MICROCHEAP

The Integration of Micro-CHP and Renewable Energy Systems

A European Commission Co-ordination Action

Sustainable development, global change and ecosystems
Sustainable Energy Systems

TREN/04/FP6EN/S07.32890/503138

WP 5
Investigation of links between renewable energy systems and micro-CHP

Deadline 31. March 2005

Project co-ordinator: Chalex Research Ltd.
Work Package Leader DGS e.V.

A.) General Instruction

Contrinutors will have to identify the designated technologies within their field of expertise. They will report on the potential of these technologies to form new renewable micro-CHP systems, or to convert existing micro-CHP systems to operate using renewable energy sources.

Technologies will be identified and analysed using the following criteria:

- Efficiency of energy conversion
- Cost of production
- Reliability and expected maintenance requirement
- Cost of integration into the existing energy system, compared to existing micro-CHP
- Environmental benefits and impact
- Expected payback time through electricity savings in comparison to cost of modern central heating systems
- Expected costs of energy production in future scenarios outlined within WP1

conducted and documented regarding the new or converted technologies, compared with existing technologies and analysed for expected market penetration. Evaluation of the results will allow the most promising technologies to be highlighted, and allow future research to be focused towards systems that offer the highest potential for future markets, or for overcoming the barriers of implementation highlighted within WP1.

The contributions by the partners are separated into two sections :

C.) Technology contributions

and

D.) Market contributions

The partners should only fill in the template where they are obliged to and send the document back to dobelmann@dgs.de for further processing.

On the project meeting in we expect a short summarizing report of each partner or team on its findings and then will jointly pick the promising technologies for further investigation.

B.) Overview of Partner tasks:

DGS with Assistance of ISET :

Co-ordinate all technological investigation, to ensure no duplication between partners. Lead analysis of technologies to highlight the most promising systems. Investigate technologies that can be linked to geothermal, and solar systems

EC NET :

Lead consideration of industrial, and market relevance of potential technologies. Cost analysis of technologies compared to existing micro-CHP systems and modern central heating systems

BTG :

Specification of the most promising biomass conversion systems to be linked with micro-CHP. Documentation of the potential for liquid biofuels to be used within micro-CHP engine systems

CRES :

Investigation of the potential for biomass to be linked with fuel cells. Documentation of biomass to hydrogen conversion systems

STSL :

Evaluate the potential of non-Stirling combustion engines to be developed into renewable micro-CHP systems. Aid in the analysis of technologies for their industrial potential

FHG-ISE with Assistance of ISET :

Evaluate potential of low band-gap photovoltaic cells for the conversion of heat radiation into electricity

EAT :

Aid in the consideration of technologies for their industrial and market potential. Consider highlighted technologies with regards to market trends and predicted future market scenarios and energy pricing

GAIA :

Aid in the evaluation of technologies with regards to market trends and future scenarios

ECN with assistance of LUND :

Investigate the potential for existing types of Stirling engines for the potential to be linked with new renewable energy systems. To highlight technologies that aid the integration of Stirling engines with renewable systems

CHALEX :

Investigate the potential for thermoelectric technology to be integrated into micro-CHP systems

UB :

Investigation for the potential of biogas within existing micro-CHP systems

CODES :

Planning of format for work package review. Collection of information, preparation of documentation, and distribution to partners. Distribute documentation through appropriate dissemination channels

FORCE with Assistance of AUE and ASTON:

Evaluate potential of straw and other biomasses as fuels for CHP and micro-CHP systems

BEAMA :

Contribution from SME perspective and dissemination

AF :

Micro-CHP, small-scale combustion, renewable fuels

ARMINES :

Contribution of expertise relating to advanced modelling of complex energetic systems

C.) Technology contributions :

See below the headlines of the Work packages for technology contributions found on the next pages

(please just fill in your contribution and mail it to **dobelmann@dgs.de**)

a.) Geothermal systems *(DGS with assistance of ISET)* *page xx*

b.) Solar systems *(DGS with assistance of ISET)* *page xx*

c.) Special solar systems low band-gap photovoltaic cells for the conversion of heat radiation into electricity *(FHG-ISE with Assistance of ISET)*

page xx

d.) Biomass conversion systems to be linked with micro-CHP *(BTG)*

page xx

e.) Liquid biofuels to be used within micro-CHP engine systems *(BTG)*

page xx

f.) Fuel cells *(CRES)* *page xx*

g.) Biomass to hydrogen conversion systems *(CRES)* *page xx*

h.) Non-Stirling combustion engines *(STSL)* *page xx*

i.) Thermoelectric technology *(CHALEX)* *page xx*

j.) Biogas *(UB)* *page xx*

k.) straw and other biomasses as fuels for CHP and micro-CHP systems *(FORCE with Assistance of AUE and ASTON)*
page xx

l.) Small-scale combustion and renewable fuels *(AF)* *page xx*

a.) Geothermal systems *(DGS with assistance of ISET)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

b.) Solar systems *(DGS with assistance of ISET)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

c.) Special solar systems low band-gap photovoltaic cells for the conversion of heat radiation into electricity *(FHG-ISE with Assistance of ISET)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

d.) Biomass conversion systems to be linked with micro-CHP *(BTG)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

e.) Liquid biofuels to be used within micro-CHP engine systems *(BTG)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

f.) Fuel cells *(CRES)*

I) General short description of the technology

A fuel cell is an electrochemical device for the direct conversion of the chemical energy of hydrogen into electricity, heat and water vapour. This conversion can be done with very high electrical efficiency (35 – 55%) and with minimum environmental intrusion. These two aspects have rendered fuel cells as the most likely energy conversion devices in the medium to long term, in both transport and stationary applications and for all power ranges. The capability of fuel cells to operate with a variety of fuels is of particular interest to the present study, since this makes them a favourite candidate for the optimal use of biofuels.

The basic operation of a fuel cell is exactly the opposite of electrolysis. In an electrolyser, an electric current is passed through water which is broken into oxygen and hydrogen. In a fuel cell hydrogen and oxygen are combined producing an electric current and water. The principle was demonstrated by Sir W. Grove in 1839 and is shown schematically below.

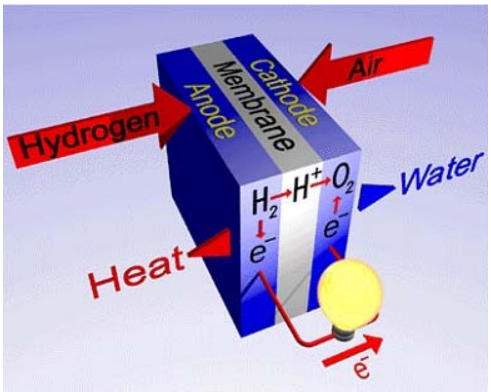

Fig. f.1. Working principle of fuel cells [fuelcellworld.org]

Fuel cells operate very much like batteries, the main difference being that in batteries the reactants are stored within the battery itself and are limited by its size, while in a fuel cell they are stored externally and energy can be produced as long as fuel is fed to the anode and an oxidant to the cathode (Fig. f.1.).

In a fuel cell the hydrogen fuel is consumed (“combusted”) in the anode in the reaction:

$$2H_2 + O_2 \rightarrow 2H_2O$$

where electrical energy and heat are produced. This electrical energy is proportional to the contact area between the gases, the electrolyte and the electrodes and inversely proportional to the distance between the electrodes. To maximise the electrical energy production of a fuel cell, electrodes are thus usually made flat with a thin layer of solid or liquid electrolyte sandwiched between them. The type of electrolyte defines the type and name of the fuel cell.

The most common types of fuel cells are:

- polymer electrolyte membrane fuel cells (PEM) where the electrolyte is an ion exchange membrane
- alkaline fuel cells (AFC), where the electrolyte is an 80% concentrated solution of KOH
- phosphoric acid fuel cells (PAFC) where the electrolyte is 100% concentrated phosphoric acid
- molten carbonate fuel cells (MCFC) where the electrolyte is alkali carbonates that in the high operating temperatures of this fuel cell form molten salts
- solid oxide fuel cells (SOFC) where the electrolyte is a solid, non-porous metal oxide

II.) Efficiency of energy conversion

Efficiency of a system is defined as the energy produced divided by the energy input. For the case of fuel cells the energy produced is electrical energy and the energy input is the chemical energy of the fuel. The latter is usually expressed by Gibbs free energy, thus efficiency is expressed as:

$$\frac{\textit{Electrical energy produced}}{\textit{Gibbs free energy}}$$

Gibbs free energy is sometimes replaced by the calorific or heating value of a fuel, since a fuel cell is to be compared with combustion or heat engines. One should note that calorific value appears as lower (LCV) or higher (HCV) calorific value, depending on whether the enthalpy of vaporisation of water has been taken into consideration. For hydrogen HCV = -285.84 kJ/mole and LCV=-241.83 kJ/mole. The LCV is most commonly used, since it gives higher values of efficiency.

For the case of combustion engines, efficiency is limited by the Carnot limit, namely $(T_1-T_2)/T_1$ where T_1 is the maximum temperature of the heat engine and T_2 the lower (exit) temperature in degrees Kelvin. The efficiency limit of a heat engine increases with increasing maximum temperature. The opposite happens for fuel cells, as can be observed in figure f.2. It can also be observed that contrary to what is commonly believed, heat engines can display higher efficiency limits than fuel cells (at high temperatures). However at such temperatures, the heat available in a fuel cell can be used in CHP or in a bottoming cycle to produce more electricity through a gas turbine.

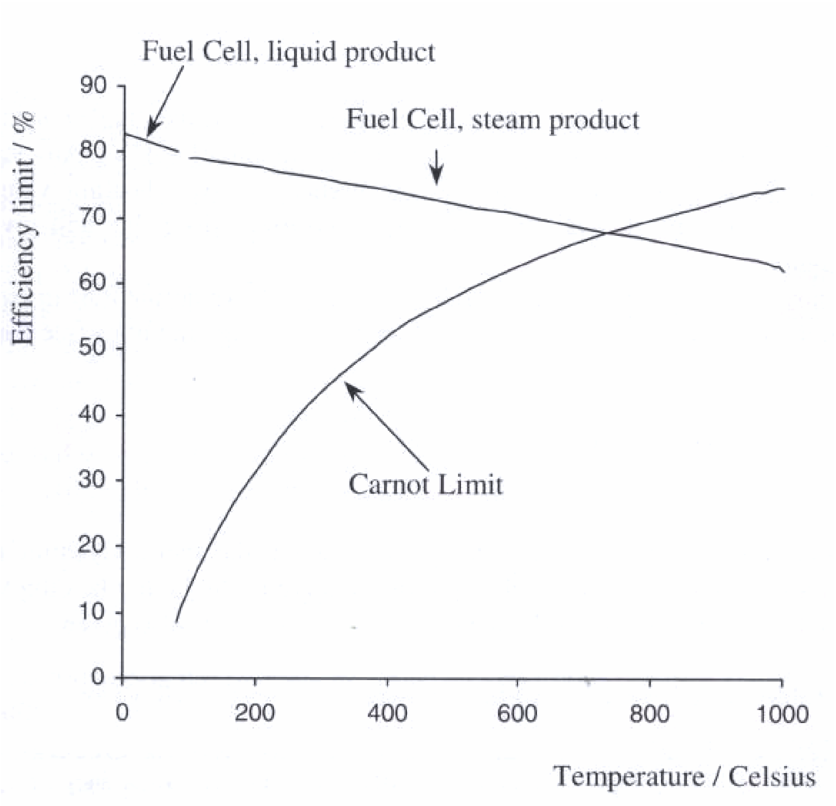

Fig. f.2. Efficiency limits vs. temperature plot for a fuel cell and a heat engine [Larminie, 2000]

III) Cost of production

Fuel cells are expensive to build since demand has not reached the level that would allow mass production, meaning many devices are still build by hand. Additionally, some fuel cells use expensive materials, such as platinum. The average cost of fuel cells (depending on type and technology) for micro CHP applications ranges between 5,000 – 15,000 €/kW. The EC cost target for fuel cells to become a commercial solution in stationary solutions is much lower (300 €/kW).

IV) Reliability and expected maintenance requirement

Even though reliability is potentially higher than that of competing technologies, currently the reliability of fuel cells and their operating life is lower, due to the immaturity of the technology. Guarantees offered by most fuel cell manufacturers are limited to 1 year or 1,500 operating hours, therefore long term O & M costs are a significant cost factor.

V) Cost of integration into the existing energy system, compared to existing micro-CHP

The cost of integration of fuel cells into an existing micro CHP energy system is considerable compared to other conventional solutions. In most cases the fuel that will drive fuel cells (pure hydrogen, biogas, other hydrocarbons) is not available on site and should also be purified so as not to poison the fuel cell catalyst. Therefore a drying and purification unit should be integrated to the energy system and this naturally increases the overall cost. In case fuel cells are driven by pure hydrogen an electrolyser with a considerable cost should also be added. These costs are eliminated when fuel cells driven by available on-site natural gas are used.

Moreover, most fuel cells with a small to medium capacity, suitable for integration in micro CHP energy systems deliver DC current, therefore a DC/AC inverter and other power electronics with a considerable capital cost, should also be added. In addition, safety precautions that should be taken into consideration in the presence of hydrogen also increase the cost of integration of fuel cells into an existing micro CHP energy system.

VI) Environmental benefits and impact

The integration of fuel cells in micro CHP systems reduces significantly emissions of the whole system. The degree of emission reductions depends on the source of fuel driving the fuel cell. When pure hydrogen produced through water electrolysis driven by Renewable Energy Sources (RES) is used in the fuel cells there are no emissions produced by the power system, since the only by-product is water. In case a hydrocarbon (such as natural gas, ethanol etc.) drives the fuel cell, there are CO_2 emissions, which are of course significantly lower compared to an Internal Combustion Engine (ICE), since approximately 1 kg of CO_2 per Nm^3 of hydrogen used is produced.

VII) Expected payback time through electricity savings in comparison to cost of modern central heating systems

As mentioned before, the capital cost of fuel cells is currently high. Moreover, the cost of electrolysers (in case fuel cells are driven by pure hydrogen) is also significant and the cost of hydrogen storage devices is still considerable, therefore the payback time through electricity savings by integrating a fuel cell to an existing conventional micro CHP will be long (greater than 10 years).

VIII) Expected costs of energy production in future scenarios outlined

The future cost of electrical energy production for a RES-hydrogen hybrid power system in the order of 25kW, taking into account a 50% reduction in the cost of electrolysers, a 40% reduction in the cost of hydrogen storage and a cost of fuel cells equal to the EC cost target (300 €/kW) is calculated around at 1€/kWh, without taking into account thermal energy production. Therefore, the future cost of total energy production will be lower than the above mentioned value [Zoulias et al, Renewable Energy Journal].

The reader could also refer to the MicroCHeaP database for a listing of fuel cell manufacturers.

References

www.fuelcellworld.org
Larminie, J., Dicks, A., *Fuel Cell Systems Explained*, John Wiley & Sons Ltd, 2000.
E.I. Zoulias, N. Lymberopoulos, “Techno-economic Analysis of the Integration of Hydrogen Energy Technologies in Renewable Energy-based Stand-Alone Power Systems”, Renewable Energy Journal, accepted for publication.
N. Lymberopoulos, “Fuel cells and their application in bio-energy”, Project Technical Assistant Framework Contract (EESD Contract N^o: NNE5-PTA-2002-003/1)

g) Biomass to hydrogen conversion systems *(CRES)*

I) general short description of the technology with examples

Reforming is the generic term used for converting hydrocarbons into hydrogen and CO_2. There are three basic reforming techniques, steam reforming (endothermic), partial-oxidation (exothermic) and autothermal reforming (combination of the previous two; close to thermal equilibrium).

Steam reforming

Steam reforming (SR) is currently the most wide spread method for producing hydrogen from light hydrocarbons thanks to the relative simplicity of the method. Fuel is mixed with superheated steam at 1,100°C under pressure and in the presence of a nickel based catalyst. Carbon in the fuel is oxidised producing carbon monoxide while hydrogen is released:

$$C_nH_m + nH_2O \rightarrow nCO + (n + m/2)\ H_2$$

The CO is then subjected to a further reaction at 400 – 500 °C, known as water gas shift reaction in which it is reacted with water to produce more hydrogen and CO_2.

$$CO + H_2O \rightarrow CO_2 + H_2$$

The temperature regime of the reactions and the catalyst used depends on the fuel to be reformed. If for example methanol is the feedstock, then this process takes place at 300 °C, making the process suitable even for transport applications. The range of feedstocks is limited to final boiling point and aromatic content. Methane (as in natural gas or biogas) can be reformed as well as propane and butane, but higher hydrocarbons need to go through a pre-reforming process producing hydrogen, methane and carbon oxides.

Steam reforming is most efficient at large scales but less effective at a scale as that suitable for use inside a car, where the energy spent would be almost 40%. At the same time steam reformers are rather bulky and since high temperatures are required, they are slow to respond to start-ups or transients in general.

Partial Oxidation

As the name implies, partial oxidation or POX is the partial or incomplete combustion of a fuel, resulting from the use of a substoichiometric amount of oxygen (air). The process is highly exothermic and self sustaining, however for small-scale applications a catalyst could be used to increase reaction rates are lower reaction temperatures. The process is mostly used for liquid fuels.

During partial oxidation the incomplete burning of hydrocarbons produces char, vapours and oils. These are quenched through the introduction of superheated steam which promotes the water-gas shift reaction (described previously under steam reforming) necessary to reduce CO and increase H_2 production.

For the case of methane:

$$CH_4 + \tfrac{1}{2}O_2 \leftrightarrow CO + 2\ H_2$$

While for pentane:

$$C_5H_{12} + 5/2O_2 \leftrightarrow 5CO + 6H_2$$

Non catalytic POX reactions can require temperatures as high as 1,000°C for the case of petrol, which implies the use of special materials. The reduction of temperatures through nickel-based catalysts means that standard materials can be used and that the amounts of CO are reduced, meaning a smaller shift reactor is required. Overall efficiency is also improved.

For heavier hydrocarbons, reaction temperatures can range from 870°C for catalytic POX up to 1,400°C for non-catalytic POX. For diesel fuel with high sulphur concentrations, reaction temperatures are 925°C for catalytic POX and 1,175°C for non-catalytic POX.

Usually POX reactors have better efficiencies than steam reformers and are more compact since no external heat transfer is required, thus more suitable for transport applications. However the high temperatures involved result to low H_2 and CO_2 selectivity and construction materials constraints, while in the case of steam reforming, the H_2 and CO_2 selectivity is higher. Designers choose among the two processes depending on the particular application.

Autothermal reforming

The autothermal reformer or ATR is a hybrid between the steam reformer and the partial oxidiser. In such a reactor heat is internally exchanged between the endothermic steam reforming reaction and the exothermic partial oxidation reaction. A catalyst is required to determine the relative extents of each reaction. Maximum temperatures are limited by the fact that the SR reaction absorbs heat from the POX reaction. Autothermal reforming provides a fuel processor compromise that operates at a lower temperature than the POX, is smaller, quicker starting, and quicker responding than the SR and results in good H_2 concentration and high efficiency that is equal or better than that of a steam reformer.

Reformers developers

Some companies active in the development of small scale reformers are listed below. Large units like those applied to refineries are considered a mature technology.

Johnson Matthey is developing an autothermal reformer called Hot-Spot aimed to be used for methanol reforming on board vehicles. The reformer starts using a POX reaction. Once water is fed in, H_2 output increases by 50% and the reaction becomes autothermal. Apparently 100% of the CH_3OH is converted leaving CO to the cleaned prior to use in a fuel cell.

The **Argonne National Laboratory** is another autothermal reformer developer, aiming for a compact, quick starting reformer. Catalysts have been developed for a variety of fossil and renewable fuels including methane, methanol, ethanol, petrol and diesel. The catalysts have shown a tolerance for up to 30ppm sulphur containing fuels. The fabrication of catalysts in the form of micro-channels has lead to a 3-5 times reduction in the size of the reformer. Designs have been made for 5-10 kW units (refers to the power of a fuel cell that can be driven from the gas of these reformers).

Ceramic Fuel Cells Ltd, is developing a pre-reformer fuel processor that will convert hydrocarbon fuels to a methane and hydrogen-rich reformate. This reformate will be directly used in an SOFC where it will be internally reformed.

Helbio S.A. is a Greek company (spin-off from the University of Patras) that is active in the development and commercialisation of hydrogen and energy production systems from renewable sources integrated with fuel cells. The main hydrogen carriers utilised include bio-fuels such as bio-ethanol, bio-gas and bio-oil. Other sources of hydrogen, such as fossil fuels (natural gas, gasoline and diesel) are also being examined. [Helbio web site]

Hexion is a Dutch company developing hydrogen generators for industrial processes, automotive fuelling and residential fuel cell applications. Its hydrogen generating equipment is based on different modules that can be combined to generate different qualities of hydrogen from different fuels covering pure hydrogen generators for industrial process applications, pure hydrogen generators for automotive fuelling stations and hydrogen generators for residential applications with fuel cells [Hexion web site]

Honeywell is developing an POX fuel processor for JP8 and diesel fuels, to be used in military applications. The reaction takes place at high temperatures and is very fast with residence times of the order of milliseconds. Fuels with a sulphur content as high as 500 ppm were utilised. The system is optimised to produce high yields of H_2 and CO and little carbon deposits.

Nuvera Fuel Cells, besides developing fuel cells is also active in the development of reformers of various types like catalytic partial oxidation, autothermal reforming and steam reforming. The ATR is used for the reformation of a variety of fuels including natural gas, petrol (85% efficiency) or diesel. The largest unit produced was for a 200kW fuel cell.

French company **N-GHY** is developing a high temperature non catalytic HSR whose Generation 1 prototype of 20kW showed multi fuel potential, with a conversion rate of more than 99%. The reformer has been tried with diesel fuel, ethanol, rapeseed oil, rapeseed oil methyl ester (ROME) and a mixture of diesel and ROME. The unit has been developed in the context of French Fuel cell network “reseau PACo”.

II) Efficiency of energy conversion

The reforming process consumes between 20-30 % of the energy contained in the fuel to be reformed.

In the case of gasification systems that are integrated in CHP plants that use conventional gas-fired engines or turbines, then overall efficiencies of 25 to 35% can be achieved [Xenergy, 2002]. For larger scale systems like IGCC, efficiencies of up to 40-45% can be achieved. Such values can be achieved with fuel cells even for smaller scales of the order of a few kWs.

III) Cost of production

The average cost of various fuels is compared with that of gaseous biofuels, which can be used in fuel cells in the following table.

Fuel Cost	**(Euro per mmBtu)**
Reformed H_2	17
Natural Gas	6
Fuel Gas from Biomass Gasification (BG)	>40
Biogas from Anaerobic Digestion of Biomass (ADG)	1.2
Landfill Gas (LFG)	1.6 to 2.5
Ethanol	10 (sugar-based) 12-15 (cellulosic)

Table g.1. Average cost of gaseous fuels [Baron, 2004]

IV.) Reliability and expected maintenance requirement

Biomass to hydrogen conversion systems, including reformers, are based on a well-established and reliable technology having standard operation and maintenance requirements.

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

The cost of integration of biomass to hydrogen conversion systems in existing micro CHP systems is significantly higher compared to conventional CHP systems due to the:

1. High cost of small reformers. Scaling down reformers is state of the art and the cost of small scale reformers remains high
2. Need for gas clean-up. Hydrogen produced through biomass should be purified in order to meet the requirements of fuel cell manufacturers and not to poison fuel cell catalysts. This, of course, adds a significant cost factor to the overall system.

VI) Environmental benefits and impact

The use of hydrogen produced from biomass in fuel cells or other devices integrated in micro CHP power systems is considered CO_2 neutral and significantly reduces emissions compared to conventional CHP engines.

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

Very few biomass to hydrogen conversion systems have been integrated in micro CHP systems, mostly in the context of demonstration projects, therefore forecasts on the expected payback time and electricity savings compared to the actual cost of modern central heating systems will not be reliable.

VIII.) Expected costs of energy production in future scenarios outlined

N/A

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www.hexion.com
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Baron, S, Biofuels and their use in fuel cells, Article downloaded from the Fuel Cell Today web site, 2004 (www.fuelcelltoday.com)
N. Lymberopoulos, "Fuel cells and their application in bio-energy", Project Technical Assistant Framework Contract (EESD Contract N^{o}: NNE5-PTA-2002-003/1, study available at http://europa.eu.int/comm/energy/res/sectors/polygeneration_presentations_en.htm)

h.) Non-Stirling combustion engines *(STSL)*

Combined Heat and Power (CHP) is a highly fuel-efficient energy technology, which puts to use waste heat produced as a by-product of the electricity generation process. CHP can increase the overall efficiency of fuel utilisation to more than 75% Gross Calorific Value - compared with around 40% achieved by fossil fuel electricity generation plants in operation today, and up to 50% from modern Combined Cycle Gas Turbines - and has the potential to save substantially on energy bills.

Within the UK a 5% VAT level is now applicable on microCHP systems and other microgeneration technologies, which now also include both air source and ground source heat pumps [i].

MicroCHP also benefits under the Energy Efficiency Commitment (EEC). Under the EEC, electricity and gas suppliers are required to achieve targets for improving household energy efficiency. In the second phase of EEC (running between 2005-08) there is an incentive for innovative action - where a supplier carries out an innovative action, though this incentive can apply to no more than 10% of each supplier's target. MicroCHP is one of the technologies that suppliers may use in order to claim this incentive. Installing microCHP therefore becomes more attractive to the energy suppliers as it facilitates meeting their EEC targets.

The UK has a target to install 10GW CHP by 2010. Current installed capacity is estimated at around 5GW. Most new CHP schemes use natural gas, but a significant proportion burn alternative, including renewable, fuels.

This report consider both the potential for both internal and external combustion engines to be fuelled from renewable sources.

The engines being considered are:

Internal Combustion Engine
Gas Turbine
Steam Piston Engine
Steam Screw Engine
Steam Turbine?
ORC?

The fuels being considered are:
Biofuel – Bioethanol, Biomethanol
Biogas
Biomass
Hydrogen
Landfill Gas
Syngas

2.1 External Combustion

External combustion occurs when the fuel is burned outside of the chamber in which the power is produced and allows a more variable quality fuel to be used.

2.1.1 Gas Turbine - Biomass

In a gas turbine a working fluid (gas) is pressurised by a compressor. Heat is then supplied by the combustion of a fuel, which causes the gas mixture to increases in temperature. The gas mixture expands and increases in kinetic energy. The gas is then passed through a turbine where it produces work, which is used to drive the compressor and the electrical generator.

Until recently it was not economically viable to build turbines under $1MW_e$ for electrical power generation. However recent developments have introduced smaller, cost effective miniature gas turbines, known as micro-turbines which are derivatives of the turbocharger. They are small (output range is 28kW- 200kW), single shaft, recuperated gas turbines. They are a relatively advanced technology and are becoming more established commercially.

Also a further development is the biomass CHP system (BCHP) where a micro-turbine is integrated with a wood heat combustion system. Such systems use a biomass combustor to drive a micro-gas turbine indirectly via a high temperature heat exchanger.

Example 1

I.) Technology Description

Talbotts, UK have developed a micro BCHP with an electrical power output of $100kW_e$ and thermal power output of about $150kW_{th}$ [ii]. Development has been supported by UK government funding and it is presently undergoing on site proving trials

In this BCHP before the fuel enters the biomass boiler combustion chamber, it is pre-heated by hot gasses passing over semi-conductive refractory ceramics. Once in the combustion chamber, primary air provides a vigorous combustion reaction, whilst secondary air ensures complete combustion of the biomass fuel and reduced emissions. The hot gasses from the combustion chamber are then drawn into the heat exchanger and through its multiple passes, before being passing through a cyclonic separator prior to being exhausted to atmosphere.

Turbine air is drawn in through an air filter into the compressor. The compressor provides the motive force to drive the mass flow of air through the heat exchanger where it is heated by the hot exhaust gasses form the boiler. The heated and pressurised air is then expanded over the power turbine, which in turn drives the compressor and high-speed electrical generator. In passing through the turbine the expanded gases are reduced in temperature and pressure. Waste heat from the turbine exhaust is captured and returned into the combustion air stream for preheating and in doing so provides a reduction in fuel consumption.

II.) Efficiency of energy conversion

Low heat losses results in overall system efficiency between 80-85%

Electrical efficiency is presently 17% and it is expected that this will rise with further development

III.) Cost of production

Initial capital costs for this unit are expected to be about £2,500/kW$_e$, though this cost is expected to fall due to economies of scale in the manufacturing process, especially in both the combustor and heat exchanger.

Larger units with higher efficiencies and lower costs per kW will provide quicker paybacks and it is expected that a 250kWe sized system will have a payback period of about 2.5 years.

IV.) Reliability and expected maintenance requirement

By using a gas turbine with an external combustor, the biomass CHP uses a novel method of power generation using biomass. It is much more tolerant of variations in fuel quality and moisture content, than other biomass generating systems such as gasification.

Unlike a biomass boiler which is typically sized at 50% of the instantaneous thermal demand to provide about 80% of the annual thermal energy demand, a biomass CHP is designed to run continuously and therefore providing the opportunity for either exporting the excess heat that is generated or using it for drying the biomass.

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

A guideline capital cost for the BCHP is £250,000 which equates to £2,500/kW$_e$ and Table 7 compares the BCHP against similar sized technologies [5]

From Section 4 typical capital costs are described for the three technologies and these are summarised in Table 7.

	Capital Cost (£/kW$_e$)
Steam	6,500
Gasification	7,750
BCHP	2,500

Table 1 Biomass CHP Capital Costs

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

2.1.2 Gas Turbine - Biogas

Power generation from biogas is seen as a significant market opportunity for microturbine manufacturers. Combustion temperatures of around 900ºC to 1000ºC are sufficiently low to allow microturbines to be tolerant to most of the compounds potentially present in biogas, which are shown in Table 2.

Compound	Biogas (% by volume)
Methane	63.8
Carbon Dioxide	33.6
Nitrogen	2.4
Oxygen	0.16
Hydrogen	0.05
Unsaturated Hydrocarbons	0.009
Saturated Hydrocarbons	0.005
Water	0.001 – 0.004
Carbon Dioxide	0.001
Halogenated Compounds	0.00002
Hydrogen Sulphide	0.00002
Organosulphur Compounds	0.00001
Alcohols	0.00001
Others	0.00005

Table 2 Typical Biogas Compounds

To date Capstone are probably the microturbine manufacturer with the most experience of using biogas within a microturbine, though it is generally landfill gas rather than biogas from other sources e.g. animal, food. The largest single project is run by the Los Angeles Department of Water and Power and uses fifty 30kW units to generate power from landfill gas. Other large projects include ten 30kW units installed at the City of Burbank’s landfill, California and twelve 30kW units at the City of Allentown Wastewater Treatment Plant, Pasadena. The Capstone landfill gas/digester gas package will operate on fuels down to 13MJ/m^3 and can be sulphur tolerant.

Historically anaerobic digestion (AD) has been mainly associated with the treatment of animal waste and sewage sludge from aerobic wastewater treatment plants. Recent environmental concerns have forced new waste management strategies to be considered and developed, and now industrial and municipal wastes are being treated by anaerobic digestion.

There are many different forms of AD systems, but in general they all follow the same process. Initially the feedstock (i.e. waste input) is separated into biodegradable and non-biodegradable material. This is either carried out at source or it is separated on-site at the AD. Once separated the feedstock is then treated so that it is of a consistency and quality for it to be fed to the AD. This pre-processing phase may involve a series of processes which include shredding, screening for solids, adding water or liquid from the AD to reduce the TS content. Once the feedstock is in the AD, microbial bacteria break the material down to produce biogas and a residual digestate. A typical process is shown in Figure 1.

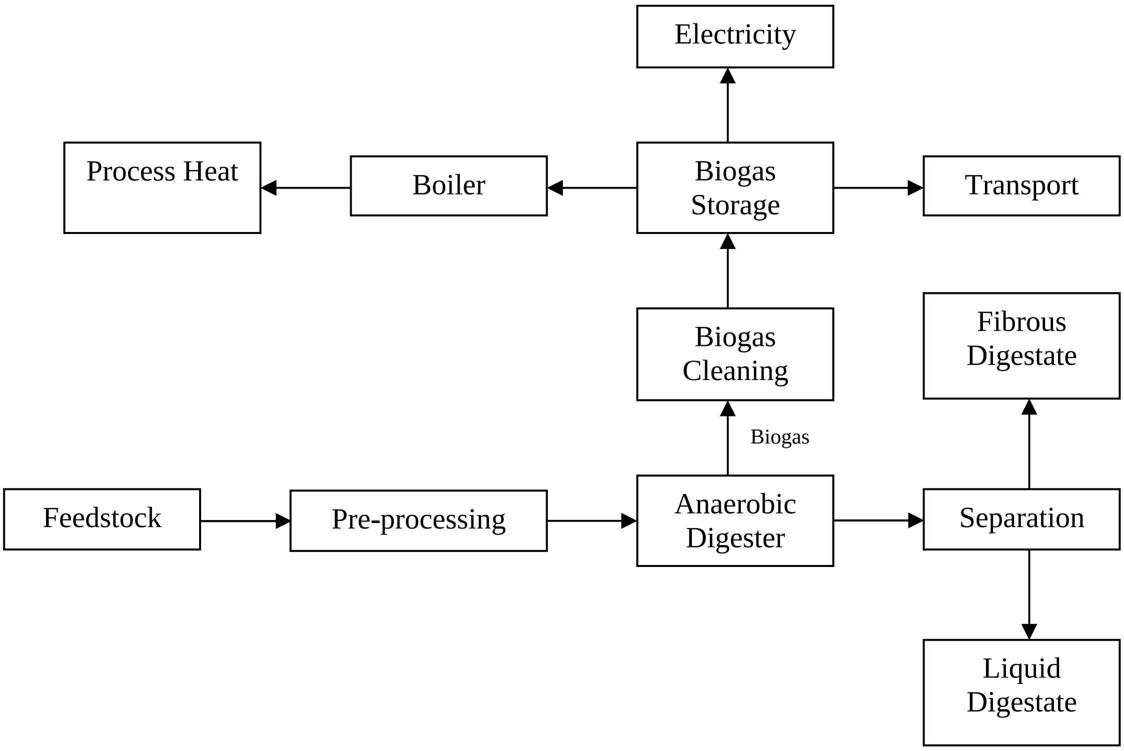

Figure 1 Typical AD Process

The biogas yield is determined from the volatile solids (VS) (i.e. biodegradable organic matter) content of the total solids (TS) (i.e. dry matter) content of the feedstock and this varies considerably on the type of the feedstock. Generally it is uneconomic to use AD for a feedstock where the volatile solids content is less than 60% of the total solids content. The AD process is driven by the VS content which is a function of the TS content. Consequently it is essential to maintain a constant and high TS content, though it may be necessary to dilute the feedstock with either liquid digestate or water to enable it to be pumped around the AD system. The TS content will also vary dependent on the consistency of the feedstock and the effect on the net electrical power with a change in the TS content is shown in Figure 2.

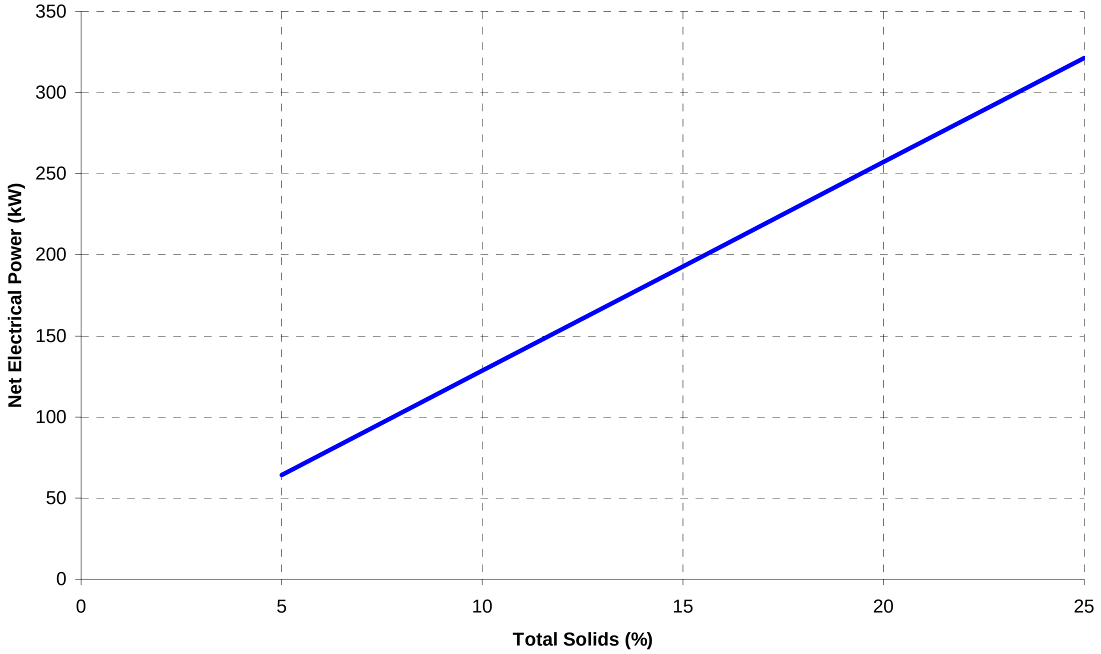

Figure 2 Effect on net electrical power with variation of TS content

Example 1

I.) Technology Description

A biogas fuelled Capstone microturbine was installed and tested on both a batch and continuous flow AD in separate trials. The microturbine was operated in a power only mode as it was not linked to a waste heat recovery unit [iii].

Figure 3 Capstone CHP operating on biogas

The feedstock for the continuous AD trial was pig slurry from an adjacent farm and was supplied at a rate of up to 1.3tonne/day. Gas production rate during the trial was an average of 1.2m^3/hr and the gas composition was stable and typically this was:

Compound	Batch	Continuous
CH_4	60 – 68%	62%
CO_2	32 - 40%	33%
H_2S	<10ppm	100ppm
H_2O	0%	5%

Though the ratio of methane to carbon dioxide entering the turbine remained relatively fixed, the water content was variable due to the biogas storage system being located outside in an uninsulated black neoprene bag. Consequently the gas temperature varied significantly from sub zero temperatures to over 50°C at different times of the year. Also significant diurnal temperature fluctuations occurred which affected the dew point of the gas and hence the moisture content.

Biogas storage acts as a buffer to even out the variation in biogas production rate. Any transient in biogas quality is likely to cause combustion instability, which makes engine control more difficult. A variation of calorific value will typically be indicated by variations in turbine speed, control temperature and throttle valve position. A rapid increase in calorific value is unlikely to cause a shutdown through flame instability.

The exhaust flue gas emissions for both trials are detailed in Table 4.

Compound	**Batch**	**Continuous**
CO	41 – 76ppm	140ppm
SO_2	0ppm	0ppm
O_2	18.5%	18.5%
NO	7ppm	1ppm
NO_2	1ppm	0ppm
CxHx	0.02% max	0ppm
H_2S	5ppm	5ppm
CO_2	2.49 – 2.62%	2.8%

Table 4 Flue Gas Emissions

II.) Efficiency of energy conversion

A microturbine and a piston engine based cogeneration system operate in different ways:

The microturbine operates at a fixed power level and this requires a fixed heat rate into the turbine. In order to achieve this, the flow rate of the fuel needs to be carefully controlled as the calorific value of the fuel varies.

The piston engine operates on a fixed speed and fixed fuel flow rate. Therefore as the calorific value of the fuel decreases, the output from the engine will reduce correspondingly. From an operational perspective the fixed output from the turbine would be the preferred option, however the improved efficiency of the reciprocating engine would give better financial performance.

Biogas consumption over the trial period for the batch AD equated to an electrical efficiency of 26%.

Trials on natural gas and biogas indicate that the efficiency remains stable across part of the power range of the Capstone microturbine.

A disadvantage of the batch AD system is that as the biogas fuel is blended from the AD cells at different stages of the digestion process, the composition of the fuel changed on a regular basis.

III.) Cost of production

IV.) Reliability and expected maintenance requirement
Maintenance requirements of reciprocating engines are generally increased as the engine oil becomes corrosive as it becomes contaminated with hydrogen sulphide. The oil-free design used by the Capstone ensures that there are no contamination issues, which is potentially a significant benefit.

A number of current and emerging technologies that have traditionally been fuelled with natural gas, can also accept lower quality fuels. In particular, steam turbines, internal combustion engines, microturbines and Stirling engines accept biogas well. Fuel cells require much more stringent purification of biogas and this adds further expense to the system.

The benefits offered by the microturbine arise from its mode of operation. The fixed output, part load efficiency and low maintenance are the key benefits which improve operational effectiveness. However the reduced efficiency over piston engine may hinder market penetration.

The fixed output operation of the gas turbine simplifies load management and the part load efficiency improves economic performance. The microturbine has been demonstrated operating reliably on biogas with only a 50% concentration. Gas clean up and processing is required which increases installation costs over natural gas systems. Although the microturbine is very tolerant to gas composition, ancillaries such as the compressor and dryer are not and must be protected.

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

D. References

1 Microgeneration Strategy and Low Carbon Buildings Programme Consultation, DTI, June 2005

2 Talbotts Ltd, www.talbotts.co.uk

3 Distributed power generation using biogas fuelled microturbines, ETSU Contract B/U1/00670/00/REP, DTI/PubURN 02/1345, Advantica Technologies, 2002

i.) Thermoelectric technology *(CHALEX)*

I.) general short description of the technology with examples

There are two types of thermoelectric energy conversion. The first is cooling from the application of a current through a thermoelectric device, known as the Peltier effect. The second is the production of power from a source of heat. This relies on the Seebeck effect.

Currently thermoelectric devices are most widely employed for their temperature control abilitiy in appications such as cooling of laser diodes, and also in picnic baskets.

Their application to Micro-CHP has been limited to date. Currently the efficiency of conversion is aproximately 5% which is too low for domestic CHP to be viable.

Varmaraf are a company in Iceland who manufacture thermoelectric devices which can be used to generate electricity when a supply of steam or hot water is available. These are mainly designed for off-grid applications where geothermal energy is available or an excess of hot water.[1]

II.) Efficiency of energy conversion

Currently the efficiency of conversion of thermoelectric devices is only around 5%.[2] This is not sufficient for use in domstic CHP applications.

Using Varmaraf as an example, a generator that gets 3 litres per minute (0.8GPM) of 75°C hot water, gives about 50 Watts when also supplied with the same flow of cold water used for cooling. The hot water exits 10 to 20°C colder and the cold water exits about the same number of degrees hotter. After going through the generator the water may be used for other purposes, e.g. in a hot tub. With a temperature difference of 75 °C this would result in an efficiency of 3%.[1] This would probably be sufficient to provide the energy for lighting in a cabin.

Other uses include central heating pumps which run from the heat energy of a stove, for off-grid buildings.

With the development of new thermoelectic technologies it is anticipated that the efficiency of the devices will increase.

III.) Cost of production

Unknown.

IV.) Reliability and expected maintenance requirement

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[1] http://www.varmaraf.is

[2] S. B. Riffat, X. Ma, *Applied Thermal Engineering*, 2003, **23**, 913-935.

Thermoelectric devices are very reliable due to the absence of any moving parts. However, mineral deposits can build up from the hot water flow which will nessecitate cleaning.[1]

V) Cost of integration into the existing energy system, compared to existing micro-CHP

Currently, the investment required to incorporate a thermoelectric device into a an existing heating system would be prohibitive and it is still more efficient to use electricity from an electricity provider if possible. However, thermoelectric technology currently presents a possible solution when grid connection is not available.[1]

VI) Environmental benefits and impact

Where geothermal heat energy is available the environmental impact is excellent. Electricity can be generated without CO_2 production. However, in other situations given the low efficiency of conversion (~5%), electricity generated by public utility is still a better option (typical efficiency of a gas and steam turbine ‘combined cycle’ power plant ~60%).[3]

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

Currently, the technology would not be able to provide any payback. Incorporation of a thermator into a central heating system where the hot water temperature is 75 °C and the cold temperature is 5 °C would only provide 20 W of power.[1]

VIII.) Expected costs of energy production in future scenarios outlined

In 5 – 10 years it is anticipated that thermoelectric devices with efficiencies of up to 50% may be possible owing to new developments in themoelectric materials. This would provide a more attractive possibility for cogeneration.

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[3] http://www-g.eng.cam.ac.uk/mmg/environmental/young2.html

j.) Biogas *(UB)*

Biogas is the product of the anaerobic descomposition of biodegradable organic material. Most of it, comes form wastes, although energetic crops are every day more popular. Biogas plants can use a number of waste products from households, industry and agriculture, such as manure, organic waste from the food industry and organic municipality waste. Compared to natural gas it shows advantages of being indigenous and renewable, free of non-methane hydrocarbons with the exception of landfill gas and containing a large fraction of a methane-reforming agent (CO_2).

Residues from individual farms and small municipalities (<10,000 t per year) typically represent small power houses in the range of 5–100kWe. However centralized biogas plants and large sewage sludge or MSW digesters - which are commonplace - can produce higher power. Exploitation for such sources rather involves large farms or waste collecting schemes to large digester installations, coupled to conventional engines of the 1MWel size, where these present a reasonable efficiency (35%).

A general characteristic of biogas resources is their local nature, thus if processed individually, they need efficient micro-CHP systems. Today, many biogas sources are frequently too small to be cost effective – farms and municipal landfills, for example. The need for efficient, cheap generation equipment in the 250-750 kW range or much less in the near future is urgent and has spawned a serious interest in developing biogas-fuelled fuel cells, microturbines and Stirling engines.

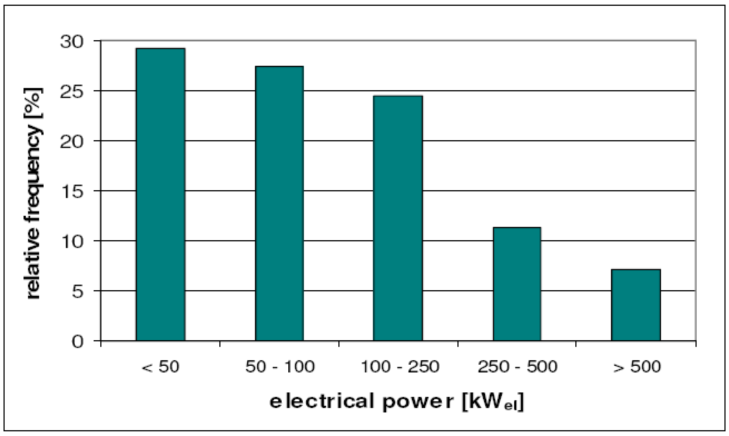


Figure 1. Electrical Power of german biogas plants Weiland et al. (2003)

Figure 1 shows the size distribution of biogas plants in Germany. As can be seen, small plants (less than 100 kWe represent more than a half of the total. (Weiland et al., 2003).

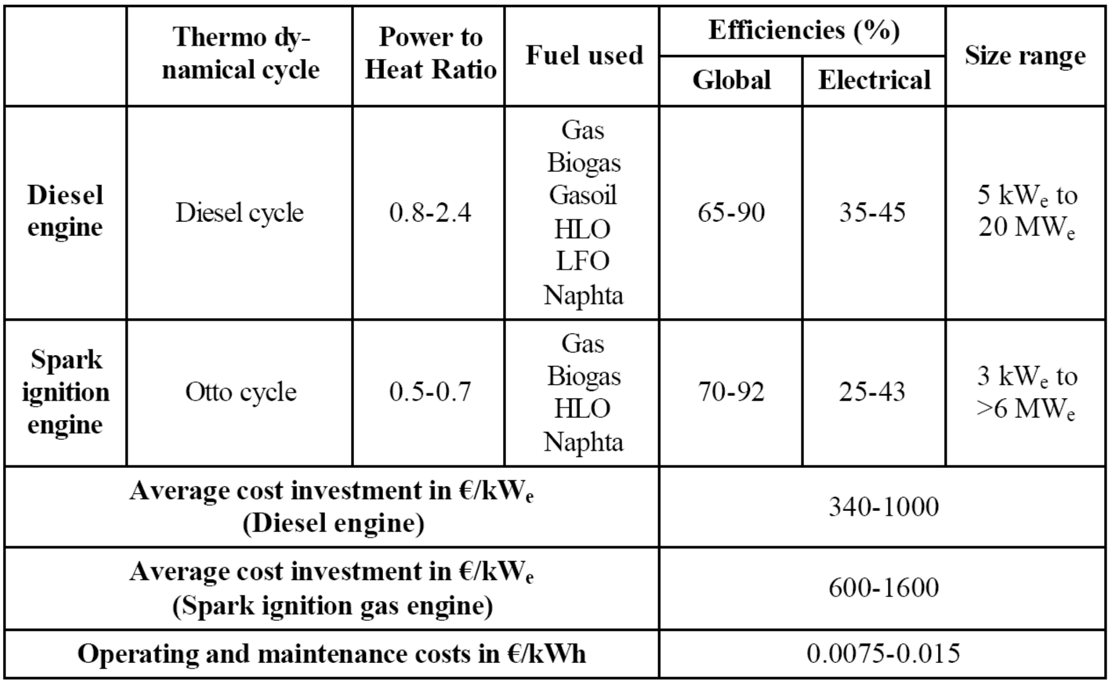
I.) General short description of the technology with examples

Micro-CHP using biogas can be achieved by different means such as reciprocating engines, Stirling engines, microturbines and fuel cells. A short description of each of the technologies is given below.

I-1 Reciprocating engines

Reciprocating engines are quite developed and well known technology, specially from cars. They are also called internal combustion engines (ICE) or endothermic engines.

Reciprocating internal combustion engines (ICE) can be spilt into two main categories: Diesel and Spark-ignition engines. The first are also called compression-ignition engines. Most Diesel engines running in CHP units are four stroke engines with a cycle consisting of intake, compression, combustion and exhaust. Spark-ignition engines follow the Otto cycle, and ignition is provoked through an electrical spark. Diesel engine present a higher heat to power ratio (from 0,5:1 to 3:1) compared to spark ignition engines, and operate through a large scale of small sizes from 5 $\mathrm{kW_e}$ for small units to a power equivalent of some 20 $\mathrm{MW_e}$ for large systems. Spark ignition engines range between 3 $\mathrm{kW_e}$ and 6 $\mathrm{MW_e}$ capacity. The heat to power ratio (from 1:1 to 3:1) is lower than the one of compression engine, yet the overall efficiency of this technology is higher. Spark ignition engines for power generation use natural gas as the preferred fuel – though they can be set up to run on biogas and other fuels. Diesel cycle, compression ignition engines can operate on diesel fuel or heavy oil, or they can be configured to burn also gases as natural gas or biogas



	Thermo dy-namical cycle	Power to Heat Ratio	Fuel used	Efficiencies (%)		Size range
				Global	Electrical	
Diesel engine	Diesel cycle	0.8-2.4	Gas Biogas Gasoil HLO LFO Naphta	65-90	35-45	5 $\mathrm{kW_e}$ to 20 $\mathrm{MW_e}$
Spark ignition engine	Otto cycle	0.5-0.7	Gas Biogas HLO Naphta	70-92	25-43	3 $\mathrm{kW_e}$ to >6 $\mathrm{MW_e}$
Average cost investment in €/$\mathrm{kW_e}$ (Diesel engine)				340-1000		
Average cost investment in €/$\mathrm{kW_e}$ (Spark ignition gas engine)				600-1600		
Operating and maintenance costs in €/kWh				0.0075-0.015		

Table I-1 General characteristics of reciprocating engines (Joerss et al., 2002)

Table I-1 summarizes the characteristics of both systems.

For CHP purposes, the engine drives an electric generator while the cooling jacket or exhaust gas stream generates steam in a boiler.

The technology has historically been the natural choice for small-scale power cogeneration applications since it was the only cheap, well-known contender For these applications there are a series of drawbacks, identified with the use of reciprocating engines:

- High maintenance requirements.
- An induction generator cannot operate as a back-up electric supply when utility service is down.
- Operating at low loads is very inefficient.
- Noise.
- Connection to the utility system may be expensive unless close to the existing service line.
- A back-up unit is required in the event of a significant component problem, or all capacity is lost.
- A significant amount of engine heat is lost to the engine room.
- Engine water temperatures are limited to a narrow range.

Engines have high efficiencies even in small sizes (see Table I-2, from Onovwiona and Ugursal, 2006). They are widely used in small plants because they allow compact modular systems, where several small modules are assembled in on system. Many units of this type are operating worldwide.

Table I-2. Reciprocating ICE cogeneration system specifications (Onovwiona and Ugursal, 2006)

Specifications	**Honda**	**Senertec**		**Cummins**	**Alturdyne**	**Coast-intelligen**	**Tecogen**	**MAN**
Electrical capacity (kW)	1	5.5 (gas)	5.3 (fuel oil)	10	40	55	60	100
Electrical efficiency (%)[a]	21.3	27.5	30.5			30	26.4	30.6
Overall[a] efficiency[b] (%) HHV	85	90	90			78	83.1	81
Engine speed (rpm)				3600	1500	1825		1800
Thermal output (kW)	3.00	12.50	10.40			87.9	128.96	125.00
Fuel input (kW)	4.7	20	17.4			183.3	227.4	277.78
Natural gas consumption (m^3/h)				5.4 at full load	13.8 at full load			

[a] Electrical efficiency = electrical output (kW)/fuel input (kW).

[b] Overall efficiency = useful heat recovered (kW) + electrical output (kW)/fuel input (kW).

I-2 Stirling engines

The Stirling engine technology is still not quite developed and represent an emerging technology although some applications already exist. They are commercially available as 55kW units and are projected to be available in 150-300 kW sizes by 2006-2007. They are also manufactured for much smaller powers of 1 kWe (or less) to a few kWe.

The Stirling engine is a heat engine: it converts heat into mechanical work. It is also an external combustion engine: Heat is supplied directly or via a heat exchanger, and electricity is produced by rotating a generator. The so-called Stirling cycle consists of the expansion and compression of a working gas, generally helium or hydrogen, inside a chamber featuring a system of pistons and crank/-shaft mechanisms to move the gas around. A unit consists of a set of pistons, heat exchangers and a regenerator. The pistons are arranged to create both a change in volume of the working fluid and a net flow of the fluid through the heat exchangers. As the working fluid is works in a closed cycle, Stirling engines operate cleanly and quietly with no combustion products coming into contact with the engine's working components and no release of high-pressure gases.

Table I-3. Some of Stirling engine manufacturers (some in the development stage)

Manufacturer / Location		Reference
DTE Energy Technologies	55 kW up to 1 MW with an overall electrical/thermal efficiency of 84%..	http://www.dtetech.com/home.asp.
Kockums AB Sweden		http://www.kockums.se/Products/kockumsstirlingm.html
Sigma Elektroteknisk AS Norway	3 kW$_e$ electrical output and 9 kW thermal output. Electrical efficiency >25%	http://www.sigma-el.com
SOLO Kleinmoteren GmbH Germany	electrical output of 2–9 kW, thermal output of 8–24 kW and an overall efficiency of 92–96%	http://sesusa.hypermart.net/solo.htm http://www.stirling-engine.de/engl/index.html.
Stirling Energy Systems Phoenix, AZ		http://www.stirlingenergy.com
Stirling Technology Co. Kennewick, WA		http://www.stirlingtech.com
Stirling Technology, Inc. Athens, OH		http://www.stirling-tech.com
Sunpower Athens, OH	7 kW of electrical power	http://www.sunpower.com
Tamin Enterprises Half Moon Bay, CA		http://www.tamin.com

The external heat source location provides flexibility in heat sources (e.g., biogas, solar, geothermal), seals out corrosive combustion byproducts, bodes well for noise and vibration levels, and generally offers opportunities for low maintenance engines. The burner supplying heat to the process can operate on different fuels (gasoline, alcohol, natural gas or butane). Heat is absorbed from the external source in the hot end, creating mechanical energy, and rejected in the cold end to the environment.

Compared to small-scale CHP in units as small as 0,2 kWe. Stirling engines provides, high efficiency, good performance at partial load, fuel flexibility, and low noise and air emission levels. A 1 kW to 5 kW output is not uncommon, though larger units are in development and systems employing multiple small units have also been demonstrated. They are generally addressed to residential, small commercial, and small farm – not industrial. In this respect, the potential for biogas and biomass applications is not lost on the developers: they see a huge worldwide market for such applications (Mears, 2001).

I-3 Microturbines

Microturbines are very small combustion turbines with outputs mainly situated in this field among 30 kWe to 80 kWe, even 300 kWe electrical output. Right now, R&D efforts are dedicated to the construction of a micro turbine with a power output of a few kilowatts.

Micro turbines stick out for their reliability, small size and low weight. The basic technology of micro turbines is derived from aircraft auxiliary power systems, diesel engine turbochargers, and automotive designs. Microturbines are typically small power plants, usually having a micro-sized gas turbine and an electric generator (and usually these components share the shaft. A combustible gas (such as natural gas or biogas) powers the gas turbine.

The systems are capable of producing power at around 25-30% efficiency by employing a recuperator that transfers heat energy from the exhaust stream back into the incoming air stream. Refrigeration systems are air-cooled and some even use air bearings. Therefore no water or oil systems are used.

Microturbines are appropriately sized for commercial buildings or light industrial markets for CHP, including biogas applications.

Micro turbines function similar to their large-scale counterparts, but their electrical efficiency is only about 15%. This figure can be improved with the installation of a recuperator that preheats air used during the combustion process by reusing exhausting gas heat. This device also allows varying the power to heat ratio.

Although, microturbines are still more expensive than internal combustion engines, the few moving parts of the device lower their operation and maintenance costs. The life expectancy of micro turbines is 40000 hours (which is less than five years of continuous operation). On the other hand, prices are dropping. Therefore, when biogas is available and the average power output is in the order of magnitude of a few hundred kilowatts, microturbines could be the process of choice. However, the biogas burning option is not yet available in all the commercialised models. Table I-4 shows a list of the current manufacturers of microturbines below 200 kWe. (Bruno et al., 2004).

Table I-4. Current manufacturers of microgas turbines (less than 200 kWe)

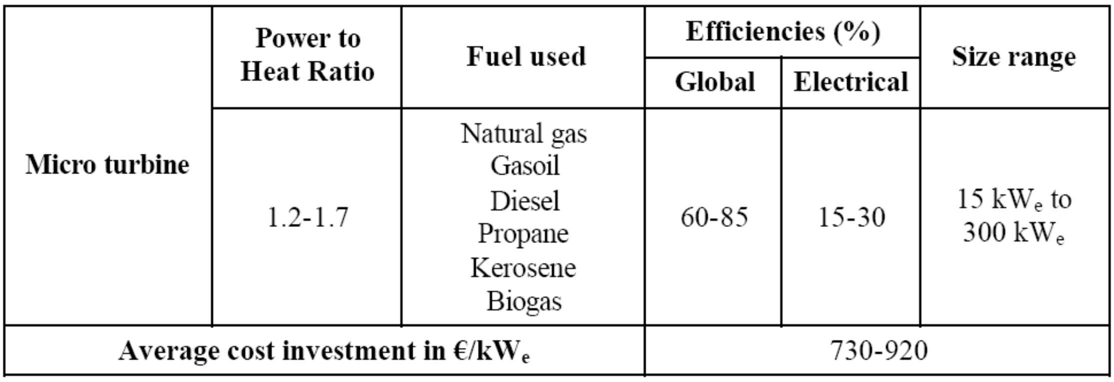
Manufacturer	Range of models
Capstone Turbine Corporation	30, 60 kWe (next 200 kWe)
Elliot Energy Systems Inc.	80 kWe
Turbec AB	100 kWe
Bowman Power Ltd.	50, 80 kWe
Ingersoll–Rand Energy Systems	70 kWe (next 250 kWe)

Advantages for microturbines compared to conventional ICE include the following:

- Quieter operation.
- Higher temperature exhaust for cogeneration and heat recovery.
- Lower air emissions.
- Lower maintenance.
- Higher reliability due to fewer moving parts.

Finally, Table I-5 shows the main characteristics of microturbines and Table I-6, the general specifications according to the manufacturers.

Table I-5. General characteristics of microturbines (Joerss et al., 2002)



	Power to Heat Ratio	**Fuel used**	**Efficiencies (%)**		**Size range**
			Global	**Electrical**	
Micro turbine	1.2-1.7	Natural gas Gasoil Diesel Propane Kerosene Biogas	60-85	15-30	15 kW_e to 300 kW_e
Average cost investment in €/kW_e			730-920		

Table I-6. General specifications of some market microturbines cogeneration systems (Onovwiona and Ugursal, 2006)

Type of fuel used	**Capstone micro-turbine**[a]					**Elliot/Bowman**[b]	**Turbec**[c]
	Natural gas /gaseous propane	**Diesel or kerosene**	**Biogas (landfill or digester as)**	**Natural gas**		**Natural gas, propane, LPG, and butane**	**Natural gas**
Electrical capacity (kW)	30	30	30	28	60	80	105
Electrical efficiency (%) LHV	26	25	26	25	28	28	30
Overall efficiency (%) LHV	91	90	91	91	89	75	78
Engine speed (rpm)	96,000	96,000	96,000	96,000	96,000		70,000
Thermal output (kW)	85	85	85	85	150	136	167
Fuel input (kW)	126.91	127.49	126.91	123.09	235.64	288	350

[a] http://www.microturbine.com/
[b] http://www.bowmanpower.com/DataSheets/TG80RC-G.pdf
[c] http://www.socalgas.com/business/powergeneration/docs/Turbec_100kW.pdf

I-4 Cell Fuels

The process of electrolysis uses electric current to break down water (H2O) into its constituents: hydrogen (H2) and oxygen (O2). Fuel cells reverse the process – they combine hydrogen and oxygen to produce electricity.
Although the principle of using a chemical reaction to produce electrical energy has been with us for more than 150 years, there are still technical barriers to overcome, like fuel toxicity, storage, electrolyte poisoning and fuel infrastructure. Additionally, the concurrent technology is significantly cheaper than the fuel cell (FC) alternative.

There are at least five types of fuel cells:

- Alkaline fuel cells, like those long-used in spacecraft, have thermal efficiencies of up to 70%. They were the first in the market, but are typically too expensive for commercial use.

- Proton exchange membrane (PEM) fuel cells have the potential for the low costs that would make them suitable for home, farm, and similar small applications. A particular example is the direct methanol fuel cell (DMFC).

- Phosphoric acid fuel cells (PAFC) are already commercially viable for some applications and can approach thermal efficiencies of 85% if the steam byproduct is applied rather than wasted.
- Molten carbonate fuel cells (MCFC) operate around 1,200ºF and are thus probably limited to industrial applications.
- Solid oxide fuel cells (SOFC) operate around 1,800ºF and are thus probably limited to industrial applications and large power plants.

For example SOFC modules in the range of 1 kWe to 1MWe are being demonstrated or in construction and will therefore be able to cover all biogas power sites. Molten carbonate fuel cell modules are commercialised in 1MWel size and phosphoric acid fuel cells in 50–200kWel size, meaning they cannot cover many small agricultural sites, where the largest biogas potential lies These technologies, of lower system efficiency than SOFCs, are also more sensitive to biogas impurities. Molten carbonate fuel cell modules are commercialised in 1MWel size and phosphoric acid fuel cells in 50–200kWel size, meaning they cannot cover many small agrosites, where the largest biogas potential lies. These technologies, of lower system efficiency than SOFCs, are also more sensitive to biogas impurities

In a liberalised market small generation plants require less investment capital per plant. New technologies such as micro turbines and fuel cells are likely to be serious contenders for this market as compared to the ICE options. There are currently 5 or 6 competing FC technologies, all of which have specific pros and cons. Each one is likely to find use for specific applications but at present no clear choice is made for a specific technology application (Joerss et al, 2002).

Aside from the technology of FC, there are two other key technologies typically required for fuel cell application: producing the hydrogen fuel (e.g., from biogas) and converting the electricity produced to a useful form (e.g., 120V, 50 Hz). Producing the hydrogen fuel from biogas (or other gaseous or liquid fuel) is done by “reforming” or “fuel processing,” and developments in this area are as critical to commercialization as the fuel cell developments themselves. In this sense, for biogas application a key issue is the gas purification: a cost effective and sustainable system is essential; In addition the whole test set up is sensitive towards environmental impacts as it is still a lab system in may systems Trogish et al. (2005)

I-5. Examples

Reciprocating engine.

There are many applications, as ICE are a mature technology. One that deserves citation, for the farmer volunteer is the Kalmari farm in the village of Leppävesi, 15 km from city of Jyväskylä in Central Finland (Lampinen, 2005). It is a model example at farm scale of a polygeneration facility. The biogas production system is a result of an individual farmer's vision The biogas system overview comes from the farmer own design. The main feedstock for the reactor originates from 40 cows and 60 calves in an open cow. Additionally, biowaste is also used, coming from the local food industry (sweet factory), kitchen waste from the farm and plant waste from the farm. Digester operates at mesophilic temperature. The resulting gas contains about 60-65% methane and 35-40% carbon dioxide. The micro-CHP engine used in the farm for power and heat production is a Finnish Sisu Diesel-based, factory-converted Otto cycle fuel oil engine that was optimized for raw biogas at the farm. Such Diesel engines are most commonly used in Valtra tractors. It has 30 kWe electric power capacity and additional 60 kWt heat production capacity.
In addition, a separate 80 kWt gas boiler is in use. The raw biogas where hydrogen sulphide and water has been removed can be used directly in the CHP unit and the gas boiler. Carbon dioxide removal is not needed. Electricity is used in the farm and especially during winter also sold to the grid. About 40 MWhe 250 MWht of heat (including the boiler) are produced annually.

Stirling engine example

In accordance with Water Online there is an ongoing project in Brookling WWTP New Yourk City.
See (http://www.wateronline.com/content/news/article.asp?docid=%7b0706EF3E-AE77-48AD-B2B7-52682483E45C%7d&VNETCOOKIE=NO)
This water treatment site will be the first wastewater facility in the USA to install multiple Stirling engines to generate electricity. Striling engines are manufactured by STM Power. The systems is composed by three 55-kilowatt Stirling external combustion engines and it is estimated that the system will provide an overall net reduction of up to 765 tons of CO2 per year as well as significant reductions in NOx and SO2 emissions. Finally, by generating its electricity onsite, the facility will help reduce congestion on the area's over-stressed utility grid.

The project is also part of a larger initiative on the part of the City of New York to voluntarily increase renewable energy capacity in an effort to reduce overall greenhouse gas emissions

Microturbine examples

A couple of recent developments regarding application of microturbines to biogas use include (Mears, 2001):

In a November 15, 2000 press release announced a set of NYSERDA projects including two single-dairy-farm demonstration projects involving microturbines: one in Cortland County ("Anaerobic digestion to make electricity using microturbines") and one in Columbia County ("Microturbine cogeneration system for cheese-making facility").

The City of Allentown, Pennsylvania's Wastewater Treatment Plant installed twelve 30 kW Capstone units to convert biogas to electricity for on-site use. The biogas comes from three digesters. Each of the single-shaft microturbines rotates at up to 96,000 rpm, produces variable-frequency AC power, and exhausts more than 65% of its input energy to a heat recovery system to produce hot water. The performance contract for the system is based on a ten-year investment recovery period

In accordance with Capstone, web page, over 100 waste fuel microturbine projects are already operational. They have enjoyed considerable popularity for small-scale power generation and the 30 kW Capstone unit has been applied at landfills and wastewater treatment plants in many locations. As larger units become available, they will become applicable to feedlots and farms.

Fuel Cell examples

The farm "Maison Blanche" in Lully, Switzerland, has exploited since 9 years biogas production from livestock (37 cattle units), sometimes mixed with municipal waste from 1500 surrounding inhabitants, at a typical rate of 70m3 per day (0.55 TJ per year or 17kWtot) (Lampinen, 2005). It is equipped with a small co-generation classical gas engine of the total energy module (TOTEM) type, with 5 kWe nominal and 21kWthermal. Electrical efficiency of this unit is 18% and thermal efficiency 73%; one-third of the heat is rejected. The annual load factor is 60% SOFC modules in the range of 1 kWel to 1MWel are being demonstrated or in construction and will therefore be able to cover all biogas power sites. Characteristics are as follows:

SOFC-biogas system

Biogas production (m3 per day)	35
CH_4 flow (mol/s)	0.01 (0.25 l/s)
CO_2 flow (mol/s)	0.00667 (0.167 l/s)
Air flow added to fuel (mol/s)	0.00349 O_2 (0.417 l/s)
Power equivalent (kW)	8 (LHV), 8.9 (HHV)
Electrical efficiency (%)	42.8 (LHV), 38.6 (HHV)

2nd example of FC application

In 2000, in the WWTP in Cologne was installed the first fuel cell power plant in Europe that operating on anaerobic digester gas (Sammes et al. 2004**).** Of particular interest was the design of a gas-processing unit (GPU) that removes contaminants from the biogas before it enters the fuel cell. The GPU design includes a gas dryer stage, a gas chiller stage, and an adsorption stage. The gas dryer stage removes condensate, and is cooled by the cold gas coming from the chiller stage. The chiller stage further cools the gas to below minus 25 ºC, which is lower than the dew point of many higher organic compounds, particularly siloxanes. The adsorption stage removes organic sulfur and halides, if present. The gas processing unit design was verified using a continuous run in excess of 5000 h. Unfortunately, the gas-processing unit was too maintenance intensive, and was, thus, redesigned after two years to simplify it.

Figure I-2. Fuel cell-anaerobic digester integrated system in Cologne.

II.) Efficiency of energy conversion

See description in Section I and the summary in Table II-1 (at the end of the document, before Annex I).

III.) Cost of production

CHP system in biogas applications have a very variable cost of production. Main contribution comes from capital costs. Table II-1 1 (at the end of the document) gives a comparison of the different capital costs of the different micro CHP systems (Pointon and Langan, 2002). Annex-1 lists the prices of some microturbines and and ICE and Finally, Figure III-1 shows installation costs of CHP systems in accordance with Kottner (2000).

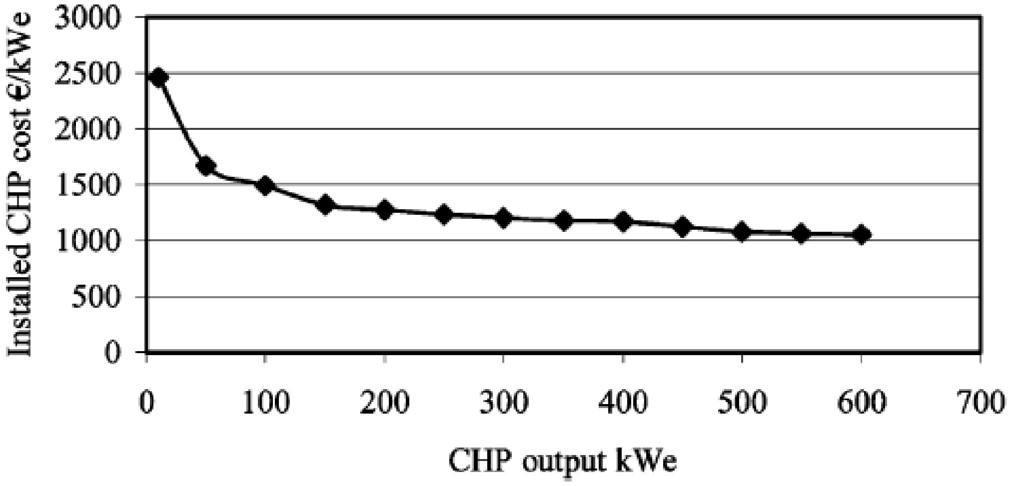


Figure III.1. Installed CHP costs Kottner M. 2000.

IV.) Reliability and expected maintenance requirement

IV-1. Reciprocating engines

Routine inspections, adjustments and periodic maintenance are required with reciprocating internal combustion engines. These involve changing of engine oil, coolant and spark plugs, often carried out for every 500–2000 h. Manufacturers often recommend a time interval for overhaul, from 12,000 to 15,000 h of operation for a top-end overhaul and 24,000–30,000 h of operation for a major overhaul. A typical maintenance cost for reciprocating internal combustion engines that include overhaul is from 0.012 to 0.020 €/kWh (Onsite, 2000; Onovwiona and Ugursal, 2006).

With proper maintenance, modern internal combustion engine based cogeneration systems operate at high levels of availability. In a demonstration project conducted in UK involving three reciprocating internal combustion engine based cogeneration systems, the availability was found to be in the 87–98% range, which agrees well with the manufacturers' specifications.

IV-2. Stirling engines.

Unlike the reciprocating internal combustion engines, Stirling engines have sealed operating chambers resulting in low wear with long maintenance intervals. Stirling engines with small capacity under 20 kW have service internals from 5000 to 8000 h, which are long compared with Otto gas engines of the same range. This considerably reduces the operating costs compared with Otto gas engines (Technical Documentation Solo Stirling 161 CHP Module. Germany: SOLO Stirling Engine. http://www.stirling-engine.de/engl/index.html.)

Due to the tight sealing of the casing, free piston Stirling engines are expected to eliminate mechanical contact, friction and wear, therefore eliminating mechanical maintenance during an operating lifetime of about 10 years (Onovwiona and Ugursal, 2006).

From the Brookling example, and taking into account the experience with other wastewater treatment facilities, in their report state that Stirling external combustion engines require less frequent maintenance than microturbine or reciprocating engine technology. Brookling facility is expected to experience increased uptime and reduced parasitic system loads. The engines also offer the potential for reduced gas cleanup and less gas compression than other technologies, which can reduce installation costs.

IV-3. Microturbines

Due to their simple construction and few moving parts, micro-turbine systems have the potential for lower maintenance costs than that of reciprocating internal combustion engines. For example, since the lubricating oil is isolated from the combustion products, micro-turbines do not require frequent oil changes. Moreover, if air bearings are used in single shaft machines, there is no requirement for lubricating oil or water, reducing maintenance requirements even further. Normally, scheduled maintenance is carried out once annually, with maintenance costs in the 0.007–0.015 €/kW h range (Onsite, 2000). Most product developers offer 0.02 €/kW h for specialized maintenance that includes periodic inspections of the combustor, oil bearing in addition to regular air and oil filter replacements. An overhaul is required every 20,000–40,000 h depending on the product developers, design, and service (Nexus, 2002) . An overhaul involves the replacement of the main shaft with the compressor and turbine attached, and if necessary, replacing the combustion chamber. In addition, other components are inspected to determine if wear has occurred so that necessary replacements can be made. (Onovwiona and Ugursal, 2006).

IV-4. Fuel cells

Fuel cells have the potential for very low maintenance costs because they have fewer moving parts when compared to reciprocating engines and micro-turbines.

Fuel cell system maintenance requirements vary with the type of fuel cell, size and maturity of the equipment. Major overhaul of fuel cell systems involves shift catalyzer replacement, reformer catalyzer replacement, and stack replacement (Nexus, 2002). Stack replacement is expected between every 4 and 8 years.

Routine maintenance includes replacement of ancillary parts such as fuel filters, reformer igniter or spark plug, water treatment beds, flange gaskets, valves, electronic components, sulfur absorbent bed catalysts and nitrogen for shutdown purging. In addition, these ancillary systems can cause an increase in both scheduled and unscheduled downtime.

Fuel cells are expected to have higher availability and reliability than reciprocating engines since they have fewer moving parts. The commercially available 200 kW PAFC has been operated continuously for more than 5500 h, which is comparable to other power plants (Onovwiona and Ugursal, 2006). Limited test data for this unit show 96% availability and 2500 h between forced outages. In demonstration projects at different US Department of Energy locations, several pre-commercial PEM fuel cell units suitable for residential application have been operational. Ten 5 kW PEM fuel cells developed by Plug Power operated from 15 to 21 January 2002 in three of the US Department of Energy locations. As of August 31, 2002, these units have been operated for total of 51,967 h with an average individual availability of 95.8% (Onovwiona and Ugursal, 2006).

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

No data available.

VI) Environmental benefits and impact

VI-1. Reciprocating engines

The primary pollutants associated with reciprocating internal combustion engines are oxides of nitrogen (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs—unburned, non-methane hydrocarbons). Other pollutants like oxides of sulphur (SO_x) and particulate matter are primarily dependent on the type of the fossil fuel and type of the engine used. Generally, SO_x emissions are related to large, slow speed diesel engines fuelled by heavy oils.

Currently, both high efficiency and low NO_x formation do not go together because to achieve low NO_x formation, spark timing needs to be optimized and air/fuel ratio of about 1.5–1.6 is required (Major, 1995).

Emissions of ICE have been reduced significantly in the last several years by exhaust catalysts and through better design and control of the combustion process (see Table VI-1)

Table VI-1 Emission characteristics of reciprocating internal combustion engines used in cogeneration units (Onovwiona and Ugursal, 2006)

	Cummins						**Coastintelligen**	
Electrical output (kW)	7.5	16	16	20	35	50	55	80
Engine/fuel type	Diesel/ diesel	SI/NG	Diesel/ diesel	SI/NG	Diesel/ diesel	Diesel/ diesel	SI/NG	SI/NG
Emission control device	None	None	None	None	None	Turbo-charger	Advanced Catalytic converter	Advanced Catalytic converter
Air–fuel ratio		16.8		16.6				
CR	18.5:1	9.4:1	18.5:1	9.4:1	17.3:1	16.5:1		
NO_x, (g/bhph)	12.6	7.8	12.6	8.2	6.99	7.97	<0.15[a]	<0.15[a]
CO, (g/bhph)	3.13	36.8	3.13	38.6	1.26	0.75	<0.60[a]	<0.60[a]
Unburned hydrocarbon (g/bhph)	1.64	1.3	1.64	1.2	0.50	0.4	<0.15[a]	<0.15[a]
SO_2, (g/bhph)					0.62	0.6		
Particulates (g/bhph)	0.66	Neglig.	0.66	Neglig.	N/A	0.13		

VI-2. Microturbines

Micro-turbines have the potential for producing low emissions. They are designed to achieve low emissions at full load, however, emissions are higher when operating under reduced load. Today's microturbines have a greater efficiency and lower emissions of greenhouse gases than internal combustion engines (Joerss et al., 2002). Low emission combustion systems are being demonstrated that provide emissions performance comparable to larger CHP-Turbines

The main pollutants from the use of micro-turbine systems are NO_x, CO and unburnt hydrocarbons, and negligible amount of SO_2. Emission characteristics of micro-turbine systems based on manufacturers' guaranteed levels are given in Table VI-2.

Table VI-2. Micro-turbine emission characteristics (Onovwiona and Ugursal, 2006)

	Capstone model 330 micro-turbine	**IR energy systems 70LM (two shaft)**	**Turbec T100**
Nominal electricity cap.(kW)	30	70	100
Electrical efficiency (%) HHV	23	25	27
NO_x, ppmv	9	9	15
NO_x, lb/MW h[a]	0.54	0.50	0.80
CO, ppmv	40	9	15
CO, lb/MW h	1.46	0.30	0.49
THC, ppmv	<9	<9	<10
THC, lb/MW h	<0.19	<0.17	<0.19
CO_2, lb/MW h	1928	1774	1706
Carbon, lb/MW h	526	484	465

[a] Conversion from volumetric emission rate (ppmv at 15% O_2) to output based rate (lbs/MW h) for both NO_x and CO based on conversion multipliers provided by Capstone Turbine Corporation and corrected for differences in efficiency.

VI-3. Stirling engines

Emissions from current Stirling burners can be 10 times lower than that emitted from gas Otto engines with catalytic converter, making the emissions generated from Stirling engines to be comparable with those from modern gas burner technology. The Stirling engine unit developed by the Germa company SOLO, uses high level preheated air for combustion to achieve high combustion efficiency while achieving low exhaust emissions (see Table VI-3)

Table VI-3. Stirling engine emissions characteristics (Onovwiona and Ugursal, 2006)

Emissions characteristics	**SOLO[a]**	**DTE energy[b]**	
Electrical capacity (kW)	2–9	20	25
Electrical efficiency (%)	22–24	29.6	29.6
Overall efficiency (%)	> 90	82	82
NO_x (gm/bhph)	0.08–0.12	0.288 (Standard)	0.288 (Standard)
		0.15 (Ultra low)	0.15 (Ultra low)
CO (gm/bhph)	0.04–0.06	0.32 (Standard)	0.32 (Standard)
		0.32 (Ultra low)	0.32 (Ultra low)

[a] http://www.stirling-engine.de/engl/index.html
[b] www.dtetech.com/pressroom/pdf/enx_25_spec.pdf

VI-4. Fuel cells

Fuel cell systems do not involve the combustion processes associated with reciprocating internal combustion engine and micro-turbine systems. Consequently, they have the potential to produce fewer emissions. The major source of emissions is the fuel processing subsystem because the heat required for the reforming process is derived from the anode-off gas that consists of about 8–15% hydrogen, combusted in a catalytic or surface burner element . The temperature of this lean combustion process, if maintained below 1000 °C, prevents the formation of oxides of nitrogen (NO_x). In addition, the temperature is sufficiently high for the oxidation of carbon monoxide (CO) and unburnt hydrocarbons. An absorbed bed helps in removing other pollutants such as oxides of sulphur (SO_x) (see Table VI-4).

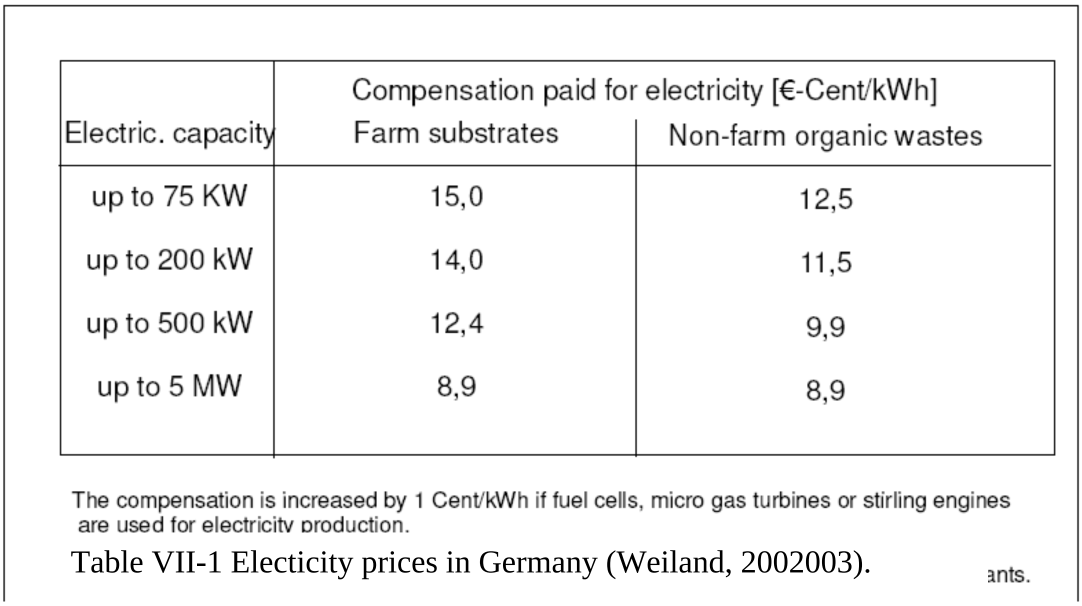
Table VI-4. Estimated fuel cell emission characteristics (Nexus, 2002; Onovwiona and Ugursal, 2006)

Fuel cell type	**PEMFC**	**PEMFC**	**PAFC**	**SOFC**	**MCFC**
Nominal electricity capacity (kW)	10	200	200	100	250
Electrical efficiency (%) HHV	30	35	36	45	46
Emissions					
NO_x (ppmv at15% O_2)	1.8	1.8	1.0	2.0	2.0
NO_x (Ib/MW h)	0.06	0.06	0.03	0.05	0.06
CO (ppmv at 15% O_2)	2.8	2.8	2.0	2.0	2.0
CO (Ib/MW h)	0.07	0.07	0.05	0.04	0.04
Unburnt hydrocarbons (ppmv at 15% O_2)	0.4	0.4	0.7	1.0	0.5
Unburnt hydrocarbons (Ib/MW h)	0.01	0.01	0.01	0.01	0.01
CO_2 (Ib/MW h)	1360	1170	1135	910	950
Carbon (Ib/MW h)	370	315	310	245	260

Notes: Emissions adjusted to 15% oxygen. Emissions do not account for cogeneration operations. Emissions expressed in lb/MW h do not account for cogeneration operations.

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

The payback time is much more depending on the electricity price then on the fuel costs, for example a 10% increase in electricity prices might reduce the payback time by 15% whereas a 10% cheaper fuel price reduces the payback time by only 6%. The sensitivity analysis should be included in an economic analysis. Factors favoring short payback times are: low investment costs, low fuel prices, high electricity prices, high annual operating hours and a high overall thermal efficiency. Electricity prices vary from country to country and it



Electric. capacity	Compensation paid for electricity [€-Cent/kWh]	
	Farm substrates	Non-farm organic wastes
up to 75 KW	15,0	12,5
up to 200 kW	14,0	11,5
up to 500 kW	12,4	9,9
up to 5 MW	8,9	8,9

The compensation is increased by 1 Cent/kWh if fuel cells, micro gas turbines or stirling engines are used for electricity production.

Table VII-1 Electicity prices in Germany (Weiland, 2002003).

ants.

is a decisive factor. Table VII-1 shows the prices in Germany. As can be seen, there is an incentive coming from the use of microturbines or stirling engine devices.

VIII.) Expected costs of energy production in future scenarios outlined

Generally speaking within Europe, in most of the countries, unless a small farmer or a small industry wants to be a pioneer in the field and risk a large investment of money and, in some cases, time. Right now, well-established commercial products are preferable alternatives to these emerging technologies. This has to change in the future, as all the micro-CHP devices, are lowering prices, and incentives through electricity prices are today common within EU members.

On the other hand, one must consider in selecting a CHP technology for a specific application, that CHP depends on many factors, including the amount of power needed, space constraints, thermal needs, emission regulations, fuel availability, utility prices and interconnection issues. The most efficient CHP systems (exceeding 80 percent overall efficiency) are those that satisfy a large thermal demand while producing relatively less power. As the required temperature of the recovered energy increases, the ratio of power to heat output will decrease. The decreased output of electricity is important to the economics of CHP because moving excess electricity to market is technically easier than is the case with excess thermal energy, and as stated it is incentivated.

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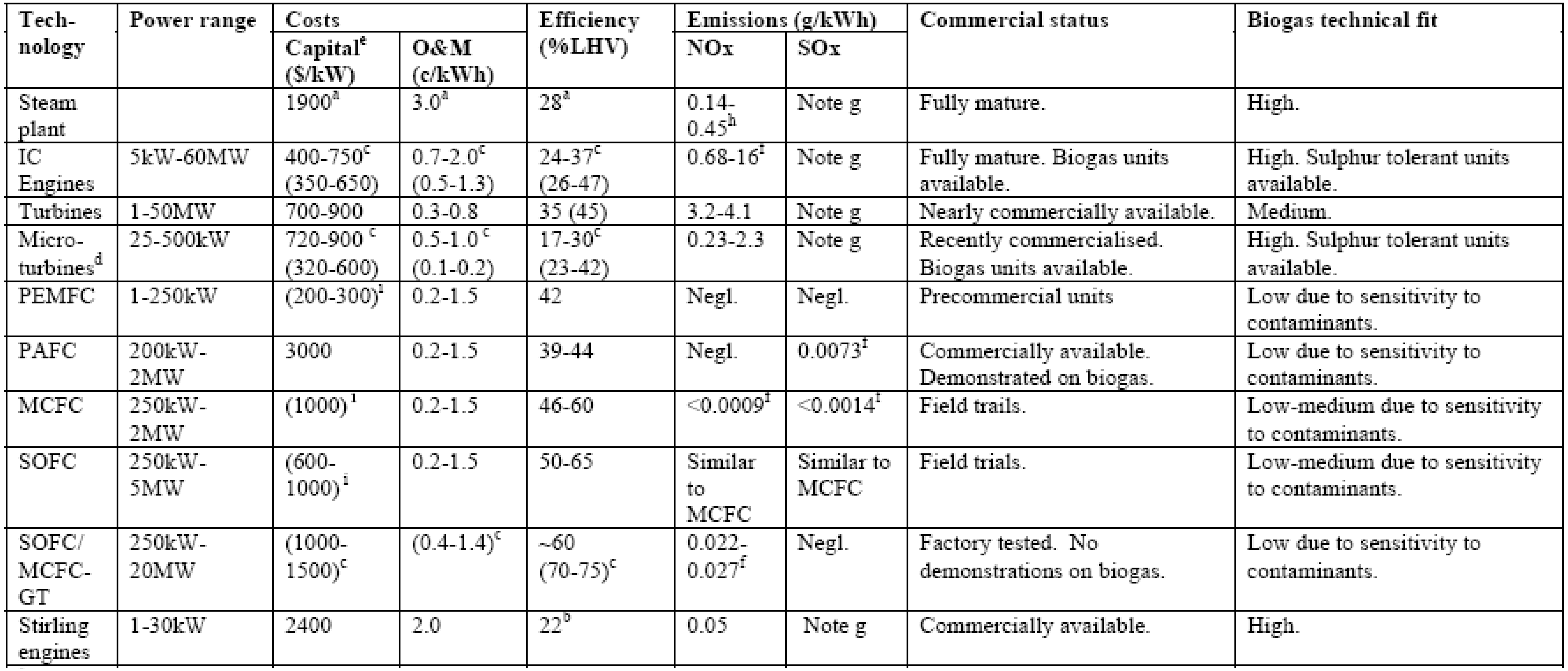

Tech-nology	Power range	Costs		Efficiency (%LHV)	Emissions (g/kWh)		Commercial status	Biogas technical fit
		Capital[e] ($/kW)	O&M (c/kWh)		NOx	SOx		
Steam plant		1900[a]	3.0[a]	28[a]	0.14-0.45[h]	Note g	Fully mature.	High.
IC Engines	5kW-60MW	400-750[c] (350-650)	0.7-2.0[c] (0.5-1.3)	24-37[c] (26-47)	0.68-16[f]	Note g	Fully mature. Biogas units available.	High. Sulphur tolerant units available.
Turbines	1-50MW	700-900	0.3-0.8	35 (45)	3.2-4.1	Note g	Nearly commercially available.	Medium.
Micro-turbines[d]	25-500kW	720-900 [c] (320-600)	0.5-1.0 [c] (0.1-0.2)	17-30[c] (23-42)	0.23-2.3	Note g	Recently commercialised. Biogas units available.	High. Sulphur tolerant units available.
PEMFC	1-250kW	(200-300)[i]	0.2-1.5	42	Negl.	Negl.	Precommercial units	Low due to sensitivity to contaminants.
PAFC	200kW-2MW	3000	0.2-1.5	39-44	Negl.	0.0073[f]	Commercially available. Demonstrated on biogas.	Low due to sensitivity to contaminants.
MCFC	250kW-2MW	(1000) [1]	0.2-1.5	46-60	<0.0009[f]	<0.0014[f]	Field trails.	Low-medium due to sensitivity to contaminants.
SOFC	250kW-5MW	(600-1000) [i]	0.2-1.5	50-65	Similar to MCFC	Similar to MCFC	Field trials.	Low-medium due to sensitivity to contaminants.
SOFC/ MCFC-GT	250kW-20MW	(1000-1500)[c]	(0.4-1.4)[c]	~60 (70-75)[c]	0.022-0.027[f]	Negl.	Factory tested. No demonstrations on biogas.	Low due to sensitivity to contaminants.
Stirling engines	1-30kW	2400	2.0	22[b]	0.05	Note g	Commercially available.	High.

Table II-1. Summary of different parameters for micro-CHP (Pointon and Langan, 2006).

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[a] For a 50MW plant (from ref 117).

[b] From ref 4.

[c] From Reference 142.

[d] Including unrecuperated microturbines.

[e] For power-only units. For CHP units, add ~150$/kW for engines and 30% for turbines. Little difference for fuel cells, which are generally CHP units.

[f] From ref 174

[g] Values for combustion-based devices will be highly dependent on sulphur content of fuel. For natural gas fuelled systems, this will be typically less than 0.05 g/kWh. Biogas-fuelled units may approach 20 g/kWh.

[h] From reference 47.

[i] From refresence 175.

ANNEX – I

Cost of microturbines

Source: http://www.wtb.tue.nl/woc/ptc/education/4P570/CHP.pdf

To compare the costs of the CHP's with a gas turbine as a prime mover to those of the CHP's with a combustion engine, we use the prices of one manufacturer. It is a manufacturer in Germany, called Kw-energietechnik. This manufacturer offers CHP's with gas turbines on natural gas, fluid gas and biogas in a range from 8 to 43 kWe. The modules are delivered in several designs:

- Netzparallelbetrieb: these can only be used parallel to the existing grid.
- Netzparallelbetrieb mit Notstromfunktion: these can also operate when the grid fails. The conversion happens automatically.
- Inselbetrieb: these are for application, where there is no grid available. Parallel connection is not possible.

Betriebsart	Bezeichnung	Generator	el. Leistung	th. Leistung	Verbrauch	Preis
Gas / Netzparallelbetrieb	KWE 12G-4 AP	Asynchron	12 kW	27 kW	41,00 kW/Std.	21 400 €
Gas / Netzparallelbetrieb	KWE 17G-4 AP	Asynchron	17 kW	37 kW	58,00 kW/Std.	24 400 €
Gas / Netzparallelbetrieb	KWE 30G-6 AP	Asynchron	30 kW	67 kW	105,00 kW/Std.	32 600 €
Gas / Netzparallelb. mit Notstromf.	KWE 12G-4 SPN	Synchron	12 kW	26 kW	41,00 kW/Std.	24 800 €
Gas / Netzparallelb. mit Notstromf.	KWE 17G-4 SPN	Synchron	17 kW	35 kW	58,00 kW/Std.	27 800 €
Gas / Netzparallelb. mit Notstromf.	KWE 30G-6 SPN	Synchron	30 kW	65 kW	105,00 kW/Std.	36 000 €
Gas / Netzparallelb. mit Notstromf.	KWE 43G-4 SPN	Synchron	43 kW	72 kW	127,00 kW/Std.	47 900 €
Gas / Inselbetrieb	KWE 12G-4 SI	Synchron	12 kVA	26 kW	41,00 kW/Std.	21 000 €
Gas / Inselbetrieb	KWE 17G-4 SI	Synchron	17 kVA	35 kW	58,00 kW/Std.	24 000 €
Gas / Inselbetrieb	KWE 30G-6 SI	Synchron	30 kVA	65 kW	105,00 kW/Std.	32 200 €

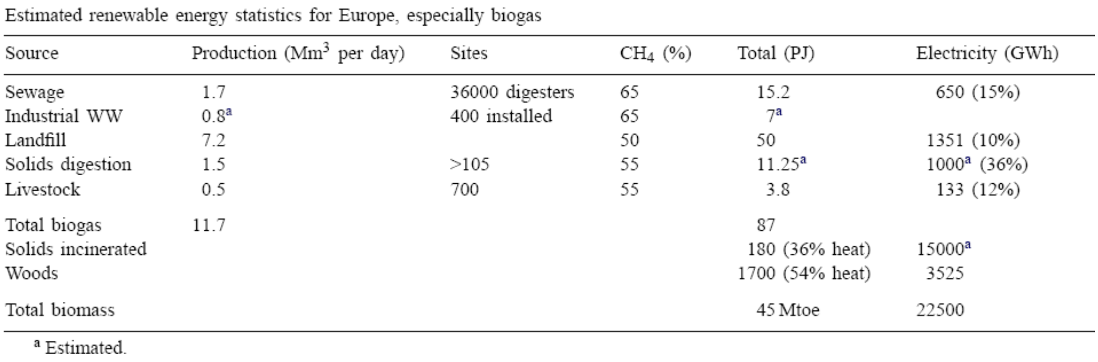
Cost of ICE

Source: http://www.wtb.tue.nl/woc/ptc/education/4P570/CHP.pdf

Diesel engines

Betriebsart	Bezeichnung	Generator	el. Leistung	th. Leistung	Verbrauch	Preis
Diesel / Netzparallelbetrieb	KWE 6D-3 AP	Asynchron	6 kW	14 kW	2,30 l/Std.	14.990 €
Diesel / Netzparallelbetrieb	KWE 10D-3 AP	Asynchron	10 kW	21 kW	3,60 l/Std.	17.800 €
Diesel / Netzparallelbetrieb	KWE 14D-4 AP	Asynchron	14 kW	28 kW	4,80 l/Std.	20.000 €
Diesel / Netzparallelbetrieb	KWE 20D-4 AP	Asynchron	20 kW	32 kW	6,20 l/Std.	26.600 €
Diesel / Netzparallelbetrieb	KWE 25D-4 AP	Asynchron	25 kW	38 kW	7,60 l/Std.	29.200 €
Diesel / Netzparallelbetrieb	KWE 35D-4 AP	Asynchron	35 kW	49 kW	10,00 l/Std.	32.800 €
Diesel / Netzparallelb. mit Notstromf.	KWE 10D-3 SPN	Synchron	10 kW	20 kW	3,60 l/Std.	18.700 €
Diesel / Netzparallelb. mit Notstromf.	KWE 14D-4 SPN	Synchron	14 kW	28 kW	4,80 l/Std.	21.800 €
Diesel / Netzparallelb. mit Notstromf.	KWE 25D-4 SPN	Synchron	25 kW	38 kW	7,60 l/Std.	31.000 €
Diesel / Netzparallelb. mit Notstromf.	KWE 20D-4 SPN	Synchron	20 kW	32 kW	6,20 l/Std.	31.000 €
Diesel / Netzparallelb. mit Notstromf.	KWE 35D-4 SPN	Synchron	35 kW	49 kW	10,00 l/Std.	34.500 €
Diesel / Netzparallelb. mit Notstromf.	KWE 50D-4 SPN	Synchron	50 kW	67 kW	14,00 l/Std.	38.400 €
Diesel / Netzparallelb. mit Notstromf.	KWE 75D-6 SPN	Synchron	75 kW	95 kW	20,50 l/Std.	46.000 €
Diesel / Inselbetrieb	KWE 7D-3 SI	Synchron	7 kVA	14 kW	2,70 l/Std.	12.900 €
Diesel / Inselbetrieb	KWE 10D-3 SI	Synchron	10 kVA	19 kW	3,60 l/Std.	16.000 €
Diesel / Inselbetrieb	KWE 14D-4 SI	Synchron	14 kVA	25 kW	4,80 l/Std.	19.000 €
Diesel / Inselbetrieb	KWE 22D-4 SI	Synchron	22 kVA	24 kW	6,80 l/Std.	25.100 €
Diesel / Inselbetrieb	KWE 28D-4 SI	Synchron	28 kVA	43 kW	8,60 l/Std.	28.200 €
Diesel / Inselbetrieb	KWE 35D-4 SI	Synchron	35 kW	49 kW	10,00 l/Std.	31.000 €

ANNEX-2 Different biogas sources in Europe (Pointon and Langan, 2006)



Estimated renewable energy statistics for Europe, especially biogas

Source	Production (Mm^3 per day)	Sites	CH_4 (%)	Total (PJ)	Electricity (GWh)
Sewage	1.7	36000 digesters	65	15.2	650 (15%)
Industrial WW	0.8[a]	400 installed	65	7[a]	
Landfill	7.2		50	50	1351 (10%)
Solids digestion	1.5	>105	55	11.25[a]	1000[a] (36%)
Livestock	0.5	700	55	3.8	133 (12%)
Total biogas	11.7			87	
Solids incinerated				180 (36% heat)	15000[a]
Woods				1700 (54% heat)	3525
Total biomass				45 Mtoe	22500

[a] Estimated.

k.) straw and other biomasses as fuels for CHP and micro-CHP systems *(FORCE with Assistance of AUE and ASTON)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

I.) Types of fuels included in the evaluation
- Shredded straw
- Straw pellets
- Wood chips
- Wood pellets

II.) Handling and processing of fuel
- Description of processing technologies
- Energy consumption
- Storage
- Areas and distances
- Characterization of fuels (water and ash content etc.)

III.) Identification of technological barriers and gaps concerning possible conversion technologies

- Stirling engine [1]
- Gasification + gas turbines [2]
- Gasification + fuel Cells [3]
- Organic Rankine Cycle (?) [4]
- Screw engine (?) [5]

(The chosen conversion technologies should off course be consistent with the technologies described in the report.)

IV.) Conclusion

Fuel	Energy needed for processing and transport	Needed production area	Conversion technology				
			1	2	3	4	5
Shredded straw							
Straw pellets							
Wood pellets							
Wood chips							

*The fuels are given marks where 0 is unsuitable, 1 is suitable with a major technological development, 2 is suitable with a minor technological development and 3 is suitable as for today.

I.) Small-scale combustion and renewable fuels *(AF)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

m.) Contribution of expertise relating to advanced modelling of complex energetic systems *(ARMINES)*

I.) general short description of the technology with examples

II.) Efficiency of energy conversion

III.) Cost of production

IV.) Reliability and expected maintenance requirement

V.) Cost of integration into the existing energy system, compared to existing micro-CHP

VI) Environmental benefits and impact

VII.) Expected payback time through electricity savings in comparison to cost of modern central heating systems

VIII.) Expected costs of energy production in future scenarios outlined

D.) Market contributions :

a.) Consideration of industrial, and market relevance of potential technologies. Cost analysis of technologies compared to existing micro-CHP systems and modern central heating systems Consider highlighted technologies with regards to market trends and predicted future market scenarios and energy pricing *(EC NETwith assistance of EATand GAIA)*

Free text

b.) Planning of format for work package review. Collection of information, preparation of documentation, and distribution to partners. Distribute documentation through appropriate dissemination channels *(CODES)*

Free text

c.) Contribution from SME perspective and dissemination *(BEAMA)*

Free text

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[i] Microgeneration Strategy and Low Carbon Buildings Programme Consultation, DTI, June 2005

[ii] Talbotts Ltd, www.talbotts.co.uk

[iii] Distributed power generation using biogas fuelled microturbines, ETSU Contract B/U1/00670/00/REP, DTI/PubURN 02/1345, Advantica Technologies, 2002