PERGAMON

Applied Thermal Engineering 22 (2002) 2003–2014

APPLIED THERMAL ENGINEERING

www.elsevier.com/locate/apthermeng

Mini- and micro-gas turbines for combined heat and power ☆

P.A. Pilavachi *

Research Directorate-General, European Commission, 200 Rue de la Loi, 1049 Brussels, Belgium

Received 15 March 2002; accepted 25 August 2002

Abstract

The use of mainframe gas turbines for power generation has increased in recent years and is likely to continue to increase. The proportion of power generation using combined heat and power is also growing mainly due to efficiency improvements and environmental benefits.

Mini- and micro-turbines offer a number of potential advantages compared to other technologies for small-scale power generation, particularly for distributed power generation, although there are some technical and non-technical barriers to the implementation of the technology. There is an uncertainty about their market potential but they could be used for power generation in the industrial, commercial and residential sectors. The market potential could increase substantially if the cost, efficiency, durability, reliability, and environmental emissions of the existing designs are improved.

Keywords: Mini-turbines; Micro-turbines; Combined heat and power; Distributed generation; Market potential of micro-turbines

1. Introduction

All forecasts of future world energy supply anticipate an increase across the globe. The projection of the POLES, business as usual, model [1] shows almost a doubling of the world primary energy supply between 2000 and 2020 (Fig. 1) in agreement with other models (IEA, World Bank, etc.). Electricity demand is projected to increase by the same order of magnitude over the same period (Fig. 2). The emissions of CO_2 are likely to increase by at least the same amount because

☆ The content of this article does not necessarily reflect the official position of the European Commission and the Commission is not responsible for the use which might be made of this information. The views expressed here are those of the author and do not necessarily reflect those of the European Commission.

* Tel.: +32-2-295-3667; fax: +32-2-296-4288.

E-mail address: petros.pilavachi@cec.eu.int (P.A. Pilavachi).

PII: S1359-4311(02)00132-1

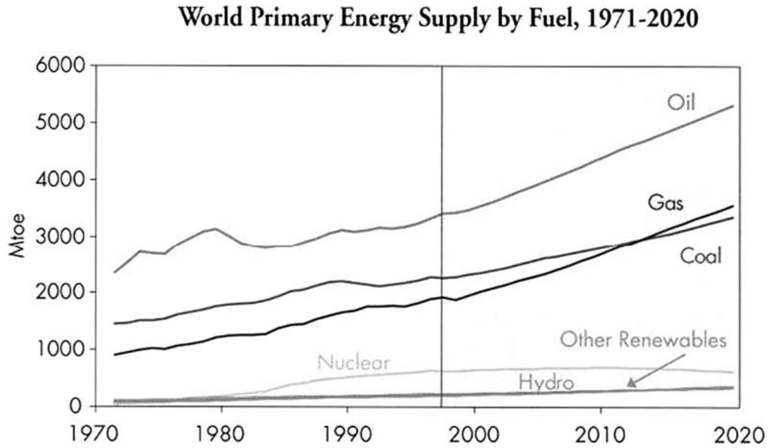

Fig. 1. World primary energy supply (EC, POLES model).

advanced technology introduced into developed countries' network will be offset by increased use of fossil fuels for transport as well as lower cost and lower efficiency plants in developing countries. Micro-turbines for combined heat and power may contribute to reductions of CO_2 emissions depending on the way in which the sector develops. In this paper, I would define micro-turbines to range up to 150 kWe while mini-turbines to range from 150 kWe up to 1 MWe. There is no standard definition and each author defines these ranges more or less arbitrarily.

The world wide dependence on fossil fuels is still likely to be around 90% in 2020 unless major measures are taken to introduce renewable energies into the system. Oil, coal and natural gas will have the largest share of energy supply. Nuclear electricity will remain relatively stable and renewables will increase.

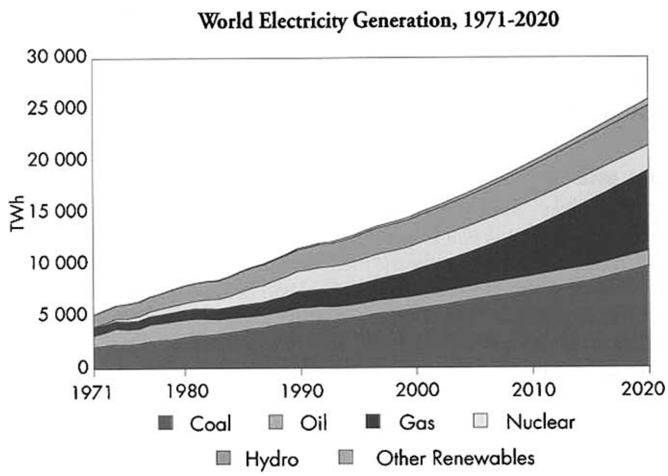

Fig. 2. World electricity generation (EC, POLES model).

The major increase in fuel for power generation in industrialised countries is foreseen to increasingly become natural gas. The European Union's electricity generation from natural gas has tripled in the last 10 years.

With these scenarios, major attempts will have to be made if CO_2 emissions are not to increase and countries take steps to meet the targets they committed to at the Kyoto Conference in 1997.

The largest increase in the use of natural gas for power generation will principally be accommodated by the continuing introduction of gas turbine plant in simple cycle, complex cycle and combined cycle forms.

Europe has a substantial stake in the gas turbine market with manufacturers producing machines with ratings from less than 1 MWe (mini- and micro-turbines), up to the biggest gas turbine combined cycles, which produce over 400 MWe on a single shaft. For the purposes of this paper, both mini- and micro-turbines will henceforth be referred to as micro-turbines.

With the increasing use of natural gas as a fuel, the output of gas turbines for power generation are projected to increase from around 570 GW in 1999 to 2035 GW in 2020; an increase of over 6%/yr. The value of this market is around 20 bn Euro/yr. The increase of power demand will be met by large combined cycle turbine (CCGT) plant (up to 400 MW), but with a growing importance in distributed power applications in the 30–150 MW range.

In addition, micro-turbines in combined heat and power (CHP) applications may take an increasing share of this market. The trend towards deregulation of the electricity supply market will influence the speed of the potential introduction of what has become known as "distributed generation" [2]. Distributed generation is a revolutionary concept, which consists of local generation of electric, thermal or mechanical energy.

Various technologies are used in distributed generation including gas turbines, reciprocating engines, fuel cells, solar systems and wind turbines. There is a particular interest in the potential of technologies such as micro-turbines and reciprocating engines. However, for micro-turbines and other distributed energy resources to be competitive in power markets, the price of electricity production will need to be more attractive than today. Without cost reductions, most electricity users will prefer grid-connected power and energy-efficient distributed energy resources will be confined to a relatively small market niche.

2. Advantages and disadvantages of micro-turbines and combined heat and power

Micro-turbines offer a number of potential advantages compared to other technologies for small-scale power generation [3]. For example, compact size and low-weight per unit power leading to reduced civil engineering costs, a small number of moving parts, lower noise, multi-fuel capabilities as well as opportunities for lower emissions (in the CHP context).

In addition, gas turbines enjoy certain merits relative to diesel engines in the context of mini- and micro-power generation. They have high-grade waste heat, low maintenance cost, low vibration level and short delivery time.

The absence of reciprocating and friction components means that balancing problems are few, and the use of lubricating oil is very low. In the lower power ranges reciprocating engines have higher efficiencies, but these are now being challenged by gas turbine power plant derived from high-efficiency aero-engines and the increasing efficiency of industrial gas turbines, particularly when they are used in the CHP mode.

Fuel options other than natural gas include diesel, landfill gas, industrial off-gases, ethanol, and other bio-based liquids and gases.

Main technical barriers to the implementation of micro-turbine technology are that, at present, the gas turbine has a lower efficiency in its basic configuration than an equal power output reciprocating engine. In addition, the efficiency of the gas turbine decreases at partial load and burning of lower heating value fuels may not be feasible, depending on the type of the turbine. In addition, electricity distribution systems are generally unsuitable for the installation of a large number of small plants and they require modification, the costs of which have to be taken into account. Also, micro-turbine plant, require power conditioning to produce electricity at grid frequency and this brings further additional costs to an installation.

Main non-technical barriers to the implementation of gas turbine technology are that maintenance requires more skilled personnel than does the reciprocating engine and that small gas turbines are expensive compared to reciprocating engines. Grid connection standards are also a non-technical barrier.

Main non-technical barriers to the implementation of CHP systems are that the investment payback period could be high (up to six years), the costs of grid connection might be high, the access to the electricity network for reasonably price services is not always possible (i.e. export power, back-up power and top-up power), access to the gas network is not always possible and there are still administrative and institutional barriers to CHP in several countries. In addition, CHP technology and its benefits are not widely known, there is possibility of increasing local pollution and there is the requirement of a close matching of electric and heat load.

3. The market for micro-turbines

Micro-turbines could be used for power generation in the industrial, commercial and residential sectors but there is an uncertainty about their market potential.

They could be used for: continuous power generation; premium power; peak shaving; emergency standby; remote power; combined heat and power; mechanical drive; and wastes and bio-fuels.

Industries that have the greatest estimated market potential for micro-turbines include chemicals, food and drink, pulp and paper, and textiles. Remote power applications are for off-grid locations such as oil, gas and mining operations. The market for wastes and bio-mass burning micro-turbines are found in those industries that produce solid, liquid, or gaseous fuels as a waste or by-product such as pulp and paper and food processing.

However, the largest use for micro-turbines could be in combined heat and power systems. The exhaust heat from a gas turbine is of high quality i.e. high temperature, and can be used to produce heat for industrial processes or space heating (CHP). For micro-turbines to get the high efficiencies, the exhaust gas is passed through a recuperator to increase the electrical efficiency and therefore the final heat grade available is of lower quality (temperature). In CHP applications, gas turbine plants can reach an overall efficiency exceeding 80%. However, for micro-turbines and other distributed energy resources to be competitive in power markets, the price of electricity production will need to be more attractive than today.

But, there are also other obstacles to the market development potential of gas fired micro-turbines [4]. Micro-turbines must not only compete with centralised power stations using less expensive fuels and having high efficiencies, but must also face the continuous technical progress of large-scale gas-fired combined cycles as well as of the other gas-fired prime movers already present in the combined heat and power market. The recent trend of energy cost, characterised by an increase of the natural gas cost and a decrease of the electricity cost, makes the competitiveness of gas turbines (of all sizes) even harder.

4. Combined heat and power systems

This section deals with CHP systems, in general. CHP has been one of the most important energy technology options for improving the efficiency of the energy sector in Europe, currently supplying about 10% of Europe's heat and electricity [5]. The use of CHP is targeted to increase to 18% of European electricity production by the year 2010 and could eventually reach 30% in the long term, according to COGEN Europe (The European Association for the Promotion of Co-generation). The principal reasons for the ambitious targets set is CHP's contribution to mitigating greenhouse gas emissions, reducing energy demand and developing a more robust and competitive energy sector.

In many of the envisaged new applications, micro-turbines may be used as a component of a combined heat and power system.

CHP should reduce CO_2 emissions when compared with separate production of heat and power. At present, this saving can be up to 1000 tonnes of CO_2 per GW h of power production, depending on the displaced sources of heat and electricity.

Currently at least 200 million tonnes/yr of CO_2 are avoided by already operating CHP plants [5]. If the EU target is met of doubling its use by 2010, then Europe will reduce its CO_2 emissions by around 150 million tonnes/yr. This amount is even greater when the Accession Countries are included. Here at least a further 50 million tonnes/yr of CO_2 reductions are possible. In the long term, a penetration potential of CHP in Europe is at least 30% [6]; this would result in a further 150 million tonnes of CO_2 avoided per year. In total, therefore, around 500–600 million tonnes of CO_2 could be avoided by using CHP by 2020. A substantial contribution to sustainable development.

In addition to CO_2 reductions, CHP also has a positive impact on other pollutants such as SO_x, NO_x and dust. CHP is applied at the place where energy is required and therefore it reduces the need for grid system reinforcement, visual impact of large power stations, and thermal pollution caused by large, old and inefficient stations.

5. The elements of a micro-turbine generator

Much of the micro-turbines technology owes its origins to the military and aerospace industry where the need for light weight, compact, high-powered generators has traditionally outweighed the significant development and production costs. Riding on the back of these development efforts, manufacturers are now turning their attention to new market areas. In recent years the technology has found its way to hybrid electric vehicles and now to small-scale power generation, where the manufacturers believe it has its greatest potential.

Micro-turbines are, for the most part, single-stage, single-shaft, low pressure ratio gas turbines. Systems may be either *simple cycle*, where no heat is recovered from the exhaust for preheating of the combustion gases, or *recuperated*. Recuperation typically doubles the electrical efficiency of the unit whilst reducing the amount of recoverable heat from the boiler; this may or may not be desirable depending on the application.

The main features of a single-shaft recuperated system are shown in Fig. 3. It works as follows: incoming air is compressed and then passes through the *recuperator* where it gains heat before entering the *combustor*. Here, compressed natural gas (or other fuel) is introduced at high pressure and the hot high-pressure gases are exhausted through the *turbine*, which extracts energy and uses it to drive the compressor and shaft-mounted alternator. The exhaust gases are then fed through the recuperator and into a boiler or absorption chiller for CHP and cooling applications. The alternator is a high-speed device (typically rotating at 75,000–100,000 rpm) producing a high-frequency output; this is converted to the desired mains frequency and voltage in the power conditioner. Because most micro-turbines typically generate high-frequency AC that must be converted to DC and then back to grid compatible AC, the systems require reliable and efficient electronic power conditioning devices.

The simple cycle ideal efficiency (without use of a recuperator) is given by [7]

$$\eta = 1 - (1/r)^{(\gamma-1)/\gamma}$$

the efficiency (η) being dependent on the pressure ratio (r) and on the nature of the gas ($\gamma = c_p/c_v$).

For $3 < r < 5$ we obtain an efficiency of 40% and in order to obtain an efficiency beyond 60% we need $r > 10$ (we practically have to choose an r between 3 and 5 since conventional turbines can withstand up to 1000 °C without blade cooling).

However, small machines cannot reach these theoretical efficiencies and micro-turbines have efficiencies substantially lower than the efficiency of competing systems such as reciprocating

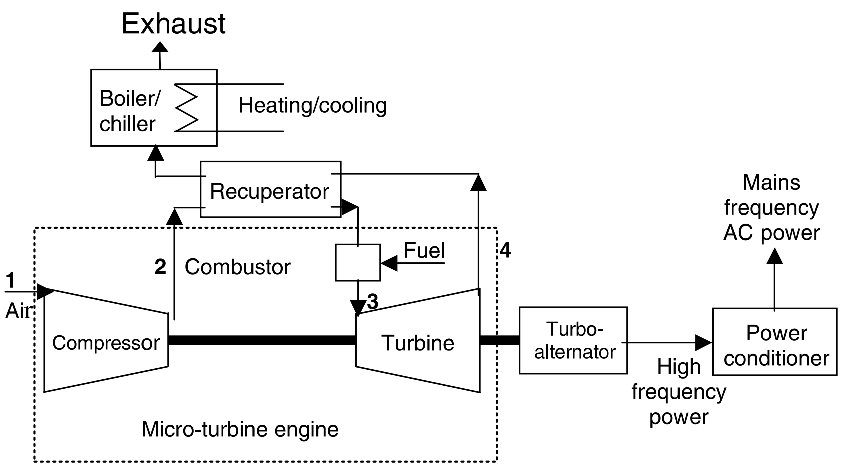

Fig. 3. Schematic of recuperated micro-turbine system.

engines or large power stations, particularly in high-load factor applications with base-load or intermediate-load requirements. However, for applications such as emergency power, where the duration of operations is relatively low and fuel costs are of secondary concern, where other factors such as ease of installation and maintenance are considered, unrecuperated micro-turbines may be used.

The simple cycle ideal efficiency with heat exchanger (i.e. with recuperation) is given by

$$\eta = 1 - r^{(\gamma-1)/\gamma}/t, \quad \text{where } t = T_3/T_1$$

Here, with $3 < r < 5$ we obtain efficiencies beyond 60%.

Since r is low by comparison to large machines, the complexity of axial compressors is not justified and the simpler to design and construct radial compressor is universally used. The comment generally applies to compressors alone except at very small powers, say below 10 kW, when high speed make the radial turbine necessary for structural reasons.

The simplicity of the core gas turbine masks the leading edge technology used in its design, manufacture and operation in certain parts such as the bearings technology and the high-speed alternator.

High efficiency can only be obtained when the machine operates at high pressure and temperature conditions, which challenge the skills of engineers and materials technologists. In addition, higher temperatures lead to challenges to reduce NO_x emissions. As efficiencies increase, the resulting potential increase in NO_x has to be dealt with using ever more sophisticated combustor design.

The important role that the recuperator has on turbogenerator performance has been discussed in [8].

Fuel savings of 30–40% from preheating can be produced from the most effective conventional metal recuperators. Conventional stainless steel recuperators, however, can be used only when exhaust-gas temperatures are below 650 °C. A considerable increase in gas turbine efficiency can be achieved with large increase in engine operating temperatures, and the appropriate materials to accomplish this are ceramics. Present designs use metallic components without air-cooling and the high-metal temperature result in shortened lifetimes. Advanced metal or ceramic recuperators will be required as engine operating gas temperature increase to enhance efficiency [9].

The materials used for recuperators could be classified according to maximum operating temperatures: 650 °C (stainless steel), 800 °C (Inconel) or >870 °C (ceramics) [9]. These limits are imposed by existing material properties such as strength and corrosion, oxidation, and creep resistance which affect recuperator failure. Metallic alloys are now used for the two lower temperature ranges while ceramics would be required for the higher temperatures. A further analysis of this subject is, however, outside the scope of this article.

Fuel gas compression equipment will be needed in locations where the gas pressure is too low for direct firing in micro-turbines and this can become so expensive as to be uneconomical. The starting and stopping of multiple, gas-powered micro-turbines could also place strain on the natural gas supply system.

In certain circumstances, users that have deep concerns about the reliability of the grid or about power quality may be willing to pay more for on-site power generation than for grid-connected electricity. System reliability is a top priority since power interruptions or sags in voltage or frequency can be very expensive to companies in lost production and damaged equipment. Therefore, extensive RAMD (reliability, availability, maintainability, durability) testing is needed before turbines will gain acceptance. There are also concerns related to interconnection with the grid.

The capability of gas turbines to use multiple fuels without increasing emissions would greatly increase the number of opportunities for micro-turbines. Note that the relatively low turbine temperature means that the amount of NO_x generated by the micro-turbines is relatively low compared to large turbines.

Since economies-of-scale do not apply in the smaller size ranges, design simplification and production economics assume greater importance.

In general, micro-turbines have design features as follows [9]:

- radial flow compressors,
- low pressure ratios (with single-or two-stage compression),
- very high-rotational speeds (25,000 rpm for a 500 kW machine, around 75,000 rpm for a 100 kW one),
- minimal use of cooling of vane or rotor,
- exhaust heat recuperation for air preheating,
- use of materials with low production cost.

6. Current and future status

The size of micro-turbines varies considerably. Existing micro-turbine systems range in size from 25 to 80 kW; future products up to 500 kW or even 1000 kW are planned. In addition, research is being carried out in the range <25 kW (e.g. 1 kW, 10 kW).

In Europe, some companies are developing micro-turbines. Turbec in Sweden is developing a product with an output from 100 kWe. Turbec was formed in 1998 and is joint venture between ABB and Volvo. The company's base product is the T100, a 100 kWe cogeneration unit using a Volvo engine and Bowman alternator and electronics. The T100 is a single shaft recuperated micro-turbine that rotates at 70,000 rpm and uses oil bearings. It is fuelled by natural gas and uses a lean, pre-mix, low emission combustor producing less than 15 ppm NO_x. Turbec is starting to ship micro-turbine cogeneration packages to the European markets and delivered around 20 units in 2000.

Turbec amongst others is also involved in a European project which deals with optimal design, installation and operation of 15 micro-gas turbine based CHP units in different applications including development of necessary control and peripheral equipment [10]. The core engine/CHP unit of 100 kWe (Turbec) will be used for all installations. The tests, which spread over five countries, will be industrial, commercial as well as domestic. They will cover a number of applications: flexible steam generation; drying processes; CO_2 fertilisation in greenhouses; cooling; traditional CHP (hospitals, leisure centres, etc); cluster installation of micro-turbine CHP units. Besides natural gas, the development and testing will also include the use of alternative fuels such as biogas and methanol. Data on energy efficiency, availability, emissions, O/M costs etc. will be recorded and reported. The data obtained will form the basis for possible enhancement of energy savings and reduced emissions through the use of efficient micro-turbines in CHP applications.

Micro-turbo in France is developing micro-turbines in the range from 200 up to 350 kW. The objective of the project is to study, define and test the most critical and innovative components to be further integrated in a high efficiency, low cost and low emission, small gas turbine CHP system [11]. The most critical components of the high-efficiency gas turbine system, in the power range from 200 up to 350 kW are: the high-efficiency aerodynamic components of the advanced, inter-cooled, recuperated gas turbine; the heat exchanger recuperator; the catalytic combustor; and the integrated, into the turbo-machinery shaft High-Speed Alternator (HAS) for cost reduction.

The development of the major critical components of an efficient, innovative, small gas turbine CHP system will create an improved combined heating and power system. The more efficient thermodynamic gas turbine cycle, which will increase the efficiency of the small gas turbine from between 20% and 25% to more than 35%, will produce a reduction of more than 10% in CO_2 emissions. The innovative catalytic combustor, which is one of the main developments, is an effective way to reduce the emission of pollutants (NO_x and CO) to a level which will be required in the near future (one 'digit' emission level). It will also enable low heating value fuels issued from biomass (biogas) to be effectively burnt.

Turbec, amongst others, is the turbine manufacturer which will demonstrate the integration of three technologies: micro-turbine; hot water fired absorption chiller; ice storage thermal system [12]. It will aim to show the main benefits resulting from the micro-trigeneration systems and a flexible financing mechanism. The benefits embrace customers (cost-effectiveness, reliability, power quality, integrated energy service), investors (low capital exposure and risk, market opening, possibility to avoid major investments in new centralised power plants) and the community as a whole (reduction of energy intensity and GHG emissions, transfer of know-how, demand side management tool, reduction of external costs). The project will contribute towards new perspectives for micro-turbine applications namely in South Europe with exports to Brazil.

In the US, three manufacturers made commitments to enter the micro-turbine market. Capstone has a 30 kW product, Elliott has 45 and 80 kW products, and Northern Research and Engineering Company will have several products in the 30 to 250 kW size range [9].

Other companies such as Allison Engine Company, Williams International, and Teledyne Continental Motors have expressed interest in developing micro-turbine products [9]. Japanese (Toyota, Nissan, Hitachi, Kawasaki, etc) companies are also developing micro-turbine products.

The current status of key micro-turbine developers is given in Fig. 4 [13].

Ways to improve the performance of several types of gas turbine cycle will be a major objective in the coming years. The targets for small gas turbines are efficiencies above 35% and designs for the use of fuels with less than 25% heating value of that of natural gas [14].

The use of micro-turbines for *continuous generation* will typically involve applications requiring over 6000 h of operation per year [9].

The potential market could increase substantially if the cost, efficiency, durability, reliability, and environmental emissions of the existing designs are improved.

The aim of the US micro-turbines programme [9] is to produce "ultra-clean, highly efficient" micro-turbine design(s) by fiscal year 2006 ready for commercialisation with the following targets:

- *High efficiency*—at least 40%.
- *Environmental superiority*—NO_x emissions lower than 7 ppm for natural gas turbines in normal operating ranges.

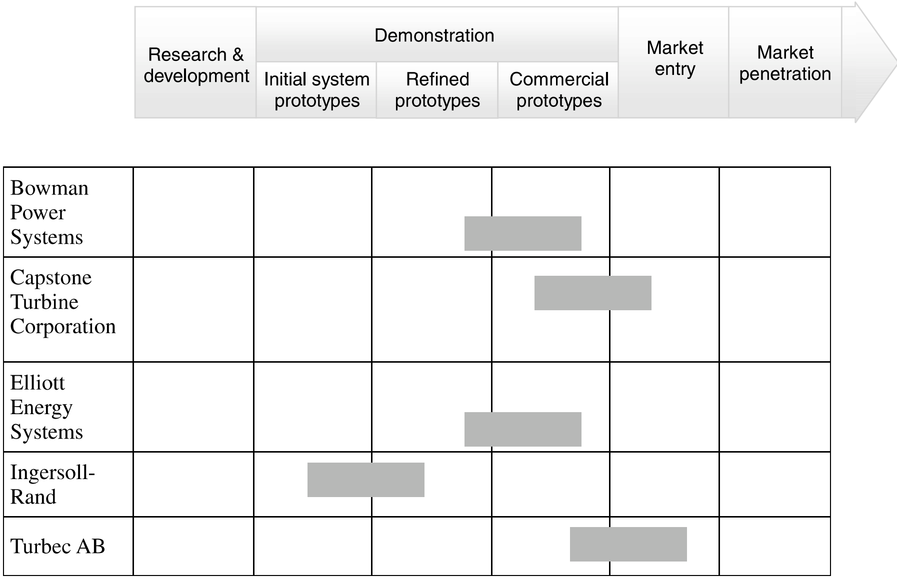

Fig. 4. Estimated status of micro-turbine generation technology in 2002.

Table 1
Projected performance characteristics for micro-turbines for CHP applications

Year	Electrical efficiency (%)	Overall efficiency (%)	Installed cost (Euro/kW)	Non-fuel O&M costs (c/kW h)	Life time (h)	NO_x emissions (ppm)	Noise (dBA at 1 m)
Unrecuperated							
2000	17–20	70–80	800–1000	0.5–1	40,000	<9	70–80
2010	23–30		450–700	0.1–0.2			
Recuperated							
2000	23–30	65–75	1050–1300	0.5–1	40,000	<9	70–80
2010	38–42	70–80	550–850	0.1–0.2			

- *Durable*—designed for 11,000 h of operation between major overhauls and a service life of at least 45,000 h.
- *Economical*—with costs lower than $500 per kW.

Table 1 summarises the current and projected cost and performance characteristics of micro-turbines for CHP applications [13].

Back-up power users require 100% reliable electricity [9]. Some users, like hospitals and airports, are required by regulations to install and maintain back-up power units. Back-up power systems may run less than 100 h/yr but they must be ready to come on line in the event of a power outage. Diesel generators currently have a large fraction of the back-up power market. A variety of factors, particularly their ability to start-up rapidly and reliably may drive the use of micro-turbines in this market. Relatively low expected O&M costs could also be an advantage for micro-turbines in back-up power applications.

7. Conclusions

The power generation industry uses a large amount of the primary energy demand in the European Union. There is therefore a continuing need for improved energy efficiency within the European Union coupled with a pressing need to reduce emissions.

The use of gas turbines for power generation has increased in recent years and is likely to continue to increase, particularly for distributed power systems.

The proportion of power generation using CHP is also growing mainly due to efficiency improvements and environmental benefits.

There is much uncertainty about the market potential of micro-turbines. Manufacturers have to commit themselves and define whether they will produce micro-turbines for a volume or for a niche market. A major problem includes the very high cost of the regenerator.

In commercialising advanced micro-turbine designs, manufacturing scale-up techniques will be significant in lowering system costs.

Achieving fuel flexible systems will be a major technical challenge. Testing will be needed to determine the optimal combustion conditions for different types of fuel.

Interconnection with the electric grid poses a significant barrier to micro-turbines and regulations need to be established.

There are advantages and disadvantages in the use of micro-turbines for CHP. The future depends on the market niche for such turbines and on government policy.

References

[1] POLES 2.2: Prospective outlook on long-term energy systems, Office for Official Publications of the European Communities, Report EUR 17358 EN, 1996.

[2] Integration of renewable energy sources and distributed generation in energy systems, Conference organised by the EC, 25–26 September 2001.

[3] P.A. Pilavachi, Power generation with gas turbine systems and combined heat and power, Appl. Therm. Eng. 20 (2000) 1421–1429.

[4] E. Macchi, S. Campanari, Future potential developments of MTG: hybrid cycles and tri-generation, in: Conference on Microturbine Generators, Institution of Mechanical Engineers, 1 December 2000.

[5] S. Minett, Thematic network on combined heat and power—CHAPNET, EC ENERGY contract no. ENK5-CT2001-00155, 2001.

[6] S. Minett, COGEN Europe, private communication, 2002.

[7] H. Cohen, G.F.C. Rogers, H.I.H. Saravanamuttoo, Gas Turbine Theory, Prentice Hall, 1996.

[8] C.F. McDonald, Low-cost compact primary surface recuperator concept for microturbines, Appl. Therm. Eng. 20 (2000) 471–497.

[9] Advanced Microturbine Systems, Program Plan for Fiscal Years 2000 through 2006, US Department Of Energy, March 2000.

[10] H.J. Rasmusen, Optimised microturbine energy systems, EC ENERGY Contract NNE5/20128/1999, 2001.

[11] A. Romier, R&D of high efficiency components for an intercooled recuperated CHP gas turbine for combined heat and efficient power, EC ENERGY Contract ENK5-CT2000-00070, 2000.

[12] G. Prata Dias, Trigeneration and integrated energy services in south of Europe and Brazil, EC ENERGY Contract NNE5/275/2001, 2002.
[13] S. Minett, Mini and micro CHP—market assessment and development plan—MICROMAP, EC SAVE II Contract 4.1031/Z/00-023-2000, 2000.
[14] Work Programme: Energy, Environment and Sustainable Development. Programme for Research, Technological Development and Demonstration under the Fifth Framework Programme, European Commission, 1999.