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A techno-economic analysis of biomass gasifiers integrated with high and intermediate temperature solid oxide fuel cells

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SUMMARY

In this paper the ECLIPSE process simulation package is used to model and make a techno-economic analysis of a range of systems that combine biomass gasification with SOFC stacks.

Two forms of the SOFC are considered: the intermediate temperature (IT) solid oxide fuel cell and the standard high-temperature solid oxide fuel cell. The biomass gasification technology, which was selected for integration with the SOFC stacks, was the air-blown downdraught gasifier, because of its simplicity and relative cheapness. Willow and miscanthus were taken as the biomass fuels for the power plants.

In addition, the sensitivity of the COE to variations in the fuel cost, the fuel cell cost, the fuel cell lifetime, and the waste heat selling price were examined and compared.

From the ECLIPSE simulations, the efficiencies of both the HT and IT 250 kWe systems were found to be around 39% when willow was used as fuel and around 38% with miscanthus, the difference being due to moisture content, rather than any intrinsic property of the biomass. Similarly, for the 25-kWe systems, the efficiencies were found to be around 35 and 34% respectively. These values are higher than for any other biomass-fired electricity generation technologies of similar scale. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS

solid oxide fuel cells; intermediate temperatures; biomass gasification; CHP; techno-economic analysis; specific capital investment; break-even electricity selling price

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1. INTRODUCTION

1.1. Background

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 biomass gasification may offer a combination for delivering heat and electricity cleanly and efficiently, even at small scales.

Solid oxide or molten carbonate fuel cells offer the best potential for integration with biomass gasifiers since these are the fuel cells with the highest operating temperatures [1], which are similar to those of the downdraught gasifiers and so could benefit from heat exchange. They are also the most efficient in terms of production of electricity (Table I).

However, these high operating temperatures are a mixed blessing; they require longer start-up and heat-up times [3], making them unsuitable for transportation applications. High-temperature operation also means that suitable materials, such as high-Cr ferritic steels, are needed for the metallic interconnects in the stacks to deal with these high temperatures, the stresses of changing temperature and have similar coefficients of expansion to the ceramic parts of the SOFC. If the SOFC were to operate at intermediate temperatures

Table I. Comparison of some standard fuel cell properties [2].

Type	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Ion exchange	Potassium hydroxide	Phosphoric acid	Alkali carbonates mixture	Yttria stabilized Zirconia
Operating temp (°C)	60–100	60–120	160–220	600–650	600–1000
Charge carrier	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Electrolyte state	Solid	Liquid	Immobilized liquid	Immobilized liquid	Solid
Cell hardware	Carbon or Metal based	Carbon based	Graphite based	Stainless steel	Ceramic
Catalyst	Platinum	Platinum	Platinum	Nickel	Perovskites/Ni
Recoverable CHP heat	None	None	Low quality	High	High
CO Impact	Poison	Poison	Poison	Fuel	Fuel
S Impact	Few studies	Unknown	Poison	Poison	Poison
External reformer for CH_4	Yes	Yes	Yes	Yes/No	Yes/No
Fuel cell efficiency (%)	30–45	30–50	30–45	45–60	45–75

(IT) (around 600°C), then the interconnects could be much thinner and less expensive [4].

The high-temperature SOFCs (HTSOFCs) use an Yttria Stabilized Zirconia electrolyte for ionic conduction between 800 and 1000°C. Recently, a lot of research has been undertaken to find and develop novel electrolyte materials or charge carriers that operate in the IT region (500–800°C) and the low temperature (LT) region (300–500°C). For example, in the IT region salt-ceria composite electrolytes were found to be binary ionic, having O^{2-}/H^+ charge carriers [5,6]; samarium-doped ceria (SDC) and Li/Na carbonates were used in a composite that has ternary conduction from $O^{2-}/H^+/CO_3^{2-}$ charge carriers [7]; thick oxide-carbonate composites with co-doped ceria were found to have enhanced conduction from O^{2-}/CO_3^{2-} charge carriers [8].

In the LT region novel core-shell SDC/amorphous Na_2CO_3 nanocomposite electrolytes show superionic activity above 300°C [9], where the conduction is presumed to be dominated by interfacial oxygen ion carriers, rather than bulk conduction [10], and the thermal stability of these nanocomposites has been confirmed up to 750°C, above which the Na_2CO_3 layer begins to degrade and volatise [11]. Lower operational temperatures will permit the use of conventional stainless steels for interconnects, substantially reducing fuel cell costs and conventional sealing materials can also be used. Start-up and heat-up times would be reduced as well as the response time to changing power loads [12] when operating at LTs. Lower operating temperatures would also extend the lifetime of the fuel cell [13].

Global production of hydrogen depends primarily on the steam reforming of fossil fuels, with 30% coming from oil products and 48% from natural gas, with 18% coming from coal gasification [14]. In the future biomass could become an important sustainable source of hydrogen and a low-cost option for some countries. Biomass gasification is thought to provide the earliest and most economical route for the production of renewable hydrogen [15]. The integration of biomass gasifiers with fuel cells has been proposed [16] and CHP applications suggested for low-pressure oxygen (LPO) gasifiers with either molten carbonate or phosphoric acid fuel cells for an isolated community [17] or for selected buildings [18]. There are many gasifiers technologies and the most suitable should be selected for the fuel cell integrated in the system [19]. Although the LPO gasifier produces a gas without the inert N_2, the air-blown downdraught gasifier is chosen in this case, because of its relative cheapness.

In this study the integration of a biomass gasifier with a HTSOFC (operating temperature around 900°C) and with a IT solid oxide fuel cell (ITSOFC) (operating temperature around 600°C) in a CHP power plant are compared. Two biomass fuels, miscanthus and willow, are considered as the fuel for the air-blown downdraught gasifier at atmospheric pressure. In addition two system scales, 25 and 250 kWe, were compared.

The ECLIPSE process simulator [20] was used for the simulation and analysis of these proposed systems, and more details of them are given elsewhere [21].

2. FUEL PROPERTIES–CALORIFIC VALUE, PROXIMATE AND ULTIMATE ANALYSIS

In this study the biomass fuels were chosen to be miscanthus and willow, which are promising energy crops in Western Europe. The proximate analysis of these fuels is shown in Figure 1.

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2.1. Proximate analysis

The (as received) moisture contents of these fuels are 25–30%, which means that they must be dried to around 15% for successful gasification. Drying requires energy, thus lowering the energy efficiency of the system. The volatile contents are above 80%, which are typical for biomass and considerably higher than for coal. The fixed carbon values and the ash contents are also lower compared with most coals. This has implications for biomass gasification, since it makes it very easy for large (long-chain) molecules to be released into the producer gas stream and they could condense on cool spots in the system.

2.2. Ultimate analysis

The ultimate analysis of miscanthus and willow are shown in Figure 2.

The dry ash free properties of these fuels are relatively similar. It can be seen that there is no sulphur, and low chlorine and ash content in both fuels. This is significant for emissions of SOx, or HCl. What is not shown is that there are very small amounts of silica in

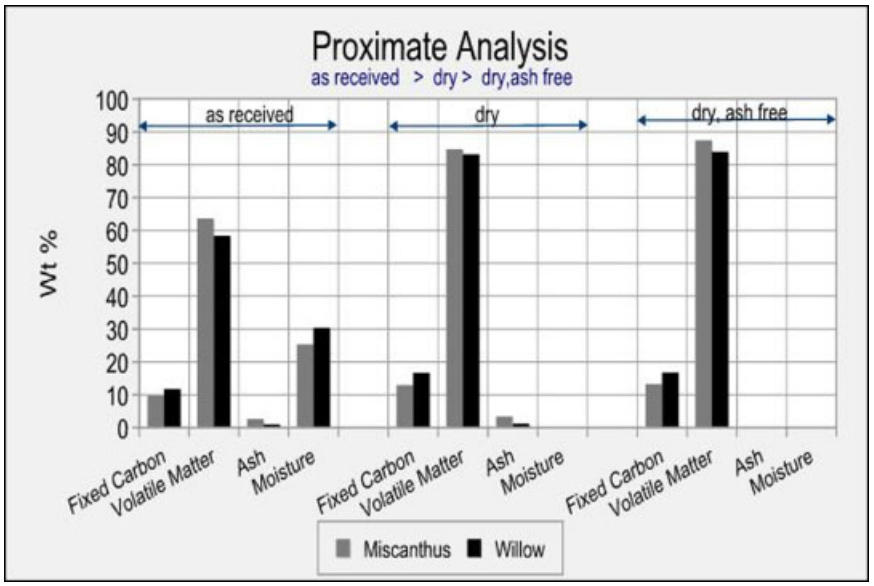

Figure 1. Proximate analysis of miscanthus and willow.

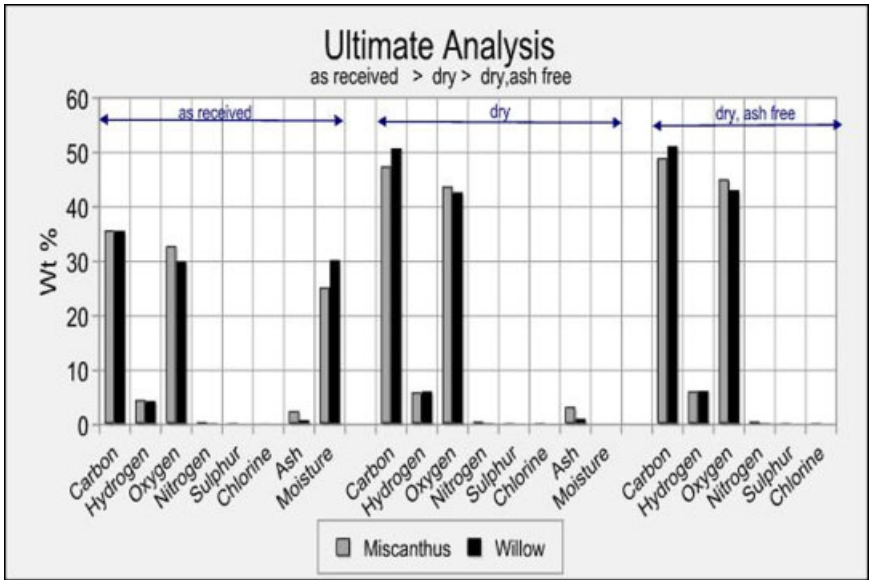

Figure 2. Ultimate analysis of miscanthus and willow.

the miscanthus, which can affect ash melting and sintering temperatures and potentially lead to slagging in the gasifier.

2.3. Calorific value

These are typical biomass fuels, with low calorific values (17–18 MJ kg^{-1}) compared with coal (25–35 MJ kg^{-1}) (Figure 3).

This is particularly apparent in the 'as received' mode as they both have comparatively high moisture contents.

As has already been mentioned, an air-blown gasification system was chosen for integration with the solid oxide fuel cell stack for the CHP system. The gas composition from such a gasifier, using miscanthus or willow for fuel, is given in Figure 4.

As can be seen, nitrogen is the main constituent of the producer gas from the air-blown downdraught gasifier, causing this gas to have a relatively low calorific value, since it is inert. There is a small amount of methane present in the gas, and there may also be traces of HCl or NOx.

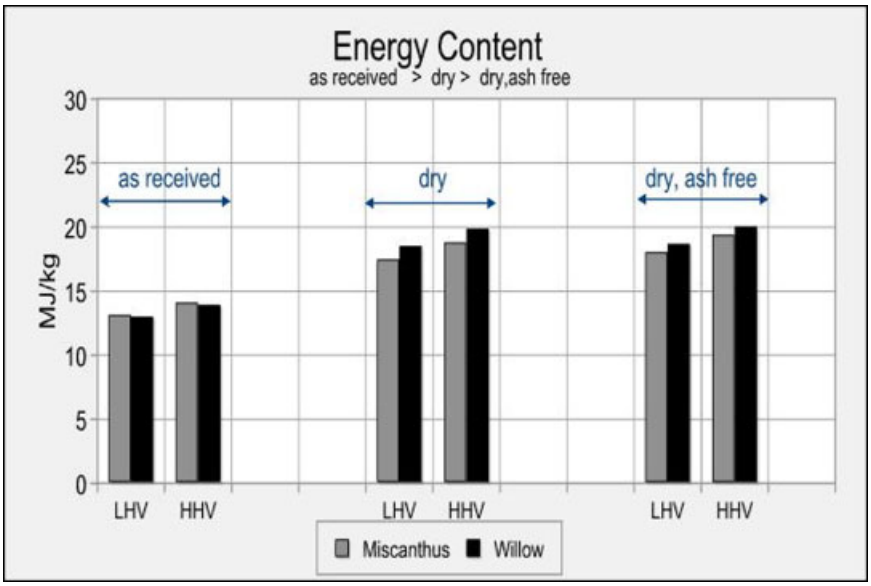

Figure 3. Calorific value of miscanthus and willow.

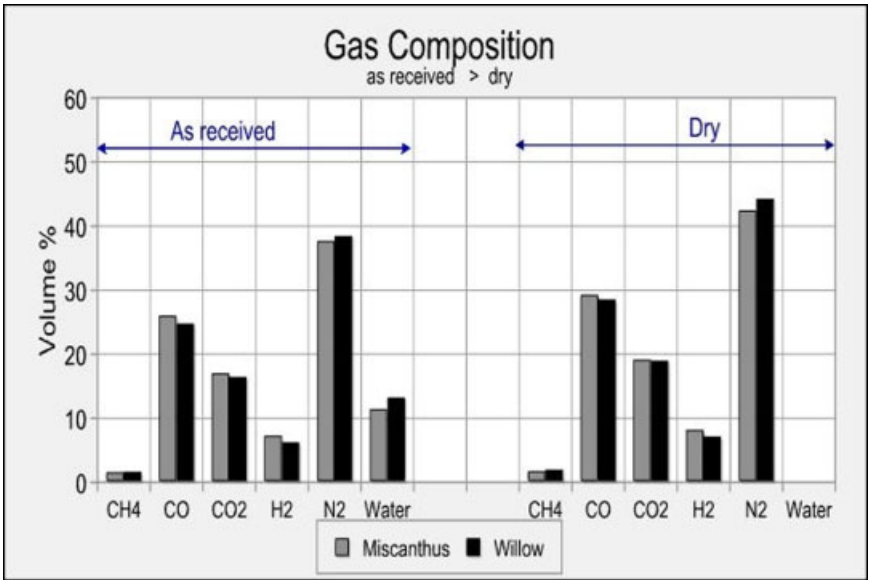

Figure 4. Typical gas composition from a downdraught gasifier fuelled by miscanthus or willow.

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3. TECHNICAL SIMULATION RESULTS

A simplified schematic of the system model is shown in Figure 5. The biomass is dried to 15% by the exhaust gases before entering the gasifier, with air also preheated from the exhaust. Around 85% of the hot producer gas arriving at the SOFC is consumed, so the remainder can be combusted to provide heat for the pre-reformer, air heater and boiler, where steam is raised for the reforming, as well as the hot water heating. The distribution of heat, and the amount available for hot water, will depend on the operating temperature of the SOFC, the amount of steam required at the pre-reformer and the moisture content of the biomass used.

The technical results for the ECLIPSE simulations for the 25 and 250-kWe CHP systems, with willow as the fuel, are summarised in Table II and with miscanthus as the fuel in Table III. Simulations have been made for both the HT and IT versions of the SOFCs.

With willow as the fuel, the 250-kWe systems were found to be about 5 percentage points more efficient than the 25-kWe systems. The systems with the HTSOFCs were found to recover more heat and emit less CO_2 than those with the ITSOFCs.

With miscanthus as the fuel, the 250-kWe systems were found to be about 4 percentage points more efficient than the 25 kWe systems. The systems with the HTSOFCs were found to recover more heat and emit less CO_2 than those with the ITSOFCs. The electricity usages shown in Tables III and IV account for the

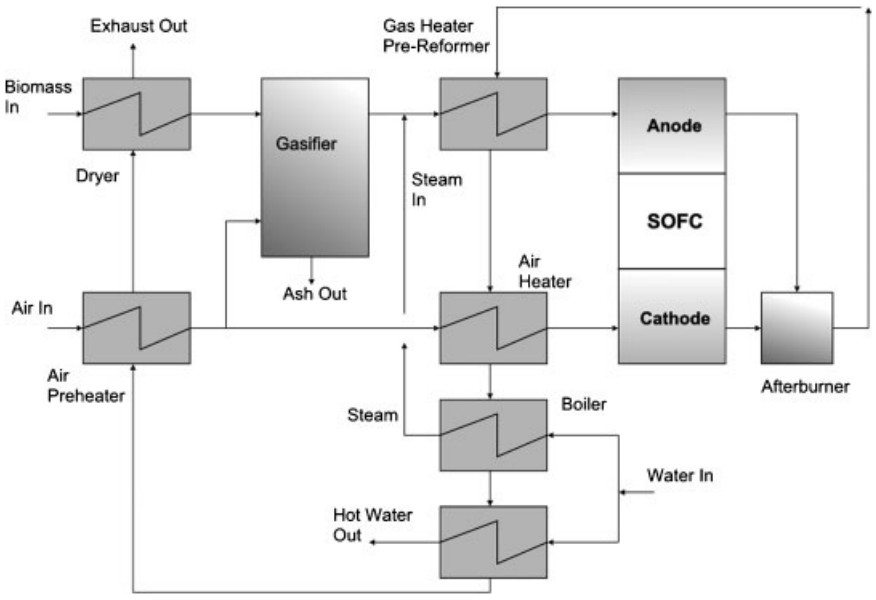

Figure 5. Simplified schematic of the proposed biomass gasification–SOFC CHP system.

Table II. Summary of the technical simulation results for willow as the fuel.

System output (kWe)	250	250	25	25
SOFC Temperature (°C)	913 (HT)	616 (IT)	911 (HT)	607 (IT)
Fuel	Willow	Willow	Willow	Willow
Biomass flow (daf t day^{-1})	3.04	3.07	0.35	0.35
Thermal input (kWth), LHV	655.4	661	74.48	74.48
Electricity usages (kWe)	10.7	11.8	3.9	4.3
Heat recovered (kWth)	121	44	9	0
Gross electricity out (kWe)	264	264.4	29.4	30
Net electricity out (kWe)	253.3	252.2	24.9	25.1
Electrical efficiency, LHV (%)	38.65	38.33	33.4	33.7
CHP efficiency, LHV (%)	57.1	44.8	45.5	33.7
CO_2 (g kWh^{-1})	841	850	998	1118

Table III. Summary of technical simulation results for miscanthus as the fuel.

System output (kWe)	250	250	25	25
SOFC temperature (°C)	953 (HT)	647 (IT)	944 (HT)	614 (IT)
Fuel	Miscanthus	Miscanthus	Miscanthus	Miscanthus
Biomass flow (daf t day^{-1})	3.16	3.16	0.35	0.35
Thermal input (kWth), LHV	657.7	657.7	74.48	74.48
Electricity usages (kWe)	14.3	15.7	4.2	4.5
Heat recovered (kWth)	231	124	13	3
Gross electricity out (kWe)	264	266	29.2	29.8
Net electricity out (kWe)	249.5	250.5	24.9	25.1
Electrical efficiency, LHV (%)	37.94	38.09	33.8	34.07
CHP efficiency, LHV (%)	73.06	56.94	51.44	38.14
CO_2 g kWh^{-1}	887	889	983	1133

Table IV. Typical economic indices for large and small systems.

Economic indices and factors	Power station >100 MWe	Power station <100 MWe	Small CHP <1 MWe
Construction time (years)	4	2	1
Commissioning time (years)	0	0	0.25
Discounted cash flow rate (%)	8.0	8.0	8.0
Capital fees (%TCI)	2	2	2
Working capital (%TCI)	2	2	2
Contingency (%TCI)	10	10	10
Plant occupancy (%) (1st year, 2nd, Rest)	40/60/85	60/85/85	85
Plant life (years)	25	25	30
Operating cost (%TCI)	1.1	1.1	1.1
Maintenance cost (%TCI)	2.3	2.3	2.3
Insurance cost (%TCI)	2.0	2.0	2.0

electricity used within the system for fans, pumps and conveyors.

4. METHOD OF ASSESSMENT OF THE SYSTEM ECONOMICS

A full economic analysis was carried out for all systems using the ECLIPSE process simulation package.

The Total Capital Investment (TCI) is the total capital investment of building the power station, starting from a 'green field' site, including the normal infrastructure that would be contained within the boundary fence, i.e. roads, offices, control rooms, services, utilities, etc. Added to this is an allowance for the working capital, capital fees and contingency. There is no allowance for additional capital cost for 'first-of-its kind' costs and no costs due to the additional risks incurred with financing the construction of a novel, prototype or demonstration plant. A Northern European location is assumed for the plant, with similar construction costs to the United Kingdom.

The calculation of the specific capital investment (SI) requires a value for the electricity production, or electricity sent out. The electricity sent out is the gross power generated by the power station, less the power required by all the auxiliaries on site and less the losses from the on-site transformers. It assumes that the power station operates at design load for the defined plant occupancy; no allowance is made for part load operation. The calculation of the electricity sent out is performed using a consistent set of environmental conditions, such as ambient air and cooling water conditions.

The BESP is the price that the generator must charge for the electricity that is sent out to the grid in order that, over the lifetime of the station, its net present worth is zero. In other words, the present day value of the net income is equal to present day value of the capital investment. The present day value of the net income is the sum of the net annual income over the lifetime of the plant, discounted back to the present day value, using a given discounted cash flow rate. The present day is taken as the first day that the commissioned power station starts operation. The net annual income includes the income from selling the electricity produced and any other valuable by-products as well as the cost of fuel, raw materials, services (water, effluent, solids' disposal), operating and maintenance labour and supplies, and insurance. The net annual income is of course affected by the occupancy of the power station. The present day value of the capital investment is the TCI appreciated over

Table V. Example of typical economics for the CHP plant.

CHP plant size (kWe)	250	25	250	25
Fuel cell operating temperature	HT	HT	IT	IT
Fuel cell lifetime (yrs)	5	5	5	5
Fuel cell output gross (kWe)	264	30	264	30
Fuel cell cost rate ($\$\,kWe^{-1}$)	1300	1300	1300	1300
Costs ($ 2008)				
Fuel cell costs for years 0–5 ($)	343 200	39 000	343 200	39 000
Fuel cell costs for years 5–10	240 240	27 300	240 240	27 300
Fuel cell costs for years 10–15	168 168	19 110	168 168	19 110
Fuel cell costs for years 15–20	117 717	13 377	117 717	13 377
Fuel cell costs for years 20–25	82 402	9363	82 402	9363
Fuel cell costs for years 25–30	57 861	6554	57 861	6554
Total fuel cell cost ($)	1 009 588	114 704	1 009 588	114 704
Downdraught gasifier	187 000	45 300	187 000	45 300
Burner	83 500	17 000	83 500	17 000
Gas cleaner	46 300	26 600	46 300	26 600
Biomass conveyer	28 500	24 500	28 500	24 500
Dryer	18 200	10 700	18 200	10 700
Fans	22 800	9000	22 800	9000
Pumps	10 800	0	10 800	0
Heat exchangers	197 000	86 000	102 000	42 000
Total balance of Plant (BOP)	594 100	219 100	499 100	175 100
Total system costs ($)	1 603 688	333 804	1 508 688	289 804
Specific investment ($\$\,kWe^{-1}$)	6415	13 352	6035	11 592

Fuel cell lifetime is 5 years and fuel cell cost rate is $\$1300\,kW^{-1}$. Discounted cash flow rate is 8%.

the construction and commissioning times of the plant using the given discounted cash flow rate. No allowance is made for inflation, payment of taxes or profit, except as is allowed for setting a value for the discounted cash flow rate.

The typical values for the capital and operating cost indices and factors large and small power stations are given in Table IV.

5. ECONOMIC SIMULATION RESULTS

These analyses are too detailed to show here, but certain indicators have been selected. The economic indicators for a system are taken to be: (a) the TCI in $M (2008); (b) SI, i.e. Capital Investment (in 2008 $) per Installed Net kWe; and (c) the Break-even Electricity Selling Price (COE) in US $\$\,MWh^{-1}$ (or US cents kWh^{-1}).

The economics of these systems depends heavily on the cost of the fuel cells and their lifetimes. It has been assumed that each of the CHP 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 (assumed to be 30 years) and has been taken to be 5, 10 or 15 years. This implies that the fuel cell stack would need to be replaced a number of times throughout the lifetime of the CHP system.

The fuel cell cost is also not well established, and values of $400, $600, $800, $1,000, $1,200 and $1,400 per kilowatt were considered here.

There was little difference found between the capital costs of the systems when they used miscanthus or willow, so only the economics for the systems using willow are shown in Table V.

Two particular indicators, the SI and the Break-even Electricity Selling Price (COE), are chosen to assess the economic state of the system.

The CHP plants were modelled for all these variations: plant size (25 or 250 kWe); fuel (miscanthus or willow); fuel cell cost rate ($400, $600, $800, $1,000, $1,200 and $1,400 per kilowatt) and fuel cell lifetime (5, 10 or 15 years).

The TCI for the CHP system was calculated using ECLIPSE for all these variations and the SI (which is the TCI/net plant output in $\$\,kWe^{-1}$) evaluated. The SI for the large (250 kWe) systems is shown in Figure 6 and SI for the small (25 kWe) systems is shown in Figure 7.

It can be seen that the SI increases with increasing fuel cell cost rate and with decreasing fuel cell lifetime for both plant sizes.

6. COMPARISONS AND CONCLUSIONS

There are several uncertainties related to some of the factors in the economics of novel systems, such as

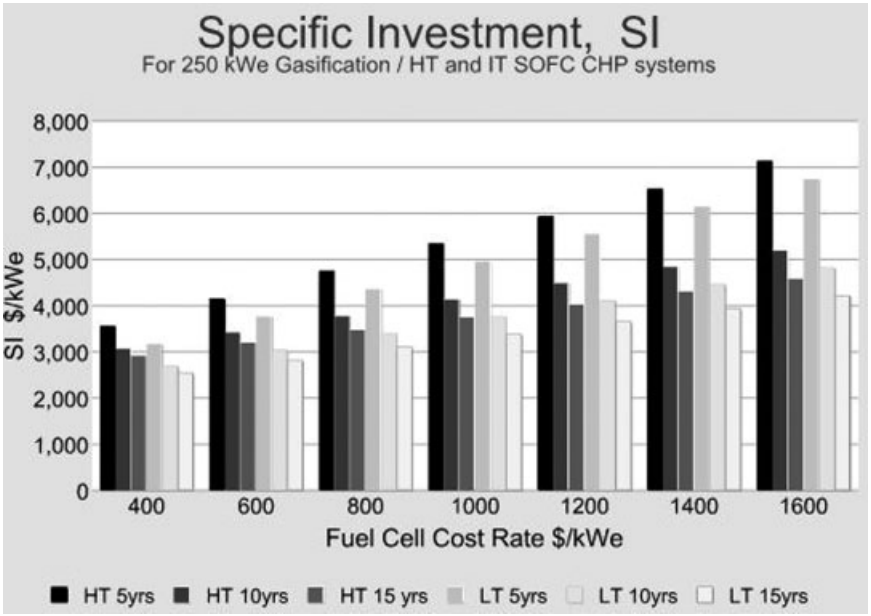

Figure 6. Variation of the SI with fuel cell lifetime and fuel cell cost rate for large plants.

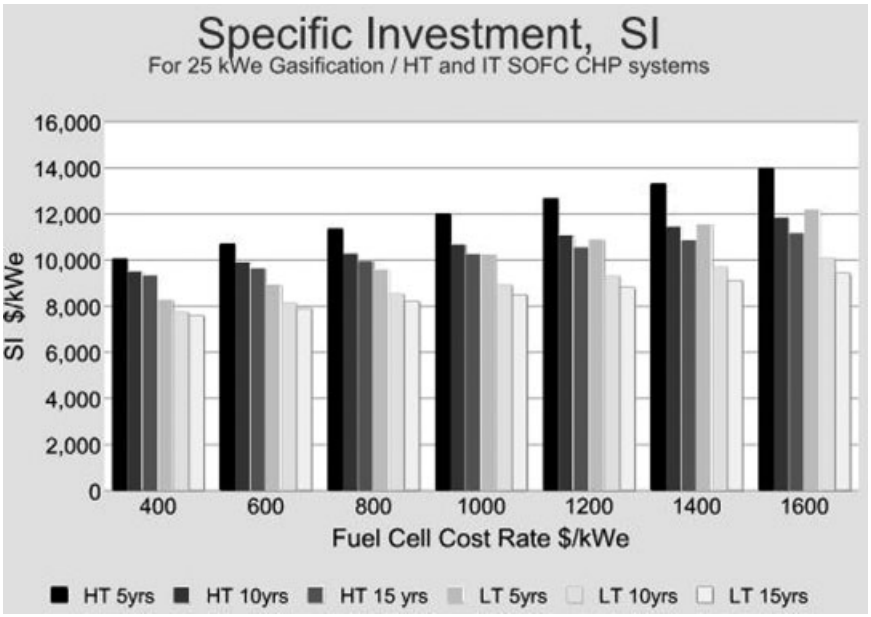

Figure 7. Variation of the SI with fuel cell lifetime and fuel cell cost rate for small plants.

those proposed here, which can affect the cost of electricity generated by the system. Those uncertain factors, which are considered here, are the fuel cell cost rate, the fuel cell lifetime, the cost of the biomass fuel and the selling price for hot water generated by the waste heat. For this reason, a 'sensitivity analysis' is performed, where the COE is calculated for up to $\pm 100\%$ change in the best estimated value of the uncertain factors. The current, best estimated values for these factors are taken as the 'base case', and these are assumed to be: fuel cell cost rate is \$800 kWe^{-1}; fuel cell lifetime is 10 years; biomass-fuel cost is \$60 wet $tonne^{-1}$ (around \$45 daf $tonne^{-1}$); and waste heat selling price is \$1.5 GJ^{-1}. Obviously these values will change with time, location and other factors, so a case-by-case analysis will always be necessary, but they are useful for making general estimates and comparisons.

For the 250-kWe version base case with the HTSOFC, the economic analysis performed by ECLIPSE gives the results in Table VI (Figure 8).

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The same sensitivity analysis was performed for the small-scale systems and is shown in Figure 9.

6.1. Conclusions—technical

The 250-kWe version of the system had a LHV efficiency for electricity generation of about 39% and the 25-kWe version around 33% when using willow and around 38 and 34%, respectively when using miscanthus. The type of biomass did not cause the change in efficiency, this was solely due to the moisture content differences. There was little difference in efficiency between the plants using the HTSOFCs and those using the ITSOFCs.

These efficiency values for electricity generation are higher than any other power plant fuelled by biomass [22], and at least as good as fossil-fuel-fired plants, of this size.

Table VI. Economic analysis of the 'Base case' for the 250-kWe plant with the HTSOFC.

Total equipment costs (TEC) ($)	948 439
Annual insurance (2% TEC) ($)	18 969
Annual maintenance costs (2.3% TEC) ($)	21 814
Annual operating costs (1.1% TEC) ($)	10 433
Contingency (10% TEC) ($)	94 844
Working capital (2% TEC)	18 969
Capital fees (2% TEC) ($)	18 929
Total capital costs (TCC) (inc. Contingency, working capital and fees) ($)	1 085 014
TCC (inc. construction & commissioning time) ($)	1 209 313
Levelised COE (US $ MWh^{-1})	123.89
Payback period (Years)	22
SI, (TEC/250) ($ kWe^{-1})	3794

Some waste heat can also be recovered, but less than with some other biomass power plants. More heat could be recovered when miscanthus (Moisture Content 25%) rather than willow (Moisture Content 30%) was used. The overall energy efficiency for the 250-kWe version was found to be $<73\%$ using miscanthus and $<53\%$ using willow; for the 25-kWe version they were <52 and $<46\%$, respectively. This could probably be improved with better optimisation. However, the financial returns from electricity generation are more lucrative than from the selling of waste heat.

Because of their high efficiencies these plants would be low gross emitters of CO_2, around 850 g kWh^{-1} for the 250-kWe versions using willow, 890 g kWh^{-1} using miscanthus and around 1000–1100 g kWh^{-1} for the 25-kWe versions using miscanthus. The CO_2 emissions from the willow-fired 250-kWe versions are comparable with those from large-scale coal-fired power plants, and their net CO_2 emissions are considerably less, if the willow comes from sustainably grown plantations. There will also be no SOx and little or no NOx from these biomass-fuel cell systems.

6.2. Conclusions—economic

From Figure 5, it can be seen that the SI for the power plants using the ITSOFCs are lower than those using the HTSOFCs. From Table IV, it is clear that the heat exchangers are more expensive for the high-temperature applications making the TCI, SI (and consequently COE) higher for the systems using the HTSOFCs.

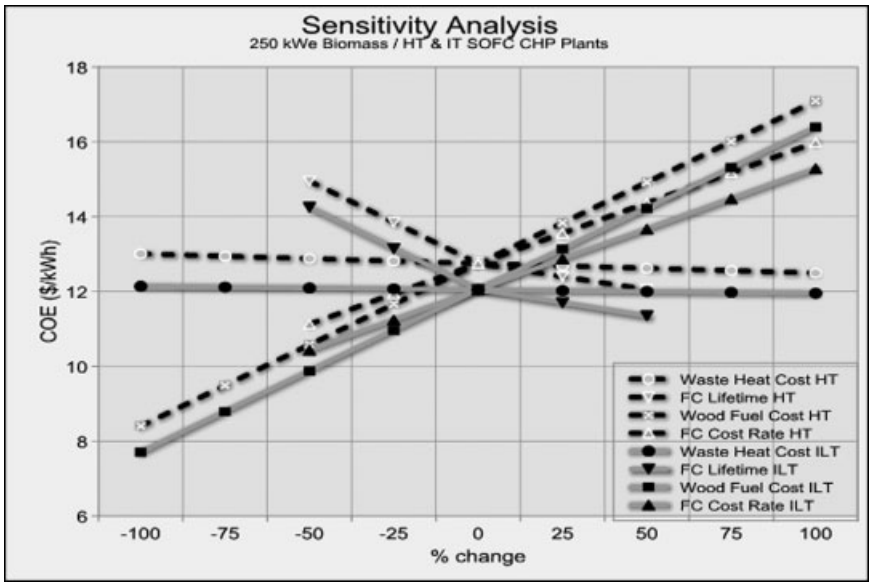

Figure 8. Variation of COE for the 250-kWe system using either the ITSOFC or the HTSOFC with fuel cell lifetime, fuel cell cost rate, waste heat selling price, and fuel cost.

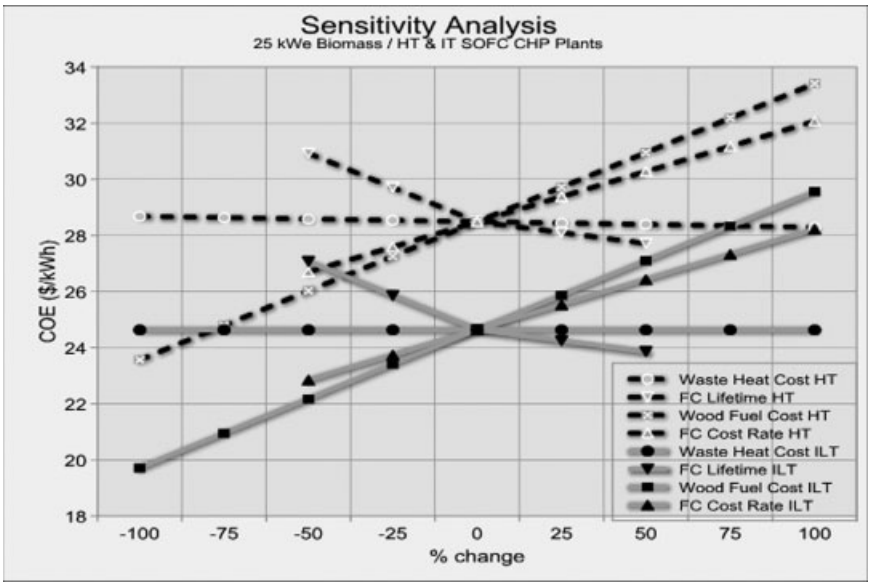

Figure 9. Variation of COE for the 25-kWe system using either the ITSOFC or the HTSOFC with fuel cell lifetime, fuel cell cost rate, waste heat selling price, and fuel cost.

The COE for the base case of the 250-kWe plant is around 120 $\$\,MWh^{-1}$ and around 128 $\$\,MWh^{-1}$ (equivalent to 12.0 US cents kWh^{-1} and 12.8 US cents kWh^{-1}) depending on whether the ITSOFC or HTSOFC is used. This is quite a bit higher than the 64 $\$\,MWh^{-1}$ achieved by 600 MW pulverised coal power plants [23]. However, these small biomass-fuel cell systems are novel and small, so could not be expected to compete with large-scale mature technologies. It can be seen from the sensitivity analysis in Figure 7 that in the best circumstances around 77 and 84 $\$\,MWh^{-1}$ (with the ITSOFC and HTSOFC, respectively) can be achieved by the 250-kWe biomass-SOFC systems.

For the 25-kWe version of this biomass-fuel cell CHP plant, the base case COE was found to be around 245 $\$\,MWh^{-1}$ and around 285 $\$\,MWh^{-1}$ for the ITSOFC and HTSOFC version, respectively, falling to about 197 and 235 $\$\,MWh^{-1}$ in the best circumstances (Figure 9).

The systems proposed in this paper have the potential to generate electricity at high efficiency with low emissions relative to their small scales and compared with other CHP plants at these scales. They would be most suitable where high electricity to heat ratios are required.

Their investment costs are high, at the fuel cell costs and lifetimes proposed here, but these costs are expected to fall in the near future to nearer $\$200\,kWe^{-1}$, in fact the US DOE set up a research programme to achieve $\$400\,kWe^{-1}$ by 2010 [24]. Solid oxide fuel cells, which can operate at even lower temperatures, such as those using nanocomposites [10], would be made from cheaper materials and allow low-cost heat exchangers to be employed. Therefore, if the Balance of Plant costs decrease too, the overall COE from the 250-kWe version could even approach competivity with large-scale fossil-fuel power plants, particularly those with emissions reduction technologies.

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