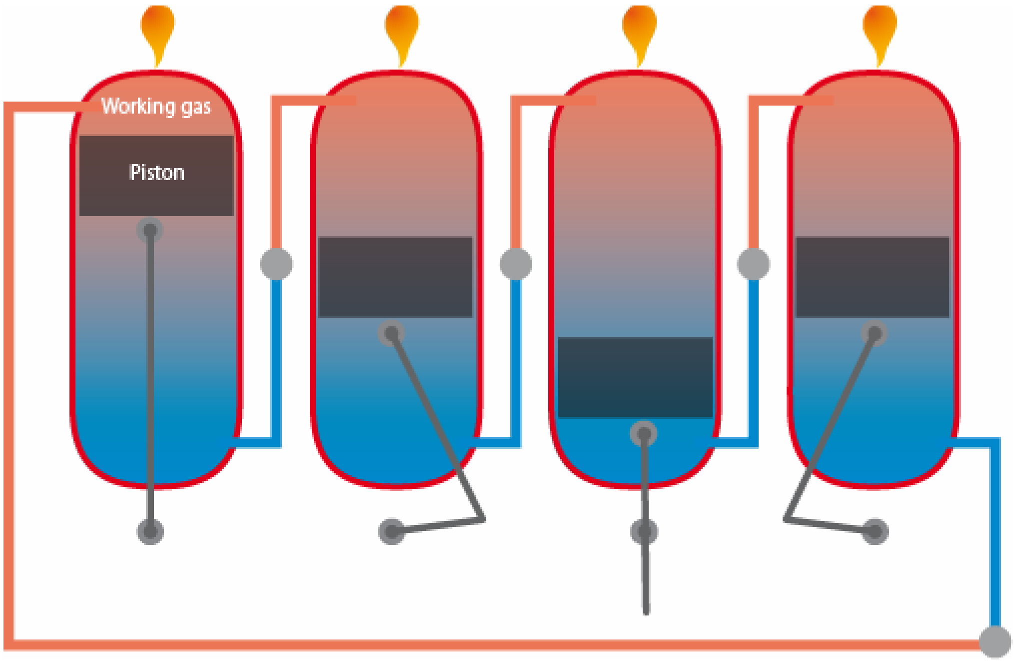
Operating principle: This technology relies on an external combustion engine in which a working gas (e.g. helium) is alternately heated and cooled in a closed system, which results in a reciprocating motion of a piston to drive a generator.

The working gas is heated externally (using a natural gas burner or equivalent), causing it to expand and push the piston downwards into the cylinder. Some of the working gas is displaced from the cold side below the piston to the hot side of the next cylinder, thus cooling the hot side down. The vacuum pressure created this way draws the piston back up for the cycle to start again.

Development status: Micro-CHP units with Stirling engines manufactured by companies like Solo Stirling GmbH are already available on the market. Their output range (8 to 22 kW of heat and 2 to 7.5 kW of power) makes them particularly suited for single-family homes, public buildings as well as commercial and industrial facilities.

Stirling engine-based power-generating heating systems developed by companies like WhisperGen are currently undergoing field trials. They are expected to be launched on the market in a few years once the results of the current field test have been incorporated into the design and the units have gone into series production.

Assessment: Stirling engines are supposed to have very low noise and pollutant emissions and almost zero wear, which reduces maintenance costs. Because of the high heat losses, their electrical efficiency is relatively low (approx. 15 %). Yet thermal efficiencies are extremely high, which is why they achieve overall efficiencies in excess of 90 %.



Operating principle of a 4-cylinder Stirling engine (WhisperGen)

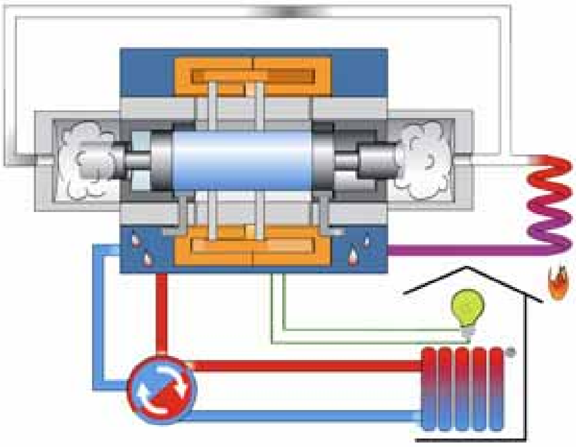
3.3 Steam expansion engine

Operating principle: This system has a closed water circuit in which the water is heated by an external heat source (natural gas burner, etc.). The steam is piped to a working chamber where it is depressurised. The heat released by the condensing steam is recovered for the heating system. Expansion of the steam during pressure letdown causes a piston inside the working chamber to reciprocate, thereby driving the generator.

Development status: Power-generating heating systems based on the use of steam expansion engines are also in a trial stage. Otag has teamed up with various sales partners to launch its "lion Powerblock", which will initially be manufactured in smaller numbers.

Assessment: As for Stirling engines, the emissions of a steam expansion engine are lower (because of system-inherent reasons) than the emissions from internal combustion engines. This technology, too, has comparatively low electrical efficiencies of 10 to 15 % and high overall efficiencies in excess of 90 %. Maintenance requirements are somewhat lower.

OTAG lion Powerblock



Source: Otag Vertriebs GmbH & Co. KG

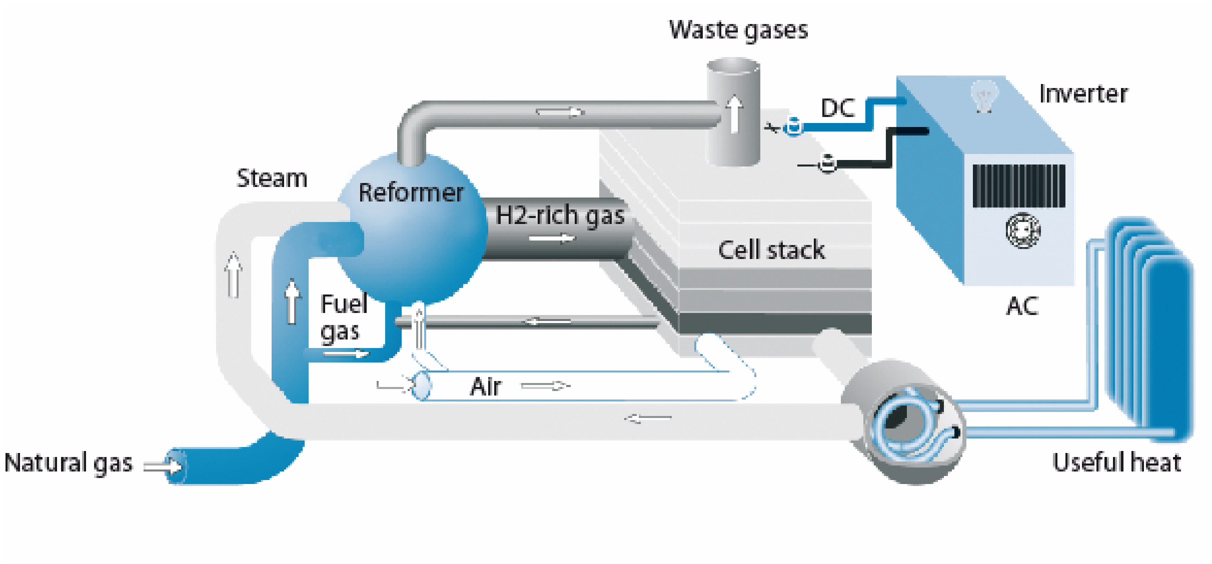
3.4 Fuel cell

Operating principle: Conventional heat engines used for power generation produce mechanical energy by burning fossil fuels (e.g. in an engine) which is then converted by a generator into electrical energy. Unlike these engines, fuel cells use the energy of a fuel (e.g. hydrogen produced from natural gas in what is known as a reformer) for direct conversion into electrical and thermal energy in what is a purely electrochemical processes. Because of the low conversion losses, fuel cells have high electrical efficiencies and low pollutant emissions.

Fuel cells essentially consist of two electrodes (anode and cathode) separated by an electrolyte. The hydrogen flows into the fuel cell on the anode side where a catalyst allows the molecules to dissociate into electrons and protons. While the protons pass through the electrolyte to the cathode, the electrons have to travel through an external circuit to the cathode, thereby producing electricity. At the cathode, the protons and electrons combine with oxygen to produce water (steam).

Development status: Various manufacturers (Hexis, Viessmann, etc.) and cooperation projects (Vaillant/Webasto, etc.) are currently looking into the use of fuel cells for power-generating heating systems (known as fuel cell heaters). Some units are currently undergoing field tests. The hydrogen needed is usually generated from natural gas and steam by a catalytic process in a reformer integrated into the unit.

Of all the technologies described here, fuel cells are widely seen as still having the longest way to go to reach market maturity. However, given their inherent benefits (high electrical efficiency and good partial load behaviour), they are expected to a play a major role in future energy supply. For this goal to be achieved, various problems still need to be resolved to allow series production at competitive prices.



4 Market Availability

Systems based on the cogeneration principle have been available on the German market for many years. The ASUE brochure entitled "Packaged CHP System Data" provides an overview of all small-scale CHP systems operated with natural gas, biogas, sewage gas, rapeseed oil and fuel oil. Given their output range, only a few of these systems are suited for use as power-generating heating systems, i.e. in single, two or multi-family homes or for small commercial businesses.

The following tables show some of the systems already available for this application or about to be introduced to the market.

Units with a low electrical output
under development/undergoing trials

Manufacturer	Honda Motor Co. Ltd.	Enatec micro-cogen b.v.	OTAG Vertriebs GmbH	WhisperGen Ltd.
Unit	Ecowill		lion Powerblock	WhisperGen
Principle	Otto engine	Stirling engine	Steam expansion	Stirling engine
Electrical capacity (kW)	1.0	1.0	0.2-2.2	1.0
Thermal capacity (kW)	3.25	4.0-35.0	2.5-16.0	7.5-14.0
Weight (kg)	approx. 81	approx. 100	approx. 190	approx. 150
Status	Sold in Japan since 2003, sales the US started in 2006, test rig trials under way in Germany	Prototype tests in Japan and the Netherlands	Delivery of pre-series units starting in late 2006	Field tests in Germany and Switzerland, sales in the UK and the Netherlands
Website		www.enatec.com	www.otag.de	www.whispergen.com

Units available on the market

Manufacturer	Senertec GmbH.	PowerPlus Technologies	Solo Stirling GmbH	EC Power
Unit	Dachs HKA	ecopower	Soloe Stirling 161	XRGI 13G-TO
Principle	Otto engine	Otto engine	Stirling engine	Otto engine
Electrical capacity (kW)	5.5	1.3-4.7	2.0-9.0	4.0-13.0
Thermal capacity (kW)	12.5	4.0-12.5	8.0-26.0	17.0-29.0
Weight (kg)	approx. 530	approx. 395	approx. 450	approx. 700
Status	available	available	available	available
Website	www.senertec.de	www.ecopower.de	www.stirling-engine.de	www.ecpower.de

For more up-to-date information, go to www.stromerzeugende-heizung.de.

5. Use of power-generating heating systems

In order to maximise efficiency improvements, it is important to select the unit in line with the place of installation and the individual requirements.

5.1 Demand-based requirements

These requirements depend on the energy situation of the building. Parameters include the annual demand for space heating, hot water and electricity but also load profiles, i.e. the distribution of energy demand over a year and over a day.

Buildings for which the Energy Conservation Ordinance has been implemented (particularly new buildings) have a lower heat energy demand, allowing smaller units to be used. For units to have a high annual fuel use efficiency, they either require a wide modulation range (if they are the only heat source in the home) or they have to be used in combination with a peak-load boiler (if the power-generating heating system is designed to only cover the home’s thermal baseload requirements).

The building’s electricity demand is determined from the baseload, a higher permanent load over extended periods and from short-term peaks. The baseload essentially depends on the number of appliances in the household, the number of users and – as with heat energy demand – on user behaviour.

5.2 Installation requirements

These requirements relate to the power-generating heating system, the ancillary units and the way the system is integrated into the building’s infrastructure. Issues to be considered include electrical and hydraulic connections, combustion air supply and flue gas discharge. Apart from the thermal and electrical capacities, operators also have to take account of the thermal capacity of any peak-load boiler already installed (or required), the type of hot water production and the size of the hot water storage tank.

In new as well as existing buildings, power-generating heating units must

- have the right size and weight to allow them to be handled like conventional heating systems,
- allow installation in cellars or the attic,
- allow easy integration into existing space heating and domestic hot water systems,
- allow a tie-in into the power supply system with the ability to also feed into the public grid.

Another important parameter is the technology (combustion engine, steam expansion, etc.) because it essentially determines how the system can be used (see page 14) and what the likely noise emissions will be. To allow these systems to be installed at the usual places (attic or cellar), noise levels are reduced to those of conventional heating systems using appropriate noise insulation.

5.3 Economic requirements

Whether or not a power-generating heating system is economically viable depends on several aspects. First, there are the capital costs (investment), which have to be recovered. Apart from the capital cost, there are consumption-related costs for the energy used and for services such as maintenance and repair. Long service intervals and low maintenance can help keep operating costs down.

The option to produce electricity makes power-generating heating systems more expensive than conventional systems. These additional costs can be recovered in a number of ways:

- reduction of the amount of electricity taken from the public grid (utility tariffs tend to be the highest for single-family homes)
- earnings from resale of excess electricity to the grid
- no electricity tax for the electricity generated (currently 2.05 ct/kW_e)
- energy tax refund for the natural gas used (currently 0.55 ct/kWh of natural gas (provided it can be demonstrated that the power-generating heating system has an annual fuel use efficiency of more than 70 %, which is usually the case)

The tariff for, and the amount of, the electricity actually sold into the public grid can have a significant impact on the economics of power-generating heating systems. The price paid for electricity fed into the grid is determined by the "prevailing price", which is the average baseload price quoted at the Leipzig power exchange EEX for the preceding quarter. It is published online at www.eex.de.

Honda Ecowill (left)
PowerPlus Technologies ecopower (centre)
Solo Stirling 161 (right)

5.4 Operating modes

The mode of operation of a CHP system depends on the power and heat demand and the related costs. There are basically two operating modes: heat-controlled and power-controlled operation.

Heat-controlled systems are designed to meet a specified heat demand. They are only operated when heat energy is required. The power generated is either used on site or fed into the grid.

Power-controlled operation is the exact opposite, i.e. the CHP system is operated in line with the site's electricity needs, and the heat generated is either used directly or stored for later use.

Power-generating heating systems are usually designed for heat-controlled operation.

Regardless of the actual power and fuel prices and the tariffs paid for electricity fed into the grid, there are various options for using power-generating heating systems installed in single or two-family homes:

Power is used at the place of generation while the heat is either stored or also used (if necessary in combination with a peak-load boiler to cover peak heat demand)	This mode of operation allows maximum savings in comparison to taking electricity from the public grid. The power-generating heating system should therefore always be designed to allow most of the power generated to cover the building's own needs, both at the system's rated load and the minimum load.
Power is purchased from the public grid while the heat is drawn from the storage tank when power-generating heating system is down	Power costs will in this case be higher than on-site generation costs. However, use of the heat stored provides the possibility to generate power later on for on-site use.
Power is fed into the public grid while	This mode of operation makes sense if there

the heat is used	is a demand for heat and the tariff for selling into the grid is attractive.
Power is fed into the public grid while the heat is stored	If the on-site heat demand is low, the heat can be piped into storage to be able to produce power for extended periods.

Given the varying power and heat demands of residential buildings, the consumption options outlined above only provide a general overview. Generally, the system should be operated to meet the building's own power and heat demand.

Rate of load change

What is also important to consider is how fast power-generating heating systems can change between different load points or how often the system is started / stopped to adapt to changing load requirements. Frequent starts and stops indicate that the system has not reached its ideal operating point. The reason could be that the system has been designed incorrectly, i.e. that it is either too large for the operator's actual demand structure or that the storage tank is too small. It may be possible to minimise short-cycling by choosing an appropriate control system.

Because of their relatively long heat-up times, other technologies such as fuel cells are at a clear disadvantage when it comes to load changes. Combustion engines and steam expansion systems on the other hand can respond relatively quickly to sudden load requirements.

5.5 System integration and installation

For system integration, there are various influential variables to take into account, resulting in different tie-in options. Given their complexity and importance, the hydraulic connections are described in a separate brochure entitled "Einbindung von kleinen und mittleren Blockheizkraftwerken / KWK-Anlagen" ("Tie-in of small and medium-sized CHP systems").

Power-generating heating systems are mostly used in combination with the grid, which is why on-site systems such as mirco-CHP units are usually connected to a building's power supply system in parallel with the public grid.

For systems designed to be used in parallel, a meter has to be installed for the power taken from the grid. A second meter is needed if excess electricity is fed back into the grid. Maximum fuel requirements are determined by the rated capacities of the micro-CHP system and the peak-load boiler.

In existing buildings, the hot water demand is usually the key parameter determining the design of the gas supply piping, the meters and the flow switches. Before installing a power-generating heating system, home owners should have the capacity of the gas service connection checked by their utility.

On the combustion air side, heating systems are designed to be operated either as open or room-sealed systems. Where possible, the system should be installed so that it can tie into the existing flue piping without requiring any modifications. If at all possible, the heating system and any peak-load boiler should be connected to a common flue pipe in the room where they are installed, making sure that pressure differences in the flue gas from the power-generating heating system and the peak-load boiler are taken into account.

Further information is available at www.stromerzeugende-heizung.de and from the ASUE brochure entitled "Einbindung von kleinen und mittleren Blockheizkraftwerken / KWK-Anlagen" ("Tie-in of small and medium-sized CHP systems").