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SOME CHP OPTIONS FOR WOOD-FIRED FUEL CELLS

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ABSTRACT

The possibility of integrating biomass gasifiers with fuel cells has already been explored and shown to offer a method for using renewable energy to generate electricity at a small scale. A preliminary study of applying such a system for use in an isolated community and for several selected buildings has been made and the results of these studies reported earlier.

In this study wood gasification integrated with fuel cell (WGIFC) systems in CHP configurations for five building systems with different energy demand profiles, are assessed. These are a hospital, a hotel, a leisure centre, a multi-residential community and a university hall of residence. Heat and electricity use profiles for typical examples of these buildings were obtained and the WGIFC system scaled to the power demand. Detailed technical, environmental and economic analyses of each version are made, using the ECLIPSE process simulation package. Various factors influencing the economic viability of each application are examined and a sensitivity analysis for each system produced.

The WGIFC system was modelled for two different types of fuel cell, the Molten Carbonate and the Phosphoric Acid. In each case an oxygen-fired gasification system is proposed, in order to eliminate the need for a methane reformer.

Technical, environmental and economic analyses of each version were made, using ECLIPSE. Since fuel cell lifetimes are not yet precisely known, economics for a range of fuel cell lifetimes have been produced.

While the wood-fired Phosphoric Acid Fuel Cell (WFPAFC) system was found to have low electrical efficiency (13 – 16%), the wood-fired Molten Carbonate Fuel Cell (WFMCFC) system was found to be quite efficient for electricity generation (24 to 27%). Much of the waste heat could be recovered for the WFPAFC, so that the overall efficiency was 64 to 67%, and some waste heat, but potentially of higher grade, could be recovered by the WFMCFC to give an overall energy efficiency of 60 to 63%. The capital costs of both systems are still expected to be very high, but the examination of wood fuel prices, fuel cell costs, fuel cell lifetime and waste heat selling prices on the break-even selling price for electricity, as well as comparative sensitivity analyses, can help identify which other factors would have the main impacts on the system economics.

KEYWORDS

Fuel cell systems; biomass; wood gasification; CHP; computer simulations.

NOMENCLATURE

Some of the abbreviations used in the paper are as follows:

CHP	Combined Heat and Power
PV	Photovoltaics
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
LPO	Low Pressure Oxygen
WGIFC	Wood Gasification Integrated with Fuel Cell system
LHV	Lower Heating Value
COE	Cost of Electricity, in this case the break-even cost of generating electricity
SI	Specific Investment, the capital cost per kW of electricity generated
WFPAFC	Wood-Fired Phosphoric Acid Fuel Cell
WFMCFC	Wood-Fired Phosphoric Acid Fuel Cell

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INTRODUCTION

There are several benefits in using fuel cells, rather than gas engines, to generate electricity at small scales: they are silent, produce no SO_x or NO_x emissions and are very efficient even in small systems. Renewable energy sources could be used to provide the fuel for the fuel cell in different ways. For example, wind turbines or PV cells could generate electricity for the electrolysis of water to provide hydrogen, which then must be stored for use when needed. Another option would be to gasify biomass to provide a hydrogen-rich gas. The gasifier can be scaled appropriately for the chosen power output of the fuel cell stacks. Some applications of the latter option will be considered in this paper.

McIlveen-Wright et al. [1,2] described an integrated system using a wood gasifier with fuel cells and the advantages over using them separately. Efficient power generation from a renewable source could be provided for small scale CHP applications, such as commercial or multi-residential buildings, by a combination of these two technologies. Waste heat from the fuel cells could be used to pre-dry the wood fuel for the gasifier, as well as heating water for CHP applications and for raising steam for the "shifter", where used. The gas from the gasifier could help to preheat the air used in the fuel cell. The efficiency of this integrated system would be improved by using potentially wasted energy from one element of the system in the other.

Energy profiles of typical examples of certain building types have been obtained for this study and a CHP system, based on the integration of a wood gasifier with fuel cell stacks, was sized by McIlveen-Wright et al. to provide a "reasonable" amount of each building's heat and electricity requirements over the whole year [3]. Technical, economic and environmental assessments were made for each CHP system modelled using the ECLIPSE process simulation software developed by Williams and McMullan [4]. Any shortfall in electricity would be made up from the grid and any heat deficiency from an auxiliary boiler.

1.1 SYSTEM TECHNOLOGY

1.1.1 CHOSEN FUEL CELL TYPES

The phosphoric acid fuel cell (PAFC) and the molten carbonate fuel cell (MCFC) are the two fuel cell types chosen to be part of the system. The properties of the fuel cell electrolyte must be taken into account when considering what gas conditioning is necessary for the syngas, the gas resulting from wood gasification.

The *Phosphoric Acid Fuel Cell (PAFC)* is (a) CO_2-rejecting i.e. is insensitive to CO_2 and other acid components, (b) can tolerate 1-2% CO at the operating temperature of 200°C, and (c) can use the waste heat from the electrochemical cell stack efficiently for steam reforming and for providing space heating or hot water [5]. Since the PAFC can only tolerate a small percentage of CO, a "shifter" is needed to convert the CO to hydrogen. In addition, steam is required for the shift reaction.

The *Molten Carbonate Fuel Cell (MCFC)* (a) can tolerate CO_2, (b) can use both H_2 and CO as "fuel" to produce electricity, (c) has an operating temperature of 600-700°C, (d) has recoverable waste heat at high temperatures which could provide high grade steam, as well as low temperature waste heat for hot water. The MCFC can use both hydrogen and CO in generating electricity, so no shifter is required.

1.1.2 TYPE OF GASIFIER

The features of the chosen fuel cells should be taken into account when selecting the gasification technology. The type of gasifier technology used and the oxidant employed determine the composition of the gas produced, and this gas should be suitable for efficient operation of the fuel cell.

The typical composition of producer gas formed by the gasification of wood with air is shown in Table 1.

Table 1. Typical Composition (by volume) of wood producer gas

Carbon Monoxide	18-25%
Hydrogen	13-15%
Methane	3-5%
Heavy Hydrocarbons	0.2-0.4%
Carbon Dioxide	5-10%
Nitrogen	45-54%
Water Vapour	10-15%

The carbon dioxide in the producer gas comes mostly from incomplete reduction i.e. not all of the carbon dioxide is able to come into contact with the hot carbon in the bed. The nitrogen is from the air. The nitrogen and the carbon dioxide are non-combustible and their presence in the producer gas decrease its energy content. Typically the producer gas would have a calorific value (LHV) of 4-6 MJ/ m^3. If the gasification is carried out using oxygen instead of air, there is no nitrogen present to "dilute" the energy content of the resulting gas, known as *synthetic gas* or *syngas*, and it has a calorific value of between 11 and 19 MJ/m^3, depending on the exact composition.

The most active common fuel for use in fuel cells is hydrogen, since it has an oxidation rate of about 4 orders of magnitude greater than that of simple partially oxidised one-carbon compounds, which themselves have the same oxidation advantage over saturated hydrocarbons under the same conditions [6]. Hydrogen can be produced from the thermochemical gasification of many biomass feedstocks, such as municipal solid waste, agricultural or forest wastes or wood chips from short rotation forestry plantations. The synthesis gas (or syngas) coming from the gasifier will contain methane and carbon monoxide in addition to the hydrogen. In general, the fuel cell electrolytes cannot use the syngas directly, it must receive the appropriate pretreatment. This pretreatment can involve adding steam at high temperature to the syngas to convert the methane to carbon monoxide and hydrogen in a

process known as *steam reforming*. At a lower temperature steam can react with the carbon monoxide to form hydrogen (and carbon dioxide) in the *shift conversion* reaction. Carbon dioxide (and sulphur compounds, if present) can be removed at a later stage, if necessary.

The equipment for converting syngas to hydrogen (methane reformers, shift reactors, CO_2-removal systems and hydrogen purification "pressure-swing-adsorption" technology) are all well-established commercial technologies in the chemical process industries.

Biomass gasifiers in various forms have been available on the pilot scale, as demonstration systems and as commercial plants. Some of these which are being developed for methanol production are also suitable for hydrogen production, since the production of syngas is the first of two stages in methanol synthesis [7]; the second stage being the recombination of carbon monoxide and hydrogen at elevated temperature and pressure (≈300°C and 70 bar), and in the presence of a Cu-Zn catalyst, to produce methanol.

BIOMASS GASIFICATION

The object in using a biomass gasifier with a fuel cell is to produce a syngas which is rich in hydrogen and carbon monoxide and poor in any other constituents, including methane. An air-blown gasifier would produce a lot of nitrogen in the syngas, which would act as a strong diluent of the gas. For this reason gasification occurs in an atmosphere of steam and/or oxygen at moderately high temperatures (up to 1,000°C), short residence times (0.5 to 20 seconds) and a range of pressures (1 to 25 bar).

Within the gasifier many reactions are possible in different temperature and atmospheric regimes. These can be simplified to demonstrate the two main reactions which give carbon monoxide and hydrogen.

$$\text{Biomass} + O_2 \rightarrow CO + H_2 + \text{Heat} \quad (\textbf{Partial Oxidation})$$
$$\text{Biomass} + \text{Steam} + \text{Heat} \rightarrow CO + H_2 \ (\textbf{Pyrolysis})$$

Both reactions occur during gasification, but the system can be designed to maximise one of these processes. The pyrolysis reaction is endothermic, requiring some means of adding heat, whereas the partial oxidation step is exothermic. The design of the gasifier and the feedstock used determine the overall heat balance of the system. Since biomass is much more reactive than coal, there are more processing options available for biomass gasifiers. More volatiles are driven off from biomass, and the remaining char is also highly reactive. Coal gasifiers must be designed to maximise the partial oxidation process in order to attain the high temperatures necessary for high gasification yields, but biomass gasifiers can use either the pyrolysis or the partial oxidation route.

Oxygen must first be separated from air to be injected into gasifiers which are designed for the partial oxidation reaction. Oxygen separation is expensive, but provides the heat for high temperature gasification, resulting in a syngas of low methane content. Gasification of the char can be improved by the addition of steam. Biomass gasifiers using partial oxidation have been demonstrated for wood in the range of 5 to 100 tonnes per day for a variety of technologies, including entrained flow, fluidised-bed and fixed bed [8, 9, 10].

Biomass gasifiers have also been designed to produce syngas using predominantly the pyrolytic reactions. These indirectly heated gasifiers use heat provided by the external combustion of some of the biomass in order to drive the pyrolysis and steam gasification reactions in the gasifier. The heat can be transferred by using fire tubes in the fluidised bed or by using multi-vessel configurations. Heat transfer via fire tubes may be limited to atmospheric pressure systems, whereas the multi-vessel systems may be operable at higher pressures. The main advantage of an indirectly heated gasifier is that it does not require an oxygen separator. Unfortunately the syngas generated has a high methane content, and so requires methane reforming.

GASIFIER TECHNOLOGIES

There are five main gasification technologies which could be suitable for hydrogen production from biomass: (1) Low Pressure Oxygen (LPO); (2) High Pressure Oxygen (HPO); (3) Indirectly Heated (IND); (4) Indirectly Heated with Hot Gas Conditioning (IND2); (5) Combined Gasification and Hydrogen Separation in a Catalytic Membrane Reactor (CMR).

These technologies are considered in reverse order.

CMR

This process is based on the catalytic steam gasification of biomass with concurrent separation of hydrogen by a permselective membrane (Pd/Ag alloy) which separates the hydrogen as it is produced [11]. The hydrogen stream produced is better than 99% pure, while the by-product stream consists mainly of carbon dioxide and water. This form of gasification and separation takes advantage of the Le Chatelier principle, enabling the gasification to take place at lower temperatures (≈350°C) and at atmospheric pressure with increased conversion and hydrogen yield over that predicted by thermochemical equilibrium considerations.

At the present time membrane reactors have only been investigated at the bench scale for limited times and reaction conditions. While they have been successful in such tests, their performance under commercial conditions has yet to be demonstrated.

IND2

The indirectly heated gasifier produces a large proportion of methane in the syngas. In the *IND2* system catalytic hot gas conditioning is used both to destroy tars and to reform methane. Hot gas conditioning is currently only at the bench scale, and since low temperature gas cleaning is required by the brief, this system will not be considered further.

IND

The Batelle Columbus Laboratory (BCL) gasifier is an example of a typical indirectly heated gasifier. The product char is burned to heat sand which is mixed with fresh biomass for gasification. A syngas with a low H_2/CO ratio, high levels of light hydrocarbons and low carbon dioxide is produced by indirect gasification. The high level of methane produced means that a reformer is required. The raw syngas can be quenched with the tars being recycled either to extinction in the gasifier or in the combustor to help provide process heat. The BCL gasifier has been operated at atmospheric pressure and temperatures up to 1,000°C, using 12 tonnes per day of biomass [12].

HPO

The Institute of Gas Technology (IGT) has developed the "Renugas" high pressure, oxygen-blown gasifier for biomass. This gasifier has been run at temperatures up to ≈980°C and pressures up to ≈24 bar at a pilot scale of 10 tonnes per day. A syngas with a high methane content is produced by high pressure operation (see following table), and so a methane reformer is required. It is assumed that such gasifiers could operate at pressures up to 45 bar and also that no gas conditioning, other than particle removal, would be required before entering the methane reformer.

LPO

The Koppers-Totzek entrained-flow gasifier, originally developed for coal gasification and considered to be representative of commercially available LPO technology [13], was considered to be appropriate for these chosen fuel cells. It has also been assessed for biomass [14]. This is a low pressure, oxygen blown gasifier which produces a syngas with a H_2/CO ratio less than 1, and with low levels of methane and other light hydrocarbons. A methane reformer may not be necessary, but a shift reactor will be required to increase the H_2/CO ratio (when used with the PAFC). As mentioned before, this gasifier requires feedstock of very small, uniform size which involves substantial preparation costs.

SUITABILITY OF GASIFIER TYPES FOR USE WITH FUEL CELLS

The LPO, HPO and IND gasifiers all offer promise for producing hydrogen-containing syngas which could be "reformed" and/or "shifted" for use in fuel cells. Some of the equipment necessary for the gasifier system is very expensive. However, it is difficult to determine capital costs for innovative technology at a commercial scale, when this has either never been produced or has only been produced on a "one-off" basis. For this reason it is difficult to determine which technology would be most appropriate without further information. The IND gasifier will not be considered because of this costing difficulty. Oxygen separation is expensive, but both the LPO and the HPO gasifiers require it.

Table 2. Comparison of Potential Biomass Gasifiers

Gasifier Type	LPO	HPO	IND
Pressure (bar)	1.013	34.4	1.013
Temperature (°C)	980	980	980
Dry Gas Production (Nm^3/tonne)	1,347.5	1,065.8	1,027.2
Dry Gas Composition (mol %)			
H_2	36.2	30.9	30.6
CO	44.4	19.8	41.2
CO_2	19.1	36.2	10.9
CH_4	0.3	13.1	14.0
C_2	-	-	3.3
H_2/CO	0.82	1.56	0.74

An atmospheric pressure gasifier is cheaper than a pressurised gasifier and the LPO gasifier system requires either no reformer, or a smaller one than the HPO system. On the other hand, the HPO system requires little or no CO to H_2 shifting, whereas this will be necessary for the LPO system when used with the PAFC (but not with the MCFC). The LPO system also requires the expensive size-reduction equipment.

It is still not clear which of these two systems offers the greater potential for use with fuel cells. However, in this paper, only the LPO gasifier, in an integrated system containing the fuel cell technology, is considered since the system cost should be kept as low as possible.

The LPO gasifier is chosen since it gives a gas low in methane, which means that no reformer is necessary for the fuel cell to "reform" the methane to hydrogen and carbon monoxide. Oxygen separation adds an additional expense to the system, but the gas produced from the gasifier will not be diluted with atmospheric nitrogen, and hence the rest of the gas-handling equipment can be of a smaller scale (and less expensive) than that associated with air-blown gasifiers.

1.1.3 PROCESS DESCRIPTION (USING THE PAFC)

As described earlier [3], the wood is harvested, chipped and transported from the short-rotation-forestry plantation to the power plant. It is assumed to have a moisture content of 100% (dry basis). {This is quite a high value, and wood of lower moisture content would offer efficiency improvements, if available [15].} The wood is dried to a moisture content of 15%, using the hot exhaust gases from the fuel cell in a rotary dryer, and then fed to the gasifier.

An oxygen-separation plant extracts 95% of the oxygen from incoming air (at atmospheric pressure) to supply the gasifier. Steam is raised using some of the waste heat from the fuel cell and is added at 175°C to the gas leaving the gasifier. The gas/steam mixture transfers heat to the air used by the fuel cell (and provides some hot water at 85°C) before entering the

Shifter. The shifted gas is cooled, cleaned in a conventional scrubber and fed to the fuel cell. The fuel cell is considered to operate in a standard configuration, at 200°C, with the waste heat providing steam (as previously mentioned, for the shift reaction) and hot water (85°C) for possible combined heat and power applications.

It is assumed that 40% of the Phosphoric Acid fuel cell's energy can be used to provide electricity. The system is scaled so that this results in a net ac output of an appropriate value from the fuel cell (the dc output is inverted to ac at an efficiency of 97%) for the selected building.

Process Identity	Hospital	Hotel	Leisure Centre	Halls of Residence	Multi-Residential
Fuel Cell Type	PAFC	PAFC	PAFC	PAFC	PAFC
Fuel Feedstock	Wood	Wood	Wood	Wood	Wood
Operating Temperature (°C)	200	200	200	200	200
CO Shifter	Yes	Yes	Yes	Yes	Yes
Gasifier Type	LPO	LPO	LPO	LPO	LPO
Wood Input (dry tonnes/ day)	2.6	1.3	1.8	1.0	0.6
Thermal Input (kW, HHV)	563.8	279.5	386.5	211.0	125.8
Thermal Input (kW, LHV)	524.1	259.8	359.3	196.1	116.9
PAFC Power Output (kWe dc)	114.6	56.8	78.6	42.9	25.6
PAFC Power Output (kWe ac)	111.2	55.1	76.2	41.6	24.8
Auxiliary Power Usage (kWe)	30.6	16.9	22.2	13.4	8.8
Net Electrical Output (kWe)	80.6	38.2	54.0	28.2	16.0
Available Waste Heat (kWth)	268.6	133.2	184.1	100.5	59.9
Electrical Efficiency (% HHV)	14.3	13.7	14.0	13.4	12.7
Electrical Efficiency (% LHV)	15.4	14.7	15.0	14.4	13.7
Overall Energy Efficiency (% HHV)	61.9	61.3	61.6	61.0	60.3
Overall Energy Efficiency (% LHV)	66.6	66.0	66.3	65.6	64.9
CO_2 (g/ kWh)	2,420	2,530	2,480	2,590	2,720

Table 3. - Technical and Environmental Results for PAFCs in “Selected Buildings”

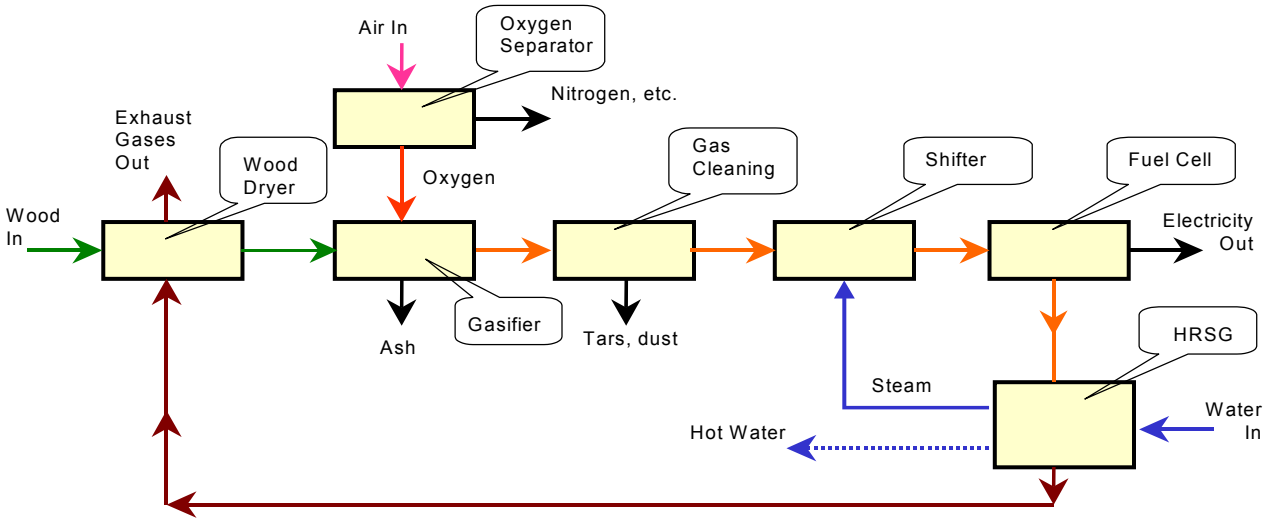
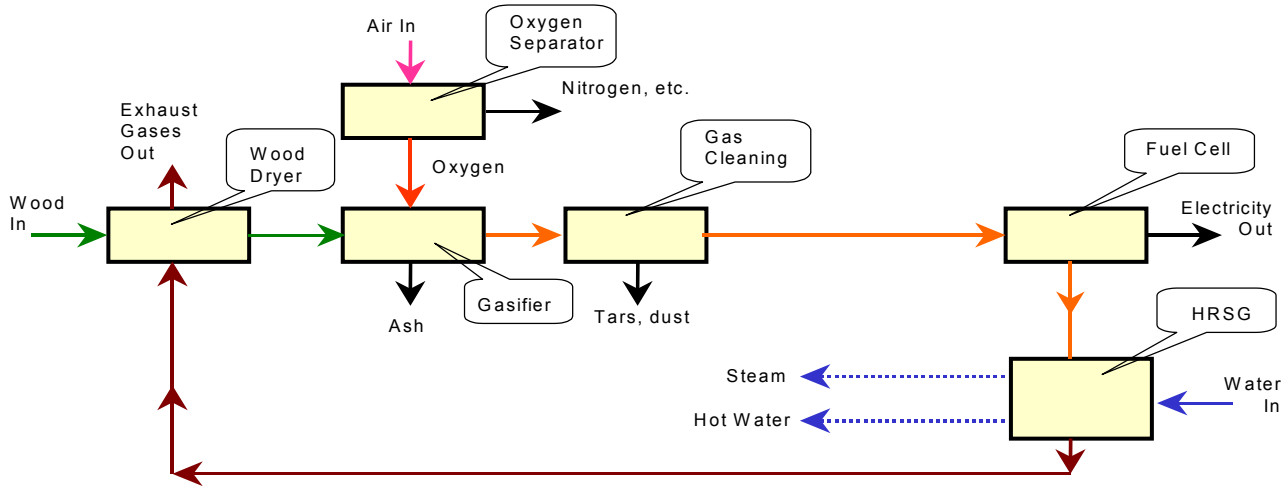


Figure 1 (above). Simplified Block Diagram of the Integrated LPO Gasifier and Phosphoric Acid Fuel Cell System

Figure 2 (below). Simplified Block Diagram of the Integrated LPO Gasifier and Molten Carbonate Fuel Cell Syste



1.1.4 MCFC IN THE SYSTEM

The PAFC can also be replaced by the MCFC in the system and this has other implications for the integrated system. First of all, the MCFC operates at 650°C instead of 200°C for the PAFC. Some higher-grade waste heat will be available from a system operating at such a high temperature, which means it could generate steam for other processes or to drive a steam turbine in a larger system. Secondly, the conversion efficiency of the MCFC is taken to be 55% compared to 40% for the PAFC, so more of the energy of the wood gas can be converted into electricity. Finally, the MCFC can use carbon monoxide as well as hydrogen to produce electricity, so no "Shifter" is required in this system.

2.0 SELECTED BUILDINGS

In this paper the objective was to assess the wood-fired fuel cell CHP systems for their suitability in supplying electricity and space heating to domestic and commercial buildings. PAFC power plants using natural gas as the fuel have been found to be suitable for a range of CHP applications in urban settings [16]. The same applications are examined here using integrated LPO biomass gasifier/fuel cell power plants in CHP configurations.

Process Identity	Hospital	Hotel	Leisure Centre	Halls of Residence	Multi-Residential
Fuel Cell Type	MCFC	MCFC	MCFC	MCFC	MCFC
Fuel Feedstock	Wood	Wood	Wood	Wood	Wood
Operating Temperature (°C)	650	650	650	650	650
Gasifier Type	LPO	LPO	LPO	LPO	LPO
Wood Input (dry tonnes/ day)	1.5	0.7	1.0	0.5	0.3
Thermal Input (kW, HHV)	321.8	157.6	219.5	116.8	69.3
Thermal Input (kW, LHV)	299.2	146.5	204.0	108.6	64.4
MCFC Power Output (kWe dc)	106.4	52.1	72.6	38.6	22.9
MCFC Power Output (kWe ac)	103.2	50.5	70.4	37.4	22.2
Auxiliary Power Usage (kWe)	23.0	12.5	16.5	9.6	6.2
Net Electrical Output (kWe)	80.2	38.0	53.9	27.8	16.0
Available Waste Heat (kWth)	107.2	52.5	73.1	38.9	23.1
Electrical Efficiency (% HHV)	24.9	24.1	24.6	23.8	23.1
Electrical Efficiency (% LHV)	26.8	25.9	26.4	25.6	24.8
Overall Energy Efficiency (% HHV)	58.2	57.4	57.9	57.1	56.4
Overall Energy Efficiency (% LHV)	62.6	61.8	62.3	61.4	60.7
CO_2 (g/ kWh)	1,420	1,470	1,440	1,490	1,530

Table 4. - Technical and Environmental Results for MCFCs in Selected Buildings

The technical and emissions results from the simulations of the systems are shown in tables 3 and 4. For the systems using an integrated PAFC, there is no reformer; no sulphur removal technology; no CO2 sequestration technology; the operating temperature of the fuel cell is 200°C; there is anode recycle; there is a CO shifter; and the gasifier type is LPO.

For the systems using an integrated MCFC, there is no reformer; no sulphur removal technology; no CO2 sequestration technology; the operating temperature of the fuel cell is 650°C; there is anode recycle; there is no CO shifter; and the gasifier type is LPO.

In this study the WGIFC CHP system was scaled according to the electricity demand curve for each application in such a way as to give high fuel cell occupancy (availability) and to maintain a constant load. If the system followed the

load, the resulting efficiency would change. The electricity demand profiles show monthly averages, but in fact more detailed demand curves, with half-hour electricity usages are taken into account to ensure that the system is not oversize, as the capital costs strongly affect the overall electricity generation costs.

Any electricity demand peaks will be supplied from the grid and using an auxiliary boiler would make up shortfalls in heat demand. This is in contrast to the system when used in an isolated community [17], where no heat or power could be imported (or exported).

2.1 EXAMPLES OF SELECTED BUILDING SYSTEMS

The wood gasification integrated fuel cell (WGIFC) system is applied to five building systems. These are a hospital, a hotel a leisure centre, a multi-residential community and a university halls of residence situated in the UK, and have already been described earlier [3]. Each building system has a different energy demand profile. Energy demand curves for examples of these building systems are shown in figs 3, 4, 5, 6 and 7. The energy profiles in these figures show the month-by-month demand, but more detailed profiles, with diurnal variations, were used in the analysis.

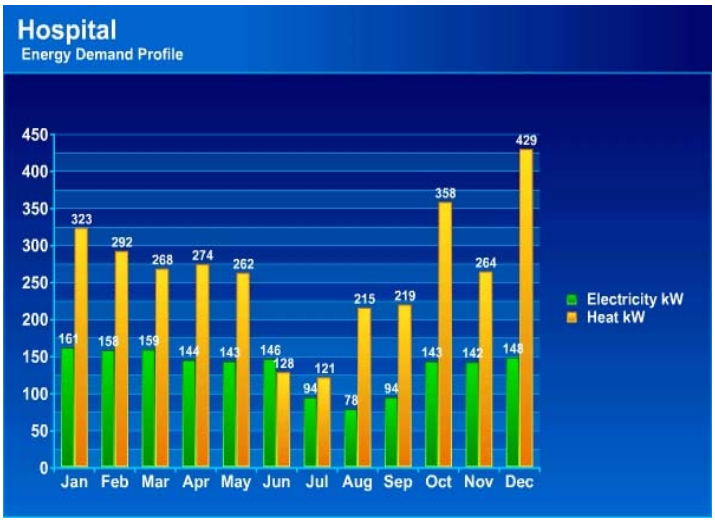


Figure 3. Energy Profile of the selected hospital

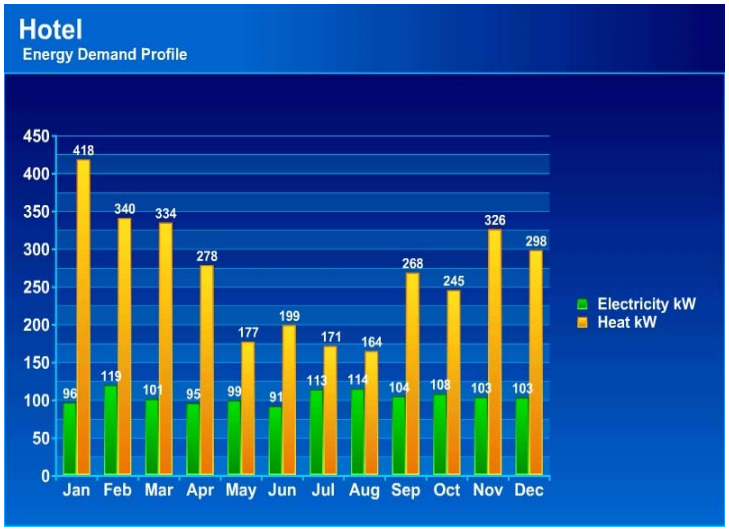


Figure 4 Energy Profile of the selected hotel

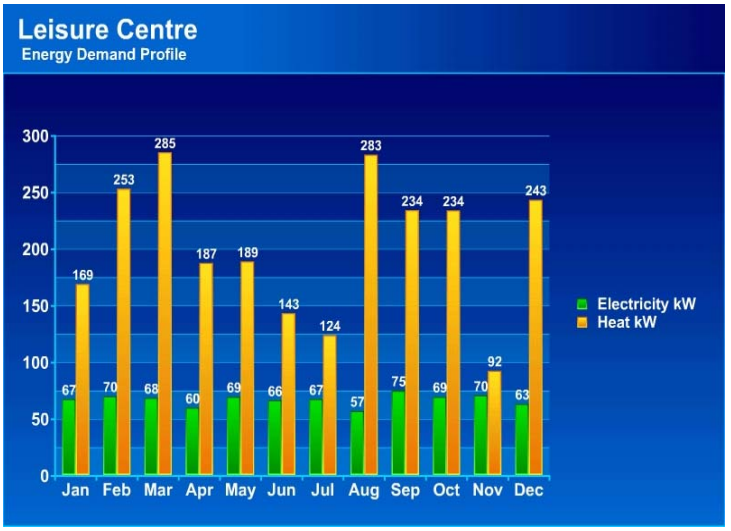


Fig.ure 5. Energy Profile of the selected Leisure Centre

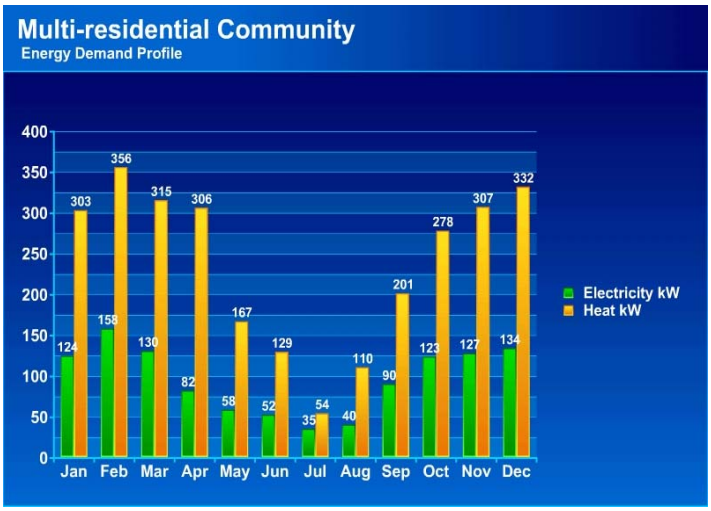


Figure 6. Energy Profile of the selected Multi-Residential Community

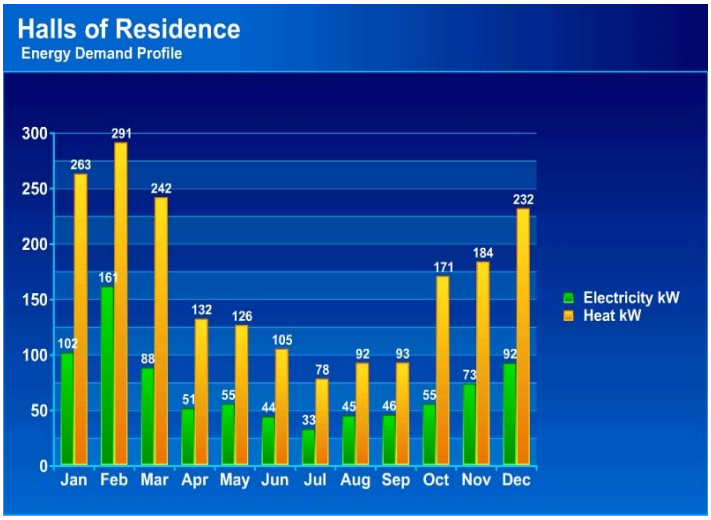


Figure 7. Energy Profile of the selected University Halls of Residence

3.0 TECHNICAL AND ENVIRONMENTAL (EMISSIONS) RESULTS FOR SELECTED BUILDINGS

The technical and environmental results for these LPO CHP systems are summarised in Tables 3 and 4.

3.1 HOSPITAL

The WGIFC system, using PAFCs, would use 2.6 dry tonnes of wood chip per day, which would give a thermal input of around 524 kWth (LHV) and result in a net electrical output of 80.6 kWe and available waste heat of 268.6 kWth. In this case the electrical efficiency would be 15.4% (LHV) and the overall energy efficiency 66.6% (LHV). The actual CO2 emissions would be about 2420 g/kWh, but the system can be considered carbon neutral, if wood from a sustainably managed plantation is used. No SOx emissions would be obtained, as there is no sulphur in wood, and NOx emissions would also be negligible, since the gasifier oxidant is nitrogen-free and fuel nitrogen is low.

The WGIFC system, this time with MCFCs, would use 1.5 dry tonnes of wood chip per day, which would give a thermal input of around 299 kWth (LHV) and result in a net electrical output of 80.2 kWe and available waste heat of 107.2 kWth. In this case the electrical efficiency would be 26.8% (LHV) and the overall energy efficiency 62.6% (LHV). The actual CO2 emissions would be about 1420 g/kWh, and there would be no SOx or NOx emissions obtained.

3.2 HOTEL

The WGIFC system for the hotel, using PAFCs, would use 1.3 dry tonnes of wood chip per day, which would give a thermal input of around 260 kWth (LHV) and result in a net electrical output of 38.2 kWe and available waste heat of 133.2 kWth. In this case the electrical efficiency would be 14.7% (LHV) and the overall energy efficiency 66.0% (LHV). The actual CO2 emissions would be about 2530 g/kWh, but there would be no SOx or NOx emissions.

The hotel WGIFC system, this time with MCFCs, would use 0.7 dry tonnes of wood chip per day, which would give a thermal input of around 146.5 kWth (LHV) and result in a net electrical output of 38.0 kWe and available waste heat of 52.5 kWth. In this case the electrical efficiency would be 25.9% (LHV) and the overall energy efficiency 61.8% (LHV). The actual CO2 emissions would be about 1470 g/kWh, and there would be no SOx or NOx emissions

3.3 LEISURE CENTRE

The WGIFC system for the leisure centre, using PAFCs, would use 1.8 dry tonnes of wood chip per day, which would give a thermal input of around 360 kWth (LHV) and result in a net electrical output of 54.0 kWe and available waste heat of 184.1 kWth. In this case the electrical efficiency would be 15.0% (LHV) and the overall energy efficiency 66.3% (LHV). The actual CO2 emissions would be about 2480 g/kWh, but there would be no SOx or NOx emissions.

The leisure centre WGIFC system, this time with MCFCs, would use 1.0 dry tonnes of wood chip per day, which would give a thermal input of around 204.0 kWth (LHV) and result in a net electrical output of 53.9 kWe and available waste heat of 73.1 kWth. In this case the electrical efficiency would be 26.4% (LHV) and the overall energy efficiency 62.3% (LHV). The actual CO2 emissions would be about 1440 g/kWh, and there would be no SOx or NOx emissions obtained.

3.4 MULTI-RESIDENTIAL COMMUNITY

The WGIFC system for the multi-residential community, using PAFCs, would use 0.6 dry tonnes of wood chip per day, which would give a thermal input of around 117 kWth (LHV) and result in a net electrical output of 16.0 kWe and available waste heat of 59.9 kWth. In this case the electrical efficiency

would be 13.7% (LHV) and the overall energy efficiency 64.9% (LHV). The actual CO2 emissions would be about 2720 g/kWh, but there would be no SOx or NOx emissions.

The multi-residential community WGIFC system, this time with MCFCs, would use 0.3 dry tonnes of wood chip per day, which would give a thermal input of around 64.4 kWth (LHV) and result in a net electrical output of 16.0 kWe and available waste heat of 23.1 kWth. In this case the electrical efficiency would be 24.8% (LHV) and the overall energy efficiency 60.7% (LHV). The actual CO2 emissions would be about 1530 g/kWh, and there would be no SOx or NOx emissions released.

3.5 UNIVERSITY HALLS OF RESIDENCE

The WGIFC system for the hotel, using PAFCs, would use 1.0 dry tonnes of wood chip per day, which would give a thermal input of around 196 kWth (LHV) and result in a net electrical output of 28.2 kWe and available waste heat of 100.5 kWth. In this case the electrical efficiency would be 14.4% (LHV) and the overall energy efficiency 65.6% (LHV). The actual CO2 emissions would be about 2590 g/kWh, but there would be no SOx or NOx emissions.

The hotel WGIFC system, this time with MCFCs, would use 0.5 dry tonnes of wood chip per day, which would give a thermal input of around 109 kWth (LHV) and result in a net electrical output of 27.8 kWe and available waste heat of 38.9 kWth. In this case the electrical efficiency would be 25.6% (LHV) and the overall energy efficiency 61.4% (LHV). The actual CO2 emissions would be about 1490 g/kWh, and there would be no SOx or NOx emissions obtained.

4.0 RESULTS OF THE ECONOMIC ANALYSIS

The economics of these systems depends heavily on the cost of the fuel cells and their lifetimes. It has been assumed that each of these systems will be generating power for 25 – 30 years. The fuel cell lifetime is not precisely known, but is considered to be currently shorter than the system lifetime and has been taken to be 5, 10 or 15 years. The fuel cell cost is also not well established, and values of £500, £750, £1,000, £1,500 and £2,000 per kilowatt were considered here. These are high in comparison with modern gas-fired power plants, but the US DOE has set targets of $400/kW by 2010 for fuel cells, so there may be considerable cost reductions in the medium term future.

4.1 SPECIFIC INVESTMENT

Specific Investment (SI, or system cost per net kilowatt of electricity generated) for each system has been estimated [3] and shown in figures 8, 9, 10, 11 and 12 for the estimated fuel cell lifetimes and costs, for both systems with MCFCs and PAFCs.

Net system electrical output kWe	80.6	80.6	80.6	80.6	80.6
					For a fuel cell lifetime of 5 years
Fuel Cell ac output kWe	111.2	111.2	111.2	111.2	111.2
Fuel Cell Cost Rate £/kWe	500	750	1000	1500	2000
interest rate %	7.5	7.5	7.5	7.5	7.5
Fuel Cell Life years	5	5	5	5	5
FC cost for 0-5 year period	55600	83400	111200	166800	222400
FC cost for 5-10 year period	38729	58093	77457	116185.98	154915
FC cost for 10-15 year period	26977	40465	53954	80930	107907
fc cost for 15-20 year period	18791	28186	37582	56373	75164
FC cost for 20-25 year period	13089	19633	26178	39267	52356
FC cost for 25-30 year period	9117	13676	18234	27352	36469
Total FC costs for plant lifetime	**162303**	**243454**	**324605**	**486908**	**649210**
PAFCs					
Oxygen Separation Costs	15407	15407	15407	15407	15407
Wood in (daf T/day)	2.6	2.6	2.6	2.6	2.6
Gasifier Costs (one off)	227867	227867	227867	227867	227867
Total System Costs	405577	486728	567879	30182	892485
SI (£/kWe)	**5032**	**6039**	**7046**	**9059**	**11073**
MCFCs					
Oxygen Separation Costs	8795	8795	8795	8795	8795
Wood in (daf T/day)	1.5	1.5	1.5	1.5	1.5
Gasifier Costs (one off)	155047	155047	155047	155047	155047
Total System Costs	326145	407297	488448	650750	813053
SI (£/kWe)	**4046**	**5053**	**6060**	**8074**	**10088**

Table 5. Capital Costs and SIs for hospital, where FC lifetime is 5 years.

Tables 5 and 6 show how the system capital costs and SIs have been estimated for the hospital application, for two fuel cell lifetimes and 5 fuel cell cost rates. A Discounted Cash Flow rate of 7.5% has been used and a total plant lifetime of 30 years assumed.

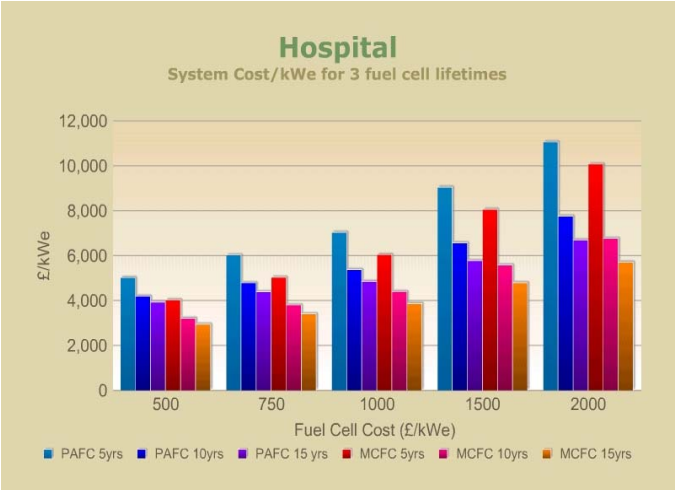


Figure 8. Specific Investment for the proposed systems for the hospital

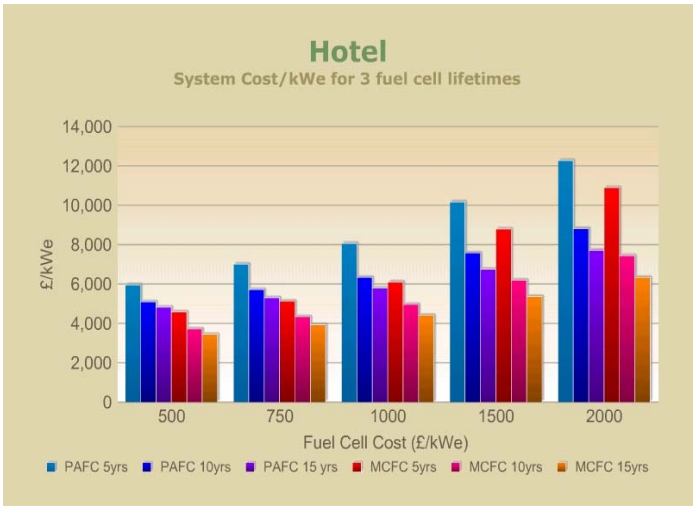


Figure 9. SIs for the proposed systems for the hotel.

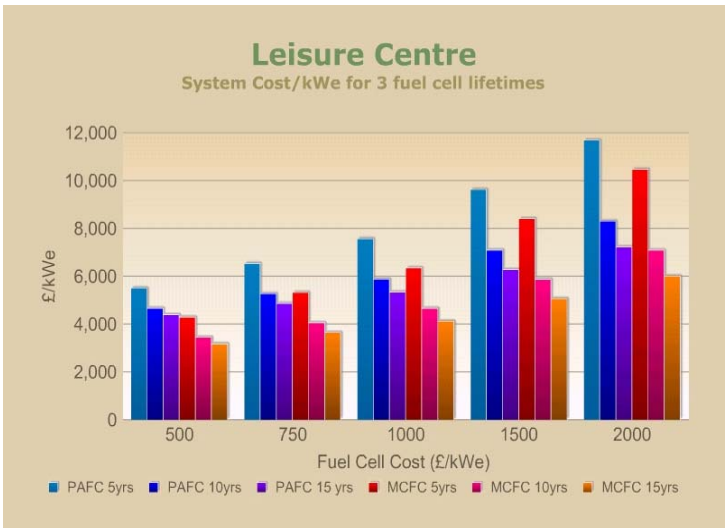


Figure 10. SIs for the proposed systems for the leisure centre

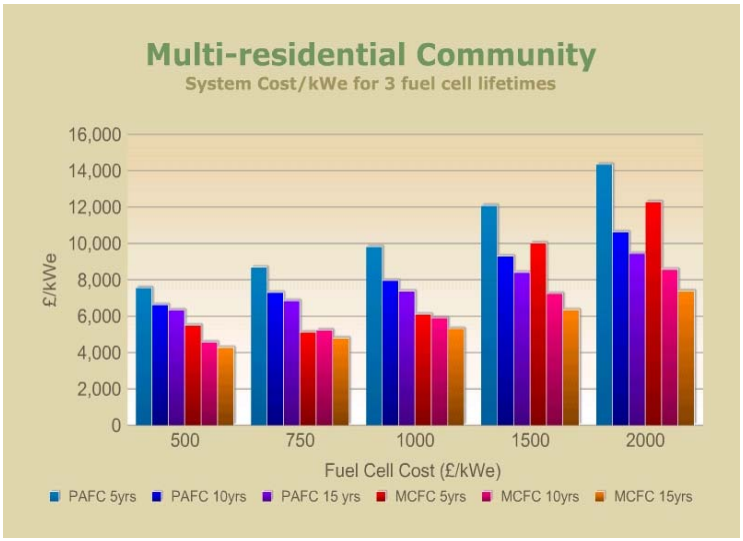


Figure 11. Specific Investment for the proposed systems for the multi-residential community

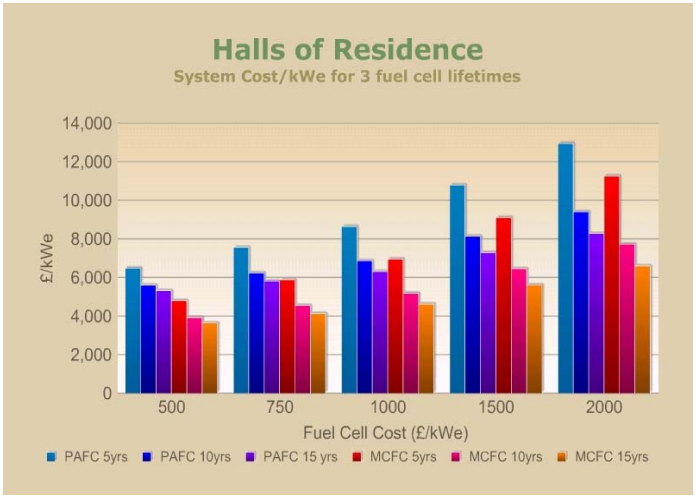


Figure 12. Specific Investment for the proposed systems for the university halls of residence

For the FC lifetime of 5 years and FC cost rate of £500/kW, the fuel cell stack can be seen (table 5) to account for about 50% of the total system cost in the case of the WGIMC, and about 80% when the FC cost rate is £2000/kW.

For the FC lifetime of 15 years and FC cost rate of £500/kW, the fuel cell stack can be seen (table 6) to account for about 30% of the total system cost in the case of the WGIMC, and about 63% when the FC cost rate is £2000/kW. These factors clearly have a major influence on the system capital costs, SIs and electricity generation costs.

For a fuel cell lifetime of 15 years					
Fuel Cell ac output kWe	111.2	111.2	111.2	111.2	111.2
Fuel Cell Cost Rate £/kWe	500	750	1000	1500	2000
interest rate %	7.5	7.5	7.5	7.5	7.5
Fuel Cell Life years	15	15	15	15	15
FC cost for 0-15 year period	55600	83400	111200	166800	222400
FC cost for 15-30 year period	18791	28186	37582	56373	75164
Total FC costs for plant lifetime	74391	111586	148782	223173	297564
PAFCs					
Oxygen Separation Costs	15407	15407	15407	15407	15407
Wood in (daf T/day)	2.6	2.6	2.6	2.6	2.6
Gasifier Costs (one off)	227867	227867	227867	227867	227867
Total System Costs	317665	354861	392056	466447	540838
SI (£/kWe)	3941	4403	4864	5787	6710
MCFCs					
Oxygen Separation Costs	8795	8795	8795	8795	8795
Wood in (daf T/day)	1.5	1.5	1.5	1.5	1.5
Gasifier Costs (one off)	155047	155047	155047	155047	155047
Total System Costs	238234	275429	312625	387016	461406
SI (£/kWe)	2956	3417	3879	4802	5725

Table 6. Capital Costs and SIs for hospital, where FC lifetime is 15 years.

4.2 SENSITIVITY ANALYSIS

The break-even cost of electricity (COE) generated was assessed for typical current values of certain factors affecting the system economics i.e. a fuel cell lifetime of 10 years (plant life of 30 years), fuel cell cost rate of £1,000/kWe, wood fuel cost of £25.20 per dry tonne and a waste heat selling price of £2/GJ for both WGIFC versions (PAFC and MCFC). Precise values for these factors are not accurately known, so ECLIPSE was used to assess how the COE would change with variation in these factors of ± 100%.

The sensitivity of COE to variations in these economic factors is plotted in figures 13, 14, 15, 16 and 17 for both versions of the WGIFC system for each of the selected buildings.

5.0 CONCLUSIONS

The following conclusions can be made for the FCIWG systems proposed for the five building with different energy demand profiles.

5.1 TECHNICAL AND ENVIRONMENTAL

Efficiencies for these systems were found to depend on plant size i.e. the larger the electrical output, the more efficient the plant.

The electrical efficiency of the LPO biomass gasifier/ PAFC CHP system decreases with electrical output from 15.4% to 13.7% as the overall energy efficiency, including low grade heat, falls from 66.6% to 64.9%. These efficiencies could be improved if drier feedstock is used (considered here to be 100% on a dry basis), or the wood can be dried without diverting energy from the system. CO_2 emissions increase from 2,420 g/kWh to 2,720 g/kWh as the electrical output decreases. Other emissions were negligible.

The electrical efficiency of the LPO biomass gasifier/ MCFC CHP system decreases with electrical output from 26.8% to 24.8% as the overall energy efficiency, including high grade heat, falls from 62.6% to 60.7%. These efficiencies could also be improved if drier feedstock is used, or the wood can be dried without diverting energy from the system. CO_2 emissions increase from 1,420 g/kWh to 1,530 g/kWh as the electrical output decreases. Other emissions were found to be negligible.

5.2 ECONOMICS

5.2.1 SYSTEM PAYBACK TIMES

Calculation of the simple payback period for these plants has shown that, in most cases, they would not be economically viable for the capital costs used i.e. the payback periods are much too long [3]. For the hospital, leisure centre and hotel, with the fuel cells costing £500/kW, payback times between 10 and 15 years can be found, which suggest that this FCIGW system could save money on power generation for at least a further 10 years. Surprisingly, little difference was usually found in the payback time for a system, whether the fuel cell used is the PAFC or MCFC.

5.2.2 SPECIFIC INVESTMENT

The capital costs and Specific Investment of each system are dominated by the current high costs of the fuel cell stacks, and their relatively short lifetimes. For example, the WFPAFC system has an SI of less than £4000/kWe when the FC cost rate is taken as £500/kW and the fuel cell lifetime taken as 15 years, whereas the SI rises to around £11,00/kWe when the FC cost rate is assumed to be £2,000/kWe and the FC lifetime to be 5 years (see Fig. 13). Clearly these two factors play a dominant role in the economics of the system.

Currently fuel cells are estimated to cost in the region of $1,000 to $1,500 per kW and have not been tested in continuous use for extended periods. Should these SIs fall to $400/kW, which is the US government's target for 2010, and fuel cell lifetimes improved, then there would be an economic case for using these FCIWG systems for the applications described here.

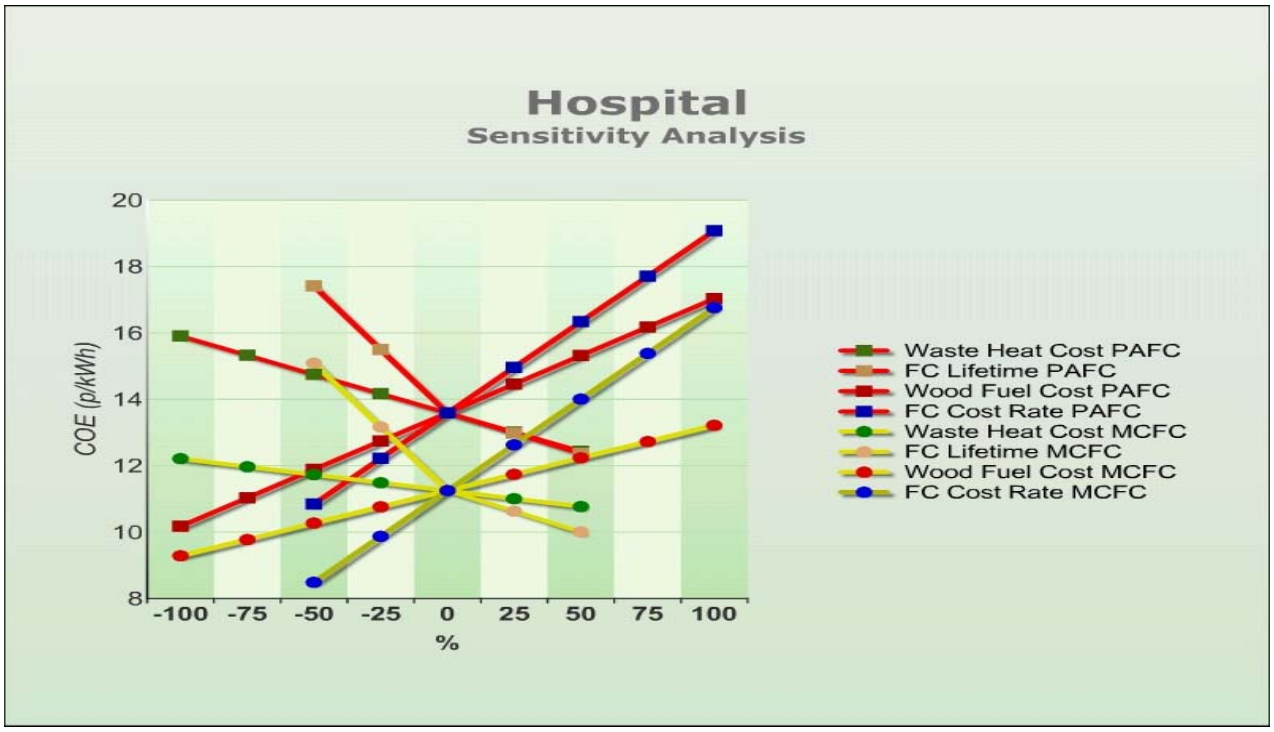


Figure 13. Sensitivity of COE to economic factors for the hospital

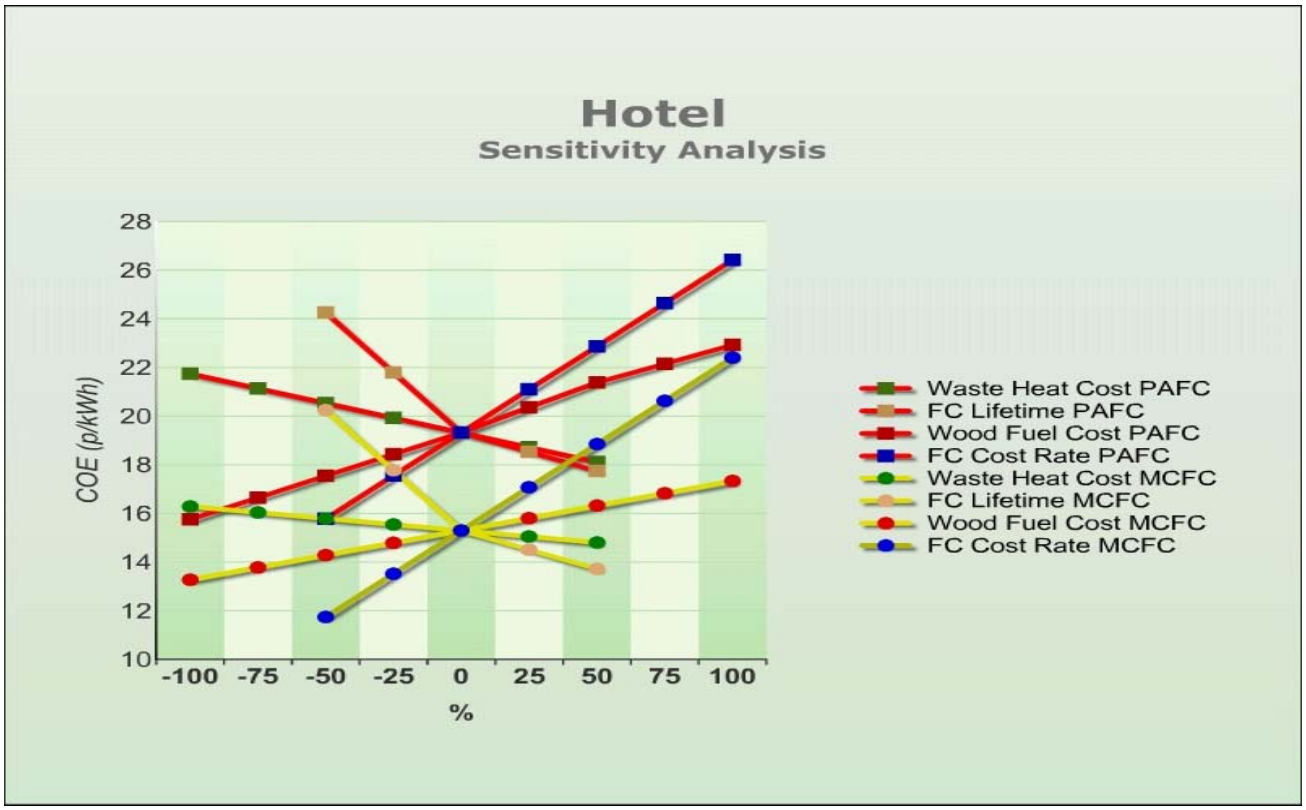


Figure 14. Sensitivity of COE to economic factors for the hotel

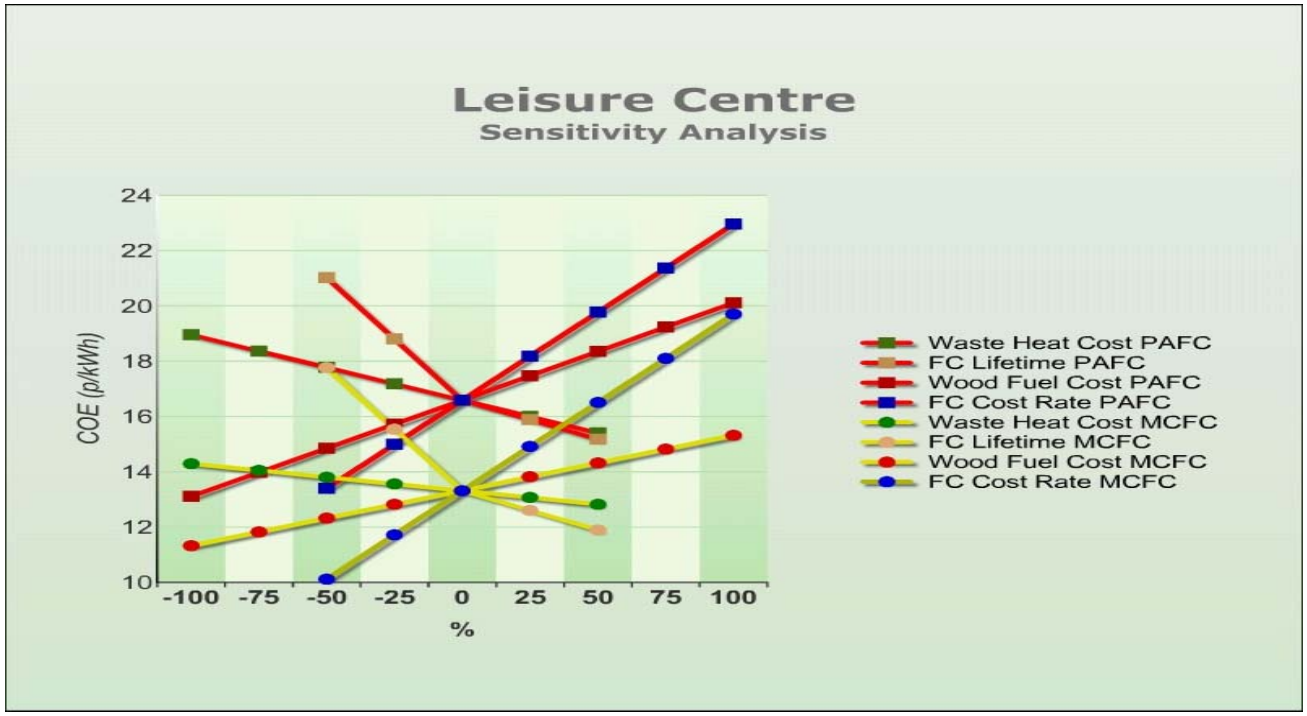


Figure 15 Sensitivity of COE to economic factors for the Leisue Centre

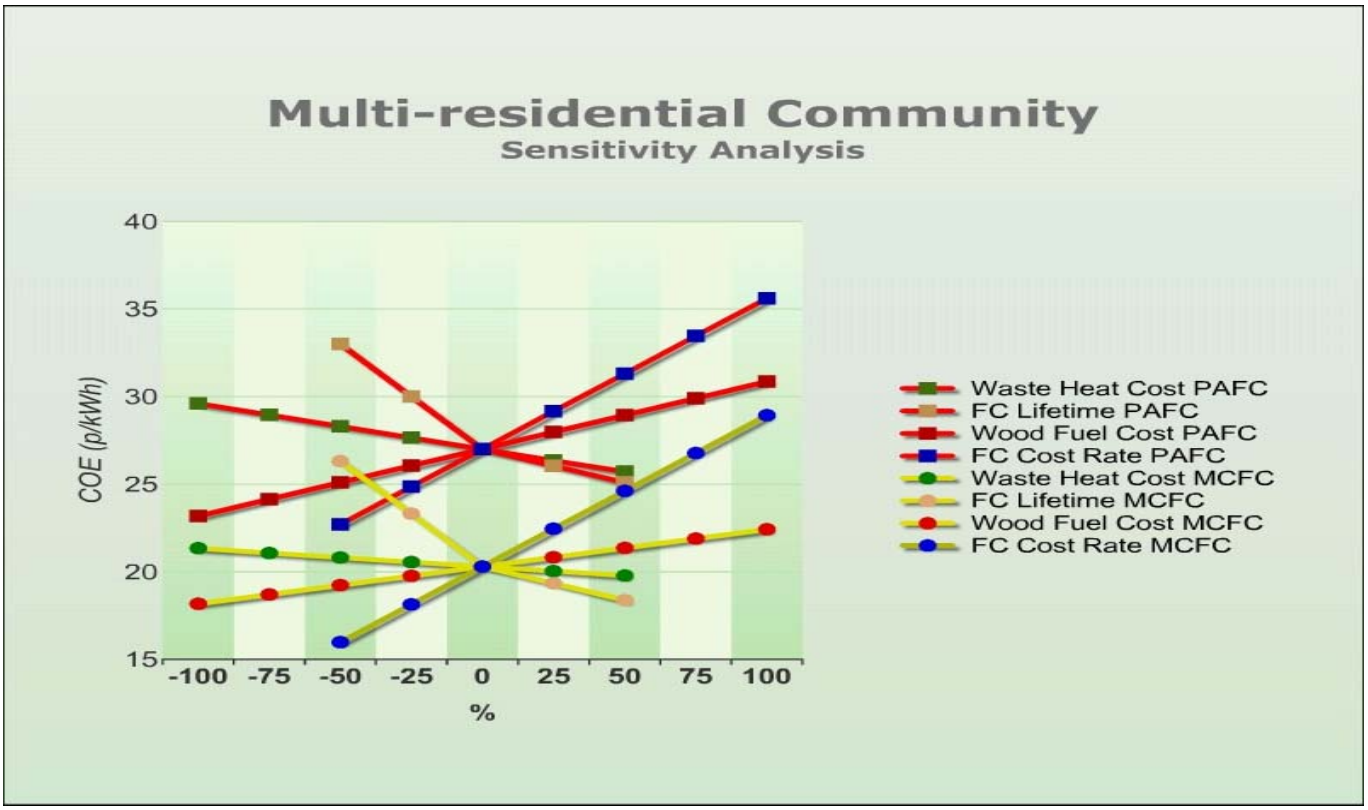


Figure 16. Sensitivity of COE to economic factors for the Multi-residential Community

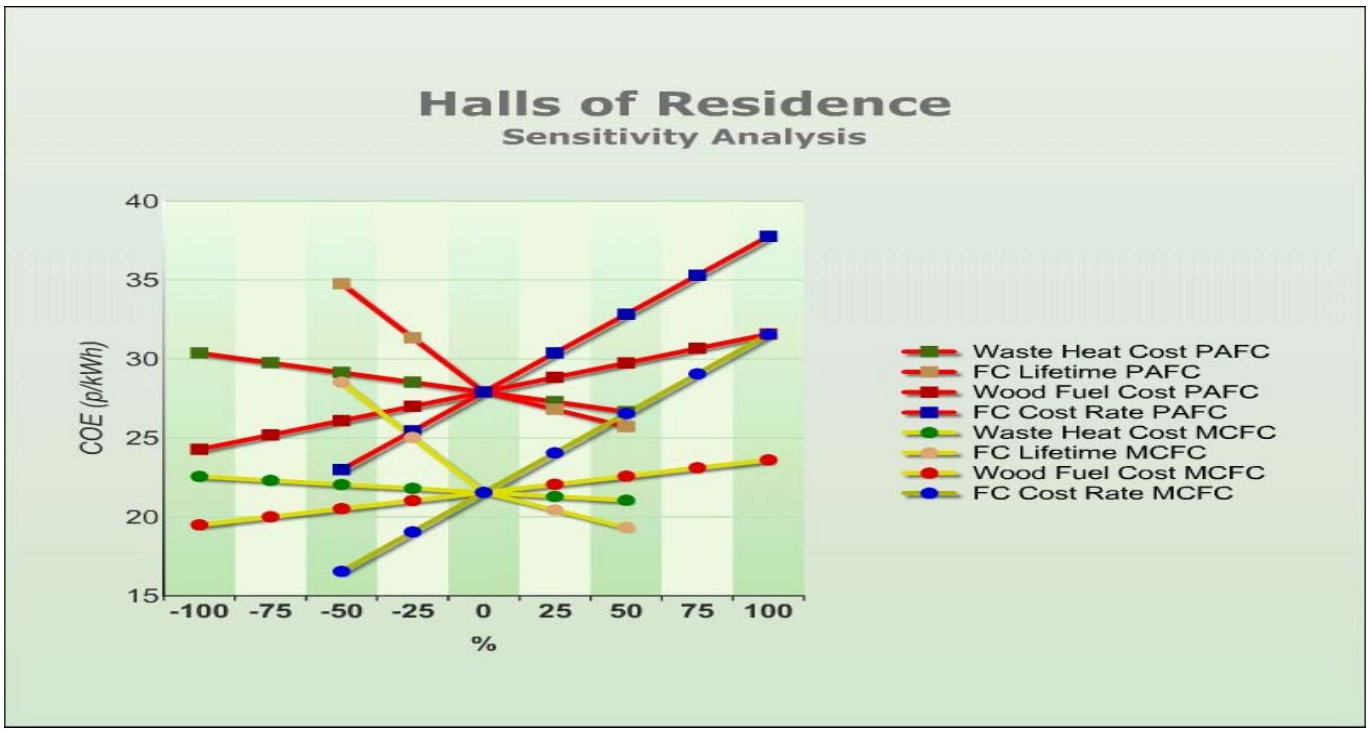


Figure 17. Sensitivity of COE to economic factors for the Halls of Residence.

5.2.3 SENSITIVITY ANALYSIS

The break-even cost of electricity generated (COE) was plotted against the variation of some of the important economic factors. The base values for each of these factors (FC lifetime = 10 years; FC Cost Rate = £1,000/kWe; Wood Cost = £25.20/dry tonne; Waste Heat Cost = £2/GJ) gives lower COEs for the systems with MCFCs than for those with PAFCs.

However, it can be seen, that there are many combinations of these economic factors which would result in the COE being higher for the systems with MCFCs than for the systems with PAFCs. Considering the WGIFC system for the hospital for example, if the fuel cell lifetime of the MCFC were reduced by more than about 30% or the fuel cell cost rate increased by more than around 30%, then the COE for the MCFC based system would exceed that of the base value of the PAFC system. Clearly it would be necessary to have a detailed knowledge of all the factors affecting system economics, rather than simply knowing the electricity generation efficiency, in order to assess the optimum system configuration for economic viability.

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