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Fuel cells for power generation and waste treatment

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Abstract

It is now becoming increasingly clear that the in situ use of biomass and organic waste streams are likely to provide the key to energy self sustainability for islands and remote communities. Traditionally biofuels have been used in combustion engines for electric power generation, however, when replaced by fuel cells there is the prospect of achieving higher generating efficiencies, coupled with, in some instances, the opportunity to produce biofuel at a cheaper rate than conventional fuels. Additionally, important environmental benefits can be achieved by way of mitigating greenhouse gas emissions, whilst providing a carbon sink. This paper presents the design details of such an installation that will provide a practical solution on an island (and be applicable in other remote and rural areas) where connection to the grid can be expensive, and where biofuels can be produced on site at no significant extra cost.

Keywords: Biomass; Biofuels; Organic waste; Fuel cells; Reformers

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1. Introduction

Community interests on the Isle of Mull, an Island off the West Coast of Scotland (Fig. 1) are collaborating with specialists to assess the feasibility and implications of local biogas production with a view to reforming the methane produced to provide hydrogen to power a fuel cell installation. The Mull and Iona Community Trust is a community led partnership and is supported by funding from Shell Better Britain Campaign to promote practical alternatives to landfill disposal of local waste.

A successful outcome will achieve social, environmental and economic benefits for the Island and hence present opportunities for transferable solutions to other West Coast Islands and remote mainland sites.

Mull is Scotland's fourth largest island, sparsely populated by fewer than 3000, but with hundreds of thousands of visitors every year. Seasonal tourism is increasingly central to the islands economy, and the high quality of the natural environment is also vital to local fishing, aquaculture and agriculture interests.

Practical arrangements for diversion and recovery of value from the estimated 3500 tonnes of material annually landfilled are, as yet, poorly developed. Whilst mainland approaches tend not to be readily transferable to remote islands, local solutions may be more readily applicable elsewhere.

Mull's abattoir helps to sustain the livelihoods of local farmers and crofters, but costly overheads, associated with regulatory compliance, may threaten the future viability of operations. With increasingly stringent conditions being applied to the disposal of animal by-products to landfill, early implementation of environmentally benign alternatives are essential. This project also aims to take a holistic view of the cost effective disposal arrangements for other non-municipal organic wastes, including particularly slurry, sewage sludge and aquaculture wastes.

The project will demonstrate that a biogas plant producing methane for applications such as (i) boiler heating, (ii) combustion engine electricity generation, and (iii) methane reforming for use in a fuel cell represents a solution. The methane/hydrogen fuel cell will operate in CHP mode alongside a cheese making facility on the island. The main regulatory drivers and technical details of the scheme are now presented, together with the waste analysis audit on which the project has been designed [1].

2. Impending EU regulations

In the UK, biogas biotechnology for the treatment of organic wastes meets the strategic objectives of both existing and

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Fig. 1. The Island of Mull on the West Coast of Scotland.

impending legislation, mostly emanating from the European Union (EU).

2.1. EU Landfill Directive

The EU Landfill Directive sets out clear targets for the reduction of the disposal to landfill of biodegradable waste. These targets are based on the amount of biodegradable waste landfilled in 1995, and the UK has agreed to the following dates:

- By 2010, the disposal to landfill of biodegradable waste must be no more than 75% of that landfilled in 1995.
- By 2013, the disposal to landfill of biodegradable waste must be no more than 50% of that landfilled in 1995.
- By 2020, the disposal to landfill of biodegradable waste must be no more than 35% of that landfilled in 1995.

These targets are in the background of an annually increasing level of waste of 3%.

There will therefore be, in the UK which has a very high reliance on landfill, increasing pressure for alternative means of disposal which are neither landfill nor incineration. This will inevitably lead to the strong development of the two biological treatment processes—composting and biogas. This will in turn provide an opportunity for the economic assessment and merits of fuel cell CHP technology demonstrated on a small scale [2].

2.2. EU Animal By-Products Regulation

The EU Animal By-Products Regulation became law in Scotland in 2003. This regulation specifies how certain materials may be safely disposed, i.e. with minimum risk to animal health. The regulation defines three categories of materials:

1. *Category 1*: Material is high-risk and must be incinerated; this includes specified risk material from abattoirs and catering waste from international transport.
2. *Category 2*: Material is medium risk and must be incinerated or rendered; this includes fallen stock and animals, which have failed inspections at the abattoir.
3. *Category 3*: Material is low risk and may be transformed in a composting or biogas plant; this includes some products from abattoirs (e.g. blood and soft offal), factory food waste, supermarket food waste, and catering waste from domestic and commercial kitchens.

The regulation specifies exacting parameters for composting and biogas plants, which transform category 3 materials, in particular:

- the process must be in vessel;
- particle size of all material must be reduced to less than 12 mm.
- there must be a pasteurisation stage, with no by-pass, where all material is held at a minimum temperature of 70 °C for a minimum period of 1 h;
- procedures must be adopted to prevent recontamination of the final product with raw material;
- *Salmonella* must be eradicated, and enterobacteriaceae substantially absent.

Member states are able to adopt national standards if the plant is treating only catering waste. However, having carried out research work we are of the view that, in order to guarantee that *Salmonella* and *E. coli* are eradicated, the EU standards should be adopted. Furthermore, should other category 3 wastes be treated, for instance supermarket food waste, then only the EU standards are permitted after December 2005.

The biogas plant will need the approval of the state veterinary service, who will scrutinise the designs, operating procedures and hazard analysis and critical control points (HACCP) prior to construction, and then supervise verification procedures after the commissioning phase. After final approval the biogas plant will be subject to inspections by the local trading standards office.

2.3. Draft EU biowaste directive

The directive is due to be prepared by the end of 2004, and if adopted in its current draft which was prepared in 2001, local authorities will be forced to collect food waste separately in order that it may be safely and beneficially utilised for improving the quality of soil across Europe; this is being depleted of organic material by the widespread use of “artificial” fertilisers. Biogas technology, as well as composting, is able to safely (i.e. with the eradication of pathogenic organisms through pasteurisation) transform biowaste into fertiliser and soil conditioner.

In summary, these three key pieces of legislation, when linked to the strategy to develop a low-carbon economy, present a significant opportunity to biogas and fuel cell technology. Furthermore, there are no significant technological barriers posed by the legislation.

3. Waste audit

The design of the biogas plant and fuel cell installation was based upon the waste audit carried out on the Island [1]. Table 1 lists the sources of waste available and the resulting dry solids (DS) and volatile solids (VS) available on an annual basis.

Table 1
Results of waste audit survey

Source	Tonnes year^{-1}	DS (%)	Tonnes DS year^{-1}	VS (%)	Tonnes VS year^{-1}
Slaughterhouse	62	15.0	9	90.0	8
Aquaculture	350	10.0	35	90.0	32
Agriculture	3000	8.0	240	77.0	185
Retail food	50	22.5	11	92.5	10
Commercial kitchens	300	22.5	68	92.5	62
Household kitchens	300	22.5	68	92.5	62
Sewage sludge	3000	5.0	150	80.0	120
Energy crops	1200	20.0	240	89.0	214
Total	8262	125.5	821	8703.5	693

The potential of sewage sludge as a feedstock was investigated with the local water company, Scottish Water. They are planning two new sewage treatment works—at Tobermory and at Salen, which will result in the production of sewage sludge.

Because of the uncertainties arising from the waste audit, it was considered advisable to include the potential of "wet" energy crops. In Germany farmers are growing maize, fodder beet and ryegrass specifically as a feedstock for their biogas plants. Using figures achieved to date, and verified by research work from Germany, 1 ha will yield 12 tonnes of dry matter per year, producing 7500 m^3 of biogas. The study assumes that 20 ha could be made available for wet energy crops, e.g. ryegrass (Fig. 2).

The use of energy crops has a number of additional benefits for the project:

- The biofertiliser can be used specifically to grow the energy crops.
- As farming economics become more challenging it is inevitable that more land will be taken out of food production.
- If ryegrass is grown as a non-food crop then the landscape, which is so important to the area, will have the appearance of traditional farms.
- It makes a significant further contribution to sustainability.

Fig. 2. Ryegrass grown specifically as an energy crop.

Table 2
Mass balance

Total feedstock delivery (tonnes year^{-1})	8262
Dry solids concentration (%)	9.9
Volatile solids concentration (%)	84.5
Dry solids (tonnes year^{-1})	821
Volatile solids (tonnes year^{-1})	694
Volatile solids destruction (%)	59.8
Volatile solids destroyed (tonnes year^{-1})	415

Table 3
Energy balance

Energy production	
Biogas production (m^3 day^{-1})	1136
Biogas production (m^3 h^{-1})	47
Biogas % methane	60.0
Biogas calorific value (LCV) (MJ m^{-3})	21.4
Biogas fuel value (MJ day^{-1})	24343
Biogas fuel value (MJ h^{-1})	1014
Biogas fuel value (kW) (fuel)	282

A summary of the feedstock proposed for the biogas plant is shown in the process calculations, which follow.

4. Mass and energy balance

Based upon the waste audit survey results of potentially available organic waste streams (Table 1), the resulting mass and energy balance breakdowns are shown in Tables 2 and 3.

5. The biogas plant

The core process of biogas technology is anaerobic digestion, which is a natural biological process by which organic material is stabilised and transformed into valuable biofertiliser and biogas; the composition of biogas is normally about 60% CH_4 and 40% CO_2, with traces of H_2S, which makes it a valuable source of renewable energy.

The footprint of the complete biogas plant is 40 m × 25 m, i.e. 1000 m^2. This area excludes the concrete hard standing in front of the building. The raw waste buffer tank, digester tank, digestate storage tank, gas holder, gas mixing compressor, and air-blast radiator are located outdoors. All other equipment,

Fig. 3. A small recycling kitchen waste biogas plant.

including the primary shredder, reception tank, pasteurisation tank, heat exchangers, pumps, CHP unit, boiler, and control panel are located in a single building which is divided into rooms. The plant will be based on previous designs and experience of operating small-scale systems [3], and such as that shown in Fig. 3.

5.1. Anaerobic digester

The anaerobic digester is the core of the biogas plant. It has a capacity of 470 m^3, which gives an average hydraulic retention time (HRT) of 22 days. The digester is a fully mixed enclosed insulated vessel, which operates at a constant level, known as a “continuous stirred tank reactor” (CSTR). Raw waste is pumped in every 6 h and digestate is pumped out every 6 h. This gives a minimum guaranteed residence time (MGRT) of 6 h. The digester is mixed by the recirculation of biogas through a series of nozzles in the digester base; this has the advantage that there are no moving parts inside the digester. The digester is maintained at a constant mesophilic temperature of 38 °C; this is achieved by circulating the digester contents through an external sludge/water heat exchanger—again there are no parts inside the digester. The mesophilic temperature has been chosen for the process since it is more stable than the thermophilic (57 °C) and since pathogen eradication is achieved by pasteurisation. However, the plant will be designed such that the plant manager can choose any operating temperature between 30 and 60 °C.

Specific details of the biogas production from the plant are presented in Table 4.

Table 4
Anaerobic digestion biogas production

Digester feedstock volume (m^3 day^{-1})	21.8
Digester hydraulic retention time (days)	22
Digester volume (m^3)	470
Digester specific loading rate (kg VS m^{-3} day^{-1})	4.0
Volatile solids reduction (%)	59.8
Volatile solids destroyed (kg VS day^{-1})	1136
Specific biogas production (m^3 kg^{-1} VS destroyed)	1.0
Biogas production (m^3 day^{-1})	1136
Biogas production: digester capacity (m^3 day^{-1} m^{-3})	2.4

Table 5
Value of energy

Gross electricity output (MWh $year^{-1}$)	816
Process electricity consumption (8%) (MWh $year^{-1}$)	66
Surplus electricity production (MWh $year^{-1}$)	751
Unit value of renewable electricity (£ MWh^{-1})	65
Value of electricity (£ $year^{-1}$)	53072
Gross heat output (MWh $year^{-1}$)	1234
Process heat consumption (MWh $year^{-1}$)	610
Surplus heat production (MWh $year^{-1}$)	624
Unit value of renewable gas (pence m^{-3})	14
Value of surplus heat (£ $year^{-1}$)	20496
Total value of surplus energy (£ $year^{-1}$)	73568

5.2. Value of energy

Table 5 itemises the value of the energy produced by the biogas plant.

6. The fuel cell system

The alkaline based FC (AFC) combined heat and power (CHP) unit will be field trialled at Sgriob-Ruadh cheese making facility, Tobermory, Mull [4]. The FC unit will be installed external to the cheese making house at Sgriob-Ruadh farm, and will be capable of supplying a portion of the electricity and heat energy demand of part of the manufacturing process. We consider AFC technology to offer significant advantages over other fuel cell types such as proton exchange membrane (PEM) technology for external use due to the very low freezing point of the potassium hydroxide electrolyte (approximately −50 °C). AFC stack units are available at a lower cost per killowatt of FC stack, and they are forecast to remain the cheapest FC technology due to the lack of expensive platinum catalyst (PEM), or high temperature ceramic materials—as used in solid oxide fuel cells (SOFC). The FC unit will be fuelled directly by hydrogen gas that will be produced by reforming a portion of the biogas output from the plant [5].

The FC unit will be operated in base load mode and coupled to a battery pack for hybrid operation. A hybrid configuration will derive maximum utilisation of an approximately ‘base load’ rated FC and a peak load supplying lead acid battery pack. Additionally it will provide a power blackout ride through capability (as frequently occurs in island situations). Such a hybrid configuration will permit high utilisation of the FC technology at the lowest possible capital cost (recognising the significant capital cost barriers present in the current FC market, and price differential between the expensive FC element and cheap battery fraction).

Thus, the hybrid configuration of a 2.4 kW FC CHP unit will be capable of supplying 12.4 kW of electrical power and approximately 1.5 kW of heat to the cheese process. The unit will be optimally controlled to meet the cyclic electrical demand of part of the cheese making process, and hence will deliver a pro-rata offsetting element of the process thermal load. A system such as this can be the basis for a significant step forward in the commercial realisation of self-sustainability for the island.

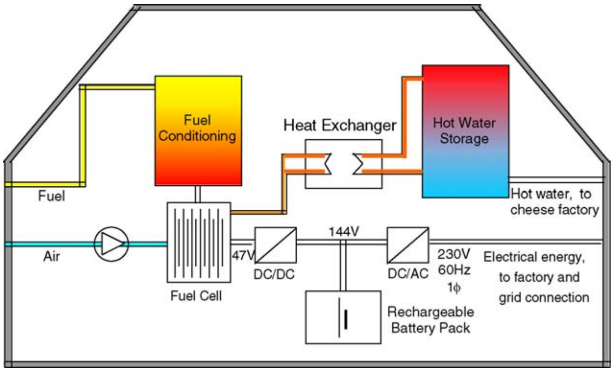

Fig. 4. Schematic arrangement of the AFC CHP unit.

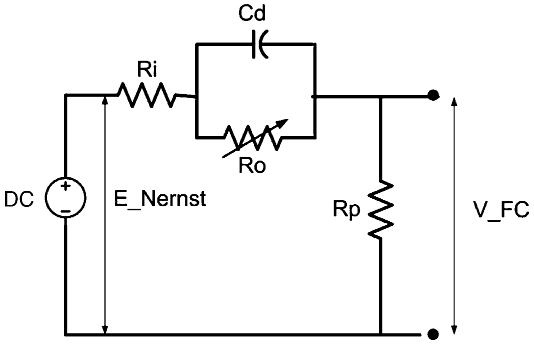

Fig. 5. Fuel cell equivalent circuit model.

The 2.4 kW_e alkaline fuel cell CHP system, complete with lead acid battery energy storage system, is arranged schematically as shown in Fig. 4. Additionally, the fuel cell/battery hybrid unit will operate as a grid connected renewable power generator, via a suitable inverter, with a dedicated load controller to off-set electricity demand. The thermal energy produced by this unit will be used to augment the cheese process existing heating system. This will be accomplished by use of both liquid–liquid and liquid–air heat exchangers allowing the recoverable portion of the fuel cell thermal energy (approximately 40%) to be delivered to the process heating system. This in turn will offset a proportion of the cheese house fuel demand that would otherwise be required to meet the entire heat load. The FC unit will be fuelled using compressed hydrogen gas, produced by reforming a portion of the output from the biogas plant. A dedicated compressed gas hydrogen storage tank will be installed. All relevant parameters will be monitored and recorded.

The battery energy storage system will comprise a lead acid battery pack of suitable capacity (12 off, 12 VDC, 70 Ah gel filled lead acid batteries) to meet the peak electrical load demands of the cheese house, whilst being able to be recharged by the parallel fuel cell unit. A dedicated battery management system, incorporating an instantaneous state of charge monitor, is an integral function within the FC control unit. In essence, the fuel cell unit will operate to provide ‘base load’ electrical power and to recharge the battery pack when the electrical load demand is <2.4 kW_e.

6.1. Key considerations

An alkaline FC unit has been chosen for two principal reasons:

(1) The alkaline FC system can be installed outdoors as a 30% (w/w) solution of liquid potassium hydroxide electrolyte will not freeze until below −50 °C. By installing these units outside, a minimum of disruptive work is undertaken. There are currently more than 100,000 installations in the UK that utilise Calor Gas rather than mains gas for heating needs. A hydrogen fuelled FC CHP unit could be employed at such locations as a much cleaner power source than either mains gas or LPG reformer fed units, however market issues concerning the current cost for a small capacity hydrogen supply is a challenge still to be addressed. A scheme such as the one proposed here based upon a biogas input is seen as a way forward. Additionally, as a consequence of the temperature characteristics of an alkaline electrolyte, the system offers significant external operational advantages over a PEM system.

(2) Alkaline technology offers a cheaper fuel cell stack price due to the absence of reliance on use of platinum as a catalyst, e.g. £2500 kW^{-1} compared to £3000 kW^{-1} for PEM.

It is fully recognised however that a high temperature fuel cell (molten carbonate or SOFC) could also provide a good technical solution due to their internal reforming capability, and thermal compatibility with the output temperature of the biogas. Such a system has been ruled out here on the basis of cost.

Never the less, there is a cost penalty for the low temperature AFC’s due to the need to reform and clean the hydrogen gas before entering the FC unit. Hence, a higher cost/kW has to be applied to the smaller unit. The composition of the biogas produced will vary depending upon the feedstock used and impurities in the gas must be removed. Typically, the gas composition will consist of 55–70% CH_4, 30–40% CO_2, 1–10% N_2, and 0–1% H_2.

6.2. Electrical characterization model of the fuel cell

The alkaline fuel cell stack has been modelled using electric circuit theory. The fuel cell equivalent circuit is shown in Fig. 5. Here, the Nernst voltage is represented by a controlled voltage source and is a function of the partial pressure of the reaction species. The internal resistance R_i of the fuel cell symbolize the ohmic resistance of both electrodes and the electric resistance due to the liquid electrolyte. Parasitic losses reduce the actual cell potential and are represented in the model by a parallel resistor R_p. The dynamic behaviour of the stack is governed by the dynamic processes listed below:

- electrode kinetics;
- the mass transport of reactants and products within the fuel cell;
- double layer capacity of the fuel cell.

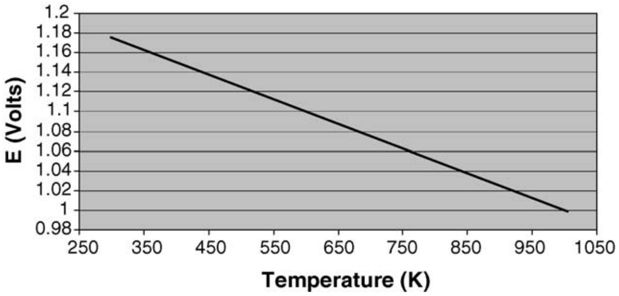

Fig. 6. Ideal standard potential vs. temperature.

These effects are expressed using a parallel RC branch. The effects of these factors on the dynamic response of the fuel cell are interactive and will depend on the current load applied to the cell, and the rate of load change. The double layer capacitance C_d, is a constant value and depends on the physical design of the electrodes. The electrode kinetics and mass transport effects have been represented by a variable resistor R_o in the model.

All model parameters have been determined through experimental tests in the laboratory. The model allows a relative simple and accurate description of the dynamic fuel cell behaviour.

6.3. Some basic considerations

The open circuit potential of the cell is an approximate linear function of temperature, as shown in Fig. 6.

6.3.1. AFC electrical losses

The theoretical EMF, which is achievable by a fuel cell, as determined by the Nernst Equation, is not achievable in reality. There are several sources of irreversible losses, which contribute to this, and they are commonly categorised as (i) activation losses, (ii) ohmic losses, and (iii) concentration losses. The ohmic losses are present at all current levels and are linear unlike the other two, which are logarithmic. Furthermore, the reaction rate losses are only present at low current densities while the gas transport loss is present at high current densities. These losses are illustrated in Fig. 7.

The losses, referred to as overpotential h, are defined as the deviation of the theoretical potential E_{th}; the cell potential E:

$$\eta = E_{OCV} - E_{FC} \tag{1}$$

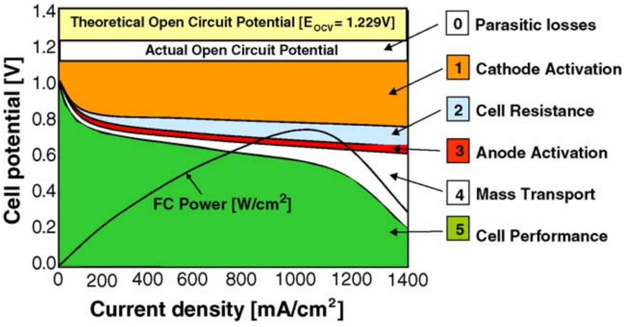

Fig. 7. Ideal and actual fuel cell voltage–current characteristics for a single cell.

where

$$\eta = \eta_A + \eta_{iR} + \eta_C \tag{2}$$

The equation for the fuel cell therefore be written as:

$$E_{FC} = E_{OCV} - \eta_A - \eta_{iR} - \eta_C \tag{3}$$

where E_{FC} is the fuel cell potential (V); E_{VOC} the theoretical fuel cell potential (V); h_A is activation losses (V); h_{iR} is ohmic losses (V); h_C is the concentration losses (V).

This graphically illustrates the fact that the performance of a FC is mainly driven by the oxygen reduction limitations on the cathode. For a single cell the fuel cell potential can be expressed as:

$$E_{FC} = E_{cat} - E_{ano} - \eta_{iR,elec} \tag{4}$$

where E_{cat} is the cathode potential (V); E_{ano} the anode potential (V) and $h_{iR,elec}$ is the ohmic losses within the electrolyte (V), where

$$E_{ano} = E_{VOC,ano} - \eta_{A,ano} - \eta_{iR,ano} - \eta_{C,ano} \tag{5}$$

and

$$E_{cat} = E_{VOC,cat} - \eta_{A,cat} - \eta_{iR,cat} - \eta_{C,cat} \tag{6}$$

The inherent electric resistance within the fuel cell causes ohmic losses, which arise from the ionic resistance of the electrolyte and electron resistance in the electrodes, and in the current collector and terminal connections.

Activation losses dominate at low current densities, caused by the kinetics of the charge transfer reaction across the electrode–electrolyte interface. Concentration losses within the fuel cell reaction takes place on the surface of the electrodes and within the catalyst layer. These are accounted for in terms of:

- diffusion of reactants to the electrode;
- absorption of reactants on the electrode;
- transfer of electrons to or from the absorbed reactant species;
- desorption of products from the electrode;
- diffusion of products away from the electrode.

At high current densities, mass transport limitations of reactants and products occur, principally due to the geometric design of the electrodes. This makes it difficult at high current densities, to provide enough reactants to the electrode surface, which in turn limits the reaction rate.

7. Summary

The biogas plant and fuel cell system proposed is viewed as the key solution to promote a practical alternative to landfill disposal of local organic waste. It is anticipated that the successful outcome will achieve social, environmental and economic benefits for the Island.

It is recognised however that a biogas reformer/direct hydrogen fuelled low temperature FC CHP unit leads to expensive capital costs compared to other units. However, this trial will assist the partners to investigate the true costs of supplying reformed biogas hydrogen as a fuel (and not a chemical feedstock).

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