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Wood-fired fuel cells in an isolated community

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Abstract

Fuel cells have the potential for generating electricity very efficiently, and because of their modular construction, retain the same efficiency at any scale. Biomass is one of the renewable energy sources which is not intermittent, location-dependent or very difficult to store. If grown sustainably, biomass can be considered CO_2 neutral. A combined heat and power (CHP) system consisting of a fuel cell integrated with wood gasification (FCIWG) may offer a combination for delivering heat and electricity cleanly and efficiently, even at small-scales.

The "isolated community" (IC) could be an island, or simply where grid-supplied electricity is weak or non-existent. The IC was taken to consist of 200 people and three retail outlets. Heat and electricity use profiles for this IC were produced 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 phosphoric acid fuel cell (PAFC) system was found to be suitable where high heat/electricity values were required, but had low electrical efficiency. The wood-fired molten carbonate fuel cell (MCFC) system was found to be quite efficient and suitable for small-scale electricity generation purposes. The expected capital costs of both systems would currently make them uncompetitive for general use, but the specific features of an IC with regard to the high cost of importing other fuel, and/or lack of grid electricity, could still make these systems attractive options.

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

1. Introduction

The supply of electricity and heat to an isolated community, which may be on an island or in some other remote location, could prove to be difficult or expensive. If grid electricity or piped natural gas are unavailable, and the transportation costs of fuels such as diesel oil are prohibitive, then other, less conventional, options must be considered.

Renewable energy technologies are the obvious alternative. In certain locations, solar energy may provide the solution, but in temperate climates insolation levels may be too low to provide sufficient output. Wind energy may be a better option in temperate zones for electricity generation, but its intermittent nature and lack of heat output means that wind alone would not be appropriate. Wave power and hydro should also be considered, but will only be applicable in a minority of cases where the locations are suitable.

Biomass may provide the best solution. Some form of biomass can be grown in almost any location. It can be stored and transported with little difficulty. There are a range of technologies for providing heat and electricity from biomass [1], but most of these technologies are inefficient in electricity production at small-scales [2].

Fuel cells are efficient in electricity generation and their modular nature means that they remain efficient even at small-scales. However, the hydrogen-rich fuel, such as natural gas, required by the fuel cell would either be unavailable or expensive to import to the isolated community.

In this paper, a system to provide heat and electricity for an isolated community in a temperate climate is proposed which integrates a biomass gasifier, producing a hydrogen-rich gas, with a fuel cell [3]. The energy demand profile of a small community is used to scale the power generation system, which is modelled using the ECLIPSE [4] process simulation package, and a technical, environmental and economic analysis produced.

The ECLIPSE simulations showed that both versions of the system could provide electricity and heat for this isolated

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community. The wood-fired phosphoric acid fuel cell (PAFC) system would be suitable where high heat/electricity values were required, but had low electrical efficiency. The wood-fired molten carbonate fuel cell (MCFC) was found to be quite efficient and suitable for small-scale electricity generation purposes. The problems in assessing future capital costs make the economic viability of such systems difficult to determine, but such systems may have an application where access to cheap fossil fuels is not possible.

2. Isolated community

In this case, a residential community of about 200 persons (and including three retail outlets) is proposed. For either technical or economic reasons, this community has no grid electrical supply or piped gas, and is to receive all its electrical and heating (hot water) requirements from a power plant which uses renewables. An integrated low-pressure oxygen (LPO) biomass gasifier/fuel cell system is assessed in this paper. In Fig. 1, typical monthly values for the electrical and heating usages are shown for such a community over a 1-year cycle. Since the system is isolated, it cannot rely on catering for any peak demands by accessing other sources such as the national grid. Therefore, its electricity generation and heat raising equipment must be scaled to cope with all the power requirements of the community at all times.

The peak electrical demand was found be around 76 kWe, and the annual average electrical consumption about 30.8 kW, i.e. for a power plant scaled to achieve the peak electricity demand, the system availability would be about 40%. From Fig. 1, it can be seen that the maximum heat/electricity requirement ratio is about 3:1. The power plant, described in more detail elsewhere [5] was re-scaled to provide the required peak electrical output, and details of this resized system are given in Table 2. It should be noted that the figures in this table describe the system when operating at maximum electrical output. For example, 2.4 dry tonnes of wood are required per day to provide this peak output for the wood-fired PAFC system, whereas the wood fuel requirement averaged over the annual cycle would be closer to 1.0 dry tonnes per day. This average wood consumption determines the size of forest, and assuming that it lies adjacent to the community in question, the cost of transporting the wood. If a yield of 10 dry tonnes per hectare per annum is assumed, and that the area is 100% afforested, then the forest area would be around 35 ha. This implies a forest radius (assuming a circular forested area, for simplicity) of around 330 m, and a minimal transportation cost for the wood (in this case, the wood fuel cost is taken as £ 25.20 per dry tonnes).

2.1. Integration of the biomass gasifier with the fuel cell

The integration of the gasifier with the fuel cell offers advantages over using the two systems separately. 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 potential waste from one element of the system in the other.

Consideration must be given to matching the fuel cell(s) and the gasifier technology chosen. The type of gasifier technology used and the oxidant employed determine the composition of the gas produced, and this gas should be consistent with efficient electricity generation by the fuel cell.

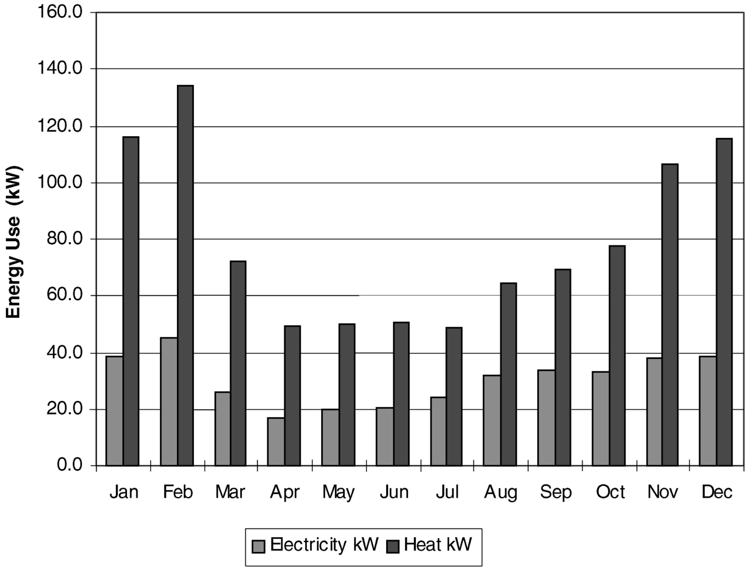


Fig. 1. Example of an energy profile of an isolated community in a temperate zone.

2.2. Choice of fuel cell

Two fuel cell types are considered in this paper, the PAFC and the MCFC. The PAFC can only tolerate 1–2% CO at the operating temperature of 200 °C, so a "shifter" must be employed 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. Power plants using these types of fuel cells have not been in use for a long time, so there is great uncertainty in their operating lifetimes and their capital costs. This makes he assessment of the economics of such systems even more uncertain.

2.3. Choice of gasification technology

A range of gasification technologies was examined [6] and the Koppers-Totzek entrained-flow gasifier, which was originally developed for coal gasification and considered to be representative of commercially available LPO technology [7], was considered to be most suitable. It has also been assessed for biomass [8]. The LPO gasifier is chosen since it gives a gas low in methane (see Table 1). This means that no reformer is necessary for the fuel cell to "reform" the methane to hydrogen and carbon monoxide.

A more complex system, involving the indirectly-heated Battelle gasifier, a MCFC and a steam turbine has been proposed [9], but may be more appropriate for larger scale power plant.

2.4. 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). 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.

Table 1
Gas composition from different gasifiers

Gasifier type	LPO	HPO	IND
Pressure (bar)	1.013	34.4	1.013
Temperature (°C)	980	980	980
Dry gas production (N m^3/tonnes)	1348	1066	1027
Dry gas composition (mol%)			
H_2	36.2	30.9	30.6
CO	44.4	19.8	41.2
CH_4	0.3	13.1	14.0
C_2	–	–	3.3
H_2/CO	0.82	1.56	0.74

LPO, low-pressure oxygen; HPO, high-pressure oxygen; IND, indirect.

It is assumed that 40% of the PAFC's 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%).

3. Wood-fired phosphoric acid fuel cells

3.1. Technical and environmental results for the system using the PAFC

Whereas Table 2 shows the main technical and environmental results for the simulations of each system at peak output, Table 3 summarises these features and their principal economic results as well. The net electrical output of the whole system is 74.5 kW and the hot water output is 249.3 kW, which comply with the maximum power and the maximum heat/electricity ratio requirements. The LHV electrical efficiency was found to be 15.4% and the overall LHV energy efficiency 66.6%. While these efficiencies are low, they are comparable with most other biomass-fed power plants of similar size. Carbon dioxide emissions were found to be 2432 g/kWh. This level of CO_2 emissions is high, due to the low efficiency of the system, but can in fact be considered to be nullified due to re-absorption by growing trees in the sustainably-maintained forest. There are no other significant emissions, as detailed for the system in the first case.

3.2. Economic analysis

Problems often occur when making an economic analysis of a system containing novel technology. Novel equipment may only exist at the design or development stage, or at a different size (usually, at a much smaller scale) than that required. Estimating the cost of the equipment is also difficult since costs can vary after several examples of the item have been manufactured or when it has been mass-produced. In addition, the longevity of the equipment may not be known if it is in the early stages of development or testing.

In this system, the costs of the biomass gasifier [10] wood conveying, screening, conveying and drying stages [11] have been estimated from sources in the literature. It has been more difficult to find reliable data for the costs and lifetimes for the fuel cells. For this reason, these have been taken as parameters in assessing the economics of the overall system.

The capital cost of the downdraft gasifier is obtained by scaling the values taken from supplier's lists [12]. Systems

Table 2
Technical and environmental results

Fuel cell type	PAFC	MCFC
Process details		
Reformer type	None	None
Fuel feedstock	Wood chip	Wood chip
Sulphur removal technology	None	None
CO_2 sequestration technology	None	None
Anode recycle	Yes	Yes
Operating temperature	200 °C	650 °C
CO shifter	Yes	No
Gasifier type	LPO	LPO
Wood input (dry tonnes per day)	2.4	1.5
Thermal input (kW, HHV)	523.2	321.8
Thermal input (kW, LHV)	486.3	299.2
Fuel cell power output (kWe dc)	103.2	104.8
Fuel cell power output (kWe ac)	100.1	103.2
Auxiliary power usage (kWe)	25.6	23.0
Net electrical output (kWe)	74.5	80.2
Waste heat available (kWth)		
>750 °C	0	0
>600 °C	0	0
>450 °C	0	0
>300 °C	0	0
∼85 °C	249.3	107.2
Electrical efficiency (%, HHV)	14.2	24.9
Electrical efficiency (%, LHV)	15.4	26.8
Overall energy efficiency (%, HHV)	61.9	58.2
Overall energy efficiency (%, LHV)	66.6	62.6
Gaseous emissions		
CO_2 (g/kWh)	2432	1422
SO_x (g/kWh)	0	0
NO_x (g/kWh)	0	0
Flue gas details		
Flow (kg/h)	694	456.9
Temperature (°C)	100	102
Composition (%, w/w)		
N_2 + argon	62.8	58.7
CO_2	26.1	24.9
O_2	6.2	5.8
H_2O	4.9	10.6
Other	0	0

are shown with the fuel cells having 5, 10 and 15 lifetimes; the remainder of the system is assumed to have a lifetime of 30 years. The system availability was taken as 40%. The total specific investment (SI) for the system depends on the values assumed for the lifetime of the fuel cell and its installed system cost. The SI was found to range from £ 4010/kWe (for a lifetime of 15 years, interest rate of 7.5% and an installed fuel cell cost of £ 500/kWe) to £ 10,930/kWe (for a lifetime of 5 years, interest rate of 7.5% and an installed fuel cell cost of £ 2000/kWe).

Break even electricity selling price (BEESP or cost of electricity, COE) is shown against a range of specific capital costs for the installed fuel cell system (in £/kWe) in Fig. 2a. Figs. 2a–5a show the variation of COE (BEESP) with various system parameters. These are shown for the sake of comparison with other systems. However, for an isolated community, there is no possibility for selling any excess electricity or waste heat that is produced by their power plant. It may be of greater relevance to simply compare SIs for power plants in order to assess the economics of the system. For example, a diesel engine/generator set system would have a specific investment of around £ 200/kWe, and a small biomass gasifier/gas engine system would have a SI between £ 800/kWe and £ 2000/kWe.

Table 3
Comparison of wood-fired MCFC and PAFC systems for isolated community

Fuel cell type	PAFC	MCFC
Reformer	None	None
Shifter	Yes	None
Operating temperature (°C)	200	650
Wood input (dry tonnes per day)	2.4	1.5
Thermal input (kW LHV)	486	299
Net electrical output (kWe)	74.5	80.2
Waste heat available (kW)	249	107
Electrical efficiency (LHV, %)	15.4	26.8
Overall energy efficiency (LHV, %)	66.6	62.6
CO_2 emissions (g/kWh)	2432	1422
Minimum capital costs (£)	299000	232000
Minimum specific investment (£/kWe)	4010	3130
BEESP (p/kWh) (electricity only)	30.0	22.6
BEESP (p/kWh) (CHP)	27.7	21.7

3.3. *Conclusions for wood gasification with PAFC*

An isolated community of around 200 persons would require a power plant producing around 75 kWe for peak demand and about three times this amount of energy in heat. An LPO biomass gasifier/PAFC system would be capable of catering for these requirements. Such a system is quite inefficient, but is not dissimilar to most other very small biomass-fired power plants. CO_2 emissions are high, but can be considered to have a net zero value, if the wood feedstock is taken from a sustainably grown forest.

Breakeven electricity selling prices are high, but may not be relevant for a system which has no possibility for importing or exporting power. The SI may provide a better benchmark for the economics of an isolated system. Depending on the values assumed for the lifetime and installed cost of the fuel cell, the SI was found to vary from £ 4010/kWe to £ 10,930/kWe. This compares very unfavourably with the SI for diesel engine systems £ 200/kWe) and for the biomass gasifier/gas engine systems (under £ 2000/kWe). For this reason, it would be difficult to justify the use of a biomass-fed LPO gasifier/PAFC system to provide power for a small isolated community.

4. Wood-fired molten carbonate fuel cells

In this section, the PAFC is replaced by the MCFC. The replacement of the MCFC for the PAFC has other implications

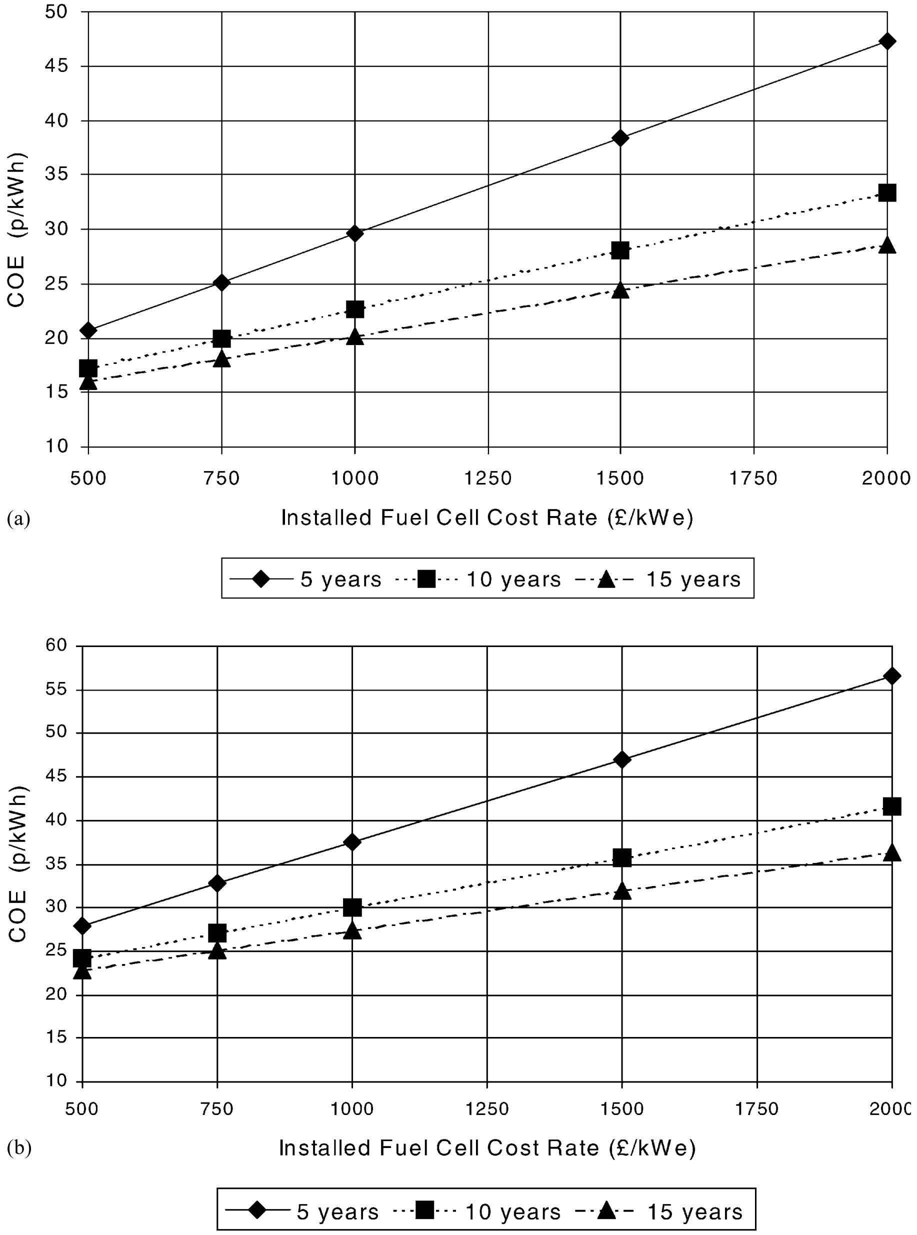


Fig. 2. (a) System with PAFC: variation of COE with installed fuel cell cost for three fuel cell lifetimes. (b) Variation of COE with installed fuel cell cost for fuel cell lifetimes of 5, 10 and 15 years (MCFC in system).

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 in detail 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.

4.1. Process description using the MCFC

The process from harvesting the wood to electricity generation closely resembles that described earlier for the LPO biomass gasifier/PAFC system. The only differences are those described in the earlier sections.

The wood-fired fuel cell system again is to provide all the energy needs to an isolated community of about 200 residents. The energy demand profile for this community shows that about 75 kW is the peak electrical requirement and that about three times this amount of heat would cover the maximum demands (see Fig. 1). The system availability was taken to be 40%, as before.

Although some waste heat was found to be available at high temperatures, it was not considered for raising steam, but only for providing hot water for space heating.

4.2. Results for the 80 kWe MCFC system

The technical and environmental results for this system are summarised in Table 2. The net electrical output was found to be 80.2 kWe, and the waste heat output was 107.2 kW. An LHV electrical efficiency of 26.8% (HHV, $\eta = 24.9\%$) and an overall LHV energy efficiency of 62.6% (HHV, $\eta = 58.2\%$) were achieved. Carbon dioxide emissions were found to be high (1422 g/kWh), but these could be considered to be nullified by re-absorption into the growing trees of the sustainably maintained coppice plantations.

4.3. Economic analysis of the 80 kWe MCFC system

Since a precise economic analysis is difficult, for the reasons given previously, once again a series of sensitivity analyses has been made and is shown in Figs. 2b–5b.

In Fig. 2b, COE is plotted against four values of fuel cell cost per installed kWe (£ 500, £ 1000, £ 1500 and £ 2000) for

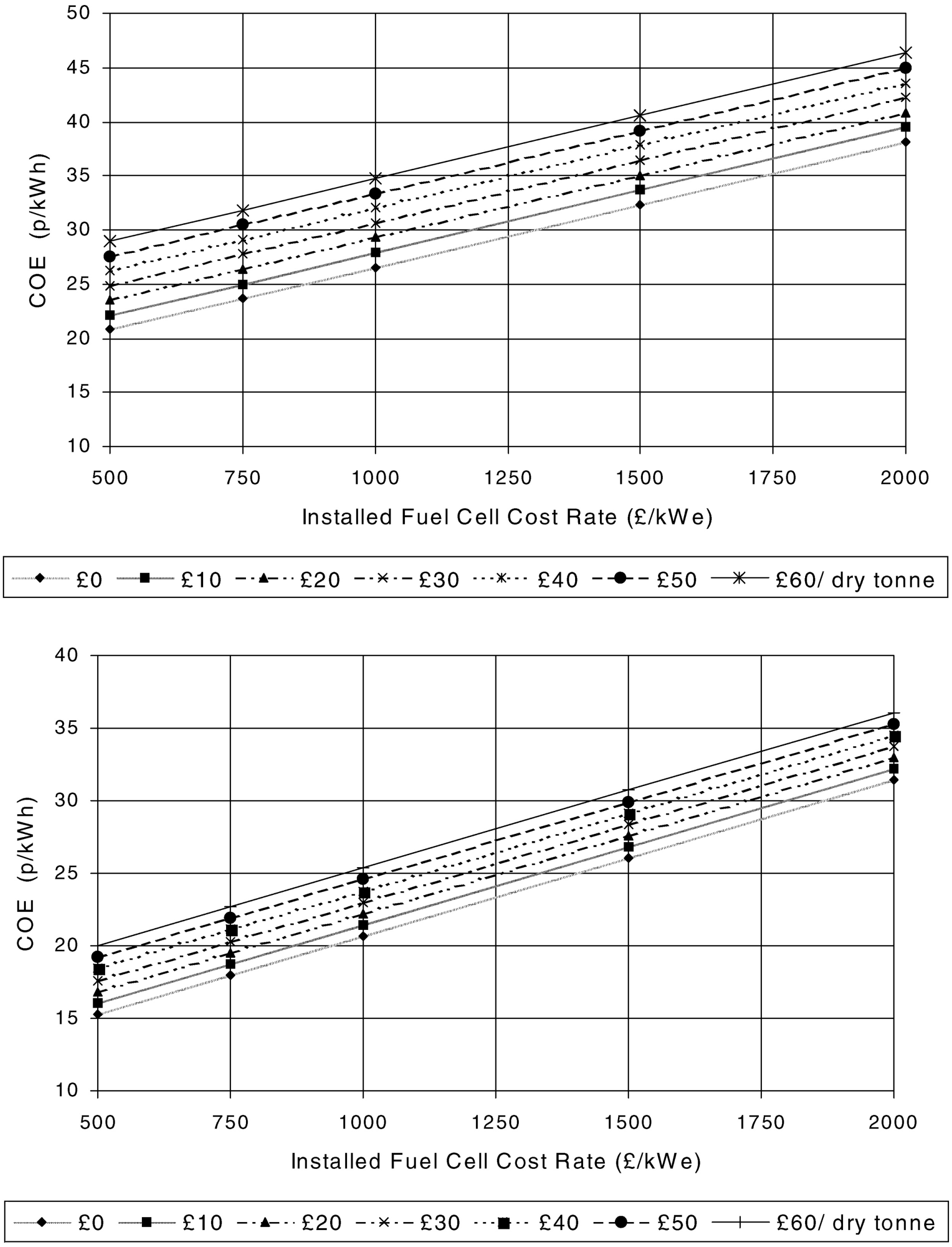


Fig. 3. (a) PAFC in system: variation of COE with installed fuel cell cost for wood costs from 0 to £ 60 per dry tonnes. (b) Variation of COE with installed fuel cell cost for wood fuel costing from 0 to £ 60 per dry tonnes (MCFC in system).

fuel cell lifetimes of 5, 10 and 15 years. The lifetime of the complete system was taken as 30 years, with an availability of 40%, and the wood fuel cost taken as £ 25.20 per dry tonnes (all as before). The total SI for this system was found to range from £ 3130 (fuel cell lifetime 15 years, installed fuel cell cost £ 500/kWe) to £ 10,050 (LT 5 years, IFCC £ 2000/kWe) and COE ranged from 16.1 to 47.3 p/kWh.

In Fig. 3b, the fuel cell lifetime is assumed to be fixed at 10 years, but the cost of the wood fuel was allowed to vary from 0 to £ 60 per dry tonnes. COE falls from 16.9 p/kWh (with wood costing £ 20.0 per dry tonnes) to 15.3 p/kWh (at zero wood cost) and rises to 20.0 p/kWh (when wood costs £ 60 per dry tonnes) for an IFCC of £ 500/kWe.

If waste heat can be sold, in the form of hot water, some reduction in COE can be made (up to 2.5 p/kWh). This is shown in Fig. 4b, where the waste heat is sold for prices from 0 to £ 3/GJ (fuel cell lifetime is taken at 10 years and wood fuel price at £ 25.20 per dry tonnes).

The variation of COE with percentage change in certain economic parameters (fuel cell lifetime, fuel cell cost and waste heat selling price) is shown in Fig. 5b. The base point of the figure has a COE value of 21.7 p/kWh when the parameter values were 10 years for the fuel cell lifetime, £ 1000/kWe for the installed fuel cell cost, £ 25.20 per dry tonnes for the wood fuel and £ 2/GJ for the waste heat selling price.

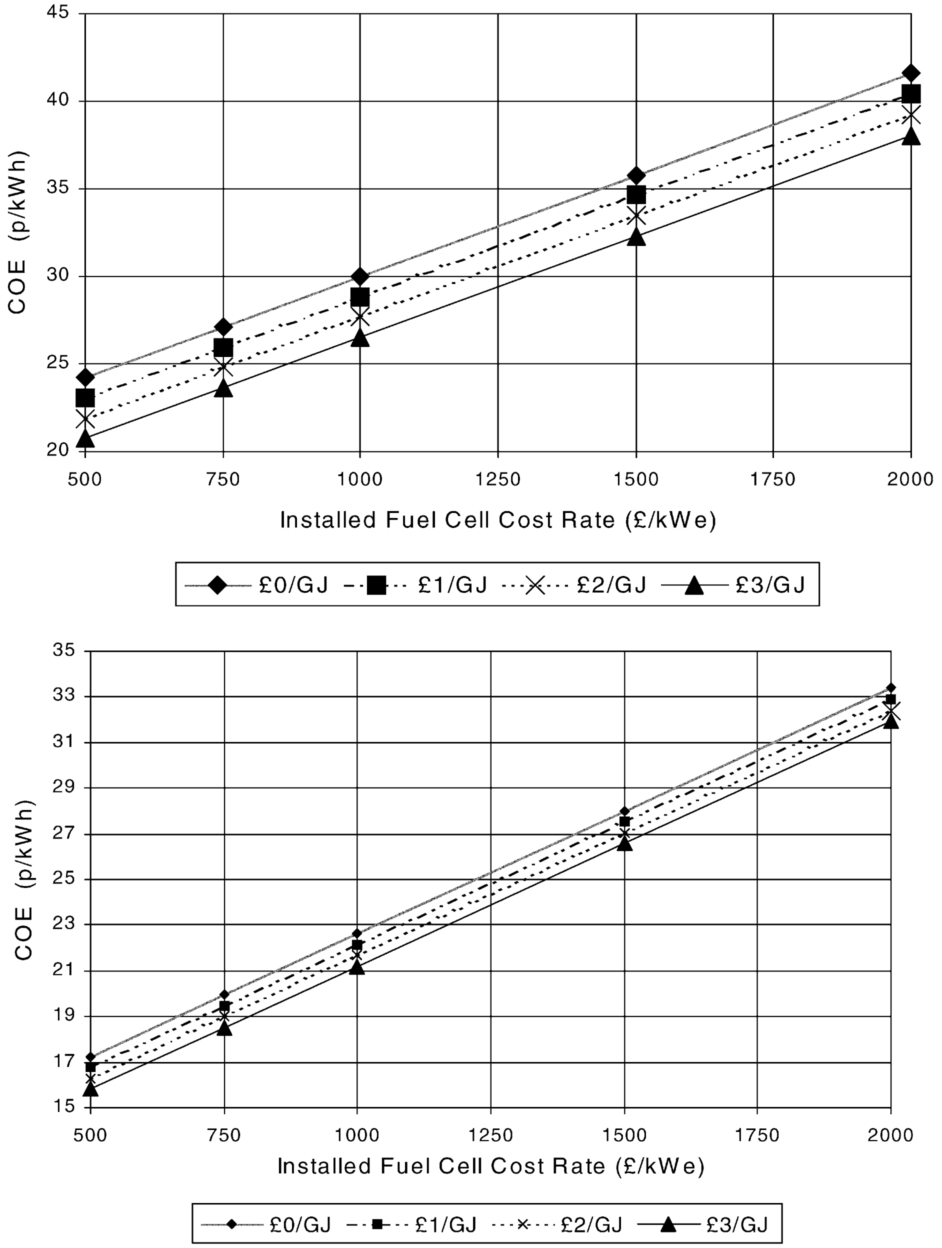
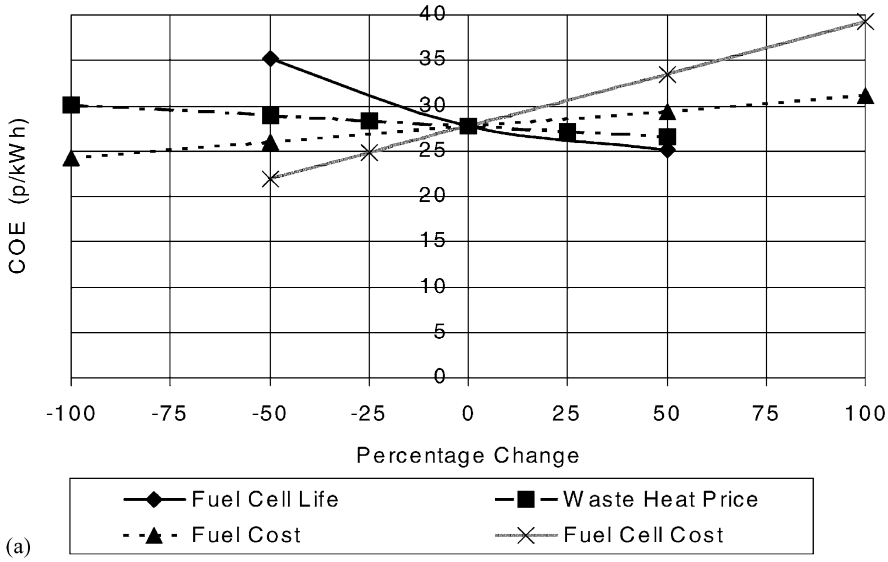


Fig. 4. (a) Variation of COE with installed fuel cell costs for wastes heat selling prices of 0 to £ 3/GJ. (b) Variation of COE with installed fuel cell cost with wood fuel costing £ 25.20 per dry tonnes and waste heat costing from 0 to £ 3/GJ (MCFC in system).



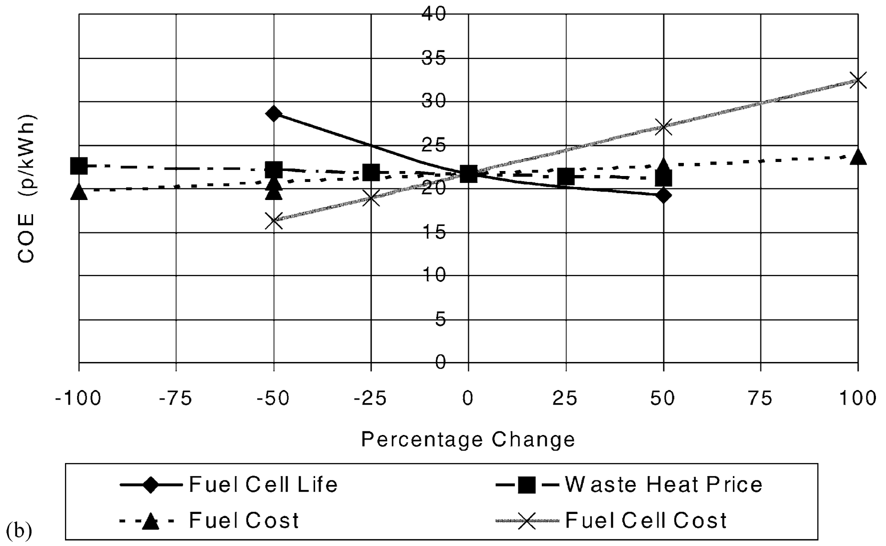


Fig. 5. (a) Percentage variation of BEESP from base case. (b) The effect of percentage variation from the base case (base case: fuel cell lifetime, 10 years; wood cost, £ 25.20 per dry tonnes; fuel cell cost, £ 1000/kWe, and waste heat selling price, £ 2/GJ) (MCFC in system).

4.4. Conclusions for the 80 kWe MCFC system

The system was scaled to provide the peak electrical demand of around 80 kWe and the recoverable waste heat was found to be 107.2 kW. Unfortunately, this is much less heat than is required at peak demand. The high electrical efficiency of the system means that more of the energy input is converted to electricity and less is available to be recovered for heating. If the system were scaled to cover the peak heat demand, surplus electricity would be produced, which could not be off-loaded. Also, capital costs would be higher for a larger system. It may be applicable to install a wood-burning boiler to provide the shortfall in heat.

The LHV electrical efficiency was found to be 26.8% for the 80 kWe MCFC system. This is of the same level as the most efficient, small-scale, biomass power generation systems, e.g. biomass gasifier/gas engine plants and is only slightly down on the 500 kWe system [13]. The overall LHV energy efficiency was found to be 62.6% after taking the recoverable waste heat into account.

The COE sensitivity analyses in Figs. 2b–5b are shown for comparison with other systems, but are not relevant in this case where neither heat nor electricity is being sold. On the other hand, SI values may be more useful, and the lowest value obtained (£ 3130/kWe) is similar to other small-scale (but usually larger) biomass power plants.

This system appears to be well suited for small-scale electricity production for an isolated community as it has a high electrical efficiency and comparable specific investment for its size, but is not suitable for high heat demands. The shortfall in heat could be made up using a centralised wood-burning boiler.

5. Comparison of wood-fired PAFC and MCFC systems

This power plant ought to provide all the heat and electricity for a small, isolated community. It was scaled to provide around 80 kWe to meet the peak electrical demand. Peak heat output should be about three times that of the electricity generated. As is shown in Table 2, the system using the PAFC complies with this requirement, whereas the system with the MCFC provides only about 25% more heat than electricity. Once again it is obvious that the MCFC system is superior to the PAFC system in most features, but the ability of the PAFC system to provide all the heat requirements means that it fulfils the selection criteria for providing all the energy needs of the isolated community (if an additional wood-fired boiler could be used to make up the shortfall in heat, then the MCFC system should probably be chosen).

6. Conclusions

Wood can be gasified to provide a gas suitable for use in a phosphoric acid or MCFC to generate electricity and recoverable waste heat. If the wood is grown in a sustainable fashion, there are negligible net emissions of carbon dioxide.

When the two types of fuel cell systems are compared, the wood-fired MCFC can be seen to generate electricity much more efficiently than the wood-fired PAFC. Consequently, for the same electrical output, the MCFC system would be smaller than the PAFC system, use less fuel, emit less carbon dioxide and waste less energy from the fuel (and produce less waste heat). The wood-fired MCFC system, is therefore, technically and environmentally superior to the wood-fired PAFC system. The PAFC system can only be preferred where the supply of recoverable waste heat (at low temperatures) is more important than the supply of electricity or high grade waste heat.

6.1. Key conclusions

- It is possible to use the producer gas from a wood gasifier to generate electricity in a fuel cell and so help in the reducing of atmospheric CO_2 emissions.
- Small wood-fired PAFC systems have a low electrical efficiency, similar to that of wood combustion plants of the same size, but they do allow a large amount of waste heat to be recovered. However, they are expected to remain too expensive to displace any of their competitors.
- Small wood-fired MCFC systems have good electrical efficiencies, similar to the best of the small-scale wood-fired systems (using a wood gasifier and a gas engine), but are likely to remain more expensive than the latter until fuel cells enter large-scale production (and their capital costs fall).
- The small wood-fired MCFC systems could be used already in certain niche markets. For example, where a CHP system is required, but the noise, smell, NO_x emissions or size of an engine would not be appropriate. The wood-fired MCFC is just as efficient, is much quieter, has practically no smell, has very low NO_x emissions and has a much smaller footprint. This system is liable to be more expensive, i.e. have a longer payback period than gasifier/gas engine systems, but cost may be of lesser concern than the benefits of the system.
- Another possible application for the wood-fired MCFC could be as a small electricity generation system in a location where electricity demand on the grid distribution network is already high, and any additional requirement would further exacerbate the losses occurring in high-load power transmission.
- If fuel cells are developed for other markets, such as transportation, costs for installed fuel cells could fall considerably. Should this occur, wood-fired MCFCs could then be economically viable for a wider range of power generation applications.

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