



CENTRE FOR RENEWABLE ENERGY SOURCES C.R.E.S.

MICROTURBINES AND THEIR APPLICATION IN BIO-ENERGY

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1. INTRODUCTION

There exist today installations that produce electricity from biomass, mostly based on combusting biomass, raising steam and expanding this steam through a steam turbine. At smaller scales that would suit the “disperseness” of biomass fuel, the cost and complexity of these units is proportionately high. Gas turbines that could fire biogas derived from biomass gasification are an alternative option, but here again commercial sizes are limited to over 1MW.

For energy crops to be able to realise their potential as a major source of energy in the power generation and transport sectors, it is important to be able to realise both centralised and dispersed installations. For the case of dispersed power generation from biomass, there is a need for energy conversion devices in the range of a few 10s of kW to 1 MW. Such technologies could be biogas engines, Stirling engines, micro-gas turbines and fuel cells.

The current study deals with the use of micro-gas turbines or microturbines for short for the production of power and heat from biomass derived fuels.

The study starts by providing some definitions of distributed generation and small scale CHP and moving on to an overview of the technical features of microturbines. Biopower technologies are then discussed, elaborating on the firing of gas turbines and microturbines with biomass derived fuels. The major manufacturers of microturbine systems are presented, placing emphasis on the European manufacturers but also covering the US manufacturers – who are the market leaders.

The EC has supported the European industry to develop and demonstrate novel gas turbine concepts, including microturbines. The study provides summaries of such EC projects related to microturbines but also of research activities of some European research labs. Respective research activities in the US are also discussed.

The study then presents some case studies of microturbines that make use of biofuels and in particular gases from landfill sites or sewage treatment plants. The study concludes with an overview of past market studies covering cogeneration, biomass cogeneration, microturbines and biomass driven microturbines.

A Strength-Weaknesses-Opportunities-Threats analysis is lastly presented for biomass-fuelled microturbines.



2. DEFINITION OF DISTRIBUTED GENERATION AND SMALL SCALE CHP

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

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

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

These technologies can be grouped as “spinning mass based” including IC engines, micro-turbines, variable speed small hydro- and wind-turbines or “inverter based” including PV, fuel cells, batteries. These two groups are sometimes referred to as “mechanical-electrical converters” or “direct converters” respectively. The recent rapid development of power electronics and microcomputer technology has led to considerable efficiency gains and cost reductions [Schmidt, 2002]. Thanks to modern inverters it is possible to generate sinusoidal voltages with synchronous phases (active power) but also to compensate for reactive power and harmonics. Some of the previously mentioned technologies are described in more detail in chapter 4, Bioenergy Specificities.

The strengths of DG can be summed up as:

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

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

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



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

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

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

Micro turbines offer a number of potential advantages compared to other distributed generation technologies [Pilavachi 2002], including compact size (less than half of an equivalent IC), low weight per unit of power leading to reduced civil engineering costs, small number of moving parts and thus low maintenance costs, low noise, low use of lubricating oil or minimal for the case of air bearings, multi fuel capabilities and lower emissions.

The following table compares typical emission values for microturbines and other distributed generation technologies utilising Natural Gas, when used for power production only [Capstone 2000]

Technology	Rating	NO_x	CO	HC
Micro turbines	30-100 kW	9-25 ppm	25-200 ppm	9-25 ppm
Gas turbines	0.8-10MW	6-140 ppm	1-460 ppm	6-560 ppm
IC engines	35kW	30-450 ppm	240-380 ppm	-
IC engines	0.17-1.5 MW	30-3200 ppm	320-830 ppm	2750 ppm
Phosphoric Acid Fuel Cells	200kW	1 ppm	2 ppm	-

Emission benefits are more prominent in the context of combined heat and power, where indeed microturbines provide high-grade waste heat compared to IC engines.

Micro-gas turbines have however some drawbacks, that have been barriers to their wider implementation. These are that, in its basic configuration, a micro-gas turbine has lower efficiency than an internal combustion engine, which decreases even more at partial load. For some turbines the combustion of very low calorific value gases may not be feasible. Appropriate power conditioning equipment would be required to allow the micro-turbine to produce electricity at the grid's frequency, increasing the cost. The fact that the existing electricity distribution networks are unsuitable for



accommodating large numbers of small generation plants, has contributed in keeping the number of microturbines rather low and certainly lower than what was expected of this market segment.

Coming back to the case of rural areas and the application of distributed generation technologies there, micro-turbines have some additional benefits to IC engine based CHP systems, like:

- by decreasing the size of biogas production plants to suit local agricultural conditions the heat content of the produced fuel varies significantly. Piston based CHP systems will only be able to operate for given complex control systems, while micro-turbines have higher tolerance in varying calorific value of the fuels
- micro-turbines can offer better quality waste heat that can be subsequently used for steam production, heating or chilling purposes [Schmidt, 2002]



3. DEFINITION OF A MICROTURBINE

Modern gas turbines are derivatives from aviation gas turbines and run on gaseous fuels (aero-derivatives) compared to liquid fuels of aviation jet engines. They are marketed as 40 – 50 MW engines and run on the Brayton cycle where the exhaust products are directly expanded through the turbine. They are thus exempt from the major drawback suffered by heavy-duty steam turbines (250 MW) that run on the Rankine cycle that involves heat transfer from the exhaust gases to the working fluid (steam) that is fed to the turbine. However, the fact that exhaust products directly cross the turbine wheel poses strict fuel purity requirements.

Microturbines are gas turbines with a power ranging approximately from 10 to 200 kW. These devices can be used in stationary, transport or auxiliary power applications. This report deals with stationary applications only, which usually come as combined heat and power (CHP) systems. Such micro-turbine based CHP systems would thus be characterised by:

- a single rotating part consisting of a shaft incorporating the compressor and turbine wheels (commonly radial), the alternator and the bearing system
- a combustor
- a recuperator and potentially a heat recovery unit (boiler / heat exchanger)
- a power conditioning system
- enclosure and balance of plant

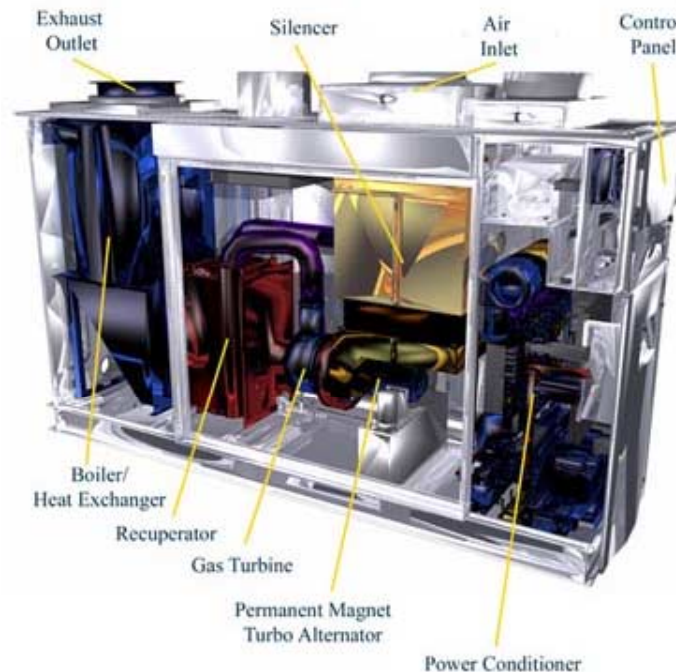


Figure 1 Layout of microturbine based CHP unit [Bowman Power web site]



They are intended to be simple, flexible and low cost devices for distributed power and heat generation. They are for stationary applications, not to be confused with gas turbines of the same range used for propulsion or for auxiliary power.

The term “microturbine” has recently been applied to devices that produce a few Watts with volumes of the order of a few cm³, which are some times better termed “nano-turbines”. Such devices incorporate micro-fabricated components and are being developed to provide power and even propulsion for micro vehicles [Spadaccini 2003, Epstein 1997]. They commonly utilise catalytic combustors and can reach temperatures as high as 1800K with hydrogen as fuel. Lastly, the term “mini-turbine” is sometimes used to describe gas turbines from 200 kW to 1 MW.

A schematic of the operation of a recuperated micro turbine is shown in figure 2 below:

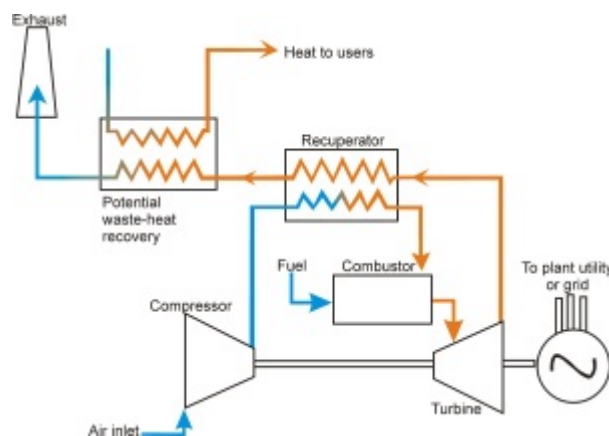


Figure 2 Diagram of microturbine operation[DER web site]

A micro-turbine operates on the same general principle as a conventional gas turbine that consists of:

- incoming air is compressed to 3 - 5 bar by a single stage centrifugal compressor
- compressed air passes through a recuperator, recovering some of the energy of the exhaust gases
- air enters the combustor where the fuel (usually natural gas or LPG) is combusted, with temperatures reaching 900 to 1000 °C
- hot exhaust gases expand through the turbine, dropping their temperature to approx. 650 °C. The turbine is usually single stage and radial and is the device producing mechanical work that is fed to the single microturbine shaft
- exhaust gases then pass through the recuperator where the temperature drops to 250-350 °C
- Depending on the application there could be another heat exchanger installed that could produce steam, hot water or air for heating or chilling (through an absorption chiller)
- Mechanical work is fed to the compressor and the high speed alternator producing high frequency power that is converted to the desired voltage and frequency through a power conditioning system



The existence or not of some components like the recuperator and the heat exchanger depends on the application and requirements on efficiency or cost. The cost of the various components or subsystems ranges from [EscoVale]:

- | | |
|---------------------------------------|--------|
| • compressor and turbine | 14-17% |
| • combustor | 9-12% |
| • bearings | 3-4% |
| • recuperator | 21-24% |
| • high speed generator | 7-9% |
| • power conditioning and control unit | 15-18% |
| • enclosure and balance-of-plant | 23-26% |

These components are briefly described below. A thorough technological characterisation of microturbines and their components can be found in a recent report of the Energy Nexus Group [Energy Nexus, 2002].

Compressor and Turbine wheels

Both turbomachinery components are radial, a technology that is simple, cost effective and efficient at this power range. Even though the compressor and turbine wheels constitute the core of the microturbine concept, their respective cost is relatively low due to the fact that the designs originate from the automotive turbocharger field. In auxiliary power units it is common that the turbine or even the compressor is/are of an axial type, but these units are more complex and for higher power machines, while radial turbomachinery have better efficiencies for powers up to 100 kW.

Materials used for compressor wheels can range from aluminium to Inconel to titanium. Turbine wheels need to operate at much higher temperatures (up to 1000 °C) so they are made of alloys like Inconel. Constant development work is underway on areas like novel rotor materials including ceramics for increased operating temperatures, aerodynamic design of compressor and rotor blades and reduction of tip clearances, aiming to maximise efficiency. This can be as high as 30% or even 35% for larger units (of the order of a few hundreds of kW). A substantial step forward can be achieved through the use of ceramic materials in all hot components, like the combustor and the turbine wheel, even in the recuperator. Silicon carbide and silicon nitride are such materials that are being investigated at the moment, looking for structural strength at elevated temperatures.

In the case of direct combustion of gaseous biofuels in order to power a microturbine, care must be taken to reduce or remove moisture, siloxanes or hydrogen sulphide (depending on the fuel source and fuel conversion technology), the existence of which would affect combustion stability or would cause slagging or fouling of the turbine wheel (refer to chapter 4.4 for more details).



Combustor

There exist three types of combustion technologies for gas turbines, namely:

1. **diffusion flame** combustion, where fuel and air mix at the same time and the same space as they react, characterised by a very hot combustion zone (around 2000 °C) and high thermal NO_x emissions, but with stable, robust flames
2. **premixed flame** combustion or **lean** combustion, where fuel is homogeneously distributed, generating lower combustion temperatures (600 K below diffusion flames) and low thermal NO_x emissions, that require high turbulence and other provisions to achieve flame stability
3. **catalytic** combustion aims to prevent NO_x formation by burning the fuel inside a porous ceramic medium

Through various improvements of combustor design, microturbines have been able to achieve the very low NO_x emission levels specified by existing stringent regulations. Combustors were originally designed for obtaining a stable flame, meaning having a primary combustion zone of high temperature, producing high NO_x emissions (diffusion flame combustion). The injection of water or steam in the combustion zone was one way to reduce these emissions but adds to system complexity and costs. Desired reduced levels of emissions were achieved through dry low NO_x systems. Such systems involve “lean” combustion that is the combustion of fuel in the presence of excess air, resulting in lower peak temperatures and reduced NO_x.

Usually a single can combustor is used but some microturbine systems utilise an annular combustor that allows for reduced size. Fuel is usually mixed with the pre-heated air exiting the recuperator prior to being injected in the combustor. Thanks to these designs, NO_x levels of the order of 25 ppm can be achieved, while single digit figures will be possible in the near future. Since microturbines can be installed in environmentally sensitive areas including urban centres, it is to be expected that their emission levels should be at least lower than those of central stations (which offer better efficiency levels, even if transition losses are included).

An important advantage of microturbines to other heat engines for distributed generation is their capability to burn a variety of fuels, ranging from natural gas, diesel and LPG, to waste and biomass derived fuels like landfill gas or gasification products from biomass, which indeed is the particular interest of this study. However, the calorific value of fuels cannot usually be lower than 4 kWh/Nm³ (40% methane content). The capability to burn a variety of fuels usually comes with a trade-off in emissions, leading to slightly higher NO_x levels. Also, low calorific value fuels often cause flame instability [Abbas 2003].

It is possible that “end of pipe devices” like selective catalytic reduction methods are used to achieve even lower emission levels for NO_x, but these come at a cost. Their use could imply that the fuel needs to be pre-treated since these methods are intolerable to sulphur.

Catalytic combustion is a technique where fuel is combusted inside a porous ceramic medium, aiming to prevent the formation of NO_x. Levels of 3ppm NO_x have been reported but the operating life of such combustors is still unknown. Recently catalytic combustion is being investigated for the combustion of very low BTU gases (down to 1.3% methane) in a project funded by the US Department of Energy Small Modular Biopower Initiative [Prabhu, 2003, Flex-energy web site]. The modification of a Capstone 30kW microturbine so as to use such a combustor is being investigated.



Additionally to the type of combustor, the type of fuel used is a significant factor that influences combustion, energy conversion performance, process control and the selection of the hot gas path materials. It is here that particularities of biomass-derived gaseous fuels come into play, where any particulate matter and alkali vapour in the fuel stream would need to be removed through gas cleaning. Some of these complications can be avoided if an externally or indirectly fired system is used, as explained in chapter 4.3.

Recuperator

Gas turbines at the size of a few tens of kW would have an efficiency that would be as low as 10% in simple cycle, a figure that could be even lower under part load. This is due to the fact that the small size of the rotating turbomachinery components makes the clearances analogically higher, while “exotic” materials and techniques available to larger units cannot be utilised here for reasons of cost. The recuperator allows for a significant increase in efficiency by exploiting the heat of the exhaust gases in preheating the air exiting the compressor. Recuperators are air-to-air heat exchangers of various shapes (box or annular), where weight and size and cost are of importance. Again most of these units come from the automotive industry and are made of high grade stainless steel, while ceramic materials are also investigated.

Bearings

Most of the available microturbines are units with a single rotating shaft, where the compressor wheel, turbine rotor and generator are incorporated. This shaft is supported on bearings that originally were oil lubricated but, in accordance again with automotive turbochargers, are now air bearings that are self-aligned.

High-speed Generator & Power Conditioning

A major stepping-stone in the development of viable microturbines was the development of reliable high speed generators that could spin at the same rpm as the turbo-machinery components, eliminating the need for a reduction gearbox. Small generators can thus go up to 120,000 rpm. The generator additionally acts as the starting motor of the gas turbine. A picture for such a high-speed generator is shown in figure 3 below.

These generators are based on either permanent magnet alternators that have an efficiency that can be as high as 95% or on permanent magnet discs that remove iron losses and eddy current losses and whose efficiency can be as high as 98%.



Figure 3 Picture of 400kW high-speed generator (courtesy of the Turbo Genset Company)



The power electronics package of a microturbine converts the output of the high-speed generator into AC of the desired frequency and voltage, through a rectifier and an inverter. Thus, the generator output has a frequency of 1,000 to 2,000 Hz and a voltage of 500V that is converted to 50 or 60 Hz and 120 or 220 V depending on location. In the case of grid-connected operation, the power electronics ensure that the voltage and frequency are matched and synchronised with the grid. On the practical side, protocols need to be developed locally for the safe operation of grid-connected microturbines.

Efficiencies of power electronic conversion devices are higher than 90%. This, for a unit of a few tens of kW, means that a few kW of heat need to be removed and special provisions must be made as in the case of installing a noise reduction container around microturbines that would not meet noise emission standards locally. This heat could be utilised in a cogeneration application, but this is not common due to the complexity that this would involve.

Enclosure and BoP

Commercial microturbines are offered in attractive enclosures (figure 4) that meet various electrical, noise attenuation and safety standards. Some of these enclosures are weather resistant; others are not and thus need to be installed in containers for outdoor operation.



Figure 4 Microturbine enclosures for Capstone (l) and Turbec (r)

Balance of Plant (BoP) items usually include filters, sensors, instrumentation and controls, wiring and plumbing. A fuel pressure booster is commonly incorporated for the cases of low natural gas grid pressure, or low pressure in the collected landfill gas. Even in this case though, it is worthwhile to include a pressure-regulating valve upstream of the microturbine's fuel inlet.

It is common that the cogeneration heat exchanger sits in a separate enclosure next to the microturbine.



4. BIOENERGY SPECIFICITIES

4.1. Biomass basics

Biomass is plant matter such as trees, grasses, agricultural crops or other biological material including wastes. Biomass is a renewable source of energy and its energetic use is CO₂ neutral. It can be used as a solid fuel, or converted into liquid or gaseous forms, for the production of electric power, heat, or chemicals or liquid biofuels for use in vehicles. Wood is the most commonly used biomass fuel for heat and power. The most economic sources of wood fuels are usually wood residues from manufacturers, discarded wood products diverted from landfills, and non-hazardous wood debris from construction and demolition activities. Use of these materials for electricity generation can recoup the energy value in the material while avoiding landfill disposal. In the future, fast-growing energy crops may become the biomass fuel of choice.

Types of biomass suitable to be used as sources of energy:

- forest debris and thinnings
- residues from wood products industry
- agricultural wastes, such as straw
- energy (fast-growing) trees and crops
- wood and wood wastes
- animal manures
- non-hazardous, organic portion of municipal solid waste

Because biomass has a relatively low energy density compared to conventional fuels, biomass is best used as a local resource. Transportation distances from the resource supply to the power generation point must be minimized. The most economical conditions exist when the energy use is located at the site where the biomass residue is generated (i.e., at a paper mill, sawmill, or sugar mill).

There are three primary types of biomass power or Biopower systems: direct-fired, co-fired, and gasification systems.

Most of today's Biopower plants are **direct-fired** systems that are similar to most fossil-fuel fired power plants. The biomass fuel is burned in a boiler to produce high-pressure steam that is introduced into the steam turbine. While steam generation technology is very dependable and proven, its efficiency is limited. Biomass power boilers are typically in the 20-50 MW range, compared to coal-fired plants in the 100-1500 MW range. The small capacity plants tend to be lower in efficiency because of economic trade-offs; efficiency-enhancing equipment cannot pay for itself in small plants. Although techniques exist to push biomass steam generation efficiency over 40%, actual plant efficiencies are in the low 20% range. State of the art fluidised bed steam cycles have achieved efficiencies of higher than 30%.

Co-firing involves substituting biomass for a portion of coal in an existing power plant furnace. It is the most economic near-term option for introducing new biomass power generation. Because much of the existing power plant equipment can be used without major modifications, co-firing is far less expensive than building a new Biopower plant. Compared to the coal it replaces, biomass is CO₂ neutral, it reduces sulphur dioxide (SO₂), nitrogen oxides (NO_x) and other pollutants. After "tuning"

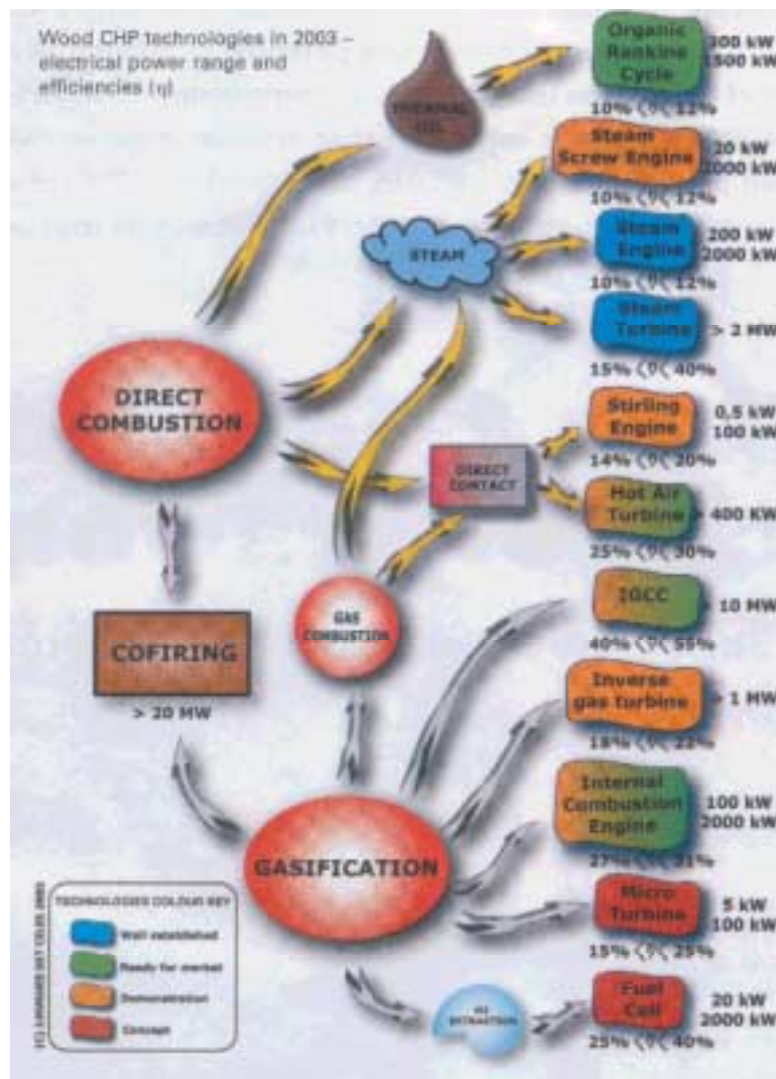


the boiler for peak performance, there is little or no loss in efficiency from adding biomass. This allows the energy in biomass to be converted to electricity with the high efficiency (in the 33-37% range) of a modern coal-fired power plant

Biomass gasifiers operate by heating biomass in an environment where the solid biomass breaks down to form a flammable gas. This offers advantages over directly burning the biomass. The biogas can be cleaned and filtered to remove problem chemical compounds. The gas can be used in combined-cycle systems, where efficiency can reach 60%. Besides combustion systems, biogas produced from gasification is suitable for fuel cells, where efficiency can be as high as 50% even for small power scales, of the order of a few kW.

4.2. Biopower technologies

A schematic of the various types of Biopower systems for woody fuels is shown below, along with the technologies suitable for the conversion to heat and power [Hugues, 2003]. The colour code shows the maturity of each technology.





The most common way of direct combustion of biomass is direct combustion in circulating fluidised bed or moving grate **boilers**. Such boilers have a power in excess of 25 MW and can burn fuels of a wide quality range, with moisture content as high as 65%. The heat produced is transferred using steam or thermal oil to the power producing device. Since most solid biomass technologies are based on similar technologies for coal, most wood fuelled power or CHP plants are based on steam.

Steam turbines are very well developed and still hold the world's largest share of electricity production. Two types of turbines are commonly used for CHP applications, back-pressure turbines where the steam is expanded to a back pressure required for the heat process and extraction condensing turbines that have a steam extraction valve between the entrance and rear, from which the required amount of heat can be drawn, so as to run from either full electricity production to full heat production. Such plants have a power range of 500kW to 240 MW. However, electrical efficiency is low below 5MW (10-20%), rising to 30% above 50MW.

Steam engines or steam expansion engines are a mature technology that has recently been further developed to run oil free with minimum need for checks. There is only one manufacturer of such engines, the German company Spilling [www.spilling.de], developing engines in the range of 25kW to 1.5 MW, with intake steam pressures of 6 to 60 bar. Their main advantage is the high flexibility for steam requirements and the excellent part load performance. Their drawback is their low efficiency (10-12%) for power applications and the high noise levels. Up to 300 units have been sold, 2/3 of which are for biomass applications.

Another way to transform heat into mechanical energy is the Organic Rankine Fluid Cycle (ORC). This technology was developed for heat recovery or exploitation applications, mostly biomass and also geothermal energy. The principle is that **thermal oil** is heated to 300°C in a biomass boiler and transfers heat through a heat exchanger to silicone oil, an organic medium with low vaporising point. This vaporises and expands in a two stage turbine. The technology has several advantages including atmospheric pressure operation (meaning no steam safety constraints), non corrosive working medium (no blade wear), no water treatment, low noise levels, good part load performance. Excellent leakage security is required since the silicon oil is flammable. Such units are available for power ranges of 300 to 1200 kWe, with a net electrical efficiency of 18%. Two companies develop such units, namely GET and Turboden, but there is no serial production yet, resulting to high investment costs.

Another way to transform heat from woody biomass into mechanical energy is through **Stirling engines**. Their efficiency is of the order of 13 to 18% for a combustion temperature of 600°C. Stirling engines fired with Natural Gas have recently been commercialised at sizes suitable for single homes (0.5 – 6 kW) by various manufacturers from New Zealand, Germany and the USA including Whispergen, Solo, STM-Power, Enatech and Sunpower. Biomass fired cogeneration units based on Stirling engines are still in the pilot demonstration phase at 35 and 75kW, where the direct firing of biomass fuel is being investigated, in relation to the fouling of the heat exchanger by ash deposits. Stirling engines are silent, require little maintenance and are the only biomass cogeneration technology that is considered economically viable under 50kW [Hugues, 2003]. Their performance under part load is however very poor.



The previous technologies were related to the direct firing or co-firing of biomass. Biomass **gasification** is a way to transform solid biomass into gaseous form by passing biomass through four steps: distillation, carbonisation, oxidation and reduction. There are two gasification technologies, fluidised and fixed beds, divided also into down-draft and up-draft. The produced biogas can be burned in boilers, gas turbines or internal combustion engines. The advantages of gasification over direct combustion technologies are:

- higher electrical and overall efficiency, specially at smaller scales
- lower emissions
- lower investment costs
- possibility to co-fire biogas with fossil gaseous fuels

For large scale projects the aim is to produce plants based on the Integrated Gasification Combined Cycle (IGCC) concept that has the potential for high electrical efficiency for solid fuels. Such plants have been built in the UK, in Sweden (Värnamo), the US and Brazil but some have shut down due to financial problems, related to the high cost of fuel wood. The gas turbines utilised in these plants have not been able to operate for more than 5,000 hours due to fouling of the turbine blades, caused by the high levels of tar and condensates in the gas produced by gasification. For smaller scale systems (under 2 MW) fixed-bed gasifiers are used and the produced gas is fed into lean gas or diesel engines, Stirling engines, micro- or mini-gas turbines.

Despite major R&D efforts, biomass gasification technologies have till now not shown promising results, perhaps also due to the fact that current research is too academic in focus, lacking input from parties with long-term field experience. Industries involved in the development of such units are too secretive, there is thus no knowledge-sharing that could help accelerate the improvement of biomass gasifiers.

4.3. Firing gas turbines with biomass derived fuels

Gas turbines that run on gaseous fuels – mostly Natural Gas – have helped reduce the installation times and costs of modern combined cycle power plants. Gas turbines of sizes ranging from few kW to tens of MWs can be utilised for the production of power and heat using biomass derived fuels, when combined into direct or indirect fired systems:

Direct or internal firing, which can be divided into two subclasses:

1. combustion of solid biomass in a combustor, with combustion gases expanding through the turbine, degrading its performance
2. gasification of biomass, cleaning of produced biogas and combustion in a combustor, with gases expanding through the turbine, with significant efficiency losses in gasification and cleaning steps

Indirect or external firing

This involves the existence of a (ceramic) heat exchanger that transfers heat from the combustion gases to the air delivered by the compressor (figure 5 [Ferreira 2001]).

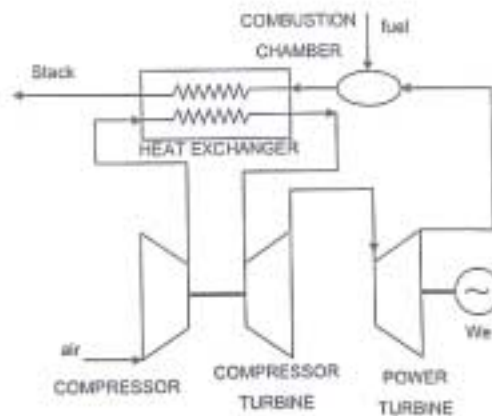


Figure 5 External firing utilising heat exchanger

The efficiency of this system is limited by the operating temperature of the heat exchanger, that means that the inlet temperature of the gas turbine is rather limited. An additional problem would be slugging and fouling of the heat exchanger tubes. Such systems have also been investigated for the firing of gas turbines with coal or other solid fuels.

There are advantages related to this system, including:

- the gas turbine operates on a clean working medium, minimising wear of the blades
- any gas cleaning system can be substituted by a heat exchanger, making the system simpler
- commercial components for the turbine and the biomass combustion system are available, as well as heat exchangers that would be suitable for this type of application
- for the case of solid fuels, there is no need for a gasifier
- increased versatility of fuel used
- minimum pre-treatment of fuel

Despite these advantages, the indirect firing system has yet to achieve commercial success. Further research and engineering efforts are still needed to overcome potential technological barriers, principally associated with the heat exchanger. Development of high temperature heat exchangers has advanced with advances in materials technology, in the same way that gas turbines have benefited from improved materials in increasing the inlet temperature capability. Specific areas that require further R&D are [USDA proposal, 2003]:

- Performance of the heat exchanger including fireside fouling, corrosion, erosion, pressure drop and material temperature limitations, effectiveness, and maintenance requirements.
- Investigations of alternative materials for the heat exchanger, temperature limitations and fouling associated with the heat exchanger and turbine components.
- Off-design performance of the system, including effects of reduced heat exchanger and turbine inlet temperatures, de-rating at elevation, effects of changes in system mass flows and gas composition.

Various other cycles are being investigated for the firing of large scale gas turbines firing biomass, such as:

- Intercooled externally fired gas turbine cycle (ICEFGT), using solid biomass



- Biomass integrated gasification gas turbine cycle (BIG/GT), using biogas
- Biomass integrated gasification intercooled recuperated cycle (BIG/ICR), using biogas

4.4. Firing micro-gas turbines with biomass derived fuels

Gases derived from biomass or wastes are a challenging fuel for microturbines, leading to a need for rigorous pre-treatment to filter out moisture, siloxanes, hydrogen sulphide and trace elements. Some microturbine manufacturers have developed special skid-mounted units that would perform this kind of fuel pre-treatment. For the case of landfill gas or digester gas such a gas pre-treatment plant would consist of:

- a gas pressure booster
- a refrigerated gas drier
- a siloxane filter

The operation and maintenance of such a pre-treatment system would be of the order of 1-2 cents€/kWh.

Moisture in the biogas causes combustion instability, while at the same time causes slugging of the turbine blades and needs thus to be removed. In some cases this consists of a desiccant drier, in others of chilling the fuel to remove moisture and other condensable impurities and then reheating the fuel to above dew temperature. Siloxanes are found in some types of wastes and once combusted can cause fouling of the turbine blades and the recuperator. Activated carbon filters are used to remove such siloxane concentrations (through adsorption), the installation and operating costs of which is considerable. However such a pre-treatment means the maintenance costs of the microturbine can be kept very low. A super-refrigerated dryer is being investigated that will eliminate moisture and siloxanes at the same time, avoiding the need to replace filters. In the case hydrogen sulphide is present in the biogas, then the heat recovery components must be made of stainless steel to avoid corrosion.

The following figures show the typical constituent limits for the gaseous fuel of a microturbine, in this case of the 70 series Ingersoll Rand microturbine

Oxygen	3% maximum
Hydrogen	5% maximum
Carbon dioxide	45% maximum
Methane	38% minimum
Ethane	8% maximum
Propane & Butane	2% maximum
Moisture	150 ppm maximum

Impurity limits in the fuel are shown below:

Hydrogen sulfide	25 ppm by volume maximum*
Halogenated organic compounds	200 ppm by volume maximum
Non-methyl organic compounds	1500 ppm by volume (maximum)
Particulates	3 micron average size
Alkali metal sulfides (Na, K, Li)	0.6 ppm by mass maximum
Siloxanes (octamethyl cyclotetrasiloxane)	10ppb by volume maximum

* Brief periods up to 250 ppm by volume allowable



5. MAJOR MICROTURBINE MANUFACTURERS

Development of microturbines commenced in the 1970s but the present phase of development started in the 1990s. Microturbines are mostly derivatives of automotive turbocharger technology but have also been influenced by military or auxiliary power unit applications. US companies have exploited their experience from these fields from early on and were the first to produce commercial products that were at the cutting edge of this type of technology. The recent “Advanced Microturbine Systems” programme of the US Department of Energy, covering the years 2000-2006 sets ambitious goals and has allocated 63 million US\$ of government funding in order to ensure that US companies will keep their lead and increase their market share in the field. There are only two major developers of commercial microturbine based CHP systems in Europe, Turbec of Sweden and UK company Bowman Power.

5.1. Turbec

Turbec was established in 1998 by Volvo Aero Turbines and ABB. It could be claimed that Turbec is the “most European” of the microturbine developers in terms of where the various parts of hardware are designed and built – the recuperator is the only part coming from outside the EU.

The microturbine technology incorporated in their T100 model was originally developed for the automotive market for hybrid vehicles. Volvo was involved in the development of 40kW and 100 kW units in the 1980s in order to overcome the limitations of batteries in electric vehicles. This expertise was sold to a separate Volvo company, which jointly with ABB formed Turbec. ABB provided their expertise in power electronics. Their aim was for developing a low cost and high reliability unit. [Malmrup, 2003]. The first 100kW T100 unit was delivered in 2000 and more than 200 units have been produced to date.

Turbec’s focus till recently has been on CHP with NG. However they appreciate that the market is very weak (July 2003). Turbec is thus looking very seriously at biomass & waste as a more promising market, that will become even better when green certificates are applied. A number of units have already been installed to operate on sewage gas or landfill gas in Sweden (OMES project), Germany and the UK. Sewage treatment plants are suitable application sites since the heat can be used locally to improve the performance of digesters. According to their experience, some problems have been encountered with gas compression in landfill applications. Similarly, turbine materials could be chosen so as to handle sour gas. The biggest problem is when the biogas is water saturated, then this moisture needs to be removed. No changes were required in the combustor for gases down to 50% CH₄. For gases with lower calorific value, external combustion is considered more appropriate, although Turbec have tested catalytic combustion for such fuels in the context of a project funded by the Swedish government.

Turbec is also well aware of the potential of microturbines that could operate in combination with fuel cells, as well as with hydrogen as fuel, but these are issues of long-term interest. Of more immediate interest is the development of a flexible combustor that can adapt to the instant properties of the available biogas.



The T100 was the microturbine used in various installations in the context of the OMES project described previously.

The main characteristics of the T100 are listed below:

General information

Dimensions of the T100:	Width 840 mm Height 1900 mm Length 2900 mm
Weight:	2000 Kg

Performance data

Net electrical efficiency:	30%	± 1%
Net electrical output:	105 kW	± 3 kW
Net total efficiency:	80%	
Net thermal output (hot water):	167 kW	
Exhaust gas flow:	0.80 kg/s	

Emission data

Volumetric exhaust gas Emissions at 15% O ₂ :	100% Load
Nox:	< 15 ppm/v
CO:	< 15 ppm/v
Noise level at 1 meter:	70 dBA

Electric data

Voltage output:	400 VAC, 480 VAC, 3 phases
Frequency output:	50 Hz alt. 60 Hz
Mains frequency variation:	± 5%
Mains voltage variation:	± 10%

Fuel requirements

Pressure min/max:	6/8.5 bar (g) 87/123 psia
Temperature min/max:	0°C/60°C (32°F/140°F)
Lower heating value:	38-50 MJ/kg

Turbec recently went through a transient state with ABB and Volvo having lost interest in taking Turbec forward due to the fact that sales are below predictions (approx. 30 units a year compared to 400). Further production was temporarily ceased. Eventually the Italian-based company API Com srl



acquired at the end of 2003 all of the share capital of Turbec AB. The fate of Turbec would be important for the fate of European industry, at this size of gas turbines.

The English company NewEnCo is the distributor of Turbec microturbines in the UK. The company has put emphasis on biomass-fired applications and has acquired related expertise for the Turbec hardware.



Fig. 6 NewEnCo's biogas fired microturbine package[www.turbec.com]

NewEnCo have installed units at the following sites in the UK that utilise biofuels:

- Masons Landfill (unit operated for 1,700 hours and is about to be moved to another site)
- Kilmington Sewage Treatment Works (3,000 hours of operation)
- Monkmoor Sewage Treatment Works
- Totnes Sewage Treatment Works (unit currently being commissioned)

A detailed case study on the application of the Turbec T100 unit to the Kilmington Sewage Treatment plant is presented in chapter 7.1.

The approach of NewEnCo has been not to pre-treat the incoming biogas but to modify the gas compression unit instead. Related research work is currently being undertaken on gas compression in collaboration with a compressor manufacturer but information is still confidential [Lewis, 2003]. For the case of the Totnes sewage treatment plant, there exist very high levels of hydrogen sulphide in the gas that make it not suitable for a conventional reciprocating engine CHP

The company considers Turbec as pivotal for the future of microturbines given the fact that the T100 is a state-of-the-art microturbine with excellent figures on efficiency, emission and reliability. However, the currently high capital and maintenance costs that result from low production volumes render the units expensive for the current energy prices, hence the problems in market penetration.



For the German market, Turbec has been collaborating with the company Pro2 Anlagentechnik GmbH. Pro2 is a company that is active in the fields of:

- installing CHP plants with gas engines or microturbines of various manufacturers
- landfill gas, sewage gas and biogas technologies (gas collection, boosters, flare stations)
- coal mine gas technology (exploration, safety)

Apparently Pro2 and Turbec intended to jointly promote the T100 in a number of biogas installations. One unit was installed at a landfill site close to Dresden and ran for 2,000 hours. Additional units were planned to be installed in different fuel applications covering landfill gas, sewage gas, biogas as well as coal bed methane (figure 7).

Gasturbine-Module

pro2

Pro2 Anlagentechnik GmbH
Schmelzerstr. 25
D-47877 Willich
Phone: +49 / 2154 / 488-0
Fax: +49 / 2154 / 488-105

Walter-Könn-Str. 1a
D-04355 Leipzig
Phone: +49 / 341 / 52556-0
Fax: +49 / 341 / 52556-11

Mühlenweg 9
D-66130 Saarbrücker
Phone: +49 / 681 / 8815-383
Fax: +49 / 681 / 8815-335

Internet: <http://www.pro-2.de>

Type		Kinds of gas	Output			Efficiency			Dimensions	
Module	Container		electr. KW	therm. KW	primary KW	electr. %	therm. %	total %	module (M) L x W x H (m)	container (C) L x W x H (m)
NTM 100	NTC 100	natural gas, coal mine gas	100	152	333	30	46	76	2,9 x 0,9 x 1,9	6 x 2,5 x 2,6
LTM 100	LTC 100	bio-, sewage-, landfill gas	95	141	313	30	45	75	2,9 x 0,9 x 1,9	6 x 2,5 x 2,6

Fig. 7 Pro2 brochure extract for a microturbine based CHP system that can also handle biomass-derived or waste gases

5.2. Bowman Power

Bowman Power was established in 1994 and is one of the two major European manufacturers of microturbine based CHP systems. Their area of expertise initially was power electronics, then expanding to high speed alternators and on to the packaging of micro-turbine based CHP systems. Today they are among the largest manufacturers of fully commercial microturbine CHP systems worldwide. 110 people are employed at the company's headquarters in Southampton, assembling their products at the premises. The heat engine at the heart of their product is the microturbine



manufactured by Elliot, the remaining components are either manufactured by Bowman Power or purchased from European manufacturers.

They currently produce a model running on NG capable of $80\text{kW}_e + 135\text{kW}_{th}$ in recuperated mode or 300kW_{th} in non-recuperated mode. The annual production of roughly 100 units per year is fed to clients in Europe, N. America and the Far East. Their markets in terms of priority are the deregulated CHP market, the Renewable Energies (biomass) market and finally the “secure” power off-grid market. Biofuels are thus an interesting potential market for Bowman Power [Robertson 2003]. They have done such applications but most of them are one-offs. The company groups various biofuels applications into:

1. low moisture solid biomass to be used with indirect or external firing: A respective research programme is being conducted with Talbott’s Heating Ltd with funding from the Department of Trade and Industry (DTI)
2. biogas produced through gasification: a downdraft fixed-bed gasifier is being investigated in the context of another DTI research contract in collaboration with Rural Generation Ltd. The suitability of the produced biofuel will be investigated in terms of how clean the fuel will be and how sustainable combustion can be achieved for low calorific value fuel. A new, larger combustor will be developed to that end. In terms of cost, the target is to reduce the cost of the gasifier so that it is almost equal to that of the CHP system. The same type of combustor could be used for other low calorific value fuels like landfill gas
3. combustion of gases produced by anaerobic digesters used in sewage treatment plants that are considered of medium calorific value (40-70% CH_4)

An interesting application of microturbines [Robertson 2003] would be greenhouses, where gases produced from the anaerobic digestion of biomass residues would be combusted in a microgasturbine producing power and heat. The exhaust gases would then be mixed with air (1:15 dilution) and fed to the greenhouse as a kind of CO_2 sequestration (plants grow better for CO_2 values of the order of 1000 ppm). Internal combustion engines could not be used in such an application since the levels of NO_x they produce are too high for the plants of the greenhouse.

The company is collaborating in a EC funded project called MOCAMI that started in 2003. The aim of the project is to combine a microturbine with a Molten Carbonate fuel cell.

Bowman Power has collaborated with the UK company Talbott’s Heating Ltd to modify a Bowman Power TG50 microturbine to incorporate a biomass combustion system that was developed by Talbott’s [Pritchard, 2000] (figures 8 and 9), a company developing a range of biomass-fired combustors from 25kW to 12,000kW that operate with steam turbines. According to Talbott’s, small scale systems of this type have poor efficiency, with typical efficiencies of 6-8%. Capital costs per kW_e of generation capacity are also high due to complex systems and low efficiencies, typically £6500 per kW_e .

The developed unit was indirect fired. The combustor was integrated with a high temperature heat exchanger. The turbine and compressor housing of the microturbine were modified to suit the combustor & heat exchanger’s characteristics.

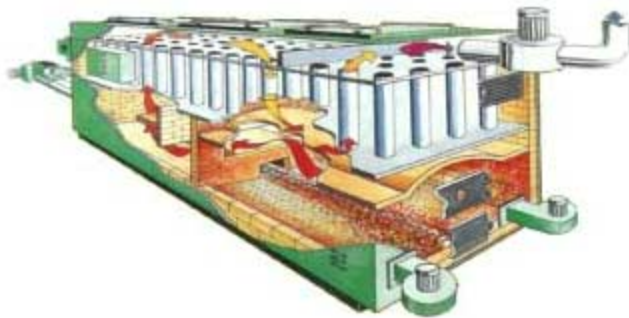


Figure 8 (l): Schematic of combustor & heat exchanger ®: picture of combustor connected to microturbine, with biomass silo on top

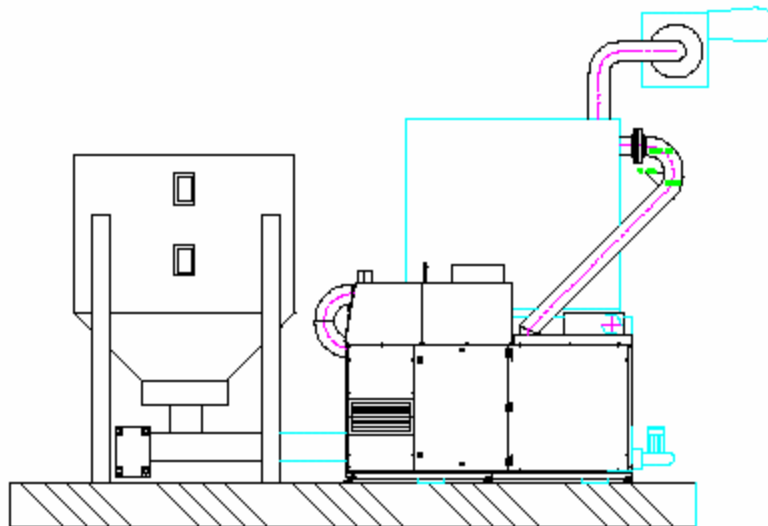


Figure 9 General arrangement of silo & combustor (l) and microturbine ®

A number of important conclusions were drawn from this study:

- The biomass combustor was capable of generating combustion gasses far in excess of 900°C
- Heat exchanger performance improved with mass flow rate.
- The biomass driven microturbine acceleration was much slower than that of the conventional unit in responding to changes
- It was possible to produce 26-34kWe of electrical renewable energy plus recoverable thermal energy (nominal power of microturbine was 50 kWe)
- Approximately 100-150kW of high-grade thermal energy was available for cogeneration or trigeneration applications.
- Low heat losses results in overall system efficiency between 80-85%
- Electrical efficiency was 17%



- Current steam based systems of Talbott's (50kW) cost around £6,500 per kW and have 8% efficiency, while the microturbine based system would cost around £2,500 per kW
- Estimated payback period of such a unit installed in a wood working factory would be 4years, while for a larger unit of 250 kW this would be reduced to 2.5 years.

5.3. Other European Manufacturers

The French company **Microturbo** of the Turbomeca group is involved in the development of a 350 kW gas turbine that would be suitable for combined heat and power applications. The unit is being developed in the context of the CHEP EC funded project that is co-ordinated by Microturbo. The project is described in detail under chapter 6.2.

UK company **Turbo Genset** is involved in the manufacturing of high speed generators and power electronics for gas turbines up to a power of 400kW. A 400 kW microturbine genset was also marketed with a Walter microturbine, capable to burn kerosene, diesel and NG. The combustor is not a low emissions one. The company is a spin off from Imperial College, UK. Turbo Genset was a partner of the TETLEI project where a microturbine was installed in a Rover vehicle to be used as a taxi. Turbogenset has been collaborating with GE of the US for the development of a 200 kW microturbine for CHP applications [Etemad 2003].

OPRA is a Dutch company manufacturing small gas turbines down to a power level of 1.5 MW. OPRA was established in 1991 in the Netherlands by the turbine developer R.J. Mowill, who created Kongsberg turbines in Norway. More than 1000 of these engines were sold world wide. In addition, a low emissions combustion system has been developed, as well as the introduction of the latest component technology for the all-radial flow path. OPRA has developed and initiated marketing and manufacturing of ultra low emissions, high efficiency gas turbines based upon patented technology. OPRA's initial generating sets include the OP16, a 1.5 - 1.8 MW gas turbine engine for use in the energy market. Such capacities are beyond the scope of microturbines, as defined in the current study.

Walter of the Czech Republic is similarly involved in the manufacturing of small turbomachinery, for stationary or aviation applications, their expertise could thus well be diversified to the manufacturing of microturbines for stationary applications. Indeed they provide such a microturbine for a genset developed in collaboration with Turbo Genset.

5.4. Capstone

The US company Capstone is the biggest manufacturer of micro-turbines and with more than 80% of the market share, is the market leader. Since the year 1998, Capstone have shipped more than 2,400 units and have documented 5 million hours of operation of their products. Capstone could even be credited with raising a major part of the awareness for microturbines.

The company, unlike other major developers, focuses solely on the production of microturbines. Most of their units have been developed for stationary applications including CHP. Some units have been applied to the transport sector, where buses have been on trial runs since 1997. Capstone was the first manufacturer to offer a recuperated series-produced microturbine, while it holds proprietary



designs for key-components like air bearings, the turbine and shaft-mounted generator, low emission combustor and others.

Following the development and testing of various proof-of-concept models that led to some changes and refinements of components, the first warrantable product of Capstone was launched in 1999 called Model 330. The model was to operate on high pressure NG in grid-parallel mode. Stand alone systems and low-pressure designs soon followed. The first model was presented as a fully engineered, compact unit with a 28kW nominal rating at 50 or 60Hz. Its size was 0.7m x 1.3m x 1.9m and weighed 320 kg. Emission levels were excellent for this level of power output with NO_x levels below 9ppm. The cost price was of the order of 1000\$/kW, with maintenance costs below 1c\$/kWh.

Today Capstone develops the following family of products:

Product	Power	Application
C30	30kW	30 kW microturbine, can come with fuel pressure booster
C30 biogas	30kW	30kW unit that can run on landfill or digester gas (down to 35% CH ₄)
C30 HEV	30kW	suitable for transport applications, CARB certified
C30 liquid	30kW	29kW microturbine that can run on diesel or kerosene
C60	60kW	microturbine fuelled by natural gas
C60 CHP	60kW	microturbine based CHP system (60kW _e – 115 kW _{th})

For sites with low pressure in the feed gas, which is often the case for biogas applications, Capstone has developed and is marketing a fuel gas booster that is suitable for their microturbines but also ICEs or FCs (figure 10).



Figure 10 Fuel gas booster of Capstone [<http://microturbine.com>]

This is a variable flow scroll compressor capable of compressing up to 60m³/hr of gaseous fuel at an inlet pressure of 0.1 bar, to a delivery pressure of 8 bar. The unit is adequate for a single C60 unit or multiple C30s and has a power consumption ranging from 4 to 6 kW. The compressor has a design life of over 20,000 hours and never requires an overhaul. Annual maintenance consists of replacing



second stage oil separator, adding oil and cleaning the heat exchanger. Some limits as to the characteristics / limits of the fuel are:

- H₂S maximum content45 ppm
- Water vapour maximum150 ppm
- CO₂ maximum content.....2.5%
- Inlet temperature50°C maximum
- Discharge gas temperature ... 65°C maximum

Capstone has similarly developed a range of “accessories” that helps in the modularisation and standardisation of their product range. These accessories include power servers that allow the networking of up to 100 units, controllers that transfer grid-connected operation to stand-alone operation in case of power failure, battery chargers, protocol converters, filter kits for various fuels, including one for sour gas, etc.

5.5. Ingersoll Rand

Ingersoll Rand is another major US manufacturer of commercial microturbine based CHP systems. The Company is a \$8.8 billion diversified, multinational manufacturer of industrial and commercial equipment. Their involvement initially was focused on recuperator technology. Based on this experience the company diversified into building complete microturbine units, trademarked as PowerWorks. In mid-2000, the company formed Ingersoll-Rand Energy Systems, based in Pease International Tradeport in Portsmouth, New Hampshire, representing a commitment to the PowerWorks concept. The first field test units went into operation in mid-2000. Presently, an all-encompassing beta field test program has been completed and IR is on track to meet its expectations of taking commercial orders for its PowerWorks product line [www.irpowerworks.com]

The current product has been designed to meet the same durability and reliability standards found in commercial chillers, boilers, and furnaces. The PowerWorks microturbine has a projected life of ten years and requires only annual maintenance. At the heart of each PowerWorks system is a recuperated gas-turbine engine with an integrated cogeneration capability, using proven turbocharger technology.





The PowerWorks microturbine typically runs on natural gas and features a clean burning low-emissions combustor that meets regulations for greenhouse-gas emissions. Since many commercial buildings and industrial facilities are not supplied by high-pressure gas lines which most microturbines require, the PowerWorks system incorporates a fully integrated gas booster based on Ingersoll-Rand's screw-compressor technology.

There are two products, a unit for 70kW and another for 250 kW.

The characteristics of the 70 kW unit are:

Nominal Electrical Power	(±5) 70 kW@59°F
Maximum Electrical Power	(±5) 92 kW@ 0°F
Voltage	480 VAC
Frequency	60 Hz
Electrical Efficiency	LHV (±2) 28% LHV including fuel-gas booster 29% LHV without fuel-gas booster

5.6. Elliot Energy Systems

Elliot Energy Systems of the Elliot Turbomachinery Co., Ebara Group, is one more US major player in the microturbine arena. It was the first company to move to commercial production at a purpose built facility in Florida, with a production capacity of up to 2,000 units a year. Their initial targeted markets are understood to be [EscoVale] niche markets of the genset business, including:

- Agricultural applications
- Marine on-board gen sets
- Mobile units for civil or military applications

Their first model was an non-recuperated 45 kW unit called T45 with a price tag of \$13,500 and an efficiency below 20%. The addition of a recuperator raises the price to \$17,000 and the efficiency to 25%. Several new models have been developed, leading to the following product range:

- TA-35R Recuperated 35 kW
- TA-45 Non-recuperated 45 kW
- TA-60R Recuperated 60 kW
- TA-80R Recuperated 80 kW
- TA-200 Recuperated 200kW

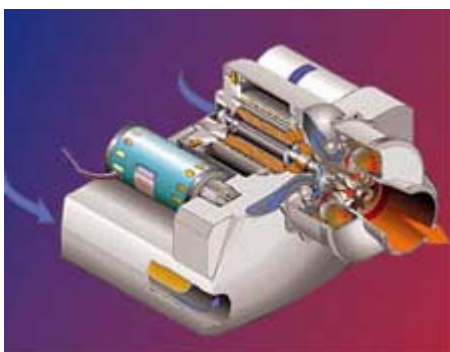


Figure 11 The Elliot TA-45 microturbine



Elliot's technology is comparable to that of the other main manufacturers with the exception that it uses high speed lubricated bearings (compared to air bearings). An oil change is thus required once a year. Elliot is the provider of the microturbine core to Bowman Power Systems. Elliot has concentrated on the manufacturing of the microturbine gen set and collaborates with other manufacturers for the packaging of the microturbine into CHP systems.



6. CURRENT R&D ACTIVITIES, INCLUDING EC PROJECTS

Turbomachines have been an area that has received considerable support from the EC for the development and demonstration of innovative systems. Some of these projects are related to microturbines, including:

- The OMES project
“Optimised Microturbine Energy Systems”
Contract No. NNE5/20128/1999
Coordinator Aksel HAUGE PEDERSEN
Dansk Olie & Naturgas A/S
E-mail ahp@dong.dk
Phone: +45 4517 1238
Fax: +45 4517 1282

- The CHEP project
“Research and development of high efficiency components for an intercooled, recuperated CHP gas turbine for Combined Heat and Efficient Power”
Contract No. ENK5-CT-2000-00070
Coordinator: Andre Romier
MICROTURBO S.A.
Chemin Pont de Rupe 8, 31000, Toulouse, France
e-mail: Andre.romier@microturbo.snecma.fr

- The MICRO_TRIGEN project
“Micro-Trigeneration and Integrated Energy Services in South of Europe and Brazil”
Contract No. NNE5-2001-275
Coordinator Gabriela PRATA DIAS:
ECOGEN - Servicos de Energia Descentralizada, SA
Rua Dr. Antonio Candido, 10-4o, 1050-076 LISBOA, PORTUGAL
Tel:+351 21 319 48 50
Fax:+351 21 314 04 11
e-mail: gdias@ecogen-sa.com

- The CAME-GT Thematic Network
“Thematic Network for Cleaner and More Efficient Gas Turbines”
Contract No. ENK5-CT-2000-20062
(<http://www.came-gt.com/default.htm>)
Co-ordinator: Mr. David Pollard (david.pollard@power.alstom.com)

- The BIOTURBINE Altener project
“Opportunities for biofuel-burning microturbines in the European decentralised-generation market”
Contract No AL-2002- 11
Co-ordinator: Dr. Rainer JANSSEN, WIP, Germany



Two EC projects related to biomass cogeneration are:

- The PROSMACO project
“Promotion of small scale cogeneration in rural areas”
Contract No XVII/4.1031/P/99-115
Co-ordinator: Dominique GIRAUD,
INESTENE, France
- The BIOCOGEN project
“Biomass Cogeneration Network”
Contract No ENK5 CT2001 80525
Co-ordinator: Kalliopi PANOUTSOU,
CRES, Greece

Projects related to the development of microturbine technology are presented below while some others related to market issues of microturbines are presented under chapter 8 of this study.

6.1. OMES project

“Optimised Microturbine Energy Systems” Contract No. NNE5/20128/1999 [Strecker 2003]

The OMES project involved an investigation of CHP systems that are based on gas turbines in the range between 20 and 200 kW (electric power). The investigation primarily evaluates the market potential from a techno-economical point of view and utilizes to some extent results from other investigations on market potential. The techno-economical investigation includes identification of which typical heat demands are well suited being satisfied with CHP based on a micro gas turbine. An attempt to evaluate the potential for other competing CHP technologies is included as it is important in the evaluation of the wide spread use of micro gas turbines. Listed below are conclusions that have been drawn from this project that involved the installation of 18 Turbec T100 microturbines in various sites across Europe.

The economics of the installation of micro CHP proved to be attractive and impacted upon the progress and interest in the project. Primary activity has been concerned with identification of sites to place 18 microturbines. 15 units have been placed and considerable difficulty experienced in locating the remaining 3 due to the higher than expected investment costs. It was however proposed that 3 plants that are currently operating outside this project are incorporated into the project to acquire the extensive operational data for analysis and reporting. At the end of the period 7 units were operational and the remaining units were undergoing installation. Operational experience exists for approximately 20,000 hours.

Country	Units	Demo host	Responsible	In operation
DK	2	Cph Airport	DGC	February 2003
DK	5	Diff. Apartment houses, Køge	Energi E2	March/April 2003 13.500 running hours end of
DK	1	M/R station, Lyngø	DONG	2002
N	1	Statoil, Stavanger	Statoil	Turbine delivery jan 2003



N	1	Fjell Borettslag	Statoil	Turbine delivery jan 2003
S	1	Mariestads Avl. Rening*. Klitte & Lundh (Green House)	SGC	Early 2002.
S	1	School at Kävlinge	SGC	Early 2002 9000 running hours end of 2002
SF	1	VTT	Gasum	Nov. 2002
D	1	Buss. Centre, Hamburg	Vattenfall	Nov. 2002
EI	1	Industry Limerick St. John of God Hosp.	SGC	Early 2003
EI	1	Dublin	SGC	Nov. 2002
EI	1	Ht. Raddisson,Limerick	SGC	Early 2003
TOTAL	18			

* The Mariestad installation that runs on landfill gas is presented in detail in chapter 7.2

The economics of micro turbine operation are not currently favourable even with the subsidies provided by the project. The cost per kW has at some sites been up to €1800 to €2000.

The market potential evaluation performed in the context of the OMES project has identified that in all member states the cost of gas and electricity over the past 5 years renders CHP based on micro gas turbines economically unattractive. In most member states the subsidy required to allow micro turbines to compete is unrealistic.

Given the present levels in specific cost for installation, cost related to overhaul & maintenance and the present levels in cost (without taxes) of gas and electricity, make it economically unattractive substituting existing heat sources, based on natural gas, with combined heat and power (CHP), based on micro gas turbines. Consequently, subsidies, in one-way or another, seem necessary for promoting the spreading of small gas turbines that eventually might lead to a new competitive industry.

Only in some special technical applications where a micro gas turbine can be well integrated with other processes (i.e. direct drying or with supplementary firing, giving very high marginal electrical efficiency, or when exhaust gas is used directly for heating and CO₂ fertilization in green houses) the economics can be attractive also with the present levels in cost for gas and electricity. The market potential in such “special applications” is naturally rather limited.

The heat in the exhaust gas for a gas turbine between 20 and 200 kW is approximately between 50 and 400 kW and is too large for typical domestic applications.

Another important issue is the fact that a micro gas turbine has to operate intensively in order to pay back within reasonable time. Three thousand hours of full load operation per year is considered as minimum. This fact sets up restrictions on heat demands in terms of base load and heat storage capacity and limits the number of locations suited for CHP based on micro gas turbines.

The electrical efficiency of micro gas turbines is still rather low compared to larger gas engines and especially to large and central advanced CHP plants. In areas with dense population it is expected



that district heating based on relatively large CHP plants is technically and economically more competitive.

Potential customers for micro gas turbines (public institutions, office buildings, hotels SME's etc.) are most often supplied with a low-pressure natural gas pipeline, implying that a gas boost compressor is required. So far low-speed compressors, which are heavy and large equipment have been used for boosting gas pressure and is considered to be a serious obstacle for the micro gas turbine technology to become successful. Development of a simple, compact and integrated solution, like for instance a direct driven turbo compressor could possibly solve this problem.

These facts limit the potential market for micro gas turbines to some special applications exploiting some advantages of micro gas turbines or to traditional CHP in a market segment characterized by having heat demand between 50 and 400 kW, at least for 3000 hours a year and situated in a rural area.

The level of subsidies that can be expected in the individual member states is uncertain. In order to come up with an estimate on the market potential, instead the required subsidies in the individual member states are calculated based on scenarios reflecting the cost levels on gas and electricity and requirement for annual depreciation. To some extent costs of electricity and fuel can be expected leveled. However this may take long time due to bottlenecks especially in the electricity grid.

The market potential in EU has been estimated roughly based on above considerations and limitations. The market potential in EU-15 for CHP based on micro gas turbines in the non-industrial sector has been estimated to 287.000 units. The average units size is estimated to 61 kW_e amounting to a total installed capacity of 17.5 GW_e.

In the industrial sector, the main market potential is expected to be in integrated solutions like Combined Heat Power Cooling (CHPC), direct drive applications and destruction of Volatile Organic Compounds (VOCs). However, such integrated applications need to be further developed, technically matured and produced in large numbers before a commercial break through can be expected.

The potential for traditional CHP solutions in the industrial sector is estimated much lower. The textile and hotel service sector is expected to be a potential market. The total potential in this sector in EU-15 was estimated to 2400 units having an average size of 175 kW_e.

6.2. CHEP project

“Research and Development of high efficiency components for an intercooled, recuperated CHP gas turbine for Combined Heat and Efficient Power”, contract ENK5 CT2000 00070. [Romier, 2003]. The partners of this project were Microturbo, Promocell, NTUA, Bowman Power, University of Liege, Politecnico di Milano, University of Brussels, ACTE, CEA.

In order to achieve the objective of the project, which was to develop a 350 kW gas turbine of high efficiency, the following two ways were investigated:

- To increase the Turbine Inlet Temperature (TIT), which requires on small gas turbine the development on ceramic components in hot parts.



- To develop new thermodynamic cycles, which are well adapted to a small co-generation gas turbine system.

Since ceramic turbine wheels of this size are not yet available, the project concentrated on a more efficient cycle and the feasibility of the major components of this cycle to satisfy the stringent requirements in terms of pollutant emissions, production and maintenance costs, and, reliability. A parametric study was conducted to compare the simple cycle with the recuperative cycle, the others possible cycles known as recuperative-intercooled cycle recuperative-under-pressurised cycle and recuperative inverse cycle.

Cycle	Recuperative	Recuperative Intercooled	Recuperative Under pressure
Shaft power (kW)	350	350	350
Turbine Inlet Temperature (°C)	950	950	950
Recuperator efficiency	85%	85%	85%
Pressure ratio	4	6	6,25
Expansion ratio	3,43	5,05	5,26
Air mass flow (kg/s)	2,49	1,97	1,97
Recuperator inlet temperature (°C)	676	604	597
Shaft power efficiency	33,60%	35,83%	34,62%
Water return temperature (°C)	40	40	40
Co-gen, thermal efficiency	46,30%	47,6%	51,10%
Global efficiency	80%	83.43%	85.7%
Electrical efficiency (with a generator efficiency of about 92%)	31%	33%	32%

To compare the efficiency of different thermodynamic cycles, the max continuous Turbine Inlet Temperature (TIT) was selected at the conservative level of 950°C (1223°K). The efficiency of all the thermodynamic components as well as the installation conditions, which have an effect on the performance, are fixed in compliance with the following table:

Component	(politropic) Efficiency	Pressure drop	Specific condition
Air inlet		2%	15°C (288°K)
Compressor	0,82		
Combustion	0,99	4%	
Recuperator efficiency	0,85 (conservative value)		
Recuperator Air side		2%	
Recuperator Gas side		5%	
Turbine	0,82		
Water boiler (co-gen)	0,75(conservative value)	2%	
Water return temp			40°C (313°K)
Gas exhaust		2%	



This parametric study lead to the following main conclusions:

- The classical recuperative cycle presents an optimum of mechanical efficiency for a turbine expansion ratio of about 3.5:1 which requires an higher airflow to develop the power of 350 kW than the other cycles (figure 12)
- The recuperative-intercooled cycle is the most efficient cycle for an expansion ratio of about 6,5:1.
- The recuperative under pressure cycle is the most efficient in term of global efficiency in co-generation application.

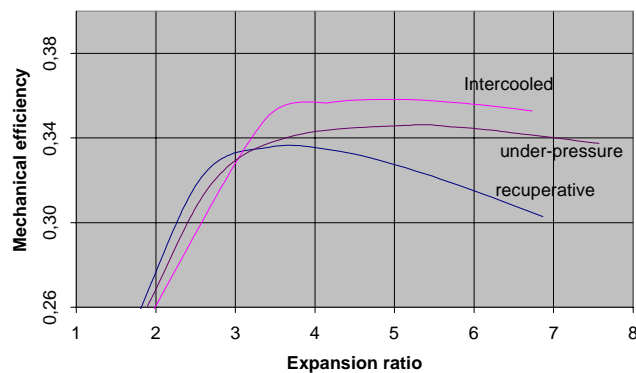


Fig 12 Mechanical efficiency for various cycles

The choice was thus made to develop the unit with the recuperative- intercooled cycle. The overall mechanical arrangement of the system is shown in figure 13:

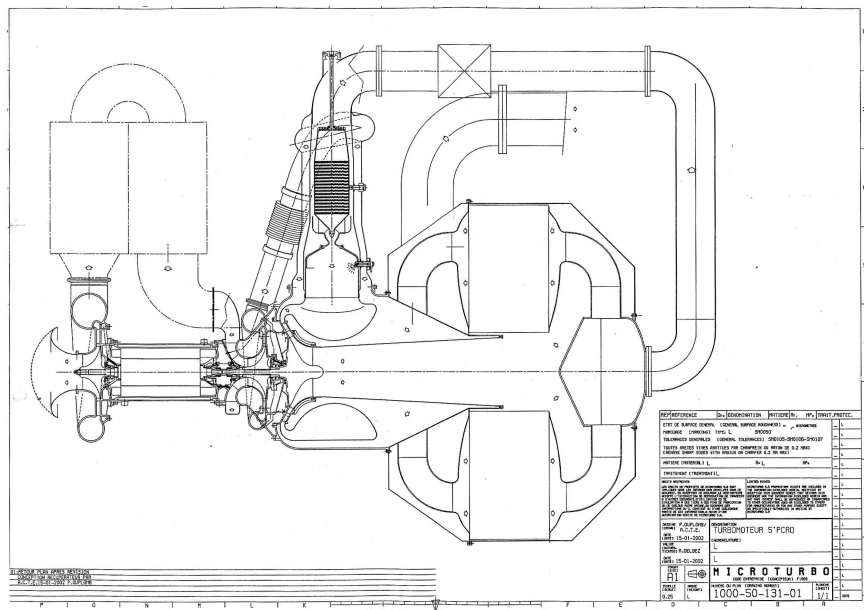


Figure 13 Mechanical arrangement of CHEP 350kW gas turbine



The 350 kW recuperative intercooled gas turbine unit has three thermodynamic rotating components, which are: Compressor 1, Compressor 2, after the intercooling heat exchanger and the Turbine wheel that is either radial or axial with two stages. The main characteristics of these components are shown below.

Parameters	Compressor 1	Compressor 2	Turbine
Nominal speed (rpm)	40 000	40 000	40 000
Air mass flow (kg/s)	1.97	1.97	1.97
Inlet temperature (°C)	15	51	950
Pressure /expansion ratio	2.45	2.45	5.05

Note that the first compressor and the High Speed Alternator are on the same shaft. The second stage compressor with the radial turbine are on a separate second shaft.

The high speed generator and the associated power converters were designed and developed to be able to provide 400kW at full load, at 42,000 rpm, at 1,400Hz. The generators rotor is air cooled but the stator needs to be cooled by either water or oil.

A spiral type recuperator with an annular shape was developed with an efficiency of approx. 88% and a weight of 426kgs.

A catalytic combustor was developed for the CHEP micro gas turbine, based on 2 steps of combustion:

- step one is a Catalytic Partial Oxidation (CPO) in rich condition, it can be considered as a fuel processing system, without NOx emission
- Step two is a homogenous combustion operating in very weak conditions. Due to high dilution, combustion, with H2 high percentage, is done at low temperature, thus keeping NOx emissions low.

The syngas issued from the CPO stage, at a temperature of 950°C is mixed with a high quantity of air at the homogenous combustion inlet. This poor combustion, at low flame temperature (<1600°C), is stabilised by the H2 contain in the syngas. A specific burner is necessary to avoid any flash back

6.3. MICRO-TRIGEN

“Micro-Trigeneration and Integrated Energy Services in South of Europe and Brazil”, contract NNE5 – 2001 – 00275 [Dias 2003]. The partners of this project were ECOGEN (P), CEEETA (P), TURBEC AB (S), CRYOGEL, SA (F), EFIENSA – EFICIÊNCIA ENERGÉTICA, S.A. (E), EDP – Electricidade de Portugal, S.A. (P), COGEN Europe.

The project aimed at demonstrating an innovative integration of three technologies: micro-turbine, hot water fired absorption chiller and ice storage thermal system, and also to demonstrate the main benefits resulting from the activity of Energy Services Companies while using the microtrigeneration systems and a flexible financing mechanism. The project further aimed at contributing towards the development of European micro-turbine technology through the experience obtained and to present new perspectives for application, namely in South Europe.



The project involved the identification of three end users in three different countries, namely Portugal, France and Spain. Each micro-trigeneration installation would be developed following a detailed energy audit and a study for the minimisation of energy losses through an intervention on RUE measures, plus a detailed techno-economic analysis. An innovative financing scheme would then be developed in the scope of the integrated energy service proposed, which included trigeneration, installation, maintenance and energy management. A low initial investment for the customers (approx. 40% of total equipment and installation cost) would result from this financing scheme.

Resolution of legal and institutional issues was also addressed by the project, in order to provide regulators and policymakers with information that aimed to contribute towards the development of strategies and policies for micro-power and ESCOs activity. The project aimed at contributing towards the development of micro-power systems certification, installation standards and grid interconnection norms. An assessment of external costs was also to be undertaken in the context of this project.

The proposed system is based on the TURBEC T100 micro-turbine for the production of heat and power, and a hot water fired absorption chiller, where the hot water was provided by the micro-turbine. The system provides an electrical load of 100 kW and a heat load of 154 kW in the form of hot water or a heat load of 102 kW in the form of cold water.

Initially efforts were undertaken by partners to identify end-users on one hand and estimate the technicalities of satisfying their demand in power, heat or cooling. The first potential end-user was an office building belonging to a Ministry. This user was abandoned because the detailed analysis showed that:

- The selling of electricity to the grid is by itself not economically viable, the use of the microturbine should thus always be considered in CHP mode
- The power demand of the particular building was 50% of the nominal power of the micro-turbine, meaning that the remaining power should be exported
- The heat demand was however less than 30% of the nominal capacity of the microturbine while during the period when cooling was required, this was 70% of what the microturbine could offer at nominal capacity
- The subsequent analysis showed that the application of the system to this particular building would lead to an increase of the energy bill by 3600Euro per annum
- Considerable refurbishment work would need to be done in order to install the microturbine based system in this building

The second potential end user was a building construction company that was developing its headquarters. This possibility also failed due to:

- Unclear legal and institutional framework (for the case of Portugal)
- the safety requirements for the interconnection of micro-cogeneration systems to the utility network are still undefined (for the case of Portugal)
- lack of confidence that performance targets will be met, independently of environmental conditions
- lack of concrete figures for major components of the cost analysis like favourable NG prices for CHP applications



- high capital cost, specially of adsorption chiller
- project would only become economically viable if:
 - 100% of the thermal energy produced could be sold to the customer on the basis of the application of a discount of 10% over the customers' thermal energy production cost
 - 50% of the electricity produced by the system could be sold to the grid at a value corresponding to the low voltage tariff plus a bonus of 0.015 EUR/kWh
 - 50% of the electricity produced could be sold to the adjacent buildings (for which the low voltage tariff apply)
 - The costs for interconnection and insurance could be neglected (when comparing with the other costs),
- Under the previous conditions the project would present an Internal Rate of Return of only 3.5% and a payback period of 8 years.

The project has thus been abandoned. Confidence in microturbine technology has not been lost however, with the project co-ordinator ECOGEN wishing to concentrate on simpler microturbine based systems (CHP) and re-visit trigeneration when conditions are more favourable.

6.4. CAME-GT

CAME-GT is a Thematic Network project supported by the European Commission in the Framework V RTD Programme. The main participants are ALSTOM Power, Rolls Royce plc, MAN GHH BORSIG, DLR, Vrije Universiteit Brussel, GASTEC and Siemens.

The objective of this Thematic Network is to co-ordinate RTD projects in industrial gas turbines, covering fossil fuels and biomass and gas turbines in CHP applications and combined cycles. Comparison with international programmes will prioritise key issues for the future and these will be used to recommend the future direction of RTD programmes in gas turbines and contribute to the development of a gas turbine sector Strategy Plan.

The following 16 EC projects related to turbomachinery have been included in the network, under four separate clusters:

Acronym	Project Title	Cluster
DITCAD	Development of innovative techniques for compressor aero-mechanical design	Turbomachinery
DAIGTS	Design and off design optimisation of highly loaded industrial gas turbine stages	Turbomachinery
FLAMESEEK	Flame sensors for efficient gas turbine engine cycles	Combustion
PRECCINSTA	Prediction and control of combustion instabilities for industrial gas turbines	Combustion
FLOXCOM	Low NO _x FLOX combustor for high efficiency gas turbines	Combustion
NGT		Combustion
DESIRE	Reliable low NO _x combustor	Combustion



FUELCHIEF	Low NOx staged rotor	Combustion
AFTUR	Alternative fuels for gas turbines	Combustion
CINDERS	CMC integration and demonstration for gas turbine engines	Materials
ALLBATROS	Advanced long life blade coating system	Materials
NANOROTOR	Hardened ferritic steel rotor	Materials
CAME-GT	Thematic network for cleaner and more efficient gas turbines	Systems
LOTHECO	Combined cycle power plant with integrated low temperature heat	Systems
CHEP	Research and development of high efficiency components for intercooled, recuperated CHP gas turbine for combined heat and power	Systems
GT-POM	Thermo-economic optimisation of whole gas turbine plant	Systems

In the context of CAME-GT two International Conferences and four Workshops and have been organised. Some important points on gas turbines (GTs) raised during the Combustion workshop held on November 13th and 14th 2003 were that:

- GTs will be the main power generation technology till the year 2050
- GTs will be able to utilise fossil fuels, syngas and hydrogen, with RES contributing to the energy mix but not in a major way
- the US dominates the GTs market, having 80% of the current market for large GTs and 70% for the small ones.
- the US is investing 1 billion \$ to the Futuregen project, aiming to produce electricity and hydrogen with CO₂ sequestration
- the US is expecting a 100 billion \$ benefit by 2020 from its GTs business
- The European GT industry has undertaken the POWER21 initiative that aims to describe the technology path towards a low and zero emission power plant, through the realisation of ambitious “lighthouse projects”
- In parallel, a Specific Support Action titled FENCO has been initiated within the EC FP6 ERANET Scheme that will establish the basis for a Concerted Action and hence an ERA in Low Emission Fossil Fuel Power Plant
- there are currently 3 IPs funded by the EU on power generation projects (8M€ each) but all are on CO₂ capture and sequestration
- the lack of EC support on turbomachinery related projects was mentioned and a desperate call was made for delegates of CAME-GT to talk with National experts so that they can ask for GTs to be reintroduced in FP7
- there is a need for the EC to form a long-term vision on power generation from fossil fuels, a vision beyond single FPs



6.5. Externally fired biomass-driven gas turbine

“A fluidised bed air biomass gasification CHP plant with an externally fired evaporative gas turbine cycle”, contract BM/367/92-BE [Maniatis, 2004]. The partners of this project were the Vrije Universiteit Brussel (VUB), Seghers Better Technology, Volvo Aero Turbines and DECOMETA.

A externally fired installation with a power of 500kW has been developed at the VUB campus. The installation aimed at demonstrating a reliable wood fuelled CHP plant using an air blown fluidised bed gasifier and an externally fired gas turbine cycle. Power and efficiency were boosted by evaporation of hot water into the gas turbine cycle.

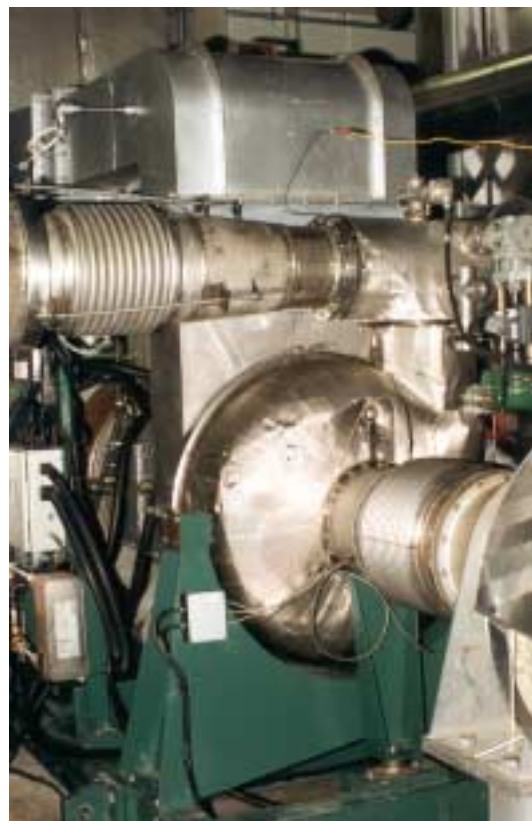


Figure 14 Pictures of the externally fired gas turbine plant: the gasifier flaring the gas (left) and the gas turbine with the external firing arrangements (right)

The main incentive to opt for external firing is to reduce the gas cleaning problems encountered in internal firing and to take advantage of the potential higher efficiency of a gas turbine cycle compared to a steam turbine. The main problem with the gas cleaning is the efficient and environmentally safe removal of tars. With external firing, the tars are not condensed but are burned with the hot gas in the combustion chamber of the heat exchanger, eliminating one of the most critical problems of biomass gasification. The critical component in such a process becomes the air heater which can be made in metal or ceramic materials. The heater chosen was metallic both for technical and economical reasons: ceramic pressurised heaters were not available at the time (1992) and would be too expensive anyway.



Wood was fed from a one-day capacity silo to the fluidised bed gasifier at a flow rate of some 400 kg/h. The air factor ranged between 0.25 and 0.3 producing a gas with a calorific value of 3.5-4 MJ/kg (excluding tars). The bed temperature was about 700°C. The produced gas was de-dusted by a single cyclone to a dust content lower than 500 mg/Nm³. The expected gas temperature was about 600°C, which was high enough to avoid tar condensation. Plant efficiency ranged from 23 to 27%, achieved through water injection.

6.6. Further EU and US R&D activities

A number of institutes in Europe and in the world are involved in research in the field of microturbines. Current research focuses on:

- advanced cycles including hybridising with fuel cells
- NO_x reduction
- alternative fuels in relation to suitable gas turbine concepts

A non-exhaustive list of some recent scientific references is presented in the Annex of this study, to whom the reader could refer to for a detailed study of the state-of-the-art in research in this field. The research activities of two European laboratories that have been visited in the context of the current study are described below. Further to this, the significant US support framework for microturbine research is also presented.

ISET, University of Kassel. The R&D division of the Biomass and Energy Conversion section of ISET based in Hanau has realised an installation for testing microturbines that run on fuels with varying heat content. A 28kW Capstone micro turbine has been installed in their labs [Krautkremmer 2003] and will form the basis of a research programme consisting of 3 parts, involving:

1. detailed measurements to determine efficiency in terms of varying fuel calorific value plus control strategies
2. verification of measurements and control strategies in field tests, exhaust gas quality, damages report
3. simulations with numerical tools, integration with grid simulation software

In the context of the present study, a visit was organised at the above mentioned premises of ISET in Hanau on the 15th of November 2003. The meeting was hosted by Dr. B. Krautkremer and Mr. J. Muller. The visit involved a tour of their laboratory facilities. These included a large “ware-house” type of building that included a portable unit in containers for biogas production through anaerobic digestion, heat engines for the energy conversion of the produced biogas, a lab for chemical analysis and an adjacent metal workshop. The energy conversion devices consist of a Sterling engine and an internal combustion engine that both run on the locally produced biogas and a microturbine that runs on syngas (figures 15 and 16). This syngas consists of CH₄ and CO₂ and its composition can be varied through a system of valves, pipes and a buffer tank.

The microturbine has been run on various syngas mixtures ranging from 40%-100% methane. There were some problems with combustion stability. Typical synthesis and quantity of gases for stable combustion is 60% CH₄ and 40% CO₂ at 20kg/hr pf fuel and 40% CH₄ and 60% CO₂ at 39kg/hr pf fuel. Other points that have been identified by ISET as important for stable combustion of biogas or landfill gas are the removal of moisture from the fuel (any droplet formation would block tubes and



cause corrosion) and the existence of a pressure regulating valve upstream of the microturbine. Another important conclusion is the fact that the quantity and quality of gas produced at a landfill can vary considerably, while the particular microturbine has a manual setting for the “fuel index” that adjusts some combustion parameters (burners, etc). ISET is thus developing a simple and robust method for relating the landfill gas analysis to an automatic setting of the “fuel index”. Tests are to be performed on the effect of varying the fuel index on efficiency and emissions.



Figure 15 General view of part of ISET lab with biomass energy conversion devices, including from left to right: microturbine, biogas IC engine, Stirling engine



Figure 16 The Capstone microturbine of ISET that runs on syngas (methane and CO₂)



The Laboratory of Thermal Turbomachines of the National Technical University of Athens (LTT/NTUA) is another research institution that includes microturbines in its research subjects. There are over 30 people at LTT/NTUA working in several research areas related to turbomachinery components and their application in energy, aeronautics and ground transport [Papailiou, 2003].

There are three sub-groups covering respectively the fields of CFD, Monitoring and Fault Detection of Gas Turbines and Design / Analysis of Turbomachinery Components. The third group has been activated particularly in small size turbomachinery components targeting high efficiencies. Although the applications ranged from micro gas turbines to air machines and chargers, the main field was that of micro turbines for energy and, transport, as this is demonstrated by the projects undertaken, funded by the European Commission, which were TETLEI, ULEV-TAP, STR and CHEP.

A particular effort was made, in order to develop a vertical approach to design, which included aerothermodynamic design optimisation with in-house software, structural integrity and rotor dynamics computation, mechanical design and testing in facilities, which were developed in the Lab. The innovative design approach adopted has lead to significant gains in the efficiency of compressor wheels that are suitable for microturbines, as shown in figure 17.

The expertise of LTT/NTUA in monitoring and fault detection systems in gas turbines was used in order to design a micro gas turbine system for the EC project TETLEI. Testing was realized on the installations developed in LTT/NTUA, two of which are shown in the figure 18, depicting the compressor and turbine testing facilities. Other installations exist, which may be found, along with a more detailed description of LTT/NTUA in the web site <http://www.ltt.ntua.gr>

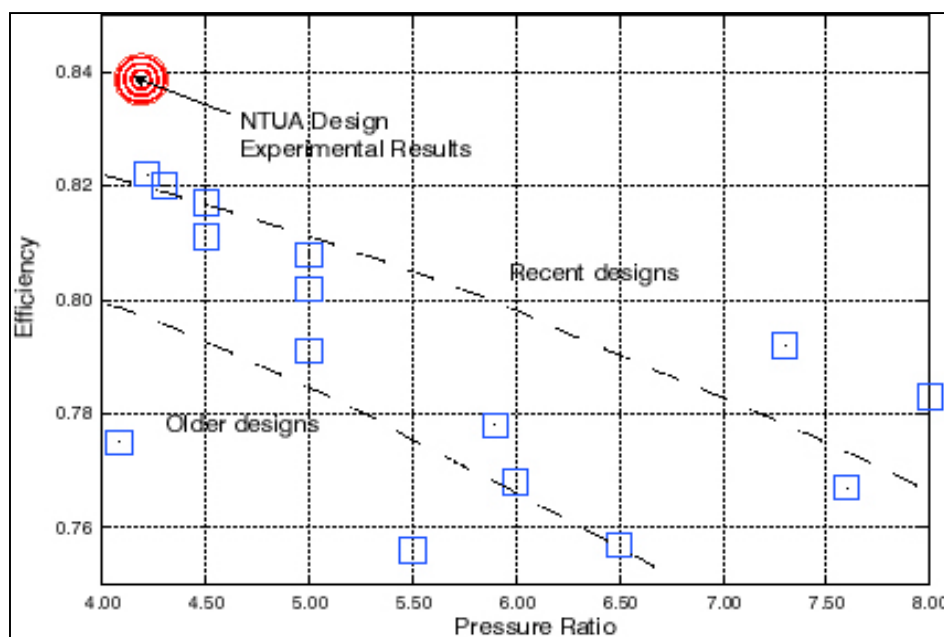


Fig. 17 Experimental total-to-total efficiency comparisons between centrifugal compressor designed by NTUA and other compressors.

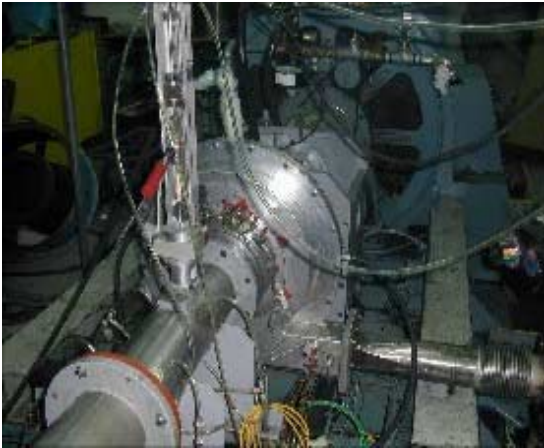


Fig. 18 The 400 KW, 80000rpm Compressor Test Rig (left) and Cold Turbine and Gas Turbine Test Rig (right) of LTT/NTUA

In the US the DOE is, in accordance to its Distributed Energy Resources (DER) programme, investing in microturbines. A baseline microturbine testing programme was concluded in 2000 and the present Advanced Microturbine Systems Program lasts from 2000 to 2006.

The “**Baseline Microturbine Testing**” program was concluded in 2000 and had a budget of \$2.1 million. It was performed by Southern CA Edison and the University of California-Irvine. Its goal was to determine the availability, operability, reliability and performance characteristics of commercially available microturbines. A dedicated testing site was developed capable of running 4 units simultaneously. Units from Capstone (28 and 30kW), Bowman (35 and 60kW), Elliot and Honeywell (75kW) were tested for a variety of conditions and operating hours and verified the performance figures claimed by manufacturers, while at the same time identified some problem areas (e.g. overspeed) that were corrected.

Aiming to “keep US manufacturers on the cutting edge of turbine technology and to enhance the competitiveness of US products in international markets”, the US DOE launched the **Advanced Microturbine Systems Program** Plan of the US for Fiscal Years 2000-2006. The funds available for this programme amount to \$63 million of public funding, indicating the importance the US government places on microturbines as a competitive solution for distributed energy sources applications.

The technical and economic aims of the programme are to contribute to the development of ultra-high efficiency and low emission microturbine engine systems [Microturbines programme web site]. The specific targets of this programme are:



- High Efficiency — Fuel-to-electricity conversion efficiency of at least 40%, with an overall efficiency in CHP mode of 80%
- Environment — $\text{NO}_x < 7$ ppm (natural gas)
- Durability — 11,000 hours of reliable operations between major overhauls and a service life of at least 45,000 hours
- Cost of Power — System costs $< \$500/\text{kW}$, costs of electricity that are competitive with the alternatives (including grid) for market applications. Maintenance costs as low as $0.011\$/\text{kWh}$
- Fuel Flexibility — Options for using multiple fuels including diesel, ethanol, landfill gas, and bio-fuels

The programme's R&D activities have been organised in four main programme areas:

- Concept development
- Components and systems development and integration
- Demonstrations
- Technology base (materials, combustion systems, sensors, controls)

Following a solicitation phase various projects were selected within the Advanced Microturbine Systems Programme, involving [Haught, 2000]:

- Ingersoll-Rand's microturbine with a power range of 100-250 kW, ceramic turbine wheel and 40% efficiency
- Capstone plans to develop a 100-200 kW unit that includes ceramic components and makes use of an annular recuperator
- Honeywell aims for a 300+ kW microturbine building on the Parallon 75 unit
- UTC plans to develop a 400kW unit with a 30% electrical efficiency
- GE will be developing a 175-350 kW unit
- Solar turbines aims to improve recuperator performance, increasing turbine exit capability from 650°C to 730°C

The use of ceramic materials and coatings as means to increase the efficiency and operability of microturbines is one of the key areas of research. Thus the effects of temperature, pressure, water vapour, and other gas species typical of advanced microturbines on the environmental resistance and mechanical stability of candidate Si_3N_4 ceramics will be investigated. Some conclusions would thus be of relevance to systems firing biomass derived fuels that could include corrosive contaminants.

Besides the previous Advanced Microturbines Systems Programme there is plenty of R&D activity in the field. An example relevant to the current study is a proposal for an externally fired microturbine concept that was recently submitted by a consortium of US partners lead by the University of California, Davis [USDA proposal, 2003]. The proposed system involves a combined gasifier and combustor unit for woody biomass (wood chips less than 5cms and with a 5-55% moisture content), a heat exchanger, the gas turbine (Capstone) and the heat recovery unit. Another innovation is the application of this system, which involves using woody biomass that has been removed from forests in order to reduce the fire risk hazard, a concept that would fit many European countries with arid climates.



7. CASE STUDIES

7.1. Turbec T100 running on sewage treatment gas, Kilmington, UK [Burgess, 2003]
South West Water (SWW) operates a sewage treatment plant in Kilmington, UK. Reciprocating combined heat and power (CHP) engines have been used to utilise the gas liberated from the sewage digestion process (62% methane, 38% carbon dioxide). SWW recently decided to install a microturbine for improved electricity and heat output, greater saving in greenhouse gas emissions, lower noise levels and minimal exhaust emissions. In May 2003 SWW thus replaced the ageing 30kW_E reciprocating CHP units at Kilmington WwTW with the UK's first sewage gas microturbine CHP unit¹, the 105kW Turbec T100.

Kilmington's new T100 is capable of generating more than three times the power of one of the engines it replaces and is well matched to the site's methane gas production. The T100 utilises all of the available gas to generate electricity and heat rather than allowing excess gas to escape to atmosphere or needing to be burnt for disposal - which is both environmentally damaging and wasteful. The sludge digestion process has also improved with the installation of the T100 as the heat recovered is available at higher temperatures than with the old engines; this is as a direct result of the new unit providing the digester heating system with a much needed boost in efficiency.

The T100 will generate over 500MWh of renewable electricity per year, most of which will be used to power process equipment at the Kilmington WwTW site, this generation will avoid over 215 tonnes of the greenhouse gas CO₂ being emitted each year. Additionally, exhaust emissions will be reduced; Oxides of Nitrogen (NO_x) are less than 15ppm, Carbon Monoxide (CO) are below 15ppm and unburnt hydro-carbons are reduced to below 10ppm.

The T100 unit runs quieter and because it has less moving parts has a less intensive maintenance programme. Because it is embedded in the site it does not require the use of the UK's power transmission and distribution networks and thus it helps avoid costly reinforcement of the country's network.

SWW have mitigated their risks by setting up a deal with NewEnCo who agreed to offer the microturbine unit free of charge as a result of Turbec's discounted energy purchase scheme (DEP), this meant that there was zero capital outlay required by South West Water to undertake the project.

Kilmington treatment plant

South West Water receives and treats more than 750 cubic meters of waste water every day. This waste, comprising around 98% water and 2% solid matter, is received at some 600 treatment works across the operating region. Here the solids are separated from the water to form a sludge and the two products are then separately treated using mechanical, chemical and biological techniques.

One sludge treatment method employed by the company is digestion, where the sewage sludge is warmed in large vats to allow a biological process of digestion to take place over a period of time.

¹ The UK has many natural gas fired turbines but this is the first known in the country to run on sewage biogas (62% methane, 38% carbon dioxide).



During digestion, the volatile components of the sludge decompose and biogas, with a typical composition of methane (62%) and carbon dioxide (38%), is evolved.

Biogas is generally burnt in a hot water boiler which is then used to provide the hot water for warming the digestion process. There is generally an excess of gas produced beyond that required by the boiler and so this is flared to prevent.

Small scale Combined Heat and Power (CHP) units on the other hand can be used to not only provide the heat required for the digestion process but also to generate a useful amount of electricity. SWW has seven such CHP plants in operation at the larger digestion sites.

One of these sites is Kilminster WwTW, near Axminster in East Devon. The sludge digestion plant at Kilminster was constructed in 1990 and as part of the digestion centre design, two, small 30kW_E CHP units were installed. The operating regime at the time was one unit working continuously with the other one working part time as gas production allowed.

In 1994, the digestion facility was extended with the addition of another digester. The additional heat load placed extra strain on the CHP units with the effect that over the years, they became a little troublesome and demanded more maintenance time. Spares were also becoming difficult to find as the market was tending to move away from smaller reciprocating engine CHPs, particularly where fuelled by biogas.

A review of the company's CHP plant showed that the Kilminster units were not as reliable as they should be, were expensive for spares and maintenance and did not support the treatment process adequately. With the replacement of the old CHP units at Countess Wear completed, it was time to consider the options for Kilminster. It was known that the gas production would support a unit of 100kW_E, but space was limited.



Fig. 19 The 30kW_E reciprocating engines at Kilminster WwTW in-situ prior to removal



The T100 Microturbine

It was around the time that Kilmington was being investigated that the T100 was developed by Turbec (1998). This unit is suited for continuous operation over long periods of time and it is designed for a 60,000 hour lifetime with simple maintenance every 6000 hours and a major overhaul at 30,000 hours. The T100 well matched to the gas available on site and would fit into the space that would be vacated by one of the smaller reciprocating engines and yet generate more than three times the power. Additionally, in recognition of the new technology being used Turbec were offering the first biogas units on a discounted energy purchase scheme (DEP) which meant that there would be zero capital outlay required by South West Water to undertake the project.



Fig. 20 The Turbec T100 gas turbine unit in-situ in the Kilmington WwTW engine house

The DEP is a flexible, cost-effective energy trading arrangement with reasonable security for NewEnCo and minimal risk to South West Water. NewEnCo provide free of charge the T100, to which biogas is delivered at a quantity and a quality that is acceptable to both parties. Electrical energy produced by the machine is purchased by SWW at a fixed unit rate (comparable to our current energy purchase rate from the national grid) and thermal energy is provided free. The DEP was underpinned by the fact that the T100 was replacing an existing CHP engine meant that much of the required pipework and ventilation was already in place.

Electricity generated by the T100 is largely consumed on site with any excess, depending upon the site demand at the time, exported. Under government rules all the electricity produced is eligible for Renewables Obligation Certificates, these can then be sold with the result that both NewEnCo and SWW receive an adequate income to support the project.

Having struggled on for a number of years with the old equipment at the site, the operators welcomed the possibility to use a microturbine. The turbine technology was recognised as superior to an equivalent reciprocating engine and even more attractive due to the benefits over the current plant installation - the higher temperatures from the turbine would certainly give their digestion process a much needed boost. This would provide a better quality and secure treatment process, consume all of the methane gas that they were producing and produce green electricity for the site and for export.



Operation so far

The Turbec unit was installed and ready for operation in May 2003. The first week proved difficult when an unknown mismatch of phase voltages meant that the unit could not synchronise successfully and kept stopping. A solution was found and generation commenced – for a while. Further problems did show. July saw a problem with flies blocking the air inlet filters. August brought some more problems as a recurrence of the voltage mismatch became apparent. These shut downs also gave rise to an additional problem of cracked fuel caused as the material cools due to operating with ‘hot’ gas from the digesters.

Environmental benefits

To date, the Turbec T100 has produced over 150,000 kWh of renewable energy, the equivalent annual energy consumption of 50 homes, and has prevented the release of over 65 tonnes of CO₂ from other generating sources. The turbine makes best use of the available biogas resource on the site without needing to wastefully flare excess gas or vent methane to the atmosphere. The small physical footprint of the unit has allowed the reuse of much of the existing infrastructure on site and has meant that no new civil engineering has had to be undertaken.

Conclusion

In recognition of the potential that the Turbec micro-turbine has shown in coping with poor quality biogas, SWW are soon to take delivery of a second unit at its Totnes WwTW. This plant suffers from very high levels of hydrogen sulphide and so would not be suitable for a conventional reciprocating engine CHP.

7.2. Mariestad sewage treatment plant , OMES EC project [Noren 2003]

General description

A T100 prototype was installed late 2001/beginning 2002 at the Mariestad sewage treatment plant. It was designed to run on the raw biogas from the sewage treatment plant. The turbine should produce heat and electricity for internal use at the plant, replacing an older oil fired boiler.

Function

The turbine room is situated just next to the digestion chamber. Raw biogas is fed through pipes and dried to a dew point of about 5°C (ambient pressure) and then compressed and fed to the T100. Promised gas production was initially exceeding 800 Nm³/hr but actual production is about 400 Nm³/hr.

Initially, it was decided to go ahead with the 800 Nm³/hr and run the turbine on part load (50-80%). Unfortunately, the gas production didn't improve after the tuning of the digestion chamber. It was only possible to run the turbine on 20-25 kW_e. The first problem was moisture in the gas, this was solved with an additional water separator. The main problem now is the low gas production.

Installation costs:

T100: 80.000 €



Fig. 21 The Mariestad Turbec T100.

Remarks

- Poor functionality, gas production is less than 50 % of what was initially promised. It is only possible to run the unit at about 20 kW power.
- Gas compressor and combustion chamber changed late 2002.
- Compressor wheel had to be replaced due to damages caused by moisture content of fuel, problem eliminated since drier was installed
- Original combustor damaged during initial tests, was replaced with a similar combustor

The unit was eventually moved to another biogas site due to lack of sufficient amounts of biogas.

7.3. US Case studies

There are indeed very few microturbines that run commercially on biofuels in Europe. The vast majority is installed in the US, running on landfill gas or gas from sewage treatment plants. Indeed, biogas applications in the US are considered to be amongst the most promising market for microturbines in the US, as commented in chapter 8.4. The following table shows a picture of this market [Hurley, 2003].

<i>Manufacturer</i>	<i>Model name</i>	<i>Model capacity (kW)</i>	<i>Status</i>	<i>Number of units running on biogas</i>
Capstone	C30 Biogas	30	commercial	215
Ingersoll Rand	EcoWorks	70 and 250	commercial	10
ETTI	TCGT	100	prototype	1
FlexEnergy	Flex-Microturbine	30	prototype	1

An overview of some US installations utilising Capstone and Ingersoll Rand microturbines is presented in the following tables [Benson 2003]



Project	total capacity (kW)	CH4 (%)	H2S (ppmv)	Siloxane D4 (ppbv)	Siloxane D5 (ppbv)	TOTAL (ppbv)
Jamacha Landfill	280	35 – 40	20	113	54	232
Calabastas Landfill	300	45 - 50	75	200	140	705
Oii Landfill	420	35 – 40	60	145	112	690
Acme Landfill	280	45 - 55	50	3158	884	5898
Butterfield Landfill	70	35 - 40	10	-	-	-
Mountain View Landfill	140	40 - 45	-	-	-	-
Allentown Wastewater Plant	390	62	800	164	1380	1600

The project cost can be broken down as follows, in k\$

Project	Design	Elec.	Well field	Pre-treatment	Infra-structure	Total cost	\$/kW
Jamacha Landfill	60	80	40	190	30	700	2,500
Calabastas Landfill	50	95	20	185	25	770	2,570
Oii Landfill	109	220	30	190	170	1,300	3,095
Acme Landfill	50	40	-	20	25	425	1,520
Butterfield Landfill	35	20	-	60	15	190	2,710
Allentown Wastewater Plant	50	55	-	200	30	-	-



Figure 22, Ingersoll Rand microturbines at Jamacha landfill, California



The largest landfill-based microturbine installation in the world is at the Lopez Canyon Landfill - Lake View Terrace, California, where 50 Capstone C30 units have been installed, with a total capacity of 1.5 MW. The landfill gas is pressurized to 80 psig then chilled to 4°C to remove moisture. The reheated gas temperature is kept at a minimum of 10°C above its dew point. Further treatment of the gas includes reducing siloxane content to less than 5 parts per billion. All other gaseous components are destroyed in the microturbine combustion chamber.



Figure 23, the Lopez Canyon landfill, California

A detailed presentation of this landfill site is presented at the web site of Global Energy (<http://www.globalmicroturbine.com/landfill.htm>) along with a very thorough listing of reports and publications on microturbines that utilise landfill gas.



8. MARKET POTENTIAL OF MICROTURBINES

There is a tremendous amount of uncertainty about the market potential for microturbines on one hand and biomass fuelled CHP applications on the other. This would mean that a combination of the two, a microturbine driven by biomass-derived fuels would have a very limited market potential. However, there are some such “niche” applications that are viable, namely landfill sites and sewage treatment plants.

Microturbines are the kind of disruptive technology that, in the right market conditions, will cause users to abandon the business-as-usual practice. There is indeed considerable interest from various sectors of economic activity to install microturbines, including the industrial, commercial and residential sectors. In the industrial sector, microturbines would be attractive in the chemicals, wood, paper, agricultural products processing, textiles industries. In the commercial market, office buildings, food and retail services, hospitals and educational facilities could well apply microturbine based CHP. Lastly in the residential sector apartment blocks or centrally based community systems could install such appliances. All potential applications would need to cover a demand for electricity and heat. The most favourable case for microturbines would be to cover simultaneous power and heat “base loads”, as a clean power source for distributed generation applications.

A number of studies have been undertaken in the past in Europe and the US on the market potential of CHP systems, on the potential of biomass based CHP and on the potential of microturbines. A brief summary of these studies is presented below.

8.1. Market potential of cogeneration

The European Commission calls for a doubling of cogeneration from 9% in 1997 to 18% by 2010. The “future COGEN” SAVE project (completed in 2001) aimed to assess the future of cogeneration in Europe [COGEN web site]. The project utilised the SAFIRE model to study 4 different scenarios, namely “present policies”, “heightened environmental awareness”, “deregulated liberalisation” and the best case “post-Kyoto”.

Simulations showed that it was only the post Kyoto scenario that could reach the 18% target. There are two factors that keep the percentages of cogeneration low, firstly, electricity generation is predicted to increase by 30% between 1995 and 2010 and secondly the observed lower-than-expected penetration of cogeneration. What is worthwhile to observe in figure 24 is the fact that the EC target of 18% can only be reached if microgeneration is included, if that is the microgeneration market is successfully created.

The fuels that will fuel this predicted impressive growth in cogeneration have also been investigated in the study. The trends show a replacement of coal and heavy fuel oil with Natural Gas and to a lesser extend with biomass. The cogeneration capacity for the post Kyoto scenario is shown in Figure 25. The total capacity triples from 67GWe to 193GWe. Natural Gas cogeneration almost quadruples from 35 GWe to 135 GWe. Biomass is expected to grow from 2GWe to 20GWe, while wastes show an increase from 2 GWe to 17GWe, or a total of approximately 40 GWe for biomass and waste derived fuels if biogas is included. Assuming that 18% of this is the capacity of micro-cogeneration plants, then this amounts to a market of approximately 8GWe.

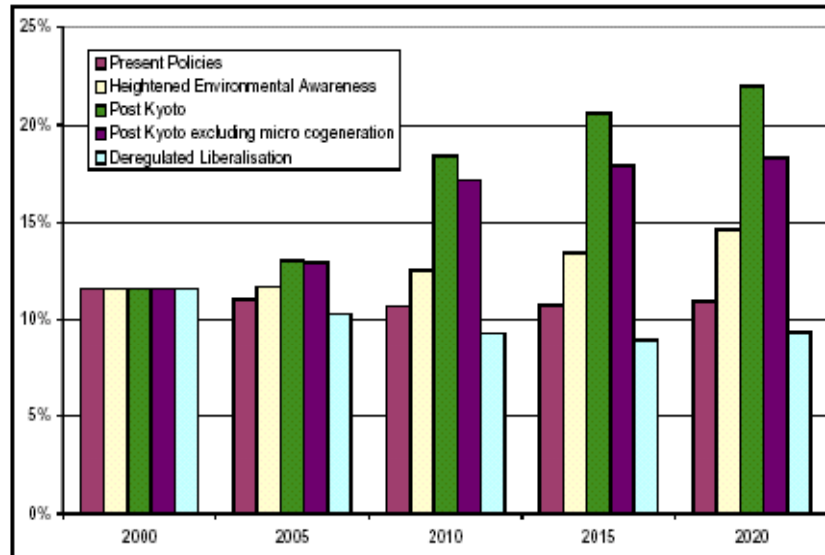


Figure 24 EU cogeneration electricity output, as a portion of total electricity generation [future COGEN, 2001]

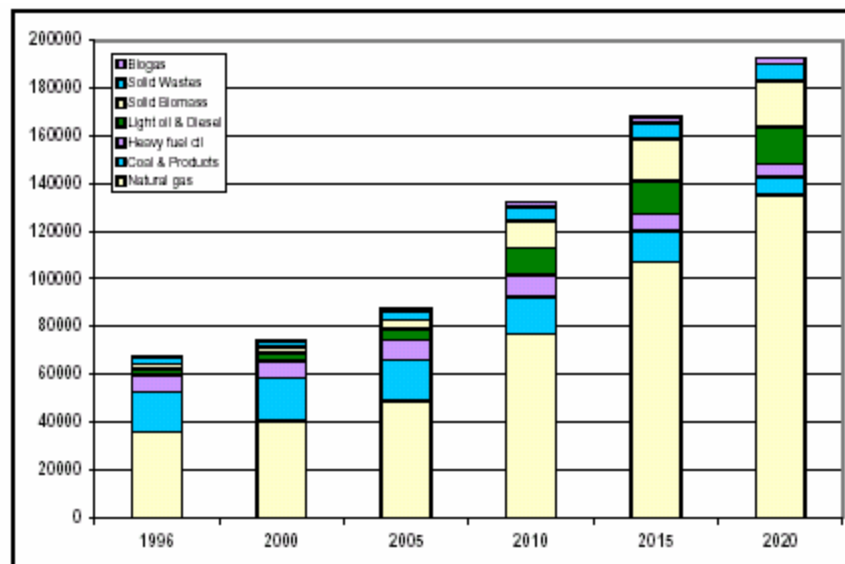


Figure 25 Evolution of EU cogeneration capacity by fuel for the “post Kyoto” scenario [future COGEN, 2001]

A key finding of this study was the determination of the effect that the policy and market conditions have on the growth of the cogeneration market and in particular the determination of the link between



the size of a cogeneration plant and its sensitivity to market conditions. This sensitivity is shown in figure 26 of the study.

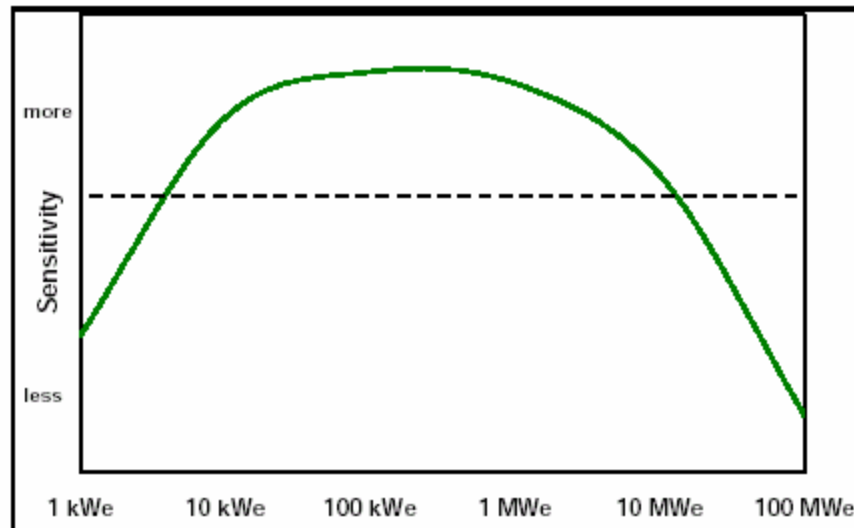


Figure 26 cogeneration risk graph.

The vertical axis of figure 26 represents the risk of a cogeneration investment. Any investment below the dashed horizontal line is likely to become economic in the long term. Referring to the graph, it can be seen that cogeneration plants below 10kW and above 50MW are less sensitive. These are expected to be cogeneration plants developed by utilities that are less exposed to market risks. Microturbine based cogeneration plants range from 30 up to 1000kW (through multiple units) are obviously “high risk”, with a high sensitivity to market conditions, since such applications will be developed by non-utility companies.

The study touches on biomass cogeneration. Finland and Denmark are the only two European countries with some biomass cogeneration. The market is under development due to various reasons like plant economics, fuel supply sources and proactive policies from government. The market’s prospects have been raised by the Renewables Directive, where biomass electricity generation is expected to play a significant part in reaching the 22% electricity from renewables target. In terms of capacity, it is estimated that 11 GW_e of biomass cogeneration will be installed in the EU by the year 2010 (8% of total 135 GW_e), with an additional 8 GW_e by 2020.

8.2. Market potential of biomass cogeneration

The BioCogen project (project No NNE5-2001-00083) of the EU was a 2-year project that was completed in Nov. 2003 [Lamb, 2003]. Its aim was to identify the benefits of biomass cogeneration through desk-based reviews, surveys and networking. The project focused on identifying:

- Biomass fuel potential
- Applications of biomass cogeneration
- Drivers and barriers

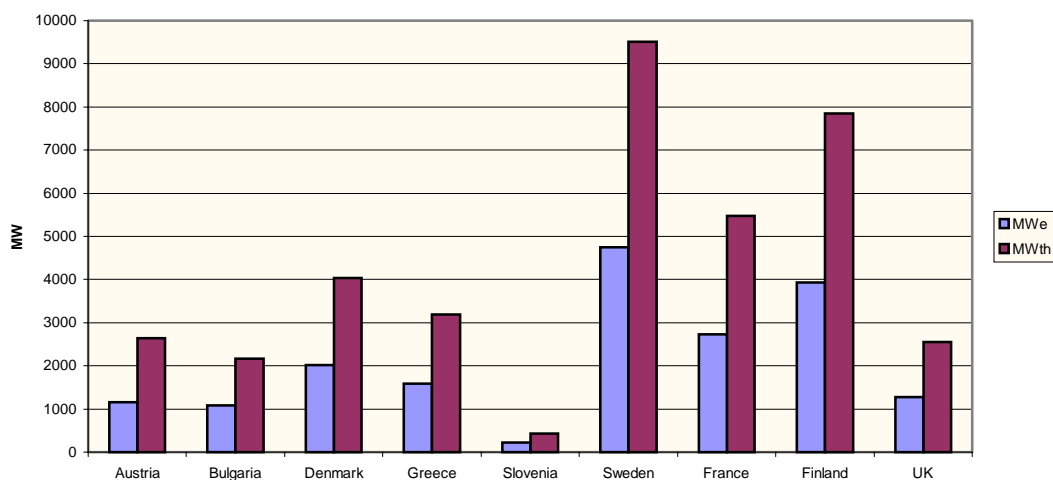


In order to identify the biomass fuel potential, the following broad categories were considered, while the main sources of this biomass were also identified:

Category of biomass residue	Main sources / biomass residues
Agriculture	All residues remaining in-situ from agriculture production or processing of agricultural crops; prunings from vines, fruit trees etc.
Forestry	All non-merchantable wood left in-situ by thinning and harvesting operations, including short rotation forestry. All non-treated residues – chips, bark etc – from primary and secondary processing of wood
Energy Crops	Potential annual or perennial dedicated energy crops. Trees grown on short rotation coppice.
Waste	The organic fraction of waste from households, commerce, industry. Untreated wood residues.
Sewage	Potential biogas production from sewage treatment

An estimate of the available biomass resource for cogeneration applications is presented in the study per country studied and type of biomass residue, from which the cogeneration potential was calculated, assuming plants operate for 6000 hours per year with 75% overall fuel efficiency and with a power:heat ratio equal to 1:2. The following schematic presents the cogeneration potential in MW_e and MW_{th} that could be achieved by currently unexploited biomass.

Cogeneration capacity estimated from currently unexploited biomass fuel potential



In the nine countries considered, BioCogen estimates that there is sufficient biomass fuel available to power an additional 15 GW of biomass cogeneration capacity. The potential of waste related biomass



and sewage gas is considered but there is limited information so as to estimate this potential accurately.

The following cases were identified as having high potential for biomass cogeneration:

- Horticulture and glasshouses
- Municipal solid waste management
- Waste water and sewage treatment
- Agro-industries
- Wood processing
- Paper and board manufacture
- District heating

The potential customers for biomass cogeneration plants are presented in the following table:

<i>Industry: Mainly private sector companies and investors</i> <ul style="list-style-type: none">• Agro-industries (eg livestock and poultry farms, greenhouses, mills, canneries)• Wood processing industries• Other industries in rural or semi-rural locations• Waste management industry
<i>Commercial and residential buildings in rural locations: mainly private sector, some government sector and some community organisations</i> <ul style="list-style-type: none">• Centers for leisure (including museums) and sport activities• Offices• Multi-residential accommodation• Hotels and resorts
<i>Various public facilities: government sector, some private sector companies</i> <ul style="list-style-type: none">• Authorities dealing with waste including sewage• Combined power and district heating• Schools and other education facilities• Military establishments

Existing biomass cogeneration plants were also reviewed in 16 European countries. With the exception of district heating, favoured applications for biomass cogeneration all have available biomass materials on site, either biomass residues are generated on site as a by-product or these industries deal with waste biomass materials. Many of these sites use heat and often there is long experience of the generation of heat-only from biomass combustion.

The largest biomass fired cogeneration plant is in Jakobstad- Finland with a power of 240MWe, and a capability to produce 100 MW of process steam and 60 MW for district heating. Usually solid biomass fired CHP plants are located in countries with a considerable forest industry. Plants with a capacity over 20MW are commonly found in N. Europe, while capacities less than 1 MW are common in central Europe.

Considerable opportunities for cogeneration in the waste management industry have been identified, including:



- Landfill gas
- Waste incineration (gasification and pyrolysis)
- Sewage gas

Power generation from landfill gas can directly compete with conventional power and is commercially attractive, particularly if there are added incentives for mitigation of greenhouse gas emissions / renewable energy. It is therefore well developed in northern Europe. There is potential for considerable additional capacity in Southern and Central and Eastern Europe, where power markets are opening up and sanitary landfills are being established. However, most landfill gas is power-only, not cogeneration, because local heat demands are limited.

8.3. Drivers & Barriers to biomass cogeneration

Biomass cogeneration enhances many of the drivers of co-generation, namely:

- increased efficiency by 15-40% of energy conversion compared to the separate supply of electricity and heat
- lower emissions
- reduction of need for waste disposal
- potential for large cost savings
- opportunity for decentralised generation, leading to further increased efficiencies
- improved energy supply at a global and local scale
- increased local employment

The previous “drivers” for biomass cogeneration are further accentuated by national or European policies, covering environmental protection, energy security and renewables, waste management, employment and others. Such policies for EC countries include:

- the White Paper for Renewable Energy
- the Directive for the promotion of electricity from RES (2001/77/EC)
- the Directive for the promotion of heat from RES (future development)
- The CHP Directive (draft)
- Strategy for Sustainable Development (COM(2001)264)
- Emissions Trading Scheme Directive (draft)
- Reformed Common Agriculture Policy
- Forest strategy for the EU (COM(1998) 649)
- The Kyoto protocol

The barriers for biomass cogeneration are similar to those identified for cogeneration in general that include [Lamb, 2003]:

- low tariffs for surplus electricity from cogeneration that is sold to the grid
- severe tariffs for standby power and, in particular, back-up power supply
- lack of third party access to the grid
- Technical barriers: Cogeneration schemes need to fulfil certain technical and safety requirements for proper operation. Sometimes the procedures take too long and are not transparent enough



Some of these barriers would be removed in a liberalised market since co-generators would be allowed to sell to any customer. Provided the market is properly structured, cogeneration can provide the most cost-effective option for producing electricity when the savings from heat utilisation are taken into account. However, reality has shown that the ongoing process of liberalization brings new barriers, including:

- Uncertainty due to changing legal frameworks
- Liberalisation has led to considerable reductions in the electricity prices. In some countries the prices have been lowered below cost and this makes it unprofitable to invest in or run cogeneration plants
- environmental costs are almost never included in the energy prices and neither are avoided costs for the use of the network
- since cogeneration is capital intensive, one needs to take a medium term view. Existing volatility and uncertainty in energy markets and energy prices may deter investors

8.4. Market potential of microturbines

Microturbines are a novel technology that has managed to get a foothold in the electrical power industry of the 21st century. They had to face major challenges (technical problems, interconnection issues, cost competition) but they have survived, as shown by a recent study of 52 early adopters of microturbines [Van Holde 2002]. Microturbines as a new player in an established industry had to find new niche fields of application.

Microturbines indeed excel in applications where their attributes give them an advantage to competing technologies, like heating greenhouses with exhaust gases, or using gases from landfills or sewage treatment plants that are available at zero cost. Many early applications had some kind of financial support but this is not required in recent installations. Some of the conclusions of the early adopters study were that:

- Tri-generation sites were by far the most expensive with a cost of the order of 4,400 \$/kW
- Gas pre-treatment facilities cause the cost of landfill applications to be also high, at 2,700\$/kW
- CHP applications had an average cost of 2,200 \$/kW
- For power only applications, not running on biogas, the cost was approx. 1,700\$/kW
- 75% of adopters were satisfied with microturbines
- 10% were not happy, mostly because they encountered reliability problems, manufacturers therefore need to be very responsive to overcome such problems when they occur
- any additional hardware required, like for fuel gas treatment, should be made clear to customers right from the start
- users of both power and heat were almost all satisfied with microturbines
- lengthy and complicated procedures for grid interconnection lead to clients becoming frustrated with the concept of microturbines
- applications occupy niche markets that are either baseload or use low/no cost fuel (landfill)
- microturbines do provide advantages over other technologies for generating electricity with low-quality gas and are especially well suited for smaller sites

In terms of the market potential for microturbines, it is estimated that world energy consumption is to increase from 9.5bn TOE in 2000 to 13.5bn TOE in 2020. Electricity will increase its share of the



energy market from 15,000 TWh in 2000 to 30,000 TWh in 2020. The contribution of distributed generation (DG) to electricity generation is expected to increase from 8% in 2000 to 17% in 2020. Small scale DG of a power range similar to that of microturbines will reach 1,200 TWh in 2020 [EscoVale].

A study of the market potential for microturbines performed by EscoVale forecasts the following market:

- for the DG market, it is estimated that the market for microturbines by 2020 will amount to 30,000 MW or 400,000 units, values at \$8bn, a third of this figure being associated with cogeneration
- other power applications (stationary or mobile) are much lower than DG and amount to 3 GW or about 60,000 units in 2020
- in the transportation sector there could be a market if fuel cells fail to provide viable solutions, with a potential of 10GW or 130,000 units in 2020 mainly for buses, military propulsion or auxiliary power

The study predicted that year 2003 would be the year where lift-off was expected with global production passing the 10,000 units (actual figures would be an order of magnitude lower). The market is assumed to develop in the following steps, 2.5 GW in 2005, 9 GW in 2010 and 40GW in 2020.

A recent report on the market prospects of microturbines was under taken by Energy and Environmental Analysis, Inc. [Energy, 2003]. The report concentrated on the market potential of microturbines provided these can meet the performance and cost targets set by the Advanced Microturbines System Programme (AMTS) of the US, described under chapter 6.5. Such units could be used for CHP, baseload or peaking applications. The following table from this study shows the overview of the economic market potential

Value Proposition	Technical Market Potential (MW)	Economic Market Potential			
		Interim Development		AMTS Goals	
		MW	Share	MW	Share
CHP New	10,520	640	6%	2,100	20%
CHP Retrofit	16,770	890	5%	2,700	16%
Direct CHP	3,370	440	13%	1,080	32%
IES-BCHP New	8,840	450	5%	1,270	14%
IES-BCHP Retrofit	8,650	380	4%	940	11%
Base (Retrofit plus New)	57,770	2,810	5%	7,840	14%
Waste Fuels/Oil Industry	2,630	2,630	100%	2,630	100%
Peaking	57,770	4,870	8%	8,250	14%
Peaking w Reliability	20,120	3,630	18%	4,450	22%



It can be observed that meeting the full AMTS goals provides 2-3 times the market of the interim goals, it is thus critical for these goals to be met for microturbines to be in a broadly competitive position. The study also predicts that microturbines will monopolise the market for waste fuels.

The same positive outlook for microturbines running on biofuels and in particular waste gases is reached by another group of US researchers [Hurley, 2003]. Indeed landfill sites and waste water treatment plants are considered the most promising applications for microturbines in general. Following interviews with operators from 11 different sites operating a total of 60 microturbines, it was concluded that:

- operators are happy with microturbines, reporting very few problems after some initial problems with this type of application have been overcome
- advanced gas processing systems have contributed to the minimisation of problems
- significant cost savings have been achieved as a result of using microturbines, specially at sites where grants are available to support the purchase of equipment
- operators claim that microturbines run cleaner than internal combustion engines (ICEs)

Provided on-site generation is appropriate for a landfill site, then microturbines could favourably complement the established ICEs due to their ability to burn low calorific value fuels and produce low NOx. The specific application for microturbines is advantageous since fuel is free or very cheap, the only cost being the collection and pre-treatment of gas. For large landfills that are capable of producing enough biogas to support capacities of a few MW, microturbines could be installed to “fill the gaps” around ICEs and make the most of the available gas, as shown in figure 27:

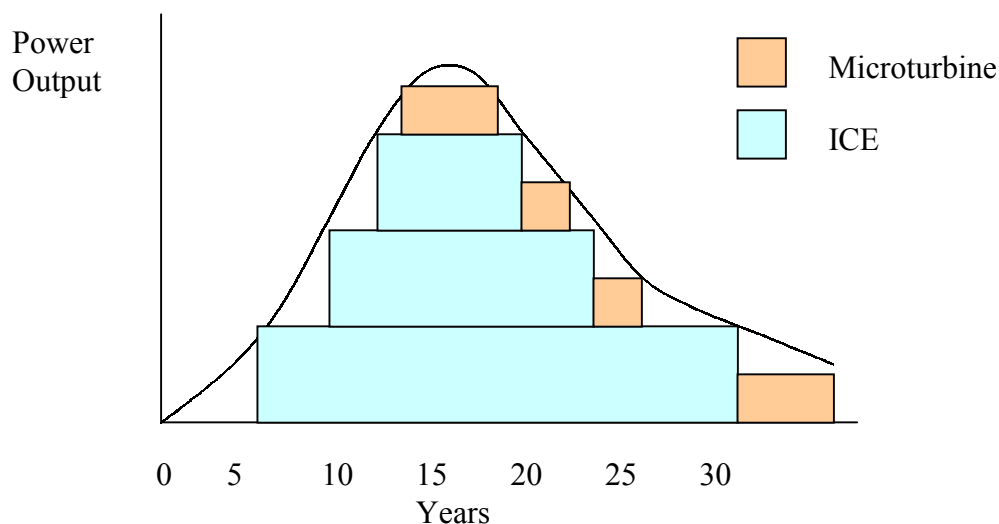


Fig. 27 Opportunities for microturbines in large landfills

For smaller landfills or for landfills in countries with an arid climate where the produced biogas has a lower calorific value, microturbines only could be used to exploit the produced biogas.



Waste water treatment plants that involve anaerobic digestion are also considered suitable application sites since there the heat produced by the microturbine can also be utilised by feeding it back to the digester to maintain the process temperature.

Conditions are not that favourable for agricultural and livestock installations due to higher costs resulting from a more complicated waste collection system and reluctance of farmers to install a collection system or a digester. It is expected that the market will consist of demonstration projects rather than widespread use of microturbines.

8.5. SWOT analysis for biomass driven microturbines

A Strength-Weaknesses-Opportunities and Threats (SWOT) analysis for biomass driven microturbines is shown below. This analysis is based on technical literature [Pilavachi 2002, Lamb 2003, Lymberopoulos, Zoulias 2003], private communications and personal experience.

Strengths and Weaknesses refer to the product itself (biomass driven microturbines) while Opportunities and Threats refer to the external environment affecting market development of the product.

Strengths

Microturbine Technology

- suitable to utilize fuels of varying calorific value
- single rotating part, meaning low maintenance requirements
- compact size, low noise
- high grade waste heat
- suitable as a DG technology for stand alone or grid connected operation
- minimal installation time, low installation cost
- lowest emissions of commercially available CHP technologies
- size of plants suitable to disperse nature of biomass

Environment

- biomass cogeneration is CO₂ neutral on life cycle basis
- achieve greater use of renewable energy
- limited emissions are restricted to sites that are far away from urban centres
- reduce impacts from waste disposal, providing solutions for waste streams

Distributed generation of heat and power

- installation close to load, avoid electricity transmission and distribution losses
- help improve local energy security, exploitation of indigenous fuels.

Biomass related issues

- biomass based CHP plants would enable diversification in agriculture and forestry
- create rural revenue streams and local jobs
- help to improve land management practices such as forestry thinning and clearing



- biomass and waste fuels can be stored, meaning that biomass driven plants are “dispatchable” (compared to other RES that are stochastic)
- parts of the fuel to energy chain are well proven, like solid biomass combustion, production of landfill or sewage gas

Weaknesses

Microturbine Technology

- low efficiency in basic configuration, that reduces even further under part load
- high capital cost
- suitable power conditioning equipment required for stand alone operation
- installation costs can be high for some cases of retrofits
- auxiliary systems required to operate with biomass derived fuels, consisting of pressure boosters, driers, filters, that increase complexity and cost

Environment

- -

Distributed generation of heat and power

- existing power grids unsuitable for accommodating large number of small power plants
- attention must be paid to issues like voltage and frequency produced, reactive power, etc.
- high cost of kWh produced.

Biomass related issues

- benefits of biomass fired CHP systems cannot be accounted for in their totality since external costs of fossil fueled power plants are not cared for in today’s energy system
- biomass energy wrongly perceived by policy makers as old and unattractive
- the establishment of biomass fuel supplies is novel and risky in some countries
- chicken and egg problem to invest in biomass cogeneration until fuel supply chains are in place and vice versa
- biomass can be transported but has relatively low calorific value to make transport viable.
- parts of the fuel to energy chain are still unproven, specially at the scale of a microturbine, including biomass gasification and pyrolysis
- many biomass applications have a low heat demand or operate seasonally (agro-industries)
- occasional mismatch between biomass cogeneration site and site of heat demand

Opportunities

Microturbine Technology

- capital costs of microturbine-based CHP systems to drop when series production levels are achieved
- trigeneration becoming commercially proven
- international standards for biomass derived fuels will lead to better conformance to specifications
- local job opportunities
- initial microturbine pilot applications utilizing biofuels running successfully and accumulating valuable experiences



Environment

- Emissions trading and the Kyoto protocol may stimulate the use of biomass in CHP plants

Distributed generation of heat and power

- costs of stand alone systems are relatively high in any case

Biomass related issues

- possible development of a Directive for renewable energy heat
- increased taxation of fossil fuels, from which biomass would be exempt
- current EU and national financing schemes for innovative RES applications
- diversification of energy companies
- some biomass fuels are available for free (mostly applies to wastes)
- increasing pressure to divert wastes from landfill into incineration or energy related projects

Threats

Microturbine Technology

- microturbines could be sidelined by the Hydrogen “hype” and leapfrogged by fuel cells running on bio-ethanol or biogas
- trigeneration even more difficult to achieve locally for the case of distributed biomass based microturbine plants
- few pure commercial applications running on biomass, most still pilot
- competing technologies (ICEs) performing perfectly adequately, specially in CHP mode

Environment

- -

Distributed generation of heat and power

- Inadequate legislative framework in terms of regulations and permits
- Current CHP market static, having negative impact on R&D of biomass based CHP
- In increasingly liberalized energy markets, direct subsidies become less available and there is a move to market-based mechanisms
- Uncertain economic conditions for investors
- Current electricity prices are very low
- Third party access to electricity networks complex

Biomass related issues

- potential end users have no experience of such technologies
- renewable energy incentives focus on electricity and exclude heat
- Changes in Common Agricultural Policy leading to uncertainties and greater financial demands for farmers and agro-industries who focus on food production, considering issues like biomass cogeneration as too high-risk

The previous SWOT analysis is summarised in the following table:



Strengths	Weaknesses
<ul style="list-style-type: none"> ➤ Microturbines suitable to utilize fuels of varying calorific value ➤ low maintenance requirements, compact size, low noise ➤ high grade waste heat ➤ suitable as a DG technology for stand alone or grid connected operation ➤ minimal installation time, low installation cost ➤ lowest emissions of commercially available CHP technologies ➤ size of plants suitable to disperse nature of biomass ➤ biomass cogeneration is CO2 neutral ➤ limited emissions are restricted to sites that are far away from urban centres ➤ reduce impacts from waste disposal, providing solutions for waste streams ➤ installation producing close to load ➤ exploitation of indigenous fuels ➤ create rural revenue streams and local jobs ➤ help to improve land management practices such as forestry thinning and clearing ➤ dispatchable biomass based plants ➤ biomass combustion, production of landfill or sewage gas well proven 	<ul style="list-style-type: none"> ➤ low efficiency in basic configuration, that reduces even further under part load ➤ high capital cost ➤ suitable power conditioning equipment required for stand alone operation ➤ installation costs can be high for some cases of retrofits ➤ auxiliary systems required to operate with biomass derived fuels ➤ existing power grids unsuitable for accommodating large number of small power plants ➤ high cost of kWh produced ➤ external costs of fossil fueled power plants are not cared for in today's energy system ➤ the establishment of biomass fuel supplies is novel and risky in some countries ➤ chicken and egg problem to invest in biomass cogeneration until fuel supply chains are in place and vice versa ➤ biomass can be transported but has relatively low calorific value to make transport viable. ➤ biomass gasification and pyrolysis unproven at microturbine scale ➤ many biomass applications have a low heat demand or operate seasonally (agro-industries) ➤ occasional mismatch between biomass cogeneration site and site of heat demand
Opportunities	Threats
<ul style="list-style-type: none"> ➤ capital costs of microturbine-based CHP systems to drop when series production levels are achieved ➤ trigeneration becoming commercially proven ➤ local job opportunities ➤ initial microturbine pilot applications utilizing biofuels running successfully and accumulating valuable experiences ➤ possible development of a Directive for renewable energy heat ➤ increased taxation of fossil fuels, from which biomass would be exempt ➤ current EU and national financing schemes for innovative RES applications ➤ diversification of energy companies ➤ some biomass fuels are available for free (mostly applies to wastes) 	<ul style="list-style-type: none"> ➤ microturbines could be sidelined by the Hydrogen "hype" and leapfrogged by fuel cells running on bio-ethanol or biogas ➤ trigeneration even more difficult to achieve locally ➤ few pure commercial applications running on biomass, most still pilot ➤ competing technologies (ICEs) performing perfectly adequately, specially in CHP mode ➤ Current CHP market static, having negative impact on R&D of biomass based CHP ➤ In increasingly liberalized energy markets, direct subsidies become less available ➤ Uncertain economic conditions for investors ➤ Current electricity prices are very low ➤ Third party accept to electricity networks complex ➤ potential end users have no experience ➤ renewable energy incentives focus on electricity and exclude heat



9. CONCLUSIONS

Microturbines are gas turbines with a power ranging approximately from 10 to 200 kW suitable for the distributed generation of power and heat. Microturbines are compact in size, can burn a variety of fuels, produce low emissions, generate low noise and have low maintenance requirements. On the other hand they have low power-only efficiency, their cost per kW installed is high while at the same time the distributed generation market is still not well developed.

The cost of microturbine-based systems for stationary power applications is considerably higher than competing systems commonly based on internal combustion engines and ranges from:

- For power only applications, not running on biogas, the cost is approx. 1,500€/kW_e
- CHP applications have an average cost of 2,000 €/kW_e
- Landfill applications have a cost of 2,400€/kW_e due to the need for gas pre-treatment facilities
- For Tri-generation of power, heat and cold, costs are of the order of 4,000 €/kW_e

Such technical and non-technical factors have meant that a product developed for mainstream use has been forced to survive in subsidised projects or to move to fringe applications. As a result the industry hasn't yet reached the critical size that will allow it to mass-produce microturbines at reduced prices that would make their products commercially competitive. On the other hand, the current hydrogen "hype" is focusing energy related R&D budgets and political will in this field, with the danger for microturbines to be leapfrogged by fuel cells, or at best finding a market in hybridising high temperature fuel cells.

However, microturbines are indeed successful in niche applications, the most successful of which are related to bio-energy and in particular waste derived fuels. This is due to the fact that microturbines have several technical features that are advantageous with respect to their application in bio-energy, including:

- suitable power range for the disperseness characterising biomass
- capability to burn fuels of varying calorific value
- lowest emissions of market-ready CHP technologies
- low maintenance requirements
- high grade waste heat
- suitable for stand-alone or grid-connected operation
- local employment opportunities

There are though some disadvantages with respect to the application of micro-turbines in bio-energy including:

- the need for auxiliary systems for boosting and cleaning biomass and waste derived fuels
- biomass gasification and pyrolysis unproven at microturbine power scale
- many biomass applications have a low heat demand that could exploit on-site the heat produced by the microturbine
- need for power conditioning equipment for stand alone operation
- the establishment of biomass fuel supplies is novel and risky in some countries



The estimated market potential for microturbines is impressive even if uncertain. Some market figures are listed below:

- the EU market for micro-cogeneration plants in 2010 is estimated at 8GW_e
- biomass cogeneration in the EU in 2010 will be of the order of 11GW_e, this figure being 2GW_e for biomass micro-cogeneration
- the market for microturbines in 2020 for distributed generation or other power applications is estimated at 33 GW – 460,000 units, however, the market for 2003 – a year that was considered the “lift-off” year was predicted to be 10,000 units but actual figures were an order of magnitude lower

Landfill sites and wastewater treatment plants are considered the most favourable applications for microturbines in general due to the low or no-cost of the available fuel. Greenhouses are also considered very attractive, in which case the microturbine would be fed by gases produced from the anaerobic digestion of biomass and part of the exhaust gases would be fed to the greenhouse as a kind of CO₂ sequestration and plant fertilisation. For microturbines to be able to commercially exploit other forms of biomass, like woody biomass, energy crops or forest debris, then gasification systems at this power range would need to be developed. An alternative option would be the external firing of microturbines, this however would call for the mass production of suitable microturbine systems. Both areas are viable for further R&D effort.

US companies are the market leaders, if not the market creators, for microturbine based CHP systems. US companies enjoy 80% of the market for large power generation gas turbines, this figure being even higher for the case of microturbines. Further to this, the US government is supporting with \$63 million worth of funds the development of the next generation of microturbines that will have an efficiency of over 40% in power only mode, NO_x emissions less than 7% and will cost less than \$500 per kW installed. Their aim is simple, to keep US manufacturers on the leading edge of this technology and enhance their competitiveness.

To this “tour de force” of US activity, Europe can only counterpoise two manufacturers of market-ready microturbine CHP systems that invariably incorporate US made components, with one of the two manufacturers being in a transient state. No specific EC framework exists for supporting the development of microturbines and the prospects are limited since even the major European manufacturers of large gas turbines are finding it hard to inspire the EC to introduce turbomachinery in the EC research agenda.

European microturbine industry should place more emphasis in the bio-energy field and produce products that would serve this type of market. This effort could be funded by EC research frameworks that fund bio-energy R&D, while their application could be boosted by legislation and policies on the extended use of biomass (Directive on RES electricity, RES heat, green certificates, etc)



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