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Wood-fired fuel cells in selected buildings

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Abstract

The positive attributes of fuel cells for high efficiency power generation at any scale and of biomass as a renewable energy source which is not intermittent, location-dependent or very difficult to store, suggest that a combined heat and power (CHP) system consisting of a fuel cell integrated with a wood gasifier (FCIWG) may offer a combination for delivering heat and electricity cleanly and efficiently. Phosphoric acid fuel cell (PAFC) systems, fuelled by natural gas, have already been used in a range of CHP applications in urban settings. Some of these applications are examined here using integrated biomass gasification/fuel cell systems in CHP configurations. Five building systems, which have 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 FCIWG system was scaled to the power demand. The FCIWG 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 the ECLIPSE process simulation package. Since fuel cell lifetimes are not yet precisely known, economics for a range of fuel cell lifetimes have been produced. The wood-fired PAFC system was found to have low electrical efficiency (13–16%), but much of the heat could be recovered, so that the overall efficiency was 64–67%, suitable where high heat/electricity values are required. The wood-fired molten carbonate fuel cell (MCFC) system was found to be quite efficient for electricity generation (24–27%), with an overall energy efficiency of 60–63%. The expected capital costs of both systems would currently make them uncompetitive for general use, but the specific features of selected buildings in rural areas, with regard to the high cost of importing other fuel, and/or lack of grid electricity, could still make these systems attractive options. Any economic analysis of these systems is beset with severe difficulties. Capital costs of the major system components are not known with any great precision. However, a guideline assessment of the payback period for such CHP systems was made. When the best available capital costs for system components were used, most of these systems were found to have unacceptably long payback periods, particularly where the fuel cell lifetimes are short, but the larger systems show the potential for a reasonable economic return.

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Keywords: Fuel cell systems; Biomass; Wood gasification; CHP; MCFC; PAFC; Computer simulation

1. Introduction

The sustainable use of biomass provides a renewable source of energy with low or zero emissions of SO_x and CO_2 for electricity generation. Fuel cells offer the potential for generating electricity at high efficiency, even at small scales. A combination of the two technologies may offer a solution for the provision of clean, efficient power generation at small scales in such applications as domestic or commercial buildings. In this study energy profiles of typical representatives of certain buildings have been obtained and a power generation plant, based on the integration of a wood gasifier with a fuel cell system, was sized to provide a ‘‘reasonable’’ amount of each building's heat and electricity requirements. Computer simulations of each of the systems were developed and technical, economic and environmental assessments were made.

The use of a wood gasifier with the fuel cell in an integrated system offers advantages over using them separately [1]. Waste heat from the fuel cell is used to pre-dry the wood fuel for the gasifier, as well as heating water for CHP applications. The gas leaving the gasifier helps to preheat the air used in the fuel cell. The efficiency of the overall system is improved by using potentially wasted energy from one element of the system in the other.

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1.1. System technology

1.1.1. Type of fuel cell

Two fuel cell types have been chosen to be part of the system, the phosphoric acid fuel cell (PAFC) and the molten carbonate fuel cell (MCFC). The PAFC can only tolerate 1–2% CO at the operating temperature of 200 °C, so a "shifter" is needed to convert the CO to hydrogen. Steam is required for the shift reaction. The MCFC operates at 650 °C and uses both hydrogen and CO in electricity production, so it does not require a shifter.

1.1.2. Type of gasifier

Appropriate gasification technology should be selected to match the requirements of the fuel cell(s) chosen. 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.

A range of gasification technologies was examined [2] and the Koppers–Totzek entrained-flow gasifier, originally developed for coal gasification and considered to be representative of commercially available LPO technology [3], was considered to be appropriate. It has also been assessed for biomass [4]. 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.

1.1.3. Process description (using the PAFC)

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 [5]). 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 (CHP) applications.

It is assumed that 40% of the PAFCs energy can be used to provide electricity. The system is scaled so that this results in a net ac output of about 100 kWe from the fuel cell (the dc output is inverted to ac at an efficiency of 97%).

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 (the use of a steam turbine will not be investigated here since the scale of the system is too small to use the larger, efficient steam turbines). 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. Selected buildings

The objective of this study was to assess the wood-fired fuel cell system for its suitability in supplying electricity and space heating to domestic and commercial buildings. PAFC power plants using natural gas as the fuel had been found to be suitable for a range of CHP applications in urban settings [6]. The same applications are examined here using the proposed integrated LPO biomass gasifier/fuel cell power plants in CHP configurations [7]. Although it would not be convenient to transport large quantities of wood fuel into densely-populated urban locations, there may be suitable applications for buildings in small towns, in rural settings or where the plant is of such a size that large amounts of fuel are unnecessary.

The first two scenarios for power provision to the buildings, which were examined in that report [8] are also investigated here. The base case scenario, where there is no CHP plant at all and where heat is supplied from a natural gas boiler and electricity is taken from the grid, is shown as the reference case. The second scenario involves a biomass gasifier/fuel cell cogeneration system scaled according to the electricity demand curve for each application to give a high fuel cell occupancy (availability). For the second case any electricity demand peaks will be supplied from the grid and shortfalls in heat demand will be made up by using a natural gas boiler. This is in contrast to the system used in an isolated community, which has also been investigated [9], where no heat or power could be imported (or exported).

2.1. Building systems

The fuel cell integrated with a wood gasifier (FCIWG) system is applied to five building applications which have differing energy demand profiles. These are a hospital, a hotel, a leisure centre, a multi-residential community and a university halls of residence, all situated in the UK. Energy demand curves for typical building systems of these types have been obtained and shown in each section.

2.2. Hospital

The hospital considered is a small one, having 50 beds, and serves a community of around 10,000 people. From the

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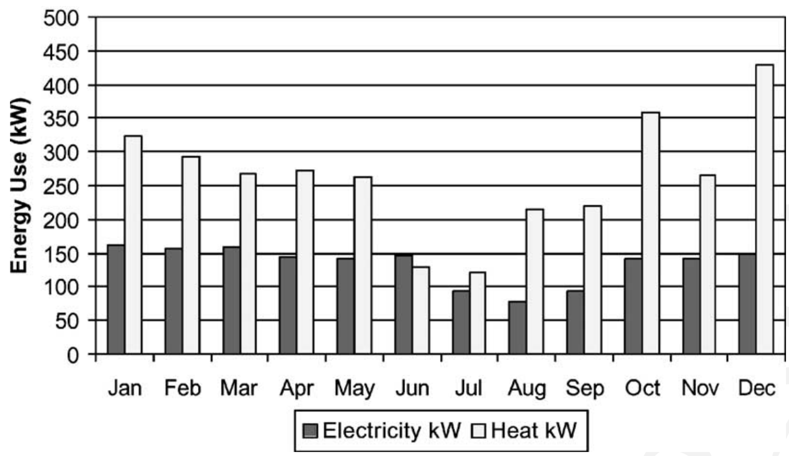

Fig. 1. Energy profile of the selected hospital.

electricity demand profile it would appear that supplying about 50% of the average demand would mean that the FCIWG system would be in operation most of the time all year round, i.e. have a high occupancy. The power plant was scaled to meet this electricity requirement (Fig. 1).

2.3. Hotel

The selected hotel has 115 beds. It has a fitness suite with a swimming pool. There is not a large seasonal variation in electricity demand, but there is a large variation in demand during any 24 h period. The electricity output of the wood-fired fuel cell CHP plant was scaled to provide 25% of the average electricity demand, which gives a reasonable occupancy value (Fig. 2).

2.4. Leisure centre

This leisure centre serves a population of about 15,000 and contains a sports hall, a gymnasium and a swimming pool. Here there is also very little variation in seasonal electricity demand, and the demand is also fairly constant during opening hours. The FCIWG power plant was scaled to provide 60% of the average electricity demand, which means that it would work at full load during opening hours (Fig. 3).

2.5. Multi-residential community

This community comprises low- and medium-rise blocks of flats accommodating 200 families. Heating usually comes from a centralised boiler. The electricity demand shows large seasonal variations as well as large diurnal variations. The electricity output of the power plant was scaled at only 10% of the average electricity demand to keep the occupancy reasonable (Fig. 4).

2.6. University halls of residence

They are made up of a small number of medium-rise blocks of flats for 240 students. There are eight single study-bedrooms with shower, a communal kitchen and lounge area on each floor of a block. Space heating is provided from a central boiler. There are large seasonal and diurnal peaks in electricity demand. However, the peaks are not as pro-

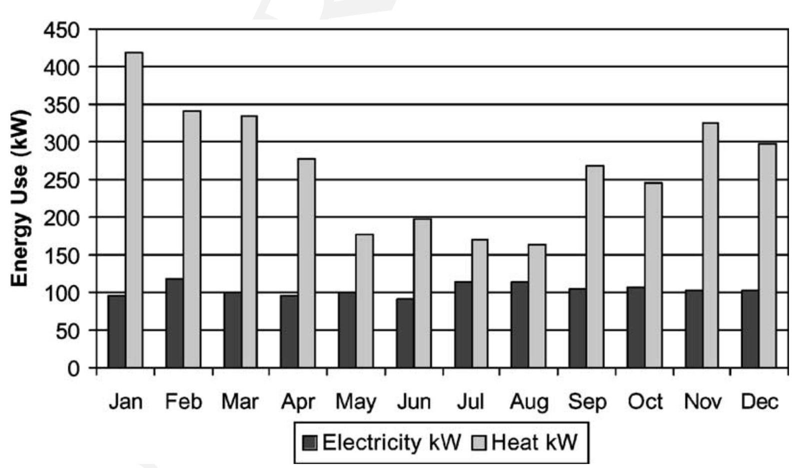

Fig. 2. Energy profile of the selected hotel.

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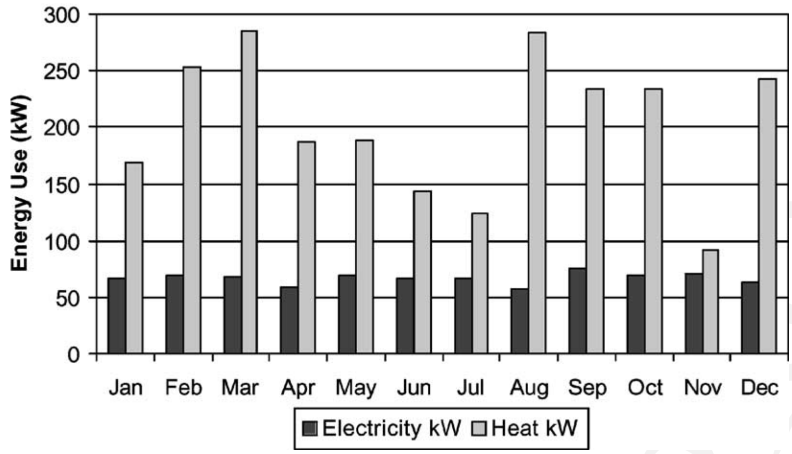

Fig. 3. Energy profile of the selected leisure centre.

nounced as for the multi-residential community. The FCIWG power plant was scaled to provide 20% of the average electricity demand. In addition electricity demand is low during the vacations, which brings the occupancy figure down (Fig. 5).

3. Results

The ECLIPSE process simulation package [10] was used to evaluate the biomass gasifier/fuel cell cogeneration systems for the different building types. The technical and

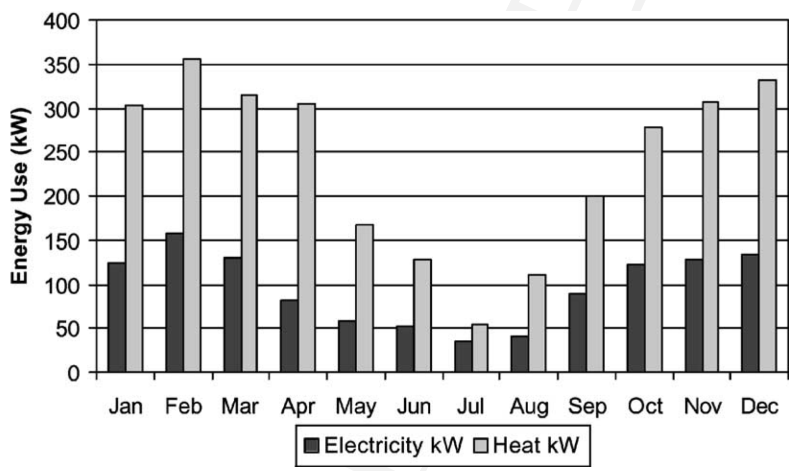

Fig. 4. Energy profile of the selected multi-residential community.

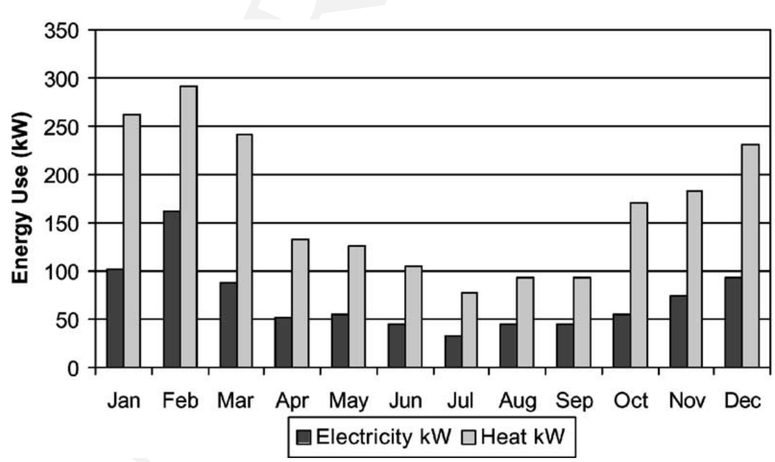

Fig. 5. Energy profile of the selected university halls of residence.

Table 1
Technical and environmental results for the PAFC systems

Process identity	Hospital	Hotel	Leisure centre	Halls of residence	Multi-residential
Fuel cell type	PAFC	PAFC	PAFC	PAFC	PAFC
Reformer type	None	None	None	None	None
Fuel feedstock	Wood	Wood	Wood	Wood	Wood
Sulphur removal technology	None	None	None	None	None
CO_2 sequestration technology	None	None	None	None	None
Anode recycle	Yes	Yes	Yes	Yes	Yes
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 per 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
Gaseous emissions					
CO_2 (g kWh^{-1})	2420	2530	2480	2590	2720
SO_x (g kWh^{-1})	–	–	–	–	–
NO_x (g kWh^{-1})	–	–	–	–	–

Table 2
Technical and environmental results for the MCFC systems

Process identity	Hospital	Hotel	Leisure centre	Halls of residence	Multi-residential
Fuel cell type	MCFC	MCFC	MCFC	MCFC	MCFC
Reformer type	None	Nome	None	None	None
Fuel feedstock	Wood	Wood	Wood	Wood	Wood
Sulphur removal technology	None	None	None	None	None
CO_2 sequestration technology	None	None	None	None	None
Anode recycle	Yes	Yes	Yes	Yes	Yes
Operating temperature (°C)	650	650	650	650	650
CO shifter	None	None	None	None	None
Gasifier type	LPO	LPO	LPO	LPO	LPO
Wood input (dry tonnes per 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
PAFC power output (kWe dc)	106.4	52.1	72.6	38.6	22.9
PAFC 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
Gaseous emissions					
CO_2 (g kWh^{-1})	1420	1470	1440	1490	1530
SO_x (g kWh^{-1})	–	–	–	–	–
NO_x (g kWh^{-1})	–	–	–	–	–

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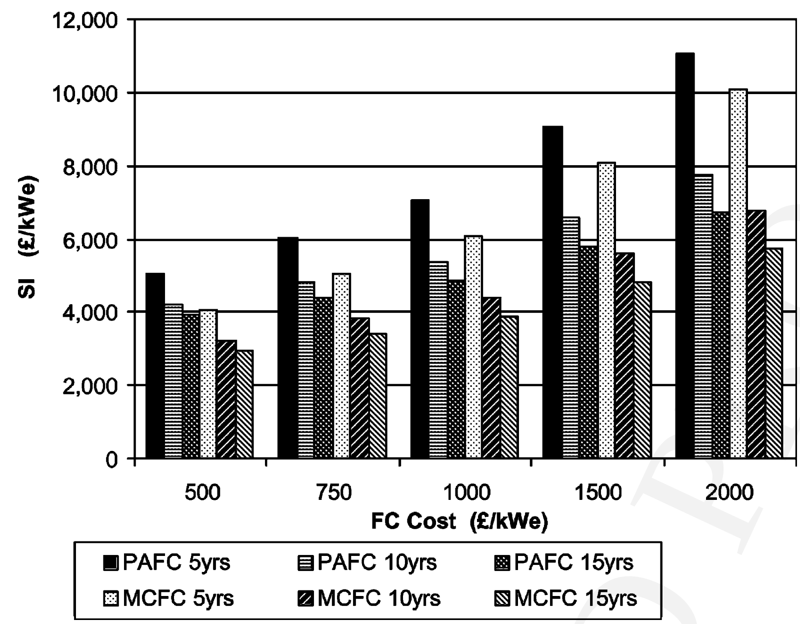

Fig. 6. Specific investment for the systems proposed for the hospital.

environmental results for the LPO biomass gasifier/PAFC CHP systems are summarised in Tables 1 and 2 for the systems using MCFCs in place of the PAFCs.

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, or the wood can be dried without diverting energy from the system. CO_2 emissions increase from 2420 to 2720 g kWh^{-1} as the electrical output decreases. Other emissions are negligible.

The CHP system using the integrated LPO biomass gasifier and MCFC has an electrical efficiency of 26.8%, dropping to 24.8% as the electrical output falls. The overall energy efficiency falls from 62.6 to 60.7%, and CO_2 emissions increase from 1420 to 1530 g kWh^{-1} as the electrical output decreases. The MCFC offers clear technical and environmental advantages over the PAFC in these CHP systems.

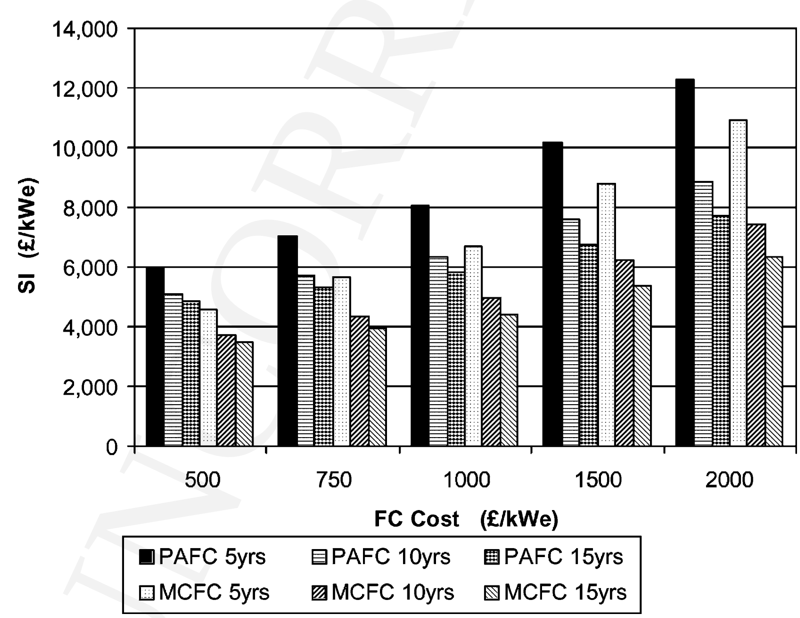

Fig. 7. Specific investment for the systems proposed for the hotel.

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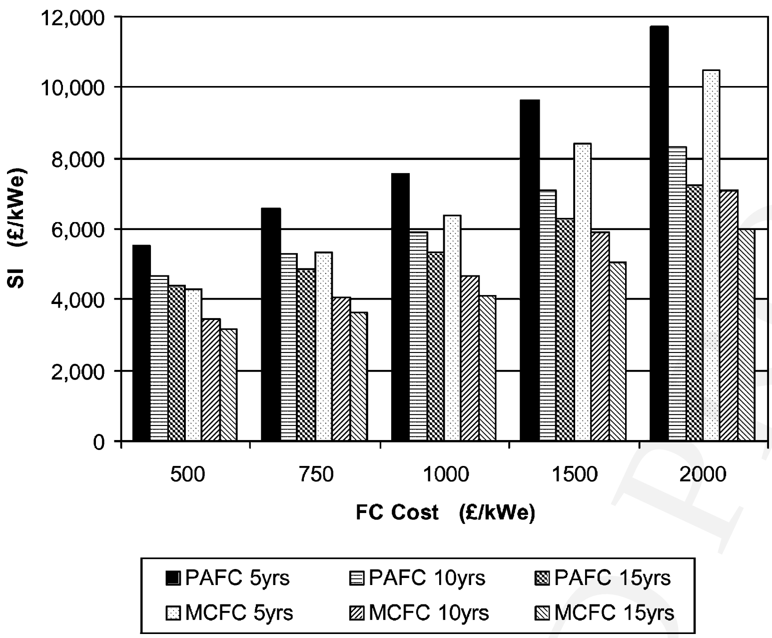

Fig. 8. Specific investment for the systems proposed for the leisure centre.

3.1. Economic analysis

Conventional fossil fuel power generation systems usually have life spans between 20 and 30 years. The gasification and ancillary equipment in the FCIWG systems would be expected to have similar lifetimes, but there is considerable uncertainty in the durability and operating life of the fuel cells. For this reason the systems have been assessed with fuel cell lifetimes of 5, 10 and 15 years considered, and their replacement (and consequent increase in system cost) taken into account.

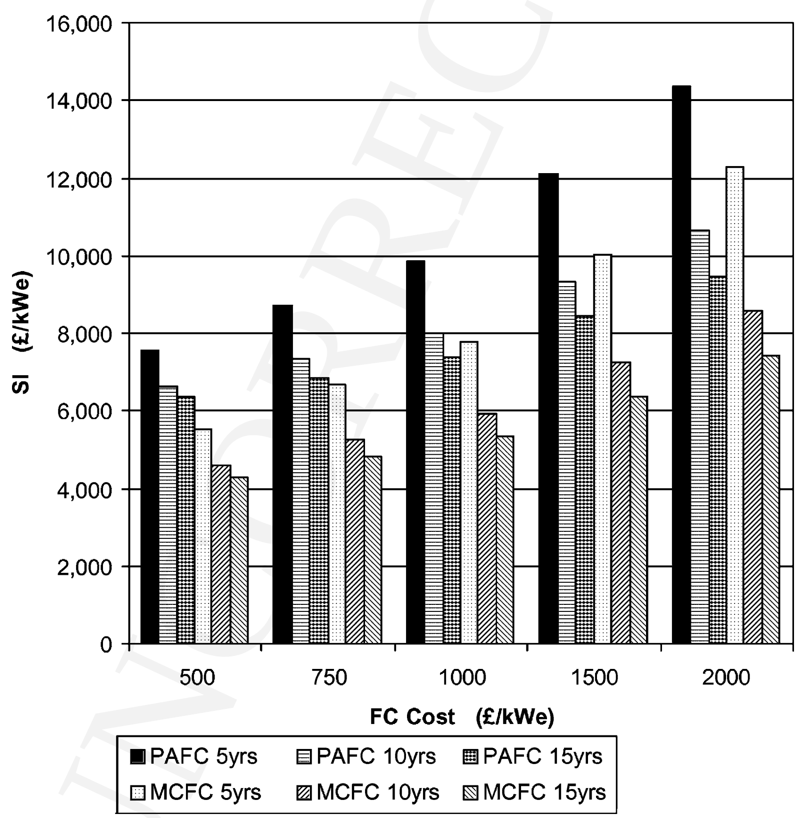

Fig. 9. Specific investment for the systems proposed for the multi-residential community.

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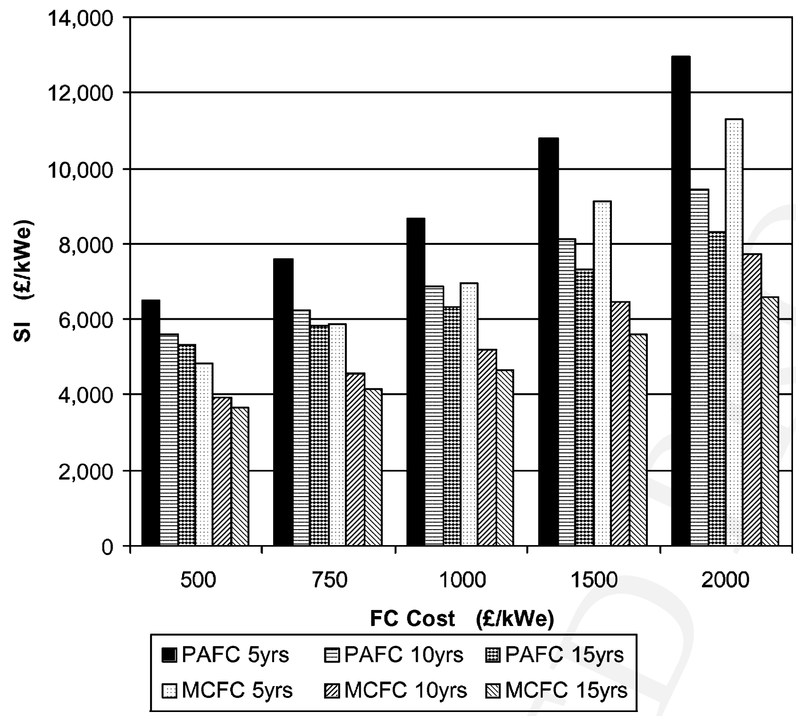

Fig. 10. Specific investment for the systems proposed for the halls of residence.

In addition, fuel cell costs are difficult to estimate, so a range of costs from £500 to £2000 per installed kilo Watt has been used in the analysis.

3.1.1. Specific investment

The assessment of the specific investment (SI, or system cost per net kilo Watt of electricity generated) of the FCIWG for each application is shown in the following charts.

In any chart each group of columns shows (from left to right) the system with the PAFC having a fuel cell life of 5, 10 and 15 years, respectively, followed by the system with the MCFC for the same fuel cell lifetimes (Figs. 6–10).

3.1.2. Simple payback scenario

In the context of these applications the heat and electricity produced by the FCIWG systems is not for sale to the public or to power utilities, but are for internal consumption in the buildings.

One method of assessing the economic viability of the system is to consider the savings in payments for electricity

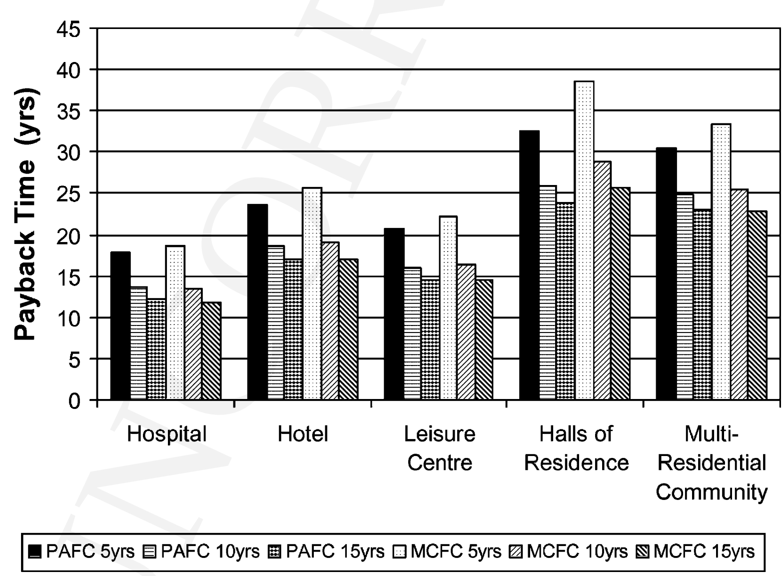

Fig. 11. Payback time for systems for all selected buildings with a fuel cell cost of £1000 kWe^{-1}.

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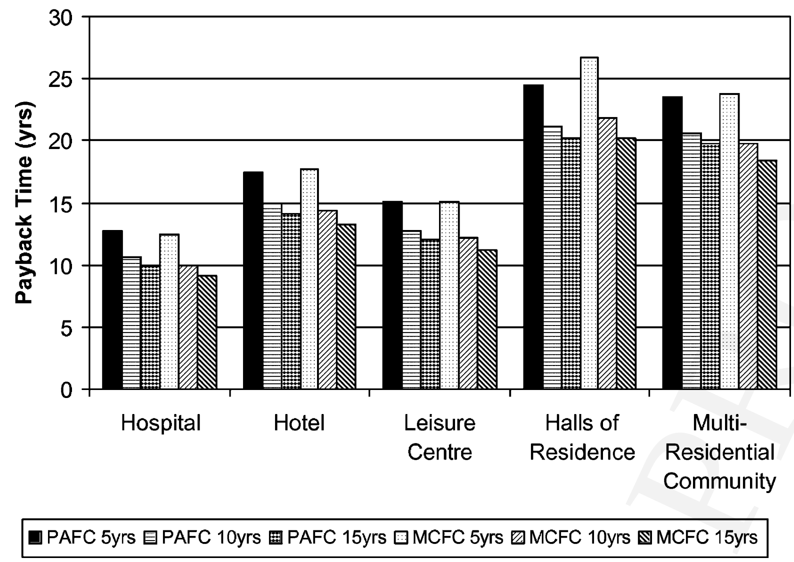

Fig. 12. Payback time for systems for all selected buildings with a fuel cell cost of £500 kWe^{-1}.

and natural gas as repayment for the capital cost of the system. It could be assumed that a building would normally have a natural gas boiler to provide heat, and would take electricity from the grid. If the FCIWG system were installed, then less gas would be used in the boiler and less electricity taken from the grid. The savings in buying in this power can be set against the repayment of the capital costs of the FCIWG system using simple payback.

This has been done for all the systems, for fuel cell lifetimes of 5, 10 and 15 years. Tables of these calculations are shown in Appendix A for a fuel cell cost of £1000 kWe^{-1}, and the payback times shown in Fig. 11.

In Fig. 11 the first three columns for each building are for systems using PAFCs (with 5, 10 and 15 year fuel cell lifetimes, respectively), and the next three have the MCFCs in the systems. Payback times can be seen to be similar, for a given fuel cell lifetime, whether the system contains a PAFC or MCFC at this fuel cell cost (£1000 kWe^{-1}).

The larger systems with higher occupancies (on the left of this figure) generate more electricity and heat, and so must buy in less power (make greater savings), thus have shorter payback times. Maximum lifetime of any of these systems is taken to be 30 years, so payback times greater than this are totally unacceptable (Fig. 12).

Calculations have also been made for the same systems, but on this occasion the fuel cell cost rate was taken to be £500 kWe^{-1}. Payback times for the hospital, the system with highest occupancy and output, are below 10 years for the longer fuel cell lifetimes.

When the payback calculations were made for the systems with a fuel cell cost of £2000 kWe^{-1} (see payback time results in Fig. 13), very high paybacks were found.

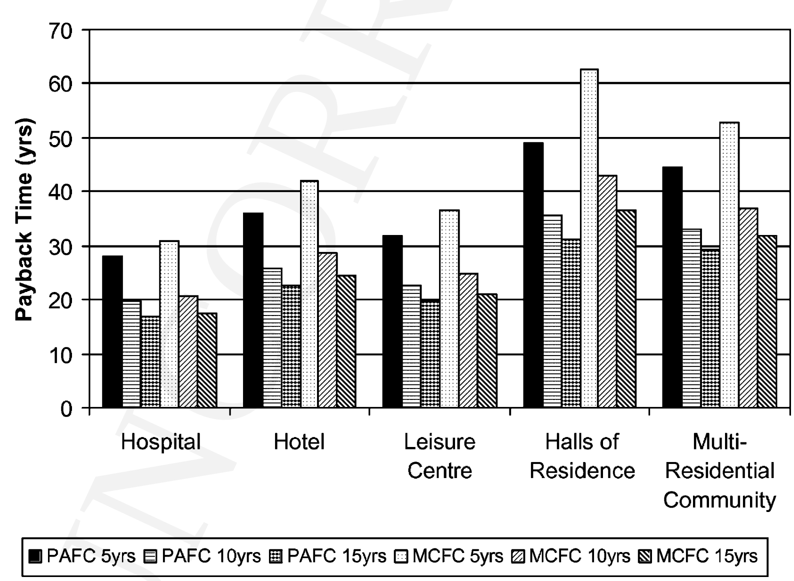

Fig. 13. Payback time for systems for all selected buildings with a fuel cell cost of £2000 kWe^{-1}.

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Table A.1
Hospital

Average electricity usage (kWe)	134.1	134.1	134.1	134.1	134.1	134.1
Average heat usage (kWth)	262.6	262.6	262.6	262.6	262.6	262.6
Base case scenario						
Annual electricity cost (£)	57663	57663	57663	57663	57663	57663
Annual natural gas cost (£)	27100	27100	27100	27100	27100	27100
Total annual energy bill (no CHP) (£)	84763	84763	84763	84763	84763	84763
Second scenario with WIGFC CHP system						
Fuel cell type	PAFC	PAFC	PAFC	MCFC	MCFC	MCFC
Fuel cell life (years)	5	10	15	5	10	15
Fuel cell size (kWe)	80	80	80	80	80	80
Fuel cell occupancy (%)	84	84	84	84	84	84
Average electricity generated (kWe)	67	67	67	67	67	67
Average electricity purchased (kWe)	67.1	67.1	67.1	67.1	67.1	67.1
Annual cost of electricity purchased (£)	28853	28853	28853	28853	28853	28853
Average recoverable heat from fuel cell (kWth)	269	269	269	107	107	107
Average heat from boiler (kWth)	0	0	0	155.6	155.6	155.6
Wood used by fuel cell (dry ton per year)	950	950	950	540	540	540
Annual wood cost (£)	23940	23940	23940	13608	13608	13608
Annual natural gas cost (£)	0	0	0	16058	16058	16058
Total annual energy bill (with CHP) (£)	52793	52793	52793	58519	58519	58519
Total annual savings (£)	31970	31970	31970	26244	26244	26244
System capital cost (£)	567879	434606	392056	488448	355174	312625
Simple payback (years)	18	14	12	19	14	12

The unit cost for buying electricity was taken as £0.05 kWh^{-1}. The unit cost for buying natural was taken as £0.012 kWh^{-1}. The cost for buying wood was taken as £25.20 per dry ton.

4. Conclusions

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

The ECLIPSE process simulator was used to make technical, economic and environmental analyses of LPO biomass gasifier/fuel cell cogeneration plants.

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

Table A.2
Hotel

Average electricity usage (kWe)	103.9	103.9	103.9	103.9	103.9	103.9
Average heat usage (kWth)	268.1	268.1	268.1	268.1	268.1	268.1
Base case scenario						
Annual electricity cost (£)	44677	44677	44677	44677	44677	44677
Annual natural gas cost (£)	27668	27668	27668	27668	27668	27668
Total annual energy bill (no CHP) (£)	72345	72345	72345	72345	72345	72345
Second scenario with WIGFC CHP system						
Fuel cell type	PAFC	PAFC	PAFC	MCFC	MCFC	MCFC
Fuel cell life (years)	5	10	15	5	10	15
Fuel cell size (kWe)	38	38	38	38	38	38
Fuel cell occupancy (%)	68	68	68	68	68	68
Average electricity generated (kWe)	26	26	26	26	26	26
Average electricity purchased (kWe)	77.9	77.9	77.9	77.9	77.9	77.9
Annual cost of electricity purchased (£)	33497	33497	33497	33497	33497	33497
Average recoverable heat from fuel cell (kWth)	133	133	133	53	53	53
Average heat from boiler (kWth)	135.1	135.1	135.1	215.1	215.1	215.1
Wood used by fuel cell (dry ton per year)	470	470	470	266	266	266
Annual wood cost (£)	11844	11844	11844	6703	6703	6703
Annual natural gas cost (£)	13942	13942	13942	22198	22198	22198
Total annual energy bill (with CHP) (£)	59283	59283	59283	62399	62399	62399
Total annual savings (£)	13062	13062	13062	9946	9946	9946
System capital cost (£)	308749	242712	221628	256093	190055	168971
Simple payback (years)	24	19	17	26	19	17

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Table A.3
Leisure centre

Average electricity usage (kWe)	66.6	66.6	66.6	66.6	66.6	66.6
Average heat usage (kWth)	202.7	202.7	202.7	202.7	202.7	202.7
Base case scenario						
Annual electricity cost (£)	28638	28638	28638	28638	28638	28638
Annual natural gas cost (£)	20919	20919	20919	20919	20919	20919
Total annual energy bill (no CHP) (£)	49557	49557	49557	49557	49557	49557
Second scenario with WIGFC CHP system						
Fuel cell type	PAFC	PAFC	PAFC	MCFC	MCFC	MCFC
Fuel cell life (years)	5	10	15	5	10	15
Fuel cell size (kWe)	54	54	54	54	54	54
Fuel cell occupancy (%)	74	74	74	74	74	74
Average electricity generated (kWe)	40	40	40	40	40	40
Average electricity purchased (kWe)	26.6	26.6	26.6	26.6	26.6	26.6
Annual cost of electricity purchased (£)	11438	11438	11438	11438	11438	11438
Average recoverable heat from fuel cell (kWth)	184	184	184	73	73	73
Average heat from boiler (kWth)	18.7	18.7	18.7	129.7	129.7	129.7
Wood used by fuel cell (dry ton per year)	650	650	650	370	370	370
Annual wood cost (£)	16380	16380	16380	9324	9324	9324
Annual natural gas cost (£)	1930	1930	1930	13385	13385	13385
Total annual energy bill (with CHP) (£)	29748	29748	29748	34417	34417	34417
Total annual savings (£)	19809	19809	19809	15410	15410	15410
System capital cost (£)	409153	317827	288669	343478	252152	222994
Simple payback (years)	21	16	15	22	16	14

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, or the wood can be dried without diverting energy from the system. CO_2 emissions increase from 2420 to 2720 g kWh^{-1} as the electrical output decreases. Other emissions are negligible.

The CHP system using the integrated LPO biomass gasifier and MCFC had an electrical efficiency of 26.8%, dropping to 24.8% as the electrical output falls. The overall energy efficiency falls from 62.6 to 60.7%, and CO_2 emissions increase from 1420 to 1530 g kWh^{-1} as the electrical output

Table A.4
Halls of residence

Average electricity usage (kWe)	70.5	70.5	70.5	70.5	70.5	70.5
Average heat usage (kWth)	167.3	167.3	167.3	167.3	167.3	167.3
Base case scenario						
Annual electricity cost (£)	30315	30315	30315	30315	30315	30315
Annual natural gas cost (£)	17265	17265	17265	17265	17265	17265
Total annual energy bill (no CHP) (£)	47580	47580	47580	47580	47580	47580
Second scenario with WIGFC CHP system						
Fuel cell type	PAFC	PAFC	PAFC	MCFC	MCFC	MCFC
Fuel cell life (years)	5	10	15	5	10	15
Fuel cell size (kWe)	28	28	28	28	28	28
Fuel cell occupancy (%)	50	50	50	50	50	50
Average electricity generated (kWe)	14	14	14	14	14	14
Average electricity purchased (kWe)	56.5	56.5	56.5	56.5	56.5	56.5
Annual cost of electricity purchased (£)	24295	24295	24295	24295	24295	24295
Average recoverable heat from fuel cell (kWth)	101	101	101	39	39	39
Average heat from boiler (kWth)	66.3	66.3	66.3	128.3	128.3	128.3
Wood used by fuel cell (dry ton per year)	356	356	356	197	197	197
Annual wood cost (£)	8971	8971	8971	4964	4964	4964
Annual natural gas cost (£)	6842	6842	6842	13241	13241	13241
Total annual energy bill (with CHP) (£)	40108	40108	40108	42500	42500	42500
Total annual savings (£)	7472	7472	7472	5080	5080	5080
System capital cost (£)	243395	194077	178159	196485	146627	130710
Simple payback (years)	33	26	24	39	29	26

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Table A.5
Multi-residential

Average electricity usage (kWe)	96	96	96	96	96	96
Average heat usage (kWth)	238	238	238	238	238	238
Base case scenario						
Annual electricity cost (£)	41280	41280	41280	41280	41280	41280
Annual natural gas cost (£)	24562	24562	24562	24562	24562	24562
Total annual energy bill (no CHP) (£)	65842	65842	65842	65842	65842	65842
Second scenario with WIGFC CHP system						
Fuel cell type	PAFC	PAFC	PAFC	MCFC	MCFC	MCFC
Fuel cell life (years)	5	10	15	5	10	15
Fuel cell size (kWe)	16	16	16	16	16	16
Fuel cell occupancy (%)	60	60	60	60	60	60
Average electricity generated (kWe)	10	10	10	10	10	10
Average electricity purchased (kWe)	86	86	86	86	86	86
Annual cost of electricity purchased (£)	36980	36980	36980	36980	36980	36980
Average recoverable heat from fuel cell (kWth)	60	60	60	23	23	23
Average heat from boiler (kWth)	178	178	178	215	215	215
Wood used by fuel cell (dry ton per year)	212	212	212	117	117	117
Annual wood cost (£)	5342	5342	5342	2948	2948	2948
Annual natural gas cost (£)	18370	18370	18370	22188	22188	22188
Total annual energy bill (with CHP) (£)	60692	60692	60692	62116	62116	62116
Total annual savings (£)	5150	5150	5150	3725	3725	3725
System capital cost (£)	157472	127749	118259	124543	94820	85331
Simple payback (years)	31	25	23	33	25	23

decreases. The MCFC offered clear technical and environmental advantages over the PAFC in these CHP systems.

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, and has been taken to be 5, 10 or 15 years. The fuel cell cost has also been estimated, and values of £500, £750, £1000, £1500 and £2000 kW^{-1} were considered here. These are high in comparison with modern gas-fired power plants and so would make them unlikely candidates for power generation alone at present.

Calculation of the simple payback period for these plants shows that, in most cases, they would not be economically viable for the capital costs used, i.e. the payback periods are much too long. For the hospital, leisure centre and hotel, with the fuel cells costing £500 kW^{-1}, 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, there is usually little difference in the payback time for a system, whether the fuel cell used is the PAFC or MCFC. However, these costs can only be determined on a case-by-case basis, and the calculations shown here should only be regarded as a guideline.

The specific investment of each system is dominated by the current high costs of the fuel cell stacks, and their relatively short lifetimes. Currently fuel cells are estimated to cost in the region of \$1000–1500 kW^{-1} and have not been tested in continuous use for extended periods. Should these SIs fall to \$400 kW^{-1}, which is the US Government's target for 2010, and their lifetimes extended, then there would be an economic case for using these FCIWG systems for the applications described here.

Appendix A

Tables A.1–A.5 show the payback scenarios for systems with fuel cell costs of £1000 kWe^{-1}.

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