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Commercialisation of fuel cells for combined heat and power (CHP) application

Julian Packer
Combined Power Systems Ltd., Business and Technology Centre, Green Lane, Eccles, Manchester M30 ORJ (UK)

Abstract

Combined heat and power or co-generation is an ideal application for the fuel cell. This paper has been written from the perspective of a current designer, builder and operator of small-scale (i.e. sub 1 MW) combined heat and power. Conventional current CHP is described together with typical applications. The perceived advantages of fuel cells are also discussed together with the potential for fuel cells opening up currently unapproachable markets. Various matters relevant to the application of fuel cells are also described including: initial and life costs for fuel cells CHP systems; maintenance requirements, security of supply requirements. In addition to these commercial aspects, technical issues including interfacing to building systems, control, protection, monitoring, operating procedures and performance are also discussed.

1. Introduction

In the UK small-scale CHP (combined heat and power) is normally defined as describing units of less than 500 kW of electrical output. Interest in the commercial application of small-scale CHP in the UK was stimulated by the 1983 Energy Act [1], and the 1980s may now be viewed as the decade in which the technical and commercial barriers to small-scale CHP were both identified and addressed. A comprehensive review can be found in ref. 2. There is now a burgeoning interest in the application of small-scale CHP, and it is likely that the 1990s will be the decade in which its widespread application is realised. This paper is written from the perspective of a current designer, builder and operator of small-scale CHP and not by an expert in fuel cell technology.

A conventional small-scale CHP system is shown schematically in Fig. 1, and a practical realisation of the technology in Fig. 2. The key elements of a typical CHP system are:

- prime mover
- the alternator
- the heat recovery system
- the control, protection and monitoring system
- the acoustic enclosure (noise as a form of pollution is becoming of increasing importance)

Reference 3 provides a detailed description of typical, state of the art, conventional CHP.

The majority of conventional systems currently use natural gas as a fuel and so the prime mover will typically be a four-stroke spark ignited natural gas engine. In

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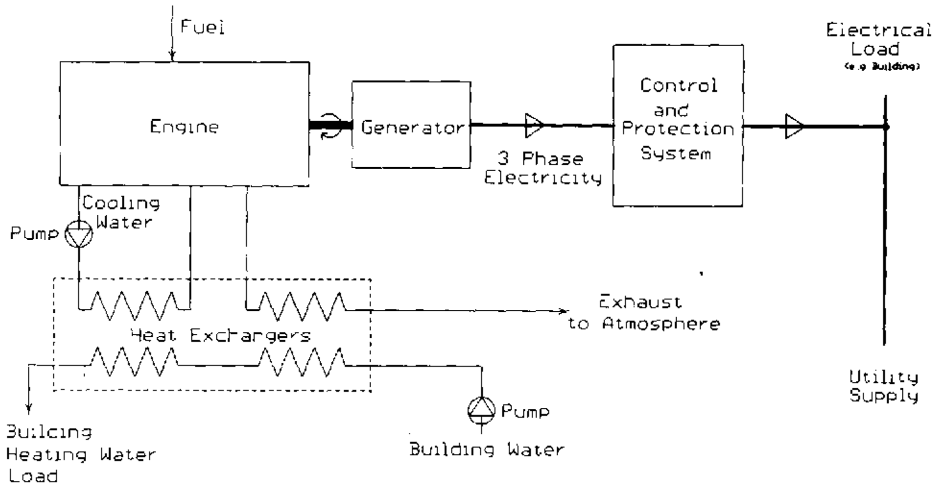

Fig. 1. General schematic of a CHP unit.

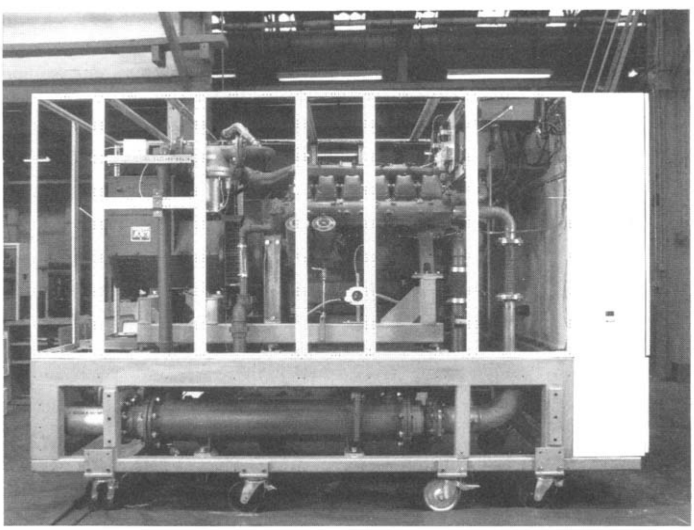

Fig. 2. A 185 kW(e) packaged CHP unit.

recent years and with increasingly more stringent emissions legislation to be met in certain areas of Europe, lean burn gas engines have become widely available. Such engines when coupled to high efficiency synchronous alternators and combined with a suitably designed heat recovery system will provide relatively impressive performance figures in terms of energy and cost saving to the user.

Table 1 is an overview of the performance of currently operating small-scale CHP systems. In it the parameter 'output value' is defined as:

$$\frac{(Ec \times Pe) + (Qc \times q)}{(Fc \times Pf)}$$

TABLE 1

Performance summary

Prime mover type	Typical electrical output range (kW)	Electrical generation efficiency (%)[a]	Heat to power ratio[b]	Output value ratio
Group1	38–75	27–29	1.8–1.84	~1.92
Group 2	85–185	30–32	1.6–1.7	~1.97
Group 3	290–945	29–32	1.41–1.45	1.86–1.9
Group 4	605–805	30	~1.30	1.78
GT	1050	25	2.2	1.89
Fuel cell	N/A	55	0.51	2.71

[a]Based on fuel gross (higher) calorific value.
[b]Based on output of useful heat.

where
Ec = electrical output of CHP system (kW)
Pe = value (cost) of displaced electricity (p/kW h)
Qc = heat output of CHP system (kW)
q = value (cost) of displaced heat (p/kW h)
Fc = fuel input (kW to CHP system)
Pf = cost of fuel (p/kW h).

Table 1 gives an overview of the basic performance of CHP systems using different types of prime mover and heat recovery interface. The survey is not exhaustive but indicative. The groups shown are defined as:

Group 1: normally aspirated reciprocating engines operating at or near to stoichiometric air fuel ratio.

Group 2: normally aspirated, lean burn engines.

Group 3: lean burn, turbocharged, intercooled reciprocating engines.

Group 4: lean burn, turbocharged, intercooled reciprocating engines operating at high jacket water temperature.

GT: gas turbine operating at 9.6:1 pressure ratio.

The Table also includes the projected figure for a high efficiency fuel cell based CHP system. Typical applications for conventional CHP include:

- leisure centres
- hospitals
- hotels
- sewage works (with the engines operating on gas from the digester system)

Other less widespread (in the UK) applications include:

- operational control centres with extended office hours, also air-conditioning applications with the heat output going to absorption chillers
- industrial processes
- greenhouses

The current minimum size of a conventional CHP system is in the range of 30–40 kW of electrical output, although units of lower output have been installed and are available.

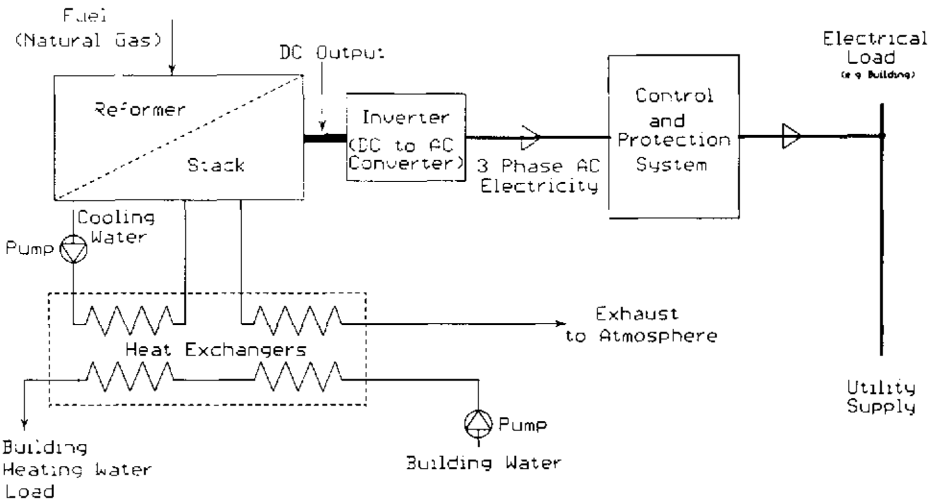

Fig. 3. General schematic of a fuel cell CHP unit.

Based upon what has been projected about fuel cells, it would appear to be the ideal combined heat and power device. It offers the following perceived advantages compared to a conventional plant:

- higher electrical generation efficiency
- lower exhaust emissions which are achievable without compromising the specific output of the prime mover
- low noise and vibration
- lower maintenance cost, although figures are not readily available

It is the author's understanding that a fuel cell system, comprising the reformer and the fuel cell stack, together with all ancillary equipment should effectively replace the conventional prime mover and 'part' of the alternator. Obviously in addition to the core fuel cell and inverter or other suitable device capable of producing a.c. would be required in order to complete the CHP scheme (Fig. 3).

In addition to the perceived technical and commercial advantages already cited above the fuel cell also offers the possibility of breaking into the sub 30 kW application market which cannot easily be addressed using conventional prime mover plant. Within this sector applications include sheltered housing, the small hotel, private residences with heated pools and, at the low kW level, the domestic application. In many of these applications the physical impact of conventional prime mover-based CHP would be unacceptable, as would the labour cost of maintenance. However the fuel cell offers the prospect of being environmentally equivalent to the wall mounted boiler but with an electrical output.

2. Commercial aspects

In the author's experience much of the time spent discussing commercial prospects for the fuel cells in CHP applications seems to concentrate upon the capital cost of the fuel cell device. However what is more important, certainly when viewed by the installer and operator of the equipment, should be the project life-cycle cost of the

CHP application. Thus when comparing the prospects for fuel cells as against conventional plant then three basic cost factors have to be taken into account; (i) the capital costs of the equipment, (ii) the installation cost and (iii) the project life operating costs. In addition to this it should be remembered that for the sub 30 kW market the fuel cell may be the only practical device to apply due to its perceived user and operator friendliness.

It has been extremely difficult to obtain information on the long term maintenance requirements and costs for fuel cells. This is a crucial area which has to be addressed in order to make a realistic assessment of the future potential for fuel cells since although conventional plant may be reaching a plateau in terms of performance, the performance is commercially acceptable and the more stringent emissions regulations will be met either through lean burn technology, or by the use of catalytic converter systems.

In addition to the above, the purchaser and operator of CHP plant has to be convinced of the long term stability and security of the supplier of the fuel cell, just as the stability and support of the manufacturer of prime mover or alternator has to be addressed when using conventional plant. It is therefore extremely important that the producers of the fuel cell systems can demonstrate long term financial security, technical support and maintain high quality product output even when production numbers soar. Bearing in mind the large investment required by fuel cell development programmes this requirement is likely to be achieved automatically.

Under normal circumstances CHP operation is heat demand led (the exceptions to this would be when operating as a peak-lopping device or as an emergency, island generator). If the heat demand led case is considered then it is possible to show that the saving in p/h for a CHP installation will be:

$$\text{saving} = Ec\left(Pe - \frac{Pf}{Ng} - Pm\right) + Qc\,\frac{Pf}{Nb}\ \text{(p/h)}$$

where

Ec = CHP electrical output (kW)

Qc = CHP useful heat output (kW)

Nb = thermal efficiency of 'competing' boiler plant

Ng = electricity generating efficiency of CHP unit

where

$$Ng = \frac{\text{nett electrical output}}{\text{fuel input (gross calorific value)}}$$

Pe = cost of displaced electricity (p/kW h)

Pf = cost of fuel (assumes CHP and boiler use fuel at the same price) (p/kW h)

Pm = cost of maintenance (p/kW h)

The above expression may be further developed to represent the saving per unit of useful heat output:

$$\text{saving/kW h (useful heat)} = R\left(Pe - \frac{Pf}{Ng} - Pm\right) + \frac{Pf}{Nb}\quad \text{(p/kW h)}$$

where R = power to heat ratio

Table 2 presents a comparison of the savings per unit of useful heat output for generating efficiency ranging from 25% (representing a simple gas turbine and low compression ratio reciprocating engine performance) up to 55% (representing the author's pereception of the upper performance limits of fuel cell systems). Sets of calculations are presented across the range of efficiencies for:

TABLE 2

Savings summary

Case description	Generating efficiency (%)						
	25	30	35	40	45	50	55
1. Overall efficiency = 83%							
(*Pe*/*Pf*) = 4; *Pm* = 0.125*Pe*							
Boiler efficiency = 75%							
Power to heat ratio, *R*	0.43	0.57	0.73	0.93	1.18	1.52	1.96
Specific saving (p/kW h)	1.12	1.43	1.80	2.26	2.85	3.61	4.64
Saving ratio	1.00	1.28	1.61	2.02	2.55	3.23	4.15
2. Overall efficiency = 83%							
(*Pe*/*Pf*) = 4; *Pm* = 0.125*Pe*							
Boiler efficiency = 95%							
Power to heat ratio, *R*	0.43	0.57	0.73	0.93	1.18	1.52	1.96
Specific saving (p/kW h)	0.84	1.15	1.52	1.98	2.57	3.33	4.36
3. *Chre* = 0.77							
(*Pe*/*Pf*) = 4; *Pm* = 0.125*Pe*							
Boilier efficiency = 75%							
Power to heat ratio, *R*	0.43	0.56	0.7	0.87	1.06	1.3	1.59
Specific saving (p/kW h)	1.12	1.43	1.78	2.2	2.69	3.28	4
4. *CHre* = 0.77							
(*Pe*/*Pf*) = 4; *Pm* = 0.125*Pe*							
Boiler efficiency = 95%							
Power to heat ratio, *R*	0.43	0.56	0.7	0.87	1.06	1.3	1.59
Specific saving (p/kW h)	0.84	1.5	1.5	1.92	2.41	3	3.72

(a) constant overall energy efficiency of 83%, boiler efficiency 75%

(b) constant CHP heat recovery efficiency, *Chre*

where $Chre = Qc/(Fc-Ec)$

Fc = fuel input to CHP

A value of $Chre = 0.77$ which is typical in practice has been assumed.

(c) constant overall efficiency but with the 'competing' boiler efficiency at 95%.

Throughout, an electricity to fuel price ratio of 4 is assumed and maintenance is assumed to cost 0.125*Pe*, which is typical in practice. The calculation also assumes that all the electricity generated can be utilised on site and the complexity of export tariffs are not considered. This should be noted since the CHP system with 55% generating efficiency is expected to have a power to heat ratio approaching 2 and on most 'normal' sites the system would most likely be exporting power.

However, the analysis is intended to emphasize the greatly enhanced value of output of the high efficiency machines when compared to currently available technology. Taking the most extreme examples then the fuel cell CHP system operating at 55% nett electrical efficiency could achieve four times the saving of the worst performing conventional system, primarily and obviously, because of the high power to heat ratio of the former. In simple terms, then providing the cell maintenance costs on a p/kW h basis are no higher than those for the conventional system, the cell project cost, installed, could be in excess of three times that of the conventional system yet still achieve a better project payback, providing both the heat and electrical outputs can be used on site.

The 'saving ratio' shown in Table 2 is a simple guide to the ratio of the project costs to achieve the same simple payback (in the UK this has to be less than 3 years under normal circumstances).

3. Technical aspects

(a) Interfacing considerations

As Figs. 1 and 3 indicate there are 4 basic physical interfaces between the CHP system and its surroundings viz.

(i) fuel input
(ii) heat load interface
(iii) exhaust gas exit
(iv) electrical interface

together with a possible fifth interface to an external Building Energy Management System (BEMS). The various interfaces are considered below.

(i) Fuel input

Conventional CHP units currently operate on a variety of fuels including

- natural gas
- digester gas
- oil
- landfill gas

and a number are equipped to operate as dual fuel engines. The fuel cell CHP system will be restricted to natural gas operation and it is possible that the effect of certain substances, other than methane, which are present in pipeline gas will have to be considered. It should also be noted that the modern spark ignited gas engine is quite capable of operating at normal domestic/commercial delivery pressures in the range 10–20 mbar. The gas train and controls will also be required to comply with relevant Codes of Practice.

(ii) Heat load interface

A CHP system will be required to interface to one or more of the following classes of heating system:

- low pressure hot water (LPHW) (70–90 °C)
- medium pressure hot water (MPHW) (110–130 °C)
- steam

The temperature ranges shown are indicative of the return and flow temperatures of the secondary water. With LPHW systems the standard temperature rise through the CHP heat recovery system will be 11 °C (e.g. 75 (return) 86 (flow)). It is anticipated that the heat recovery system will utilise a self-contained 'primary' cooling circuit which will cool the exhaust gases leaving the cell and perform any other cooling of ancillary cell equipment as required. This primary circuit will typically operate at temperatures between 5 and 10 °C higher than the secondary coolant and so for LPHW applications the solid polymer cell is a possible contender. For MPHW and steam raising applications the solid polymer cell would have to be excluded.

(iii) Exhaust exit

It is not envisaged that the exhaust from a fuel cell, having passed through the heat recovery system, will provide any particular problems. Indeed it is anticipated that the silencing problem will be greatly reduced. With conventional systems it is normal to limit the exhaust back pressure to no more than 35 to 40 mbar and this limit has a direct bearing on exhaust system sizing.

(iv) Electrical interface

The normal mode of operation of a CHP system in the UK is to be operating at rated output in parallel with the utility supply. Under these circumstances the unit's electrical protection (i.e. voltage and frequency tolerances, phase integrity etc.) are currently defined by G59 [4] and ET113 [5]. As far as fuel cells are concerned the most onerous aspect is that if a parameter exceeds the allowable limits then the generator has to disconnect in less than 0.5 s. This does not mean that the fuel cell has to be shutdown in 0.5 s but that its output must be disconnected – possibly redirected to a local dedicated load to enable the cell to unload satisfactorily. Electrical protection in conventional CHP is described in more detail in ref. 3.

(v) Control interface

There is not always a requirement to interface to an external BEMS, and in some instances the interface will be to a simple boiler sequencer which will demand on/off operation (however this does not have to be a sudden off loading). In many applications, particularly in small applications, the unit will be required to control itself and this has to be a basic feature of any CHP system.

In an increasing number of applications there is a requirement to be able to modulate heat output (and hence power output normally) either from an external controller or by the CHP's own control system. Depending on the impact on the savings economics it is possible to achieve this by dumping heat and maintaining full power output.

(b) Operational considerations

(i) Output control

As mentioned above the normal mode of operation will be constant power output in parallel with the utility supply (output governing – slow response except for sudden shutdown). There is an increasing requirement to supply CHP units that can also operate as emergency generators in the event of losing the utility supply (frequency governing – fast response to load changes). It would seem unlikely that the fuel cell will be able to immediately address the emergency generator requirement.

If the parallel operation mode is considered then this can be sub-divided into four basic phases viz.

- start-up and synchronising to the utility supply
- full output operation
- on load modulation, slow response required
- shutdown, either controlled ramp down (e.g. at the scheduled end of operation) or rapid load disconnection for protection purposes or emergency stop (requiring fuel supply shutdown)

(ii) Condition monitoring

As described in ref. 3 sophisticated performance and condition monitoring systems are fitted to state of the art conventional CHP systems. Such systems are able to communicate with centralised maintenance monitoring computers and enable maximum availability of plant to be achieved. It is envisaged that the same philosophy will be applied to fuel cell systems and as such a set of monitoring parameters need to be defined both for performance *and* condition monitoring purposes.

(iii) Emission

It is inevitable that increasingly stringent emission legislation will be applied to CHP plant which conventional prime movers will endeavour to achieve either through lean burn combustion or, if extreme and/or in in order not to excessively compromise output, through catalytic conversion. It is widely promoted that fuel cells are inherently 'clean' devices, however emissions figures, e.g. unburnt hydrocarbons, require practical quantification.

(iv) Life

Typical CHP systems will operate for anywhere between 5000 and 8000 h per annum. In addition to this, one of the early criticisms levelled against conventional CHP was that performance was not consistently maintained which had a direct influence on energy cost savings. Advances in control, condition monitoring and performance monitoring have made it possible to ensure that consistent performance can be achieved. With regard to major inspection and overhaul then for industrial gas engines this will typically be after 40 000 to 50 000 h of operation. These figures indicate the level of operational life likely to be expected from fuel cells.

4. Conclusions

The foregoing has been a brief overview of a number of issues that need to be addressed when considering the commercialisation of fuel cells in CHP applications. It is clear that there is a definite role for fuel cells, even though they are likely to be more expensive in terms of first cost, providing their performance is as has been projected and can be achieved consistently over many hours of operation. It is therefore clear that an immediate requirement is for in-field operational experience to be gained and practical performance and problems assessed and quantified.

References

1 HMSO, *The 1983 Energy Act.*
2 C. J. Linnel, The first 10 years on the U.K. market for packaged cogeneration plant, *Gas Engine and Cogeneration Seminar,* I. Mech. E, Solihull, May 1990.
3 J. P. Packer and M. Woodworth, Advanced package CHP unit for small-scale operation, *I.E.E. Power Engineering J.,* May 1991.
4 Electricity Council, *Electricity Council Engineering Recommendations G59,* 1985.
5 Electricity Council, Notes of Guidance for the protection of private generating sets up to 5 MW for operation in parallel with Electricity Boards distribution networks, *ET113,* 1989.