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PRIORITY 6
SUSTAINABLE DEVELOPMENT, GLOBAL CHANGE AND ECOSYSTEMS

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MicroCHeaP Literature Search: Biomass
Investigation related to biomass conversion technologies for Micro-CHP
Contributed by BTG

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1 DEFINITIONS AND SCOPE

1.1 DEFINITIONS

Biomass

The following generally accepted definition of biomass originates from the EU directive 2001/77/EC of 27 September 2001 on the promotion of electricity from renewable energy sources in the internal electricity market:

> *"Biomass shall mean the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste".*

Biomass cannot be regarded as a single product but consists of an almost countless group of products that can be classified according to:

- type: physical and chemical properties (moisture content, calorific value, morphology, etc.);
- genesis (energy crop, by-product/residue, waste product);
- sector of origin (agriculture, industry, waste processing sector);
- potential energy applications (electricity, heat, CHP or transport fuel);
- legal status (waste or product).

Micro-CHP

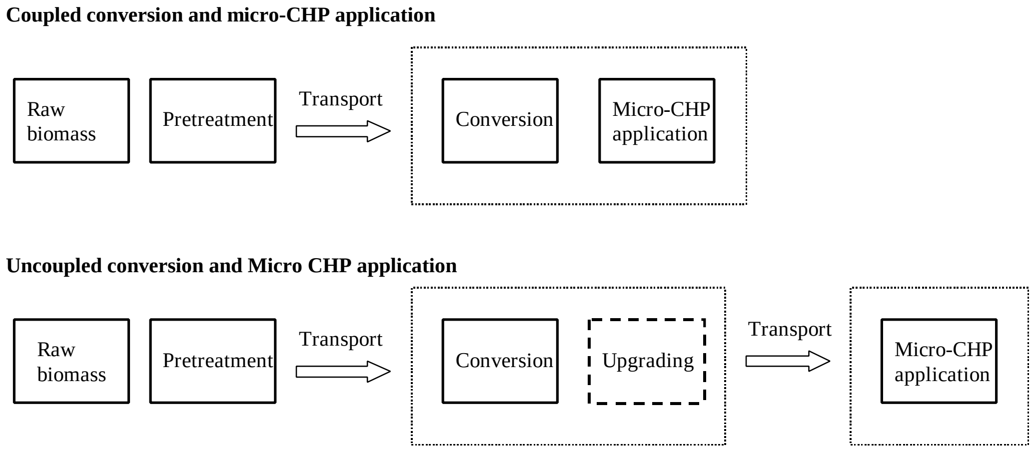
Directive 2004/8/EC of 11 February 2004 'on the promotion of co-generation based on a useful heat demand in the internal energy market' provides the following definition of micro-CHP:

> 'micro-cogeneration unit' shall mean a cogeneration unit with a maximum capacity below 50 kWe.

The database explanation indicated that applications op till 500 kWe could be considered in this project. According the European definition this would be 'small scale cogeneration' (cogeneration units with an installed capacity below 1 MWe). Although the main focus will be on micro-cogeneration (<50 kWe), capacity limits are always somewhat arbitrary and BTG accepts a capacity limit of 500 kWe.

1.2 SCOPE

Biomass can be used as a fuel for micro-CHP installations after pre-treatment and conversion into an applicable fuel. The conversion[1] of the raw biomass into an applicable fuel can take place coupled with the final application at one location, or uncoupled with conversion and application at different locations. See the figure below. Uncoupled conversion has the advantage that large scale biomass pre-treatment and conversion technologies can be used; a disadvantage is the need for a distribution system for the final product, although it must be recognised that in coupled systems also often biomass transportation to the site takes place.


Coupled conversion and micro-CHP application

Uncoupled conversion and Micro CHP application

Figure 1 Schematic overview of coupled and uncoupled biomass-to-application chains for micro-CHP

Table 1 and Table 2 provide an overview of possible biomass-to-application chains for coupled and uncoupled supply chains.

Table 1 Coupled biomass-to-application chains suitable for micro-CHP

Biomass product category	Conversion technology	Product	Application
Solid biomass	Combustion	Hot flue gas	Stirling engine
	Gasification	Producer gas	Micro-CHP
Liquid biomass	-	-	-
Gaseous biomass	Anaerobic digestion (manure)	Biogas	ICE

Examples of coupled biomass-to-application chains are the conversion of solid biomass, i.e. wood chips, pellets or briquettes into heat and application in a Stirling engine[2] For

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[1] In this overview conversion means a chemical transformation of biomass. Activities like drying, sizing, chipping, pelletising etc are regarded as pre-treatment.

[2] Wood pellets are used in domestic heating systems and might be interesting to be considered for micro-CHP applications. Briquettes and wood chips should be mentioned as well although BTG expects pellets to be a very promising fuel because of the possibility of simple and effective fully automated feeding.

use in a Stirling engine a clean gaseous heat flow of a temperature of more than 900 °C is needed. Both gasification and combustion could be used and worth to be investigated into more detail.
Anaerobic digestion of manure is a common CHP application, usually in the range of 35-300 kWe, so it can be regarded either as micro CHP or small scale CHP. Anaerobic digestion of sludge and landfill gas extraction and electricity are usually performed at capacity levels substantially higher than 50 kWe.

Liquid biomass like biodiesel, bio-ethanol, pure vegetable oil, pyrolysis oil are all the result of conversion and upgrading of the biomass at a central facility site and therefore mentioned in
Table 1.

Literature research for coupled biomass CHP-applications should be focussed on:
- Small scale gasification
- Small scale combustion
- Manure digestion.

Table 2 Uncoupled biomass-to-application chains suitable for micro-CHP

Biomass product category	Conversion technology	Product	Cleaning/ upgrading	Application
Solid biomass	Carbonization	Charcoal	-	Stirling engine
Liquid biomass	Pyrolysis	Bio-oil	Upgrading	Micro-CHP
	Fermentation	Ethanol	Distillation	Micro-CHP
	Extraction & transesterification	Biodiesel	-	Micro-CHP
Gaseous biomass	Anaerobic digestion	Biogas	Upgrading to natural gas quality for distribution network or bottling	Natural gas grid or Micro-CHP
	Gasification	Producer gas	Upgrading for various products	Micro-CHP

The central conversion of solid biomass into heat is possible and applied widely for block heating and district heating. Because of the need of a high temperature the transport of heat for use in Stirling engines is not possible. Charcoal can be produced from wood and agricultural residues. Charcoal can be transported to the site, converted into heat by gasification or combustion, like in the coupled applications. The potential advantage of charcoal is that it could lead to a cleaner producer gas and flue gas than when plain biomass is used.

Various options exist to produce liquid bio-fuels. Bio-ethanol, pure vegetable oil and biodiesel production are commercially proven as well as its application in internal combustion engines. Research is conducted to upgrade pyrolysis oil (bio-oil) to be used in an internal combustion engine. The advantage of pyrolysis oil is that it can be produced from a large number of biomass types and that the production process is potentially cheaper than bio-ethanol and biodiesel production.

Manure, plant material, sludge and land fill sites are potential sources of biogas to be extracted by anaerobic digestion. The biogas can be upgraded to the quality level of natural gas and bottled or put into a natural gas network. As many micro-CHP applications run on natural gas, the upgrading technologies are an important link between advanced micro-CHP applications and biogas production. If plain biogas is used, the use of combustion engines is currently state of the art for CHP. Of course it is also interesting to investigate in how far plain biogas can be applied in advanced mirco-CHP applications.

Producer gas from gasification is difficult to transport over large distances and is regarded not to be a realistic option. In theory, producer gas can be upgraded into a variety of products like methanol, hydrogen, dimethyl ether, methane etc. However, such an upgrading plant is not demonstrated yet.

Literature research for coupled biomass CHP-applications should be focussed on:

- Charcoal applications
- Production and upgrading of biogas
- Production and upgrading of pyrolysis oil

The following biomass to application chains were selected:

Coupled applications

Wood chips/pellets ? combustion ? Stirling engine
Wood chips/pellets ? gasification ? Stirling engine
Wood chips/pellets ? gasification ? Gas engine
Solid biomass ? Carbonisation ? combustion/gasification ? Stirling engine/gas engine
Manure ? anaerobic digestion ? micro CHP application

Uncoupled applications

Wood and agriresidues ? carbonisation ? combustion/gasification Stirling engine
Manure, LFG, sludge ? anaerobic digestion ? upgrading to nat. gas? micro CHP application
Wood and agriresidues ? flash pyrolysis ? upgrading ? micro CHP application

2 TECHNOLOGY OVERVIEW

There are various technologies available to convert biomass into modern energy carriers such as heat, electricity and fuels. See Figure 2. The main thermochemical and biochemical conversion technologies are described in this section.

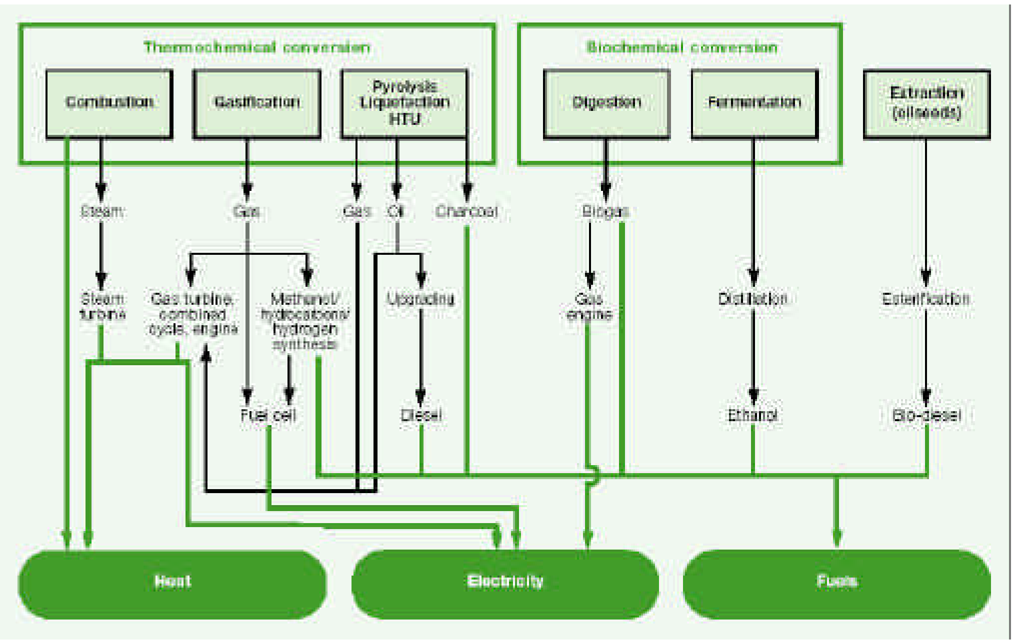

Figure 2 Main biomass energy conversion routes. Source: W. Turkenburg et al., renewable energy technologies, in World Energy Assessment: energy and the challenge of sustainability.

2.1 COMBUSTION

Combustion is the most common technology to convert solid biomass into heat and/or electricity. One can roughly distinguish the following applications of biomass combustion systems, in order of capacity, namely domestic heating, block heating, district heating, electricity generation and co-generation with existing power plantsTable 3 shows an indication of the average range of capacities of these systems.

Table 3 Classification of biomass combustion systems and their applications

Technology	Appli- cation	Capacity range (thermal)	Capacity range (electrical)	Indication yearly biomass supply[a] (tonnes)
Domestic heating systems	H	10 - 100 kWth	-	10 - 100
Block heating system	H	0.1 - 5 MWth	-	100 - 5,000
Combined heat and power system	CHP	0.3 - 150 MWth	0.1 - 50 MWe	600 - 300,000
Co-combustion	P	-	50 - 100 MWe	225,000 - 450,000

[a] Assuming 3000 hr/year for domestic and block heating, 7500hr/yr for (CHP)-district heating and co-firing; further assuming 15 GJ/tonne biomass, a thermal efficiency of 80% for heat, 60% for CHP; and an electric efficiency of 30% for CHP-district heating and 40% for co-combustion.

Domestic and block heating systems

Combustion-based systems are well established and represent mature technology for converting biomass to useful energy products. In South-Germany, Austria and North Italy heating with pellet boiler systems is popular. These systems operate -like conventional central heating systems- completely automatic. Wood pellets are made mainly of sawdust, shavings and fines leftover after processing trees for lumber and other wood products. At a pellet mill the material is dried, compressed, and formed into pellets. Block heating can be provided with boilers fuelled by pellets or wood chips.

CHP systems

Electricity generation with solid biomass typically takes place with help of a steam generation system. The steam system is generally too expensive for very small scale applications; therefore most block heating systems are heat only systems. Research is directed to apply small biomass fuelled Stirling engines.

Compared to large electricity plants, which have an electric efficiency of 40-50%, the CHP systems have a low electric efficiency of 20-30%. The reason d'être of CHP systems is that they produce both electricity and heat, which results in a total efficiency of 60-99%. An important characteristic of CHP plants is that they have to be located near the consumer of heat, which is often a district heating network or a factory using process heat.

Co-combustion

Co-combustion or co-firing means that biomass is fired in a conventional power plant together with conventional fuels like coal or natural gas. In coal power plants biomass can be co-combusted with an electric efficiency of 40%, and because an existing plant is used, the investments are relatively low. It is a popular way to increase biomass-based power generation capacity in countries like the Netherlands and Denmark. Natural gas or oil fired power plants cannot handle solid biomass, but experiments with liquefied biomass show success. See the sections below on gasification and pyrolysis.

2.2 GASIFICATION

Generally, biomass gasification is a thermal conversion technology where a solid fuel is converted into a combustible gas. A limited supply of oxygen, air, steam or a combination serves as the oxidising agent. The producer gas mainly consists of carbon monoxide, carbon dioxide, hydrogen, and methane, water, nitrogen, but also contaminants like e.g. small char particles, ash and tars. After cleaning the gas is suitable for boilers, combustion engines, and turbines for heat and power (CHP) production.

The possibility to use the producer gas in turbines and engines is an advantage of gasification compared to combustion. The use of engines makes small scale CHP-generation possible, the use of turbines allows higher efficiencies. A disadvantage of gasification is that the process is still less developed and applied, and therefore less widespread and more expensive.

Small scale gasification
Small (fixed bed) gasifiers coupled to diesel or gasoline engines (typically for systems of 100–200 kWe with an approximate electrical efficiency of 15–25%) are commercially available on the market. However, high costs and the need for gas cleaning and careful operation so far hampered widespread application.

Large gasification.
Biomass integrated gasification/combined cycle (BIGCC) systems combine flexible fuel characteristics and high electrical efficiency. Electrical conversion efficiencies of 40-55% are possible at a scale of about 30 MWe. Demonstration projects are under way in various countries and for various gasification concepts.

2.3 FLASH PYROLYSIS

Flash of fast pyrolysis is a process in which dry solid biomass like wood and agricultural residues are rapidly heated to 450 - 600 °C in absence of air. Under these conditions, organic vapours, pyrolysis gases and charcoal are produced. The vapours are condensed to bio-oil. Typically, 70-75 wt.% of the feedstock is converted into oil

Pyrolysis offers the possibility of de-coupling (time, place and scale), easy handling of the liquids and a more consistent quality compared to any solid biomass. With fast pyrolysis a clean liquid is produced as an intermediate for a wide variety of applications. The pyrolysis oil or bio-oil can be co-combusted in a natural gas or oil fuelled power plant. Research is going on to other applications for heat and power. Also upgrading of bio-oil for the production of bio-chemicals is presently investigated.

2.4 BIOGAS AND LANDFILL GAS PRODUCTION

Anaerobic digestion is the biological degradation of organic material in the absence of oxygen. This results in the production of biogas, a valuable (energy containing) product. Biogas is a mixture of several gases and vapours, mainly methane and carbon dioxide. Methane also is the main component in natural gas and contains the bulk energy value of the biogas. Biogas is a reasonable clean fuel, which can be used in a gas engine or turbine to generate electricity and heat.Biogas production occurs naturally, amongst others in swamps and lakes when conditions are right. In a tank or container optimal conditions can be created to optimise biogas production from manure and organic materials. Biogas production also takes place in landfills. The biogas is then usually called landfill gas.

Biogas production from manure and organic waste
Anaerobic digestion of manure takes place at a large scale in Germany. At least 1,700 farm scale digesters have been installed. The electricity is sold to the grid, the heat can be used for farm and stable heating.

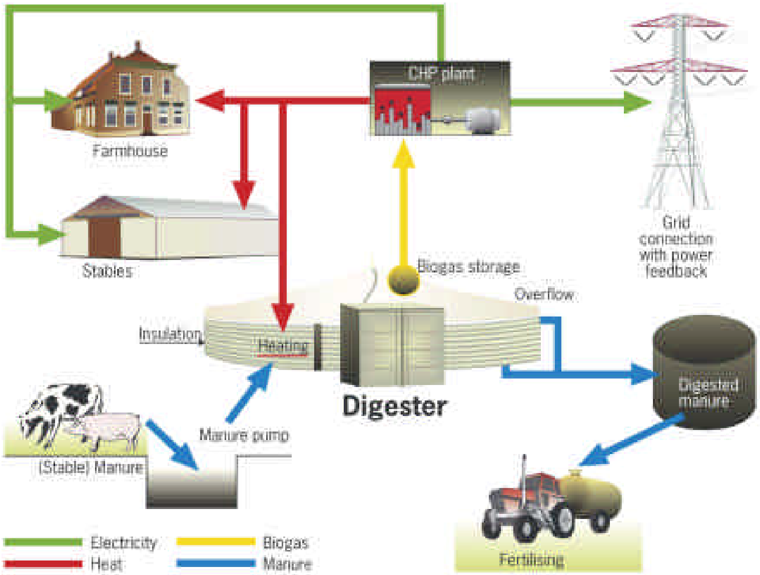

Figure 3 Anaerobic digestion of manure at farm level. Source: BTG

The digested manure can be used on the farmland, just like manure that is not digested. Research in Denmark and the Netherlands shows that digested manure has equal or better fertilising qualities than ordinary manure. Major factors of the success of manure digestion in Germany are high (subsidised) payments for renewable electricity, and the possibility to co-digest organic materials like corn or residues from the food industry, which considerably improves the biogas yield.

Wastewater treatment

In treatment of urban and industrial wastewater, sewage gas is recovered as a part of the process, which can be used for energy purposes. Usually the recovered heat is used internally. Therefore, generally not much attention is paid to this type of bio-energy generation.

Landfill gas production.

The same anaerobic digestion process that produces biogas in animal manure and wastewater treatment digesters occurs naturally underground in landfills. Most landfill gas results from the decomposition of cellulose contained in municipal and industrial solid waste. Unlike animal controlled anaerobic digestion with manure, the digestion occurring in landfills is an uncontrolled process of biomass decay. Landfills contribute to atmospheric methane emissions. In many countries, therefore, capturing landfill gas is obligatory. In many situations the collection of landfill gas and its conversion to electricity using gas engines is profitable, and such systems are becoming more widespread.

3 LITERATURE OVERVIEW

3.1 COMBUSTION

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MicroCHeaP Literature Search: Solar Energie

Investigation related to Solar energy

Contributed by FHG-ISE

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MICRO-CHEAP LITERATURE SURVEY

CONTRIBUTION OF FHG-ISE

INVESTIGATION RELATED TO SOLAR ENERGY

1. SOLAR ENERGY OVERVIEW

1.1. Photovoltaic (solar electric)

1.1.1. Description of technology and system

Photovoltaic (PV), as the word implies (photo = light, voltaic = electricity), converts sunlight directly into electricity. Once PV was used commercially almost exclusively for space applications and small appliances, such as pocket calculators. Now, higher power ranges have become technically and economically viable because of growing experience in PV system design and lower prices of modules. The output power ranges from milliwatts to megawatts due to the modularity of PV systems. Driven by large market introduction programs, an increasing share of PV capacity has been installed in grid-connected applications. Recently, these have exceeded 50% of the overall PV market in 20 International Energy Agency member countries. Due to strong interest in PV technology, further growth of grid-connected systems is expected although in the long term the larger economic potential may be found in off-grid power supplies. Indeed it has been estimated that approximately 2 billion people live remote from the electric grid. Reports show that autonomous power supplies based on PV or PV hybrid systems[1] run cheaper than diesel generator systems in many of these cases.

1.1.2. System components

Grid connected PV systems usually comprise one or several PV modules, an inverter, a power metering system and systems related to safety of operation. The most common system is shown in Fig. 1. A number of PV modules are connected in series to form a string, typically with output voltages at the maximum power point MPP of 700V. One or more parallel strings are connected to one inverter feeding the power into the grid.

Modules consist of cells (e.g. 36 or 72) usually made of semiconducting materials such as silicon. Crystalline silicon solar cells constitute approximately 90% of the market share of PV modules. The sunlight into electricity conversion efficiency varies from several percent (for some thin-film modules) to approximately 16 or 17% for monocrystalline silicon solar cells. Typical module sizes for grid connected systems range from 50 to more than 300W. The performance of PV modules depends strongly on their operation temperature. Depending on the technology used, the temperature coefficient is between -0.2 and -0.5%/K. Therefore, factors such as the type of installation (e.g. roof integration or stand-off mounting) and the degree of rear ventilation play a great role for the system efficiency.

Inverters are devices that convert the DC output of PV or batteries in stand-alone systems to AC electricity, which is to be delivered to the loads or will be fed into the grid. There are many different types of power electronic concepts used for inverters in the market.

The daily and seasonal solar irradiation and therefore the generation profile of PV systems strongly depends on the geographic location. Since for central Europe times with medium or moderate irradiation are quite frequent, inverters are usually selected with high efficiency at partial load. Their efficiency value should exceed 90% at 5% of nominal load. For economy and efficiency reason, PV inverters are chosen with a nominal power rating near or slightly below the peak power of the PV generator. Depending on regulations and inverter power, either one-phase or three-phase inverters are used. They should deliver electricity with high voltage and current quality and be capable to bear an overload of 20-30% for short periods of time. They should display precise and robust MPP tracking abilities and must provide functions to supervise the grid as well as other safety mechanisms.

To meter the electricity generated, either an extra meter is installed or the electricity is fed, for example, into the house wiring that supplies existing loads. In the latter case, if PV generation exceeds the actual load, either the meter runs backwards or an extra meter measures the excess electricity (net metering). The generation cost of PV electricity in grid-connected systems varies between approximately 30 €c in sunny regions and 60 €c in northern

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[1] Autonomous electricity supply system based on at least two sources of electricity, such as photovoltaic, wind, or diesel generator, always including a battery storage.

Europe if good practice is assumed. In grid-connected systems, the PV modules contribute the largest share of life cycle cost.

Grid connected systems either might be installed at the roofs or facades of buildings with typical system sizes from 1 to 10 kWp (some even higher) or as open land installations with system sizes up to several megawatts nominal power. While the majority of smaller house installations is owned and operated by private people, the very large systems are mostly run by holding companies or other commercial actors, like utilities.

Regarding safety, technical standards, and thus system layouts and inverter concepts, differ from country to country. Whereas in the United States earthing of the generator is mandatory, in European countries the use of isolated modules (safety class II) is standard. In addition to earthing, protection against islanding as well as fault current detection in systems with transformerless inverters are mandatory. Islanding is a phenomenon in which during a power blackout or intended interrupt (e.g. for maintenance of the grid) distributed power sources such as PV systems keep a grid segment—an island— alive. This situation is quite unlikely, yet could pose a certain danger to users, maintenance personnel, and equipment. With certified hardware equipment and maintenance personnel following the safety rules, PV systems do not pose any danger.

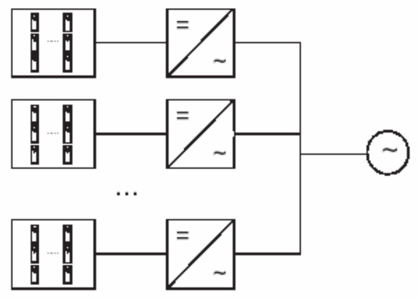

Fig. 1: Configuration of a grid-connected PV system consisting of several strings (Source: Fraunhofer ISE)

1.1.3. State of the art

Silicon wafer solar cells

This kind of solar cell is made of mono or multicrystalline silicon wafers. Commercial cells display an efficiency value between 13 and 17%, while laboratory cells achieve 24,7%. This kind of cells dominate the market place with more than 90% of share. Since 1991, costs have been reduced by approx. 60%. Nowadays, modules have a warranty of 20 years at least.

Thin film solar cells

This group encompasses mainly amorphous silicon, copper indium diselenide (CIS) and cadmium – tellurid (CaTe) cells. In this technology, the material is deposited on a low-cost substrate such as glass. Efficiency ratio achieve between 5 and 15%. This cell family has reached approx. 7% in share of the market place.

Concentrator solar cells

Photovoltaic concentrator systems offer the interesting option to significantly reduce the area of actual solar cell. Through the up to 1000 times optically concentrated sunlight, the need for cell area drops dramatically. As a consequence high-efficient but in the same time very expensive III-V semiconductors can become economically viable. Building upon experience gain from space applications, concentrating systems have reached a pre-commercial state.

Module technology

Module technology has reached high standards since the 90’s. Warranty time awarded by manufacturers usually exceeds 20 years. Nowadays, mostly glass-glass or glass-foil laminate are used. Cells are encapsulated in EVA laminate.

Grid-connected systems

Commercially available inverters display annual average efficiencies of up to 96%. Costs for inverters, wiring and erection systems have dramatically dropped in the last years. Mature products and system concept and proven business plans are now available.

1.1.4. Trends and problems

Bottleneck in the supply of solar silicon

Feedstock of the solar cell production used to be the off-grade material from the electronic industry. However, the soaring growth rate of PV will probably lead to a bottleneck situation in 2005 in the silicon supply chain. Beside the usage of high-efficient manufacturing process in terms of material consumption, it is suggested to organise a specific supply branch for “solar silicon”. This problem may by alleviated in 2007 when new silicon factories will be operated.

Price targets

Price targets of 2 €/Wp have been set for the year 2010. In 2020, it is believed that the retail price will amounts to less than 1 €/Wp. The prerequisites are:

- decrease of the wafer thickness while the conversion efficiency is increased thanks to better manufacturing processes,
- Improvement of the module’s lifetime.
- Costs reduction through innovative mass production
- R&D efforts towards specific system components

Fundamental research

New cell concepts are expected to arise from today’s fundamental research projects that will have a major impact on the performance ratio and the costs. Among them are innovative technologies such as dye and organic solar cells. Commercial maturity is not expected before many years.

1.2. Solar thermal energy

1.2.1. Description of technology and system

The solar thermal system collects energy from the sun and converts it into heat and transfers it to water or air. Solar thermal systems are usually designed for automatic daily and year round operation. This chapter will primarily handle the active solar thermal systems with external water storage tank (see Fig. 1) since these are the most common system in homes in middle and north Europe and have been used for 30 years.

The technical economical potential for solar thermal is estimated at 1.4 billion m² (EU-15) of installed collector area. The energy amount delivered would then correspond to approx. 6% of the EU final energy consumption. At present, only 1% of this potential has been realised so far.

The commercial prospect of solar thermal energy in Europe is indeed very good. The markets have shown substantial growth over the past decade. On average the glazed collector area in operation increased by approx. 12% per year and the market volume (i.e. newly installed collector area) grew by 25% in 2003 compared to 2002. The collector area in operation is highly concentrated in three countries: Germany, Greece and Austria account for more than 80% of the EU total. Relating the glazed collector area in operation to the population, the leading role was taken on by Greece (264 m² per 1.000 capita) and Austria (203 m²). However EU average amounts only to approx. 26 m². In recent years there has been a trend towards levelling the big differences between the frontrunners and the countries lagging behind. Spain, Italy and France have been growing faster than the EU average, whereas Austria and Greece have stagnated at a high level. With approx. 1 million m² of thermal collectors installed in 2004 and a growth rate expected to exceed 30%, Germany remains the biggest marketplace in Europe for this technology.

Solar thermal can be successfully implemented at all latitudes. Some of the strongest markets (Germany, Austria) are not situated in particularly sunny regions, whereas for instance Southern Italy is clearly lagging behind. Factors like general awareness of the environment, public support (financial, regulative, campaigns) and the quality of the products/services offered by the industry have proven to be at least as important as climatic conditions.

Systems are differentiated according to their application:

- System for domestic hot water (DHW) production: sized in order to meet the heat load for hot water during summertime, it usually covers between 15 and 25% of the total annual heat load of the building. This category is subdivided into DHW thermo-siphon systems that use gravity to circulate the heat transfer fluid (e.g. water) from the collector to the tank and into forced circulation systems where the fluid is pumped. DHW systems for a single-family house have typically a 3-6 m² collector area and a 150-400 litres tank.
- Combined DHW and space heating system: generally with a bigger collector area, it tends to cover between 25 and 35% of the total annual heat load of the building. The collector size of these so called combisystems is typically in the range of 7-20 m² and the tank in the range of 300-2000 litres. Its market share approaches 20% in Germany and 50% in Austria.
- Collective DHW systems: designed for multiple-family houses, apartment blocks, hotels, office buildings etc. their surface varies from ten to several hundred square meters.

1.2.2. System components

The main component of a solar thermal system is the collector that converts the incident radiation into useful heat. Glazed collectors are the most common type in Europe. Two different designs exist for glazed collectors: flat plate collectors and evacuated tube collectors. Fig. 2 illustrates the flat-plate design. These collectors are usually rectangular boxes covered by glass and containing a heat absorbing material inside. The absorber typically consists of copper or aluminium and is treated to better absorb the heat. Such treatment ranges from simple black paint to special selective coatings. Little tubes, which carry the heat transfer fluid are built in or welded on the absorber plate. The heat transfer fluid is typically water or a water/glycol solution, that prevents the collector from freezing. When striking onto the glass front, part of the sunlight is reflected (optical losses). The transmitted radiation is then caught by the absorber and transferred to the heat transfer medium (useful heat). The back of the collector is equipped with an insulation layer to decrease the heat losses with the ambient (thermal losses). In a evacuated tube collector, the thermal losses have been reduced by a quantum leap, since the absorber is enveloped by vacuum (see Fig. 3). The collector consists of long glass tubes which are usually mounted in parallel in one row. Reflectors devices concentrate the rays towards the absorber. This design is therefore suitable for higher temperatures.
Collector efficiency depends strongly upon both optical and thermal losses. Modern flat-plate collector displays an conversion efficiency of 80% that drops rapidly when the temperature difference between heat transfer fluid and surrounding increases. An evacuated tube collectors displays approx. 70% conversion efficiency but this value remains nearly constant against the growing temperature gap.

Unglazed collectors have been used for 30 years, mainly to heat open-air swimming pools. The collector consists of a set of long black thin tubes made of synthetic material (commonly EPDM). The solar system is directly connected to the hydraulic circuit used to filtrate the pool water, which is heated when flowing through the collector. Unglazed collectors for swimming pools are relatively cheap and easy to install.

Usually in forced circulation systems the collector is placed on the roof or on the facade while the hot water storage tank is placed in the boiler room. The collectors can be attached on the house’s roofs, both on pitched roofs or on flat roofs. While a south-facing slope (on the northern hemisphere) would be ideal, a roof surface facing east or west will also be fine in most cases. In the latter case, special mounting systems, usually made of steel or aluminium, will typically have the collectors tilted at 45 degrees (in moderate climate zones like Germany). Similarly, the collectors can also be placed on the ground.

Collector and tanks are connected via insulated pipes. The heat transfer fluid is displaced by an electric pump that is control by a on-off controller, that surveys the temperature difference between collector outlet and tank bottom. The tank is equipped with an internal heat exchanger in order to avoid any contact between the water/glycol mixture and the drinking water. The heat exchanger is generally manufactured entirely from copper. It consists of several copper coils. All connections are brazed and are external to the shell.

In a regular household the solar system is perfectly capable of providing on its own the necessary heat to produce hot water during summertime even in moderate climate zones (like Germany). The water stored in the hot water tank is enough to bridge some dull days in summer. In winter, an additional conventional boiler (usually running on heating oil or natural gas or wood) guarantees a constant supply of hot water, while making use of the solar collector as much as possible, thus considerably saving energy costs also during winter. Particularly low consumption of the back-up fuel can be reached when the burner is directly integrated into the solar tank.

The contribution of the solar thermal system is evaluated while considering the energy path depicted in Fig. 4. It is useful within a system analysis to express the solar contribution to a combined system in terms of fractional reduction in the amount of conventional energy usage. The solar fraction relates the effectively used solar heat, i.e. the solar system yield, to the total heat consumed.

$$\text{solar fraction} = \frac{\text{solar system yield}}{\text{solar system yield} + \text{auxiliary heat consumption}}$$

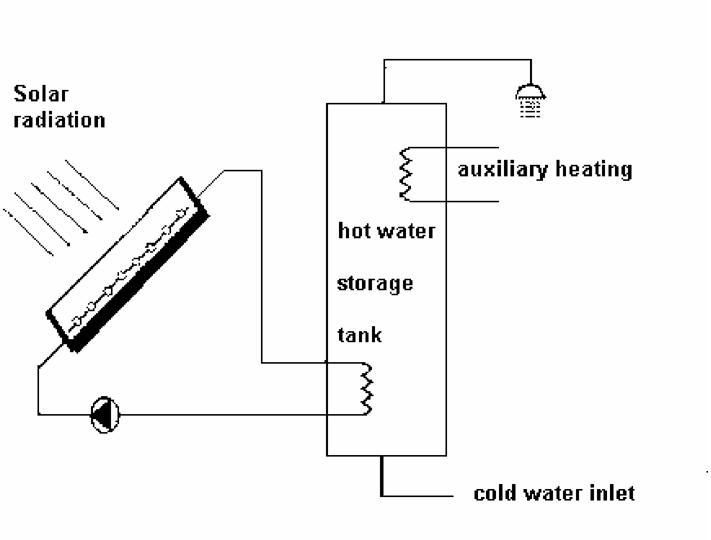

Fig. 1: Solar thermal system for hot water production with two circuits and internal heat exchanger (Source: Fraunhofer ISE)

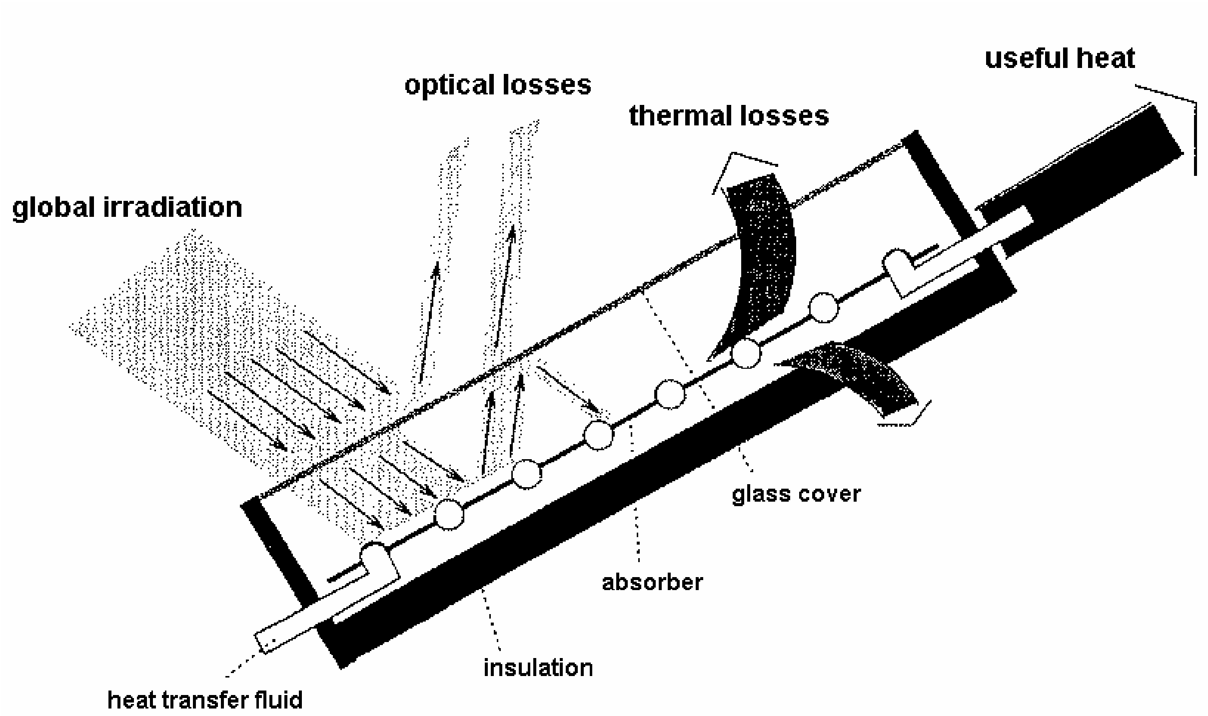

Fig. 2: Energy flow in a flat plate collector: Irradiation, optical and thermal losses, useful heat (Source: Fraunhofer ISE)

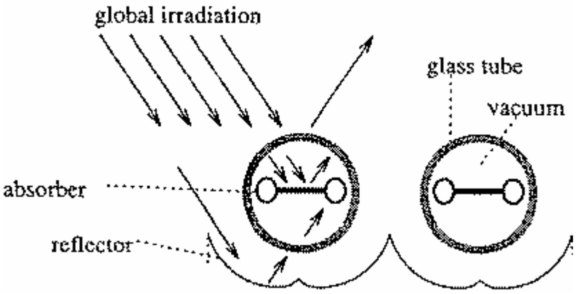

Fig. 3: Path of the irradiation within an evacuated tube collector (Source: Fraunhofer ISE)

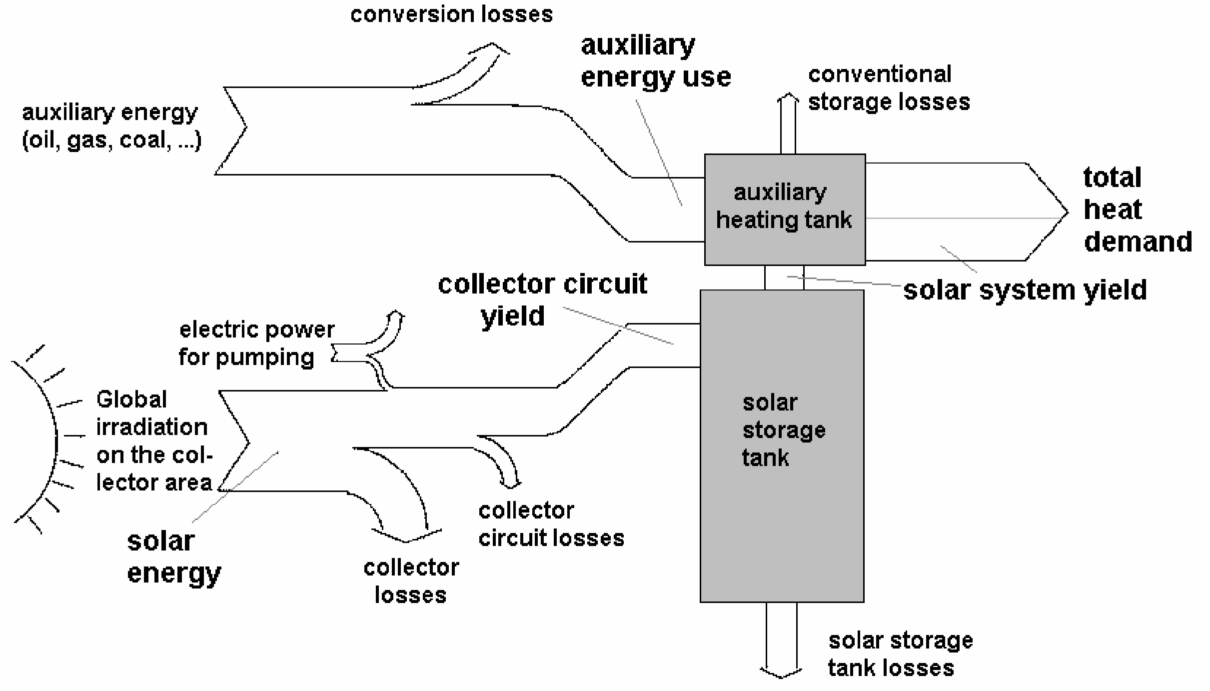

Fig. 4: Energy flow path from the sources to the user (Source: Fraunhofer ISE)

1.2.3. State of the art

High-efficiency absorber coating

Spectral-selective absorber coatings favour the absorption of the sun rays while diminishing the heat losses by re-radiation by lowering the emissivity of the absorber in the infrared bandwidth.

Absorber production techniques

High automation level in the production process from the copper foil coil up to the finishing of the absorber leads to low costs and high-quality products. High reliable bracing and laser or ultrasonic welding techniques are used to guarantee a lifetime of at least 20 years.

Micro-climate in collector space

Natural airing of the collector’s inside avoids the condensation of steam on the front glass at low surrounding temperature, thus increasing the readiness for operation of the module, especially in the morning.

Backside heat insulation

New mineral wool insulation material with low cement content is used as rear insulation layer. The concentration of cement in the insulation layer facing the absorber is very low. This reduces the vaporisation risk of the cement inside the collector box due to high absorber temperature. This removes the danger of condensation of the organic compound vapour on the front glass.

Module size and roof and facade integration

Collectors can nowadays be produced in almost all sizes and shapes. They are lighter and easier to transport. They can easily be mounted and even integrated in roof tops and facades, replacing completely the roof tiles or the wall outer rendering.

Sun glazing

Glass cover technology has reached high transmission efficiency. Less solar rays are absorbed by the front window and more radiation is transferred to the absorber.

European standards and testing procedures

In many EU-countries, the granting of financial incentives for solar systems is bound to the installation of solar components that respond to the EN technical requirements and that bear a certification mark.

EN 12975 - Thermal solar systems and components - Solar collectors

The document specifies requirements on durability (including mechanical strength), reliability and safety for liquid heating solar collectors. It also includes provisions for evaluation of conformity to these requirements. It is not applicable to those collectors in which the thermal storage unit is an integral part of the collector to such an extent, that the collection process cannot be separated from the storage process for the purpose of making measurements of those two processes. It is not applicable to tracking concentrating solar collectors.

EN 12976 - Thermal solar systems and components - Factory made systems

The document specifies requirements on durability, reliability and safety for factory made solar systems. The document also includes provisions for evaluation of conformity to these requirements. The requirements apply to factory made solar systems as products. The installation of these systems itself is not considered, but requirements are given for the documentation for the installer and the user which is delivered with the system. Moreover, the document specifies test methods for the validating the requirements for factory made systems as specified in EN 12976-1. It also includes two test methods for thermal performance characterisation by means of whole system testing.

EN ISO 9488:1999 - Solar energy - Vocabulary

1.2.4. Trends and problems

Price targets

A collector array of 4-5 m² and a hot water storage tank of 300 l is normally sufficient to satisfy the need for hot water of a family of four in summer. In winter, the solar system is used for pre-heating and the auxiliary heating system provides the major proportion. The system efficiency of such a real system can achieve 40%. The solar heat cost amounts approx. to 0,38 EUR/kWh (2000 prices). If the collector area is expanded to, say, 15 m² with the goal of assisting in room heating, the solar fraction may achieve 60% and the solar heat cost 0,24 EUR/kWh.

Larger DHW systems are generally designed for a low solar fraction (low solar coverage of the hot water demand) and operate on a lower temperature resulting in a high system performance (thermal output/m² of solar collector). Most large DHW systems are designed with forced circulation but multiple thermo-siphon systems are also used when the conditions are suitable.

Fundamental research

The newly developed anti-reflex glazing displays very high transmission efficiency so that double pane cover glazing has become a viable option to reduce even more the heat losses by convection of the collector box. This pave the way for low-cost glazed collectors to new application fields such as middle temperature process heat (water desalination, ...).

As a result, even flat plate collectors are able to reach temperature higher than 100 °C and therefore are subject to boiling. This leads to an increase of the stagnancy time of the system. A current topic of research is to better understand the boiling phenomenon inside the collector and to develop control strategies that prevent the collector from boiling but allow high outlet temperature.

2. PUBLICATIONS IN JOURNALS

In recent years, a vast amount of literature has been published, covering all aspects of Solar energy and associated technology. However, within the framework of MicroCHeaP, attention is set to focus on topics as thermal and electrical application, system design, converter technology, and some general aspects of solar energy.

Fruitful search words for a literature survey into the field of solar energy systems are ‘solar’, ‘PV’, ‘solar system’, ‘solar collector’ and ‘solar thermal’. A selection of journals, encyclopaedias or periodics are proposed below: :

Photovoltaic

1. T. Meyer, “Photovoltaic Energy: Stand-Alone and Grid-Connected Systems”, Encyclopaedia of energy; 6 print volumes; ISBN 0-12-176480-x; Elsevier; 2004
2. *Solar Energy Materials & Solar Cells*, journal published by Elsevier B.V. It is devoted to Photovoltaic, Photothermal, and Photochemical Solar Energy Conversion

Solar thermal

1. *Applied Thermal Engineering*, journal published by Elsevier B.V. The Journal deals with system designed of advanced processes related to a large range of equipment while economics plays a necessary role in the assessment of many thermal engineering projects.

Solar Energy is the official journal of the International Solar Energy Society (ISES) and is devoted exclusively to the science and technology of solar energy applications. It is targeted to engineers, scientists, architects and economists active in the fields of systems, components, materials and services for applications of solar energy.

Journal of Solar Energy Engineering is a journal of the American Society of Mechanical Engineers (ASME). It publishes technical papers and briefs on all aspects of solar-derived energy, including both active and passive solar applications.

The *Journal of Atmospheric and Solar-Terrestrial Physics* is an international journal concerned with the inter-disciplinary science of the Sun-Earth connection,

Photon, Das Solarstrom-Magazin (Solar Verlag) is a periodical in German that deals with all kind of issues related to PV.

Solar today is a bimonthly magazine — published by the American Solar Energy Society, www.ases.org — that covers all solar and renewable energy technologies, from photovoltaics to climate-responsive buildings to wind power and biomass. Regular topics include building case studies, energy policy and community-scale projects.

The German association Solarenergie-Förderverein Deutschland e.V. (SFV) publishes regularly a info mail named *Solarbrief* (more at http://www.sfv.de/)

Solar Energy Materials was a journal published between 1980 and 1991.

3. PUBLICATIONS IN CONFERENCES

The following conferences deal with solar energy topics on a regular basis:

Photovoltaic

1. OTTI Kolleg Photovoltaische Solarenergie (http://www.otti.de)
2. IEEE Photovoltaic Specialists Conference (http://www.ieee.org)
3. European Photovoltaic Solar Energy Conference
4. World Conference on Photovoltaic Solar Energy Conversion
5. International Photovoltaic Science and Engineering Conference
6. E.C. Photovoltaic Solar Energy Conference
7. Symposium Photovoltaische Solarenergie (in German)

Solar thermal

1. OTTI Kolleg Thermische Solarenergie (http://www.otti.de)
2. National Passive Solar Conference, organised by American Solar Energy Society
3. The European Solar Thermal Industry Federation *ESTIF* publishes on a regular basis market and trend information for Europe (http://www.estif.org/)

EuroSun is a conference organised by the ISES and hold every two years. It combine an extensive congress programme with a major renewable exhibition. (www.eurosun2006.org)

The largest trade fair in Europe dedicated to solar systems is named *Intersolar* and takes place annually in Freiburg, Germany (www.intersolar.de).

4. BOOKS

A number of books giving a good introduction into solar energy are:

Photovoltaic

1. A. Luque, S. Hegedus, “ Handbook of photovoltaic science and engineering” John Wiley and Sons, 2003
2. A. Bubenzer, J. Luther, “ Photovoltaics guidebook for decision makers” Berlin: Springer, 2003
3. M. D. Archer, R. Hill, “ Clean electricity from photovoltaics” London: Imperial College Press, 2001
4. W. Berger, “ Photovoltaics in Europe in the year 2020” Wien: Verlag der Österreichischen Akademie der Wissenschaften, 2001
5. International Energy Agency -IEA-, Solar Heating and Cooling Programme, “ Photovoltaics in buildings” London: James & James, 1996
6. F. Bisschop, “ Building with photovoltaics” Ten Hagen & Stam, The Hague, 1995
7. S. R. Wenham,; M.A. Green, M.E. Watt, “ Applied photovoltaics”, Centre for Photovoltaic Devices and Systems, Univ. of New South Wales, ISBN: 0-86758-909-4, 1994
8. F. Lasnier, T. Gan Ang, “ Photovoltaic engineering handbook” Bristol: Hilger, ISBN: 0-85274-311-

4 ,1990

Solar thermal

1. J. Duffie, W. Beckman, “Solar Engineering of Thermal Processes” John Wiley and Sons, 1992
2. W. Weiss (editor), “Solar heating systems for houses, a design handbook for solar combisystems”, International Energy Agency, Solar heating and cooling programme; ISBN 1 902916 46 8; James & James; London; 2003
3. A. Marko, P. Braun (editors), “Thermal use of solar energy in buildings”, Course book for the Comett project “SUNRISE” seminar, Fraunhofer Institute for Solar Energy Systems; Freiburg, Germany, 1994
4. A. Rabl, “Active Solar Collectors and Their Applications”, Oxford University Press, 1985
5. “Sun in action II - a solar thermal strategy for Europe”, European Solar Thermal Industry Federation ESTIF, volume 1 and 2, download at www.estif.org/, 2003
6. W. L. Dutré, “ Simulation of Water Based Thermal Solar Systems”, Boston: Kluwer, ISBN: 0-7923-1236-8, 1991
7. F. Peuser, K.H. Remmers, M. Schnauss “ Langzeiterfahrung Solarthermie” Berlin: Solarpraxis, ISBN: 3-934595-07-3, 2001

5. SOLAR SYSTEM MANUFACTURERS AND SYSTEM INTEGRATORS

Manufacturers of solar systems suited for energy supply to buildings are (list not exclusive):

Photovoltaic

1. Solar-Fabrik AG (Germany)
2. RWE Schott Solar GmbH (Germany)
3. Solar World AG (Germany)
4. Solarwatt Solar-Systeme GmbH (Germany)
5. Shell Solar (The Netherlands)
6. Alpha Solar Vertriebsgesellschaft mbH (Germany)
7. Q-cells AG (Germany)

Solar thermal

1. Wagner & Co. (Germany)
2. Elco Klockner Heiztechnik GmbH (Germany)
3. Paradigma GmbH & Co. KG (Germany)
4. Solvis GmbH & Co. KG (Germany)
5. Buderus Heiztechnik (Germany)
6. Viessmann (Germany)
7. S.O.L.I.D. GesmbH (Austria)
8. MEA – Maschinen- und Energieanlagen GmbH (Austria)
9. Clipsol (France)

10. VELUX (Denmark)
11. De Dietrich Thermique (France)

MicroCHeaP Literature Search: Stirling Engines
Investigation related to Stirling engines
Contributed by ECN

TABLE OF CONTENTS

MICRO-CHEAP LITERATURE SURVEY
CONTRIBUTION OF ECN
INVESTIGATION RELATED TO STIRLING ENGINES

1. STIRLING ENGINES OVERVIEW

Stirling engines are closed cycle thermal machines, which use an external heat source and heat sink to produce mechanical power. The thermodynamic reference cycle, which approaches the cycle in real engines is the Stirling cycle, shown in fig. 1. The working gas is usually helium, air/nitrogen or hydrogen.

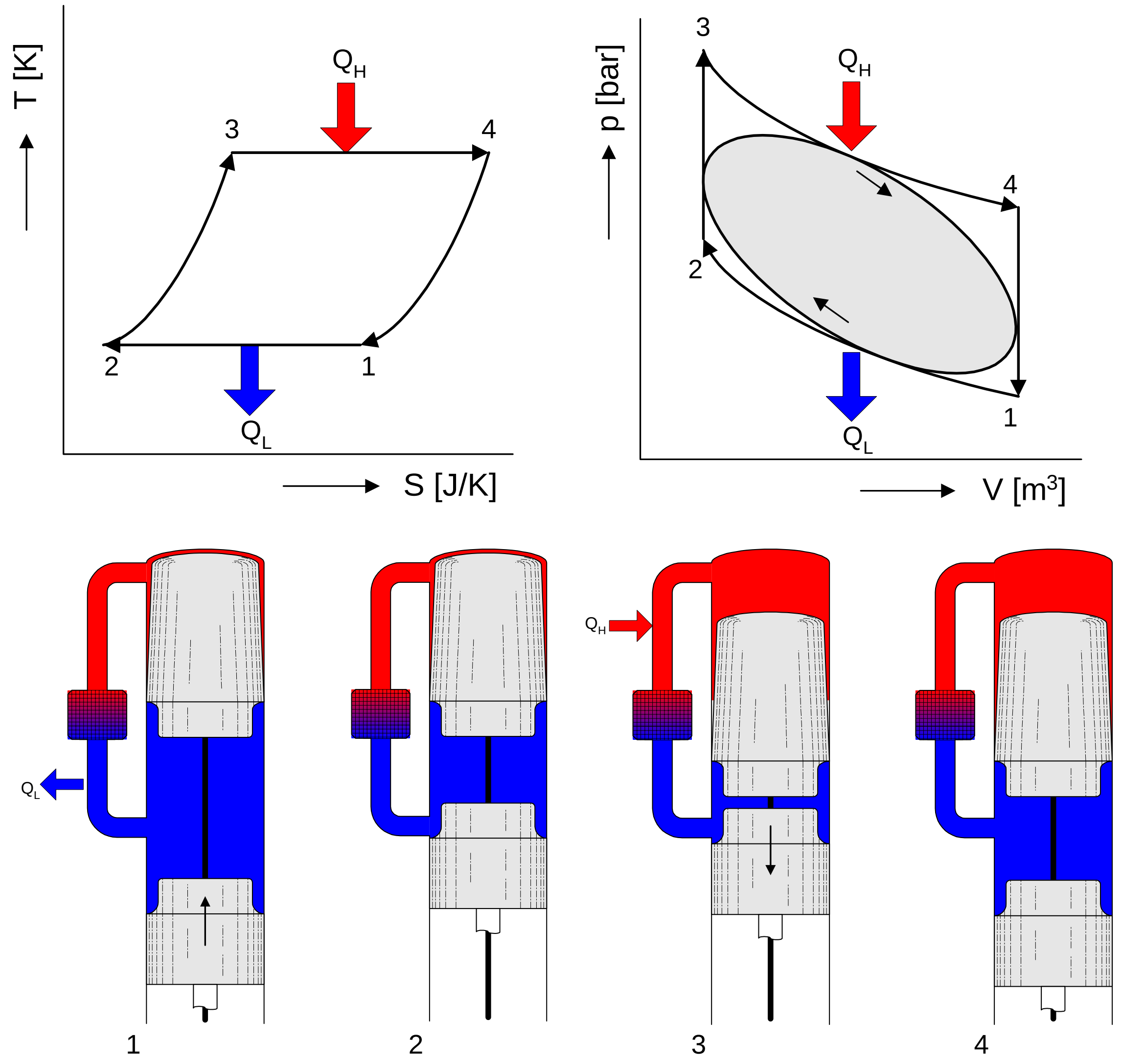

Fig. 1 *Theoretical Stirling cycle in an engine with piston and displacer not running continuously; the egg shaped body in the theoretical indicator diagram shows the indicator diagram of a real Stirling engine with the piston and displacer running sinusoidally*

The main components of Stirling engines that feature prominently in Stirling technology and research are: the heater (the heat exchanger connected to the external heat source), the regenerator, the cooler (the heat exchanger connected to the heat sink), the displacer piston and finally the (power) piston. The reciprocating movement of the power piston is used to drive a linear or via some mechanism a rotating load. The location of the main components in an engine is shown in fig. 2.

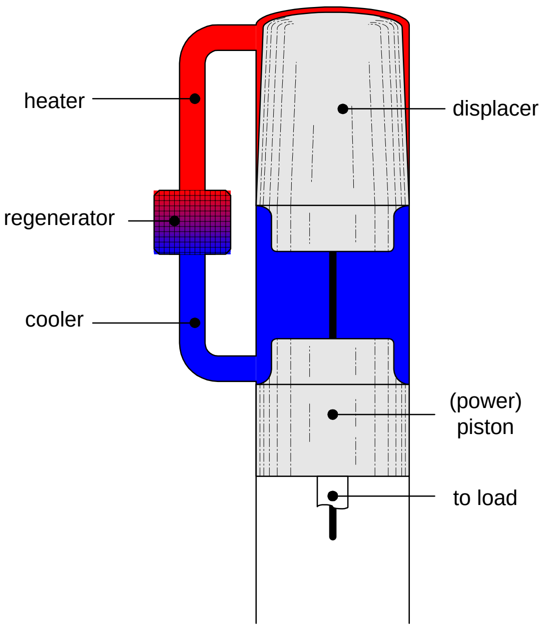

Fig. 2 Main components of a Stirling engine (single acting beta type)

The Stirling engine was first patented in 1816 by the Scottish referent Robert Stirling as an application of the regenerator he had invented. Throughout the nineteenth century, several working models were built and some were operated successfully for a while, but eventually more effective and powerful steam and internal combustion engines replaced the Stirling engines.

The development of the modern high speed Stirling engine with a pressurised gas cycle started in the nineteenthirties. The Philips electric company did pioneering work and although Philips abandoned Stirling development in the nineteenseventies, most Stirling engines that are on the market today use solutions that were originally developed at Philips. Two main families represent modern Stirling engines: kinematic and free piston Stirling engines.

Kinematic Stirling engines are the largest group of Stirling engines. In these engines, the reciprocating movement of the power piston is transferred to a rotating shaft by mechanical means. The engines can be used to drive an electric generator. Depending on the geometric arrangement of the pistons (and displacers) different variants are the alpha, beta or gamma engines. Depending on the interconnection of multiple cylinders these engines can operate with single or double acting pistons. Kinematic engines have been demonstrated in the power range from 0.1 to 500 kW.

In free piston engines the reciprocating movement of the power piston is used tot drive a linear electric generator. These engines are comparatively simple in mechanical terms and require little maintenance. Free piston engines have been demonstrated in the power range from 0.05 to 3 kW.

The main feature that distinguishes modern Stirling engines from competing technologies such as internal combustion engines and fuel cells is the flexibility of the heat source. Stirling engines can be heated by: concentrated sunlight, waste heat and depending on an appropriate burner design a host of different fuel types. Stirling engines are therefore well placed for applications involving:

- Concentrated sunlight: solar dish Stirling engines
- Combustion of biomass: biogas or oil fired Stirling engines

Because Stirling engines are also comparatively quiet and the external burners can operate with very low emission levels Stirling engines are also suitable for use in the built environment. As a result there has been an extensive effort in the past decade to develop Stirling engines custom made for (micro-) cogeneration systems.

2. PUBLICATIONS IN JOURNALS

In recent years, a vast amount of literature has been published, covering all aspects of Stirling engines and associated technology. However, within the framework of MicroCHeaP, attention is set to focus on topics as application, system design, burner technology, and some general aspects of Stirling technology.

On the topics of application and system design areas of interest are biomass fired micro CHP systems and to a lesser extent solar dish Stirling systems, which run on direct solar heat. Fruitful search words for a literature survey into the field of biomass powered Stirling systems are ‘biomass’, ‘wood’, ‘wood wastes’, ‘cogeneration’ and ‘stirling engines’. A literature search on these subjects covering the period from 2000 to 2004 produced among others the following results:

1. H. Carlsen, J. Bovin, “Four-cylinder, hermetically sealed stirling engine for small-scale power production using biomass as fuel”, VDI Berichte n 1588 (2001) 273-281, ISSN: 0083-5560
2. H. Carlsen, J. Bovin, “9 kW stirling engine for biogas and natural gas. Final report.”, Danmarks Tekniske Univ., Lyngby (Denmark) Inst. for Mekanik (2201), Available on loan from Risoe Library, P.O. Box 49 DK-4000 Roskilde Denmark
3. H.Carlsen, “Progress report – 35 kW Stirling engines for biomass”, Proceedings European Stirling Forum 2000 (2000) 193-200
4. H. Carlsen, J. Bovin, “Stirling engines in small CHP plants”, Conference: Nordic and European bioenergy conference and exhibition, Aarhus (Denmark), 25-28 Sep 2001
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14. J. Karl, “Konzepte fuer Kraft-Waerm-Kopplungsanlagen”, OTTI Orientierungsseminar: Kraft-Waerme-Kopplung mit biobrennstoffen, OTTI Regensburg (2003) 17-44
15. M. Salomon-Popa, “Small-Scale Combined Heat and Power Plants Using Biofuels”, Swedish Energy Agency, Eskilstuna (Sweden), Nov 2002 (OSTI)
16. M. Gyftopoulou et al., “Small scale heat and power (CHP) from bio-crude oil fuelled to a sterling engine”, Feb 2002 (OSTI)
17. A. Demirbas, “Utilization of Biomass as alternative Fuel for External Combustion Engines”, Energy sources v 26 November 2004 (2004) 1219 - 1226
18. L. Bowman, N.W. Lane, “Micro-scale biomass power”, 4. biomass conference of the Americas, Oakland, Ca, 29 aug – 2 Sep 1999

In the field of biomass related Stirling technology the large number of articles published by authors associated with the Technical University of Denmark (H. Carlsen et al) stand out. An interesting overview of the technology may be given by the proceedings of OTTI orientation seminar (Staffelstein, Germany, 2003) Other organisations publishing about biomass and Stirling technology include NREL, VTT, SINTEF, Centre Renewable Sources Greece.

Useful search words for a survey into solar dish systems are ‘solar thermal power plants’, ‘solar concentrators’, ‘parabolic dish reflector’, ‘parabolic dish concentrator’ along with ‘cogeneration’ and ‘stirling engines’. A literature search on these subjects covering the period from 2000 to 2004 produced among others the following results:

19. C. Andraka et al., “Dish /stirling Hybrid-Receiver Sub-Scale Tests and Full-Scale Design”, Sandia National Laboratories, 34-th IECC conference (1999)
20. R.B. Driver, J.W. Grossman, “Sandwich construction solar structural facets”, Renewable and advanced energy systems for the 21st century, RAES’99 proceedings, (1999)
21. D.R. Adkins, et al., “Test and Post-Test Analysis of a Thermocore Inc. Nickel Powder Wick Heat Pipe Solar Receiver”, report 23 p. OSTI as DE00008377 Us Govt. Printing Office
22. J. Eyer, J. Iannucci, “Market potential for distributed solar dish-Stirling power plants operated in solar-only and solar/natural gas hybrid modes”, IEEE Power Engineering Review v19 n11 (1999) 7-8
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30. P. Stouffs, “Design of a 1 kWe Stirling engine for solar CHP”, Proceedings ESF 2000 (2000)
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33. K.K. Makhkamov, D.B. Ingham, “Two-dimensional model of the air flow and temperature distribution in a cavity-type heat receiver of a solar stirling engine”, Journal of Solar Energy Engineering (Nov 1999) v. 121 (4) p. 210-216
34. K.K. Makhkamov, D.B. Ingham, “Analysis of the working process and mechanical losses in a Stirling engine for a solar power unit”, Journal of Solar Energy Engineering (May 1999) v. 121 (2) p. 121-127

Most articles about solar powered Stirling engines have been published before 2003. Organisations that stand out are Sandia National Laboratory of the USA and the German Aerospace Center DLR with Plataforma Solar de Almeria. However, the research in this field seems to be concentrated in the United States.

A survey of the components shared by different types of Stirling engines for different kinds of applications may include search words addressing these components such as ‘regenerator’, ‘heat exchanger’, ‘controls’ etc. combined with ‘Stirling engines’
Finally, important areas (and search words) for the future direction of Stirling research and development are Stirling related thermodynamics, simulation and assessment of new technology concepts.

3. PUBLICATIONS IN CONFERENCES

The following conferences deal with Stirling topics on a regular basis:

1. ISEC (International Stirling Engine Conference), International, biannual
   (1982, 1984, 1986, 1988, 1991, 1993, 1995, 1997, 1999, 2001, 2003)
   (www.isec-info.org)
2. IECEC (Intersociety/International Energy Conversion Engineering Conference), USA, annual
   (www.iecec.org) (www.aiaa.org)
3. ISF/ESF (International/European Stirling Forum), Europe, biannual
   (1996, 1998, 2000, 2002, 2004)

4. BOOKS

A number of books giving a good introduction into Stirling technology are:

1. C.M. Hargreaves, “The Philips Stirling engine”, Elsevier, 1991
2. G.Walker et al., “The Stirling alternative, power systems, refrigerants and heat pumps”, Gordon and breach science publishers, 1994
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6. M. Werdich, K. Kübler, “Stirlingmaschinen”, ökobuch Verlag, 2003

5. STIRLING MANUFACTURERS AND SYSTEM INTEGRATORS

Manufacturers of Stirling engines suited for cogeneration applications are:

1. Whisper Tech (New Zealand)
2. STC (USA)
3. Sunpower (USA)
4. STM Power (USA)
5. Tamin (USA)
6. SOLO Kleinmotoren (Germany)
7. Fa. Mayer & Cie (Germany)
8. Sunmachine (Germany)
9. BSR solar technologies (Germany)
10. Microgen (UK)
11. Enatec (Netherlands)
12. Technical University of Denmark (Denmark)
13. Kockums (Sweden)
14. Sigma Elektroteknisk (Norway) (??)

MicroCHeaP Literature Search: ORC-Process
Investigation related to the Organic Rankine Cycle

Contributed by FEE

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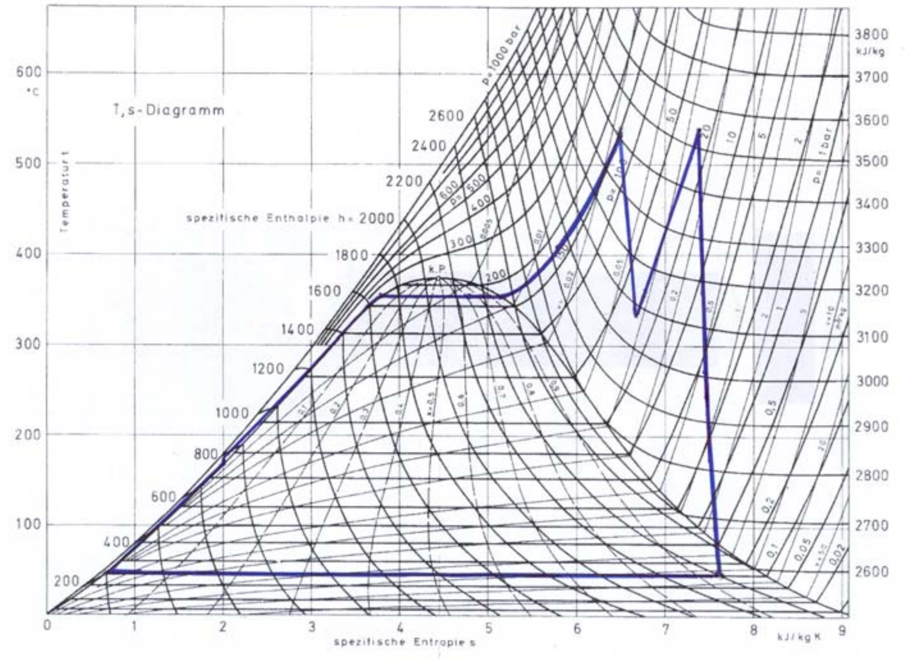
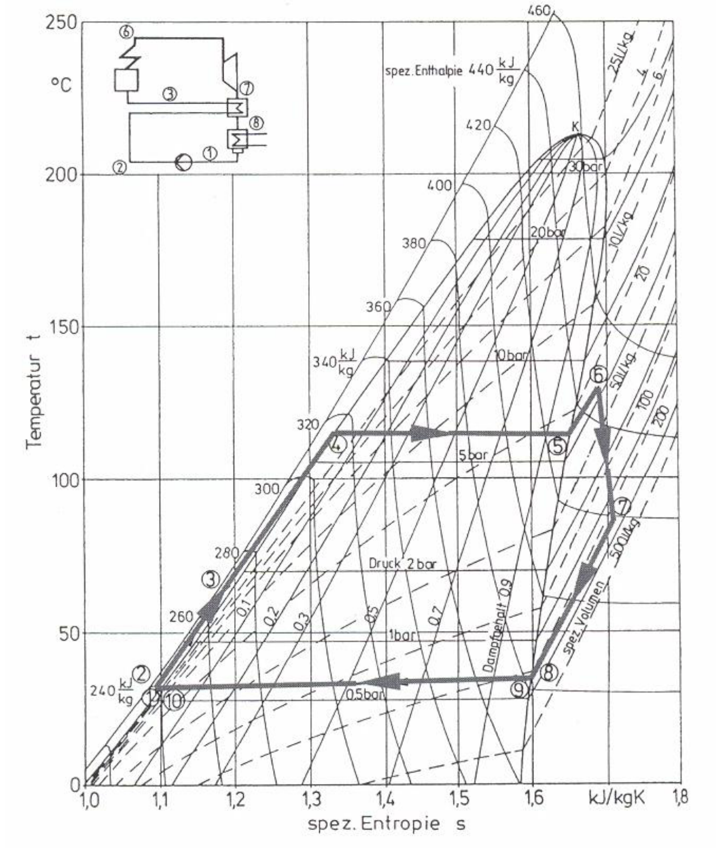
1 DEFINITIONS

In contrast to the Clausius Rankine Cycle (picture 1: exemplary t-s-diagram) the Organic Rankine Cycle process (ORC-process, picture 2) uses low-boiling organic working fluids as hydrocarbons or silicone oil instead of water. Thus, heat of a low temperature level can be used for power production.



Picture 1: t-s-diagram of a Clausius Rankine process



Picture 2: t-s-diagram of an Organic Rankine process

Further advantages are the non-corrosive and non-erosive properties of the suitable organic fluids. The last one is due to the shape of the saturation line in the technical relevant region (isentropic or increasing entropy with increasing temperature) whereas the expansion of the first process leads into the wet steam region despite the reheating.

The organic fluids can be used without (by means of a separator) or slight superheating.

These advantages add up to long operational life, high cycle efficiency, environmental friendliness and low operational cost, due to unattended, automatic operation and no water purification.

2 TECHNOLOGY OVERVIEW

The ORC technology can be considered as technology at the threshold to the market. The typical fields of application are biomass-fired plants, geothermal and heat recovery plants. Numerous plants have been installed during the last years inEurope mainly Austria, Germany, Italy and Switzerland, prevailing affected by public subsidies for erection or/and operation. Most of the projects have been accompanied by detailed monitoring programmes. The reported result show examples of a proven technology and mature design. The economic success depends mainly on the national legal framework.

Geothermal plants can obviously be excluded for further consideration in this project since the high expenses for the geological preparation leadunder EU conditions to large sized plants.

The suitability of ORC heat recovery plants depends highly on the specific local conditions.

From the MicroCHeaP point of view, the biomass-fired ORC plants be worthy of note – especially the working test facilities of the Lappeenranta University of Technology (Finland) in the power range of 25 to 1,500 kWe. The development has been focused on compact size, high-speed turbogenerators of completely hermetic design and without the need of lubricating oil. Turbine, generator and feed pump are assembled on the same shaft. The generator produces a high frequency alternating current, which is adapted to the grid frequency by an inverter. The described plants were destined to add to an existing heating plant. The further development shall be extended to a complete biomass-fired ORC plant.

Although this research and development finally aimed at a later up-scaling, there is also the creative potential for a future down-scaling in case of a serial production for the distributed power generation.

Several organic compounds have been used in ORC applications (e.g. toluene, freon, iso-pentane or ammonia) to match the temperature of the available heat. Some efforts have been made to design special fluids without a detrimental effect on the environment.

Till now the high investment cost (especially in the case of an additional thermo-oil cycle) slow down a broad application of this technology in countries without guaranteed and competitive feed-in tariffs as in Germany.

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   ISBN 88-89407-04-2, ISBN 3-936338-16-7

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   Organic Rankine Cycle Turbogenerators for Combined Heat and Power Production from Biomass.
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   BWK Brennstoff-Wärme-Kraft 36 (1984), no.: 7-8, pp. 332-335

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    ORC Plants for Power Production from Biomass from 0.4 MWe to 1.5 MWe: Technology, Efficiency, Practical Experiences and Economy.

Paper presented to the 7th Holzenergie-Symposium,
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11. Gaia, Mario:
The Altheim Rankine Cycle Turbogenerator 1 MWel Organic Rankine Cycle Power Plant Powered by Low Temperature Geothermal Water
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Fuzzy Logic Controlled CHP Plant for Biomass Fuels Based on a Highly Efficient ORC Process.
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Design and Validation of a New High Expansion Ratio Radial Turbine for ORC Application.
5th European Conference on Turbomachinery,
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Low-grade Geothermal Energy Conversion by Organic Rankine Cycle Turbine.
Proceedings of the 18th Intersociety Energy Conversion Engineering Conference, Orlando, FL., 21 – 25 August 1983. Volume 1 (A84-30026 13-44), New York, American Institute of Chemical Engineers, pp. 294 - 299

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Heißluftturbine und ORC-Prozess: Alternativen zum Dampfkraftprozess? (Hotgas Turbine and ORC: Alternatives to the Steam Power Process?)
Gülzower Fachgespräche:
Energetische Nutzung von Biomasse durch Kraft-Wärme-Kopplung,
16./17. Mai 2000, pp. 131 - 148

4 MANUFACTURERS

1. GMK Gesellschaft für Motoren und Kraftanlagen mbH
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MicroCHeaP Literature Search: Fuel Cells
Investigation related to fuel cells
Contributed by CRES

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MICRO-CHEAP LITERATURE SURVEY
CONTRIBUTION OF CRES
INVESTIGATION RELATED TO FUEL CELLS

1. DEFINITION OF DISTRIBUTED GENERATION AND SMALL SCALE CHP

A number of parameters that include the liberalisation of the energy market, environmental concerns and security of supply have increased the interest in the concept of Distributed Generation (DG). This interest has been boosted by the spreading of the Natural Gas networks and by the fact that power transmission losses are avoided if power is produced locally. The possibility to exploit on-site the heat produced further increases the benefits of the DG concept.

Suitable technologies have been developed for such distributed generation applications that are characterised by low investment costs, small size/footprint, relatively high efficiency and short payback times. Such technologies would be:

- advanced internal combustion engine-based CHP systems
- microturbines
- Stirling engines
- fuel cells
- flow batteries or regenerative fuel cells
- flywheels
- renewable energy technologies like photovoltaics, wind energy converters, geothermal energy technologies, solar thermal, etc

These technologies can be grouped as “spinning mass based” including IC engines, micro-turbines, variable speed small hydro- and wind-turbines or “inverter based” including PV, fuel cells, batteries. These two groups are sometimes referred to as “mechanical-electrical converters” or “direct converters” respectively. The recent rapid development of power electronics and microcomputer technology has led to considerable efficiency gains and cost reductions [Schmidt, 2002]. Thanks to modern inverters it is possible to generate sinusoidal voltages with synchronous phases (active power) but also to compensate for reactive power and harmonics.

The strengths of DG can be summed up as:

- low investment costs
- high efficiency, that can be up to 80% for CHP
- small times for installation
- installation close to load, avoiding transmission losses and power line refurbishment or extension
- low emissions
- capability to utilise a variety of fuels

The following points can be considered as the weaknesses of DG:

- relatively high cost of kWh, depending on fuel used
- need for attention on electrical issues like control of voltage, frequency, reactive power
- non-technical issues for connecting to the electricity grid
- installation cost can be high for the case of existing buildings that need a retrofit

Densely populated areas that, for the case of Europe accommodate 80% of the population, offer major opportunities for the development of such distributed small-scale cogeneration schemes since the demand for power and heat concentrates there. The ideal fuel for these applications would be city gas or natural gas. However rural areas also constitute an interesting market [Loffler 2002]. In such rural areas the benefits of reduced transmission losses become more obvious, while the investment in electricity transportation infrastructure is avoided. Such systems would allow commercial activities to take place, contributing in rural development programmes.

Potential users of such small-scale cogeneration systems in rural areas are:

- pig farms
- greenhouses
- sewage treatment plants
- saw mills
- hotels, refuges and resorts
- small industries
- military bases

2. FUEL CELLS OVERVIEW

Fuel cell technology is one of the most promising new electrical power technologies currently undergoing development. Fuel cell power systems have attracted attention because of their potential for high efficiency, low emissions, flexible use of fuels, and quiet operation. The state-of-the-art has advanced to the point that fuel cell manufacturers hope to begin marketing fuel cells in just a few years. Full-scale demonstration plants are currently being designed.

Stationary applications of fuel cells are being targeted for every sector of the world energy market, from small residential co-generators to large central power generating stations [Dunbar, 1993]. The application range includes:

- On-site systems from some Watts to MW´s.
- Distributed and substation systems ranging from kW´s to MW´s.
- Central stations of several hundred MW´s.

Despite their advantages, fuel cells will receive the toughest competition from new generation gas turbines, which can obtain nearly as high efficiencies with relatively low emissions at capital costs in the range of 600 to 800€/kW. Due to lower capital costs of turbines for systems greater than 10 MW, fuel cells are believed to have the best initial market penetration in the 30 kW to 10 MW range.

2.1. Typical characteristics

The principle of fuel cells was discovered by Grove and Bossel in 1839, but remained undeveloped until the late 1950s. Presently, six different fuel cell types are in varying stages of development. In general, fuel cells are categorized by the type of electrolyte used and the operating temperature. The following is a list, in order of increasing operating temperature, of the most appropriate fuel cells for stationary power generation :

- proton exchange membrane fuel cell (PEMFC) (30-90 °C)
- alkaline fuel cell (AFC) (50-90 °C)
- phosphoric acid fuel cell (PAFC) (150 – 200 °C)
- molten carbonate fuel cell (MCFC) (650 °C)
- solid oxide fuel cell (SOFC) (800 – 1000 °C)

Another fuel cell type is direct methanol fuel cells (DMFC). DMFC are in a phase of early development. Each fuel cell type has its advantages and disadvantages. Given the prospectively large power generating markets anticipated in the near future, it is very possible that all types could find a substantial market niche in the 21st Century.

Proton exchange membrane (PEM) fuel cells and alkaline fuel cells are considered suitable for off-grid stationary applications in the range of a few hundred kW due to their fast response times and the fact they run on pure hydrogen. PAFCs, MCFCs and SOFCs use natural gas or other hydrocarbons as a fuel.

Proton Exchange Membrane Fuel Cells (PEMFC)

The electrolyte of a PEMFC consists of a layer of solid polymer that allows protons to be transmitted from one face to the other. It requires hydrogen and air as its inputs, and these gases must be humidified to enable the electrolyte to function. Pressurising the air increases performance. It operates at a temperature of about 80°C (much lower than the fuel cells mentioned so far) because of the limitations imposed by the thermal properties of the membrane. The PEMFC can be contaminated by CO, resulting in a reduction of performance by several per cent for contaminant in the fuel in ranges of tenths of per cent [Pater, 1994].

There are many companies involved in manufacturing PEMFCs. Ballard is considered to be the leader in the field, though companies such as DeNora in Italy are making substantial progress. It also appears that there is a strong possibility of using the PEMFC in small-scale localised power generation as the PAFC is being used, where the heat could be used for hot water or space heating. There is also the possibility of using a heater/chiller unit for cooling in areas where air-conditioning is popular. If it does prove possible to use this type of fuel cell for both transport and power generation, the advantages generated by economies of scale and synergy between the two markets could make the introduction of the technology easier than in other cases, though the operating conditions are substantially different. This technology seems ideal for Stand-Alone Power Systems driven by renewable energy sources, mainly because of its fast response times and the fact they run on pure hydrogen, which may be produced through water electrolysis.

Alkaline Fuel Cells (AFC)

The alkaline fuel cells have been described since at least 1902, but they were not demonstrated as viable power units till the 1940s and 1950s by FT Bacon at Cambridge, England. Although PEM fuel cells were chosen for the first NASA manned space aircraft, there were Alkaline fuel cells that took man to the moon with the Apollo missions. The success of the alkaline fuel cell in this application and the demonstration of high power working fuel cells by Bacon, led to a good deal of experiment and development of alkaline fuel cells during the 1960s and early 1970s. Demonstration alkaline fuel cells were used to drive agricultural tractors, power cars, provide power to offshore navigation equipment and boats, drive forklift trucks etc.

Although many of these systems worked reasonably well as demonstrations, other difficulties, such as cost, reliability, ease of use, ruggedness and safety were not so easily solved. When attempts were made to solve these engineering problems, it was found that, at that time, fuel cells could not compete with rival energy conversion technologies, and research and development scaled down. The success of PEM fuel cells developments in recent years has furthered the decline in interest in alkaline fuel cells, and now very few companies or research groups are working in the field. The space program remained the one shining star in the alkaline fuel cell world, with the Apollo system being improved and developed for the space shuttle Orbiter vehicles. However, the fact that the new fuel cells for the space shuttle Orbiter vehicles will be PEMFCs only serves to further underline their decline in importance. Nevertheless, because of their success with the space program, alkaline fuel cells played a hugely important role in keeping fuel cell technology development going through the later half of the 20th century. Also, it could well be that the problems of this technology can be solved. For example, if the major source of hydrogen is electrolysed water from the use of solar panels, then alkaline fuel cells could well become more attractive, which is the case for Stand-Alone Power Systems power from renewable energy sources.

The major advantages of alkaline fuel cells are that the activation over-voltage at the cathode is generally less than with an acid electrolyte. Also, the electrodes can be made from non-precious metal electrodes, and no particular exotic materials are needed. The main problem with AFCs for non-space applications is the problem of carbon dioxide reactions with the alkaline electrolyte. This occurs with the carbon dioxide in the air, and would happen even more strongly if hydrogen derived from hydrocarbons (such as natural gas) were used as the fuel. These reactions result in:

- Reduction of the rate of reaction at the anode
- Increase of the viscosity which reduces the diffusion rates
- Reduction at the electrolyte conductivity leading to an increase in the ohmic losses
- Possible degradation of the electrode performance

The best possibility to confront these problems is to incorporate the cells into a regenerative system. Electricity from renewable energy sources is used to electrolyse water when the energy is available, and the fuel cell turns it back into electricity when needed. This way the AFCs disadvantages would be largely removed, since both hydrogen and oxygen would be generated on-site. Therefore, AFC's advantages of low cost, simplicity, lack of exotic materials, good cathode performance, and wide range of operating temperatures and pressures, might bring them to the fore again [Larminie et al, 2001].

Phosphoric Acid Fuel Cells (PAFC)

The PAFC is not the most efficient fuel cell for power generation (efficiencies around 37-42% LHV). Nevertheless it has been under development since 1960s and is being used in demonstration applications all over the world. It uses phosphoric acid as an electrolyte and has the advantage of being tolerant of CO_2 in its feed. PAFC stacks, like other planar fuel cell types, consist of repeating fuel cell units, each comprised of an anode, cathode, electrolyte (retained in a matrix) and a ribbed separator plate (either of substrate or bipolar type) between cells. One additional repeating stack element is the cooling plate which removes the heat generated from the cell reactions and, depending on design and cooling fluid, may be spaced every 4-7 cells. The PAFC has been running in Japan in installations from tens of kilowatts to 11 MW.

The PAFC is normally fuelled by a natural gas feed, which must be then processed to a hydrogen-rich reformate with no CO (a poison to the catalyst) though it is tolerant of CO_2 in the fuel. It has an electrical efficiency in the field of 35-45% and produces waste heat at about 200°C, suitable for small scale cogeneration applications, but not for industrial cogeneration applications or additional turbine cycles.

Onsi, a division of International Fuel Cells (IFC), has sold over 100 of its 200 kW PC25 systems at a price significantly higher than that charged for competing forms of technology. It is hoping to be able to reduce the price to about $1,500/kW from its current level of $3,000/kW over the next few years. The Japanese manufacturers have done extensive testing and analysis with Toshiba, Fuji Electric, Mitsubishi Electric, in collaboration with utilities such as Osaka Gas and Tokyo Electric. Fuels used by these organizations have been varied, with propane, naptha, methanol and others among the supplies [Hart D, 1997].

Solid Oxide Fuel Cells (SOFC)

Fuel cells of this type show higher electrical efficiencies than PAFCs and operate at much higher temperatures (up to 1000°C); therefore their heat output can be used not only in small scale CHP applications but also in industrial processing and for producing steam to run a turbine in a bottoming cycle. Their development is being pursued by companies such as British Gas and Mitsubishi Heavy Industries, but Westinghouse, with a slightly unusual form of the technology, seems to have the advantage. SOFCs are capable of internally reforming a hydrocarbon gas, meaning that they require a much less expensive and inefficient balance of plant than PAFCs, and are able to use CO as a fuel. Their efficiencies are estimated approximately in the 55-60% range with the possibility of introducing a gas turbine bottoming cycle to increase efficiency still further.

There are three fundamental designs of SOFC – the tubular, planar and monolithic types. The first of these was designed by Westinghouse Electric Corporation and operates with the fuel on the outside surfaces of a bundle of tubes, and the oxidant on the inside, the tube itself being composed of the electrolyte and electrode "sandwich". Westinghouse is bullish about the technology and has made extensive plans for production of a system that incorporates an SOFC with a gas turbine burning some additional fuel in the high temperature, high-pressure exhaust of the fuel cell. There are 3, 5 and 10 MW_e plant designs being considered.

If cost targets can be obtained, the potential commercial market sector for SOFCs is also large. A market analysis of commercial building applications indicated that there were over 500,000 potential sites for SOFCs with capacities ranging from 10 – 500 kW and operating in either stand-alone or cogeneration modes. Most probable early customers are hospitals, health care facilities, hotels, educational and office buildings that require premium power service.

Planar SOFCs are under development by a number of companies, Siemens and Fuji Electric being among them. In this technology the cells are flat plates bonded together and placed one on top of the other to form a stack. The advantages of this system over the tubular system are its relative ease of manufacture and a lower ohmic resistance of the electrolyte, resulting in reduced energy losses. Monolithic and low temperature SOFCs are currently at an early stage of design [Hart D, 1997].

Molten Carbonate Fuel Cells (MCFC)

MCFCs use a molten alkali carbonate mixture retained in a matrix, as an electrolyte. Their operating temperature is approximately 650^{o}C, therefore useful process heat is produced. In this case, in addition to the fuel provision the cathode must be supplied with CO_2 which reacts with the oxygen and electrons to form carbonate ions that carry the ionic current through the electrolyte. At the anode these ions are consumed in the oxidation of hydrogen, also forming water vapour and CO_2 to be transferred back to the cathode. The fuel consumed in an MCFC is usually natural gas, though this must be reformed in some way to create a hydrogen-rich gas to feed to the stack. An MCFC produces heat and water vapour at the anode, which can be used for the steam reformation or methane. This means that it is inherently more efficient than a cell requiring external fuel processing. Again, the MCFC can use CO at the anode as a fuel.

The MCFC is seen by many as an ideal source for large scale power generation. One reason for this is the necessity for large amounts of ancillary equipment that would render a small operation uneconomic. There is also no requirement for expensive catalysts as in low temperature fuel cells, and a third reason is that the heat generated can be used for internal reformation of methane, a bottoming cycle and for fuel processing and cogeneration. This increases the efficiency of the fuel cell system.

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3. Integrated modelling study of FC/GT hybrids (IM-SOFC-GT) – Contract number ENK5-CT-2000-00302
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5. Natural gas SOFCs for co-generation of electricity and chemicals (NG-SOFC-COGEN) – Contract number ICA2-CT-2000-10030
6. 1 MW SOFC – hybrid fuel cell/micro-turbine system (1MWSOFC) - Contract number NNE5-1999-00173
7. Pressurized IP-SOFC: a path to successful SOFC/Hybrids (PIP-SOFC) – Contract number NNE5-2001-00791
8. Biogas – MCFC systems as a challenge for sustainable energy supply (EFFECTIVE) - Contract number ENK5-CT-1999-00007
9. Integrated research on materials, technologies and processes to enhance MCFC in a sustainable development (IRMATECH) - Contract number ENK5-CT-2002-00647
10. MCFC twinstack powered – first of a kind (TWINPACK) - Contract number NNE5-1999-00236
11. MCFC/MTG hybrid power plant toward low-cost production (MOCAMI) - Contract number NNE5-2001-00651
12. Hybrid fuel cell/heat pump system (FUEL-SAVE) - Contract number NNE5-2001-00232
13. 50 kW PEM fuel cell generator for CHP and UPS (50PEM-HEAP) - Contract number NNE5-2001-00882
14. High-temperature PEMFC stack with methanol reforming (AMFC) - Contract number ENK5-CT-2000-00323
15. Clean hydrogen-rich synthesis gas (CHRISGAS) - Contract number SES6-CT-2004-502587
16. Realising, reliable, durable, energy-efficient and cost-effective SOFC systems (Real-SOFC) - Contract number SES6-CT-2003-502612
17. Biomass fuel cell utility system (Biocellus) - Contract number SES6-CT-2004-502759
18. Development of low temperature and cost effective solid oxide fuel cells (SOFCSPRAY)
19. SOFC fuelled by biomass gasification gas (GREEN-FUEL-CELL) - Contract number SES6-CT-2004-503122

20. Compact direct (m)ethanol fuel cell for portable application (MOREPOWER) - Contract number SES6-CT-2003-502652

6. BOOKS & REPORTS

1. "Bio-methane & Bio-hydrogen, Status and perspectives of biological methane and hydrogen production", Edited by JH Reith, RHWijffels and H. Barten

2. "Biogas powered fuel cells, Case studies for their implementation", Edited by S. Trogisch, WE Baaske, Steyr, Austria, 2004

3. WR Dunbar, "A General Overview of the Fuel Cell Industry",Center for Energy Studies Report, Marquette University, 1993

4. J Larminie, A Dicks "Fuel Cell Systems Explained", Wiley & Sons, LTD, New York (2001), pp. 109-122.

5. D Hart, "Hydrogen power: The commercial future of "the ultimate fuel", Financial Times Energy Publishing, 1997, p. 36-38.

7. FUEL CELLS MANUFACTURERS AND AGENTS

1. Ballard (Canada – agents in many European countries)
2. Nuvera Fuel Cells (Italy)
3. MTU Friedrichshafen GmbH (Germany)
4. EBZ GmbH (Germany)
5. Siemens AG (Germany)
6. RWE AG (Germany)
7. Ansaldo Fuel Cells (Italy)
8. Sulzer Hexis Ltd (Switzerland)
9. Intelligent Energy (UK)
10. Nedstack (Netherlands)
11. Axane Fuel Cells (Netherlands)