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"Hydrogen, Fuel Cells and the Optimisation of the LIMPET 500 on Islay"

Thesis in partial fulfilment of the degree of Master of Science in Energy Systems and the Environment

By

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Abstract

Scotland has one of the largest wave energy resources in the world. This resource is found off the west coast, far away from the central belt and the main demand centres. The technology to exploit this resource has been realised with the installation of the first grid connected wave energy device in Scotland; The LIMPET 500 on the island of Islay. Although rated at 500kW, this device is restricted by the weak local grid on Islay to supplying a maximum of 150kW.

Weak grid connections are a common problem for renewable energy and a solution needs to be found. Many renewables are intermittent by nature, such as wind and wave, and an adequate storage facility could be crucial to them realising their full potential.

This thesis examines the feasibility of the use of hydrogen and fuel cells to optimise the LIMPET 500 on Islay. A system which is all encompassing from incoming waves through to the matching of supply and demand will be studied. This will illustrate the true potential at present of this emission free, renewable storage and generation system.

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1. Methodology

To complete this study the performance of many different parts of an entire system were investigated. The results of this investigation facilitated the analysis of the system, in terms of efficiency and also to illustrate the real potential.

The reason this study was undertaken was the recognition of restrictive electricity grid problems for the wave energy device, The LIMPET 500, on Islay. Solving this problem can be done in two ways; either the grid must be strengthened, or some kind of storage medium for excess electricity must be employed. To strengthen the grid on Islay would be a costly procedure and would not address the problem from a larger perspective. The problem of weak electrical grids is common for sources of renewable energy and large investment would be necessary to strengthen all grid areas where renewable energy is plentiful. The other alternative, storage, is a solution to this problem. Not only to problems of grid restrictions but also to ensure a more balanced output from what is in many cases an inherently intermittent supply. Hydrogen has long been recognised as a green medium for energy storage, and when generated from the electrolysis of water using renewably generated electricity it is emission free. This Hydrogen can then be used to create electricity when required in a Fuel Cell. This device also is emission free and the entire system is environmentally friendly. This is a developing technology and other storage and generation methods could be the more attractive option based on economic criteria. The purpose of this study is to analyse the feasibility of Hydrogen as storage medium for the electricity and for Fuel Cells as a conversion device. The efficiency of the entire process will be found and the real potential realised by the matching of supply and demand for electrical and thermal loads.

First of all the components that would make up the entire system had to be recognised. This involved a literature review of Wave Energy, Electrolysis and Fuel Cells. By performing this review it was clear what system components would be needed. Then each part of the system had to be individually focused on to determine the necessary elements that make it up, and how the overall performance can either be calculated or predicted.

The system begins with wave energy being the primary source. Statistics for waves at the site on Islay were not available to the author. But average monthly figures were available for a site on Orkney; this data was used to predict the output from the LIMPET 500 on Islay, using wave theory and the characteristics of the device on Islay.

Electrolysis to produce hydrogen was investigated in the literature review, the results of which were used to calculate how much hydrogen was capable of being produced each month. Hydrogen storage was also investigated; compressed gas storage is the easiest and traditional method of storage and was chosen despite new methods emerging which could potentially be the future of storage.

The performance of the fuel cell is fundamental to the success of the system. To enable comparisons, one low temperature fuel cell (Proton Exchange Membrane Fuel Cell), and one high temperature fuel cell (Solid Oxide Fuel Cell) were studied. This comparison would also consider the potential for cogeneration. The state of the art of each was found as the result of the literature review. Using these results and equations governing the characteristics of fuel cells, the performance of each was found.

Fuel cells are not the only potential use for hydrogen to generate electricity, internal combustion engines can be modified to utilise hydrogen as a fuel. Also as far as the storage of electricity goes, Lead Acid Batteries and flywheels are proven technologies. But these have to be assessed by looking at the environmental, social and economic effects of each. A short comparison between these technologies and hydrogen fuel cells is carried out.

The demand profile of a typical residential building consists of thermal and electrical loads. The electrical loads used in this analysis were taken from the computer software MERIT. The energy requirements for space heating were found using degree days data for the west coast of Scotland. Therefore the true potential can be realised by calculating the electrical and thermal demands that can be met using the technology.

2. Introduction

Energy has been brought to the top of the global agenda as efforts are made to balance escalating demands with reduction in use and environmentally friendly forms of generation. Any system that results in the production of electricity needs to be assessed in its entirety to pinpoint any environmental, social or economic implications. As part of the global effort to combat climate change, many countries have signed up to meet international emissions targets such as those outlined in the Kyoto agreement. Renewable energy has the potential to play an important role in this fight. In Scotland the Renewables Obligation (ROS) is in place to ensure that renewable energy supplies a certain amount of our electricity by 2020. The Environment Minister Ross Finnie raised this target in August 2002 from 30% to 40%. Scotland has a large renewable resource, being one of the windiest countries in the world, providing opportunity for wind and wave power. It also has the type of terrain suitable for hydropower, which has been optimised and now accounts for 10% of Scottish generation, and is therefore not included in the ROS. The location and nature of these renewable resources present various hurdles for their successful exploitation.

One of the main problems with renewable energy is that the supply is often intermittent and unpredictable. Also most forms of renewable energy available in Scotland are found in areas where the national grid is too weak to support them. These problems need to be solved for renewable energy to fulfil its potential and become an important part of a diverse energy-generating sector. Some form of medium for electricity storage is necessary and many things have been considered in the past, for example batteries, but one of the most promising forms of storage for the future involves the generation of hydrogen using electrolysis, which is then used to generate electricity in a fuel cell with the only output being water. The DTI has identified that this is particularly relevant for wave power as the major resource is off the west coast away from the major centres of demand. The cost of wave energy is the major uncertainty and is halting such schemes at present. This pollution free form of energy production could become very important in a world where environmental considerations are at the forefront of the energy sector. But the technology is yet to fulfil its full potential and like so many other renewable energies is still the subject of research and development to lower costs and improve efficiencies.

The island of Islay off the west coast of Scotland is the home to the first wave energy-generating project in Scotland and feeds directly into the national grid. The LIMPET 500, which stands for Land Installed Marine Powered Energy Transformer, is operated by the Inverness based company

Wavegen[1] and operates as an oscillating water column which forces air to flow in two directions through a turbine developed in conjunction with Queens University Belfast. Although the turbine is rated at 500kW, the local grid can only support 150kW of this electricity and strengthening the grid is an expensive process. This means that this excess electricity is going to waste. The purpose of this investigation is to do an efficiency analysis of using this excess electricity to create hydrogen, using electrolysis, for use in fuel cells for electricity generation on Islay. The different options available will be investigated and the results will be used to assess the entire system as a whole in each case to reach conclusions about its feasibility and true potential.

[1] www.wavegen.co.uk

3. Background

3.1 LIMPET 500 and Islay

The Island of Islay, situated off the west coast of Scotland is famous for many reasons. It has eight remaining whisky distilleries that are popular worldwide, and is also renowned for its fabulous scenery, history and wildlife. The local population, which is around 3,500, are used to hearing about energy issues. They have experienced brown outs and black outs due to the huge strain the many distilleries on the island put on the grid, resulting in the distilleries having to adhere to a schedule to stop the problem. The indigenous whisky industry is heavily dependent on imported petroleum products, this could be reduced if an alternative heat and power source was found. With the introduction of the wave energy device in 2000, and talk of wind farms, the public have been made aware of the potentials that renewable energy has on Islay. The island energy demand is around 227 GWh/year, 192 GWh of this demand is met by electricity from the national grid[2].

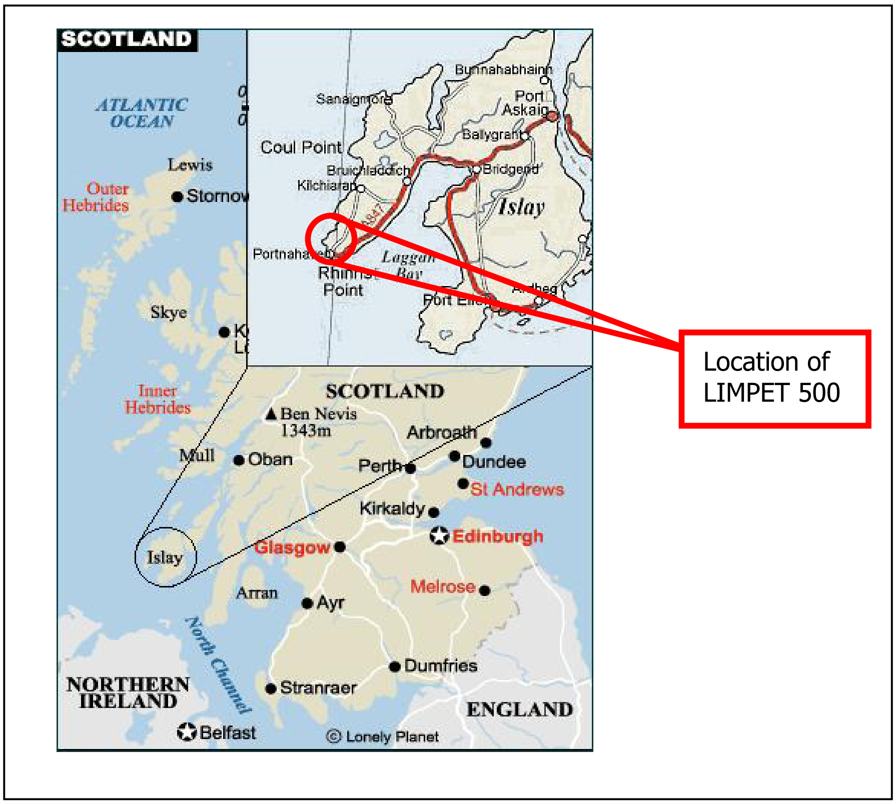

Figure 1: Map of Scotland showing Islay and location of LIMPET 500

Sourced: www.calmac.co.uk (Islay Map) and www.lonelyplanet.com (Scotland Map)

[2] www.seef.org.uk

The LIMPET 500 is the result of a 10-year research project on the Island and was deployed in November 2000. In Scotland, the Government awarded three wave energy projects under the Scottish Renewables Obligation (SRO); the LIMPET is the only device to have been installed and feeding power into the grid. The concept of the oscillating water column is that a column of air is alternatively compressed and decompressed by the movement of the waves, on Islay this is done using a wave capture chamber which is set into the rock face on the shoreline.

Figure 2: Wells turbine

Sourced: www.wavegen.co.uk

The rushes of air drive a Wells turbine developed by Professor Wells of Queens University, Belfast. The device is designed so that it has unidirectional rotational motion, turning in the same direction regardless of the direction of the airflow. The company operating the device, Wavegen, have said that at present for this technology the answer lies in focusing on meeting small local or regional demands, and not in huge operating plants. They have also said that connection to the grid is very tough on Islay, with tight limits on voltage and frequency. To meet the demands they have a short-term control algorithm, a flywheel and smoothing circuits. They view this as a problem for wave energy in general as huge investment is required to be connected.

Fuel Cells and hydrogen could play an important part in the full utilisation of the energy that can be created on a small scale by renewable technologies such as wave energy by solving the problems of weak grids and complicated control systems. But these systems need to be assessed in their entirety. Through hydrolysis the hydrogen acts as a method of energy storage that can be dictated by the electricity available from the wave turbine. The following diagram illustrates how the device works.

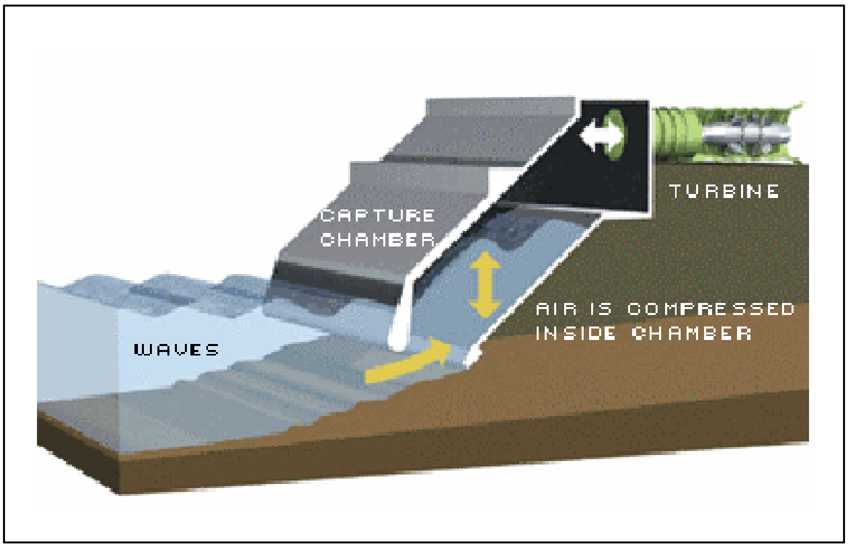

Figure 3: How the LIMPET 500 operates

Sourced www.popsci.com

The original 70kW device that was the first device to be tested on Islay can be seen in the following figure. It was installed a little further down the coast towards the village of Portnahaven. The lessons learned from this device were instrumental to the success of the LIMPET 500.

Figure 4: 70kW device installed on Islay

Sourced: www.uccee.org/RETSouthAfrica/WaveTechsEU.pdf

3.1.1 Wave Energy: The Resource

> " *It has been estimated that if less then 0.1% of the renewable energy available within the oceans could be converted into electricity, it would satisfy the present world demand for energy more then five times over."*
>
> Marine Foresight Panel

Wave energy can be considered as a concentrated form of solar energy, being the result of winds caused by the differential heating of the planet. The OWC device is one of many technologies to capture wave energy but is the only one to have been fully realised and generate electricity for the national grid. The location of this device is obviously dependent on the wave conditions in that area. This is a very site-specific characteristic and studies into the local conditions need to be undertaken. There are some computer models available that take offshore wave data and by using local information calculate the wave characteristics on shore.

When choosing a site for any device it is also very important to consider the environmental effects of the plant, not only during its lifetime but also during construction and decommissioning as shorelines can be of historic, scientific, ecological or visual importance. The predicted resource also comes with some element of uncertainty, with all things considered; the estimated UK shoreline resource is ≈ 2 TWh/year[3].

Linear wave theory assumes that the motion of the water past a point is sinusoidal. The period (T) for one wave to pass this point can be expressed by:

$$T = \sqrt{\frac{2.\pi.\lambda}{g}} \tag{1}$$

Where, λ = wavelength (m)
g = gravity = 9.81

The power contained in the wave can be expressed in terms of the length of the wave (kW/m). This is given by the following equation:

$$P = \frac{\rho.g^2.a^2.T}{8\pi} \tag{2}$$

Where, a = Wave amplitude (m)

3.2 Hydrogen

Hydrogen is the most abundant element in the universe and due to its volatile nature must be handled and transported with care, at present the global production of hydrogen stands at around 500 billion Nm^3 [4]. It can be stored as a gas at high pressure, or as a liquid at very low (cryogenic) temperatures. It has the highest energy content per unit of weight of any known fuel[5]. The public perception of hydrogen has not been good since the Hindenburg Accident and has hampered the public acceptance of research and development[6]. It has since been discovered that hydrogen played no part in that disaster and a new generation are ready to accept its suitability for many different uses. Town gas which was widely distributed in the first half of the

[3] "A Brief Review of Wave Energy", T. W. Thorpe, May 1999
[4] "Technology Status Report Hydrogen", DTI, September 2001
[5] Consumer Energy Info: EREC Reference Briefs, USDOE
[6] Alternative Energy Institute

20th century was 50% hydrogen. This was later replaced by cheaper natural gas. In end use, it is the "cleanest" of fuels[7]. Combustion of hydrogen produces only very small NO_x emissions, therefore making it much cleaner when compared to conventional fossil fuels.

> *"Hydrogen is now thought by many to be the fuel of the future. A sustainable future, based on hydrogen, relies on efficient and cost-effective methods of producing, storing, distributing and using hydrogen, with the primary source itself also needing to be sustainable."*
>
> DTI Technology Status Report Hydrogen

Hydrogen is an important industrial fuel and is used as a rocket fuel and in spacecraft propulsion, in fact when burned it produces less pollutants than fossil fuels. We know that hydrogen is in plentiful supply on Earth but acquiring the hydrogen poses a challenge on its own. Hydrogen on its own can be used as a fuel but when it is produced in conjunction with renewable energy it becomes a renewable fuel.

There are many methods of acquiring hydrogen that are in use today. It can be produced directly from sunlight and water by using biological organisms and semi-conductor based systems. It can also be produced indirectly from the thermal processing of biomass or fossil fuels. A common industrial method of producing hydrogen is through steam reforming, or as an outcome of petroleum refining and chemicals manufacturing. Within such processes, the production of hydrogen has, with time, been proven to be reliable and cost effective.

There are therefore obvious environmental advantages of using hydrogen as a fuel and for fuel cells, but the entire life cycle needs to be assessed to ensure that its production, transportation and end-use are efficient and environmentally friendly. When manufactured, using renewable energy, hydrogen combustion is a completely emission free process. If hydrogen is produced away from the point of use then the environmental implications of transporting it have to be considered in an analysis of the entire cycle. In the case of Islay, any transportation would need to be considered but would not be of considerable distance due to the geometry of the island. Any effects that storage could have would also have to be considered.

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[7] "Technology Status Report Hydrogen", DTI, 2001

According to the DTI[8], hydrogen offers prospects for, among other things:

- Assisting the development of renewable energy sources by providing an effective means of storage, distribution and conversion.
- Matching the timing of energy demand with availability of intermittent renewable energy sources such as wind and solar.
- Entirely zero emissions when derived from renewable energy sources.
- No fuel related ill effects.
- Broadening the role of renewable energy in the supply of clean fuels for transportation and heating.
- Effective energy systems where a conventional energy infrastructure either does not already or could not otherwise exist.

3.3 Electrolysis

Hydrolysis is the electrolysis of water, using electricity to split water into hydrogen and oxygen. Adding an electrolyte such as salt improves the conductivity of the water and therefore increases the efficiency of the entire process. The electrical charge is passed through the water breaking the chemical bond between the hydrogen and oxygen and splits the atomic components, in doing so creating charged particles called ions. The ions form at two poles or electrodes; a positively charged anode and a negatively charged cathode. The hydrogen is attracted to the cathode and the oxygen to the anode.

The overall chemical reaction is as follows: $\mathbf{H_2O \rightarrow H_2 + ½O_2}$

Electrolysis is done conventionally with an aqueous alkaline electrolyte. The two electrodes, the cathode and anode, are separated by a micro porous diaphragm. This prevents the mixing of hydrogen and oxygen, which are the two product gases. This diaphragm is normally made from asbestos but now new materials are being developed for this purpose, these have output pressures of 0.2-0.5Mpa. Efficiencies of 65% have been attained with these processes, relating to the lower heating value of hydrogen. New diaphragms and membranes are under development to be reliable when under fluctuating operating conditions, making their use with renewable energy technologies, such as wind energy which is intermittent, much more efficient.

[8] "Technology Status Report Hydrogen", DTI, 2001

Two developments that are expected to improve the efficiencies of hydrolysis are *High Temperature Electrolysis*, and *High Pressure Electrolysis*. High Temperature electrolysis is known as steam electrolysis, it works by adding energy to split the water as heat instead of electricity so as to reduce the electricity required, therefore improving the efficiency. High Pressure electrolysis works to find an appropriate capacity optimisation that will allow problem free connection of the electrolyser with a fluctuating supply, so as to solve intermittency problems.

A voltage of 1.24V is necessary to separate the two in pure water at 77°F/25°C and a pressure of 1.03kg/cm^2 [9]. The smallest amount of electricity required to electrolyse one mole of water is 65.3 Wh at 77°F/25°C[10]. At 20°C, an electrolyser will use 3kWh/m^3 of hydrogen produced if operating at 100% efficiency. Electrolysis devices are already in use, Munich airport has a 450kW system operating at an efficiency of around 60-65%. Electrolysis technology is still the subject of much research and development, which is expected to improve performance and system efficiencies in the future. The following diagrams show how hydrogen can be produced using hydrolysis in a laboratory environment.

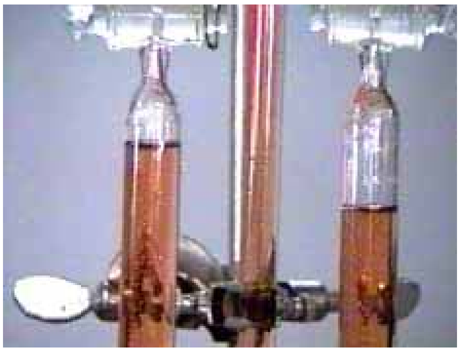

Figure 5: Resulting Gas collection, H_2 on right

Figure 6: Gases being produced at electrodes

Figure five shows the gas being captured at the top of the tubes. This view shows us that twice as much hydrogen as oxygen is produced during the process.

Figure six shows the gases being produced as the electric current is passed through the water. The water has been coloured to make it easier to view.

Pictures sourced from:

www.chem.uiuc.edu/demos/elec.html

[9] USDOE Consumer Energy Info: EREC Reference Briefs
[10] USDOE Consumer Energy Info: EREC Reference Briefs

There are some parameters which influence the performance of electrolysis. High current density can harm the membrane; adequate conditioning of the power being utilised will offset any potential problems this could cause. The voltage required to electrolyse water can be greater than the theoretical value due to various losses. This problem is solved by ensuring that the power is set with a voltage adequate to electrolyse the water. The temperature and pressure of the membrane must be carefully monitored so as to not dehydrate the membrane which leads to a reduction in conductivity and therefore efficiency. In the long term this can be damaging to the cell and cause lasting effects such as de-fluoridisation. Renewable energy produced hydrogen through electrolysis is an emission free, environmentally friendly operation but is not as efficient or as cost effective, at present, as alternative methods available such as steam reforming.

3.4 Fuel Cells

A fuel cell is an electrochemical device similar in principle to a battery, except that the fuel and oxidant are stored externally. There are several different types of fuel cells that vary according to the type of electrolyte that is used. Different fuel cells are promising for varying purposes; some for power generation plants, some for small portable applications and some for powering cars. This final option has been the subject of much work and all the major vehicle manufacturers have fuel cell programs underway. The technical challenges for the applications of fuel cells for transport are more severe than for stationary generation. They have to deal with start-up behaviour and a rapidly varying load, which is a characteristic of the vehicle. There are also issues to do with weight and volume constraints and resistance to mechanical shocks during driving. Fuel Cells are inert; they have no moving parts except for those that are a necessary part of any power producing system such as pumps, blowers and transformers. They generate very little if any noise, making them more acceptable in an urban environment.

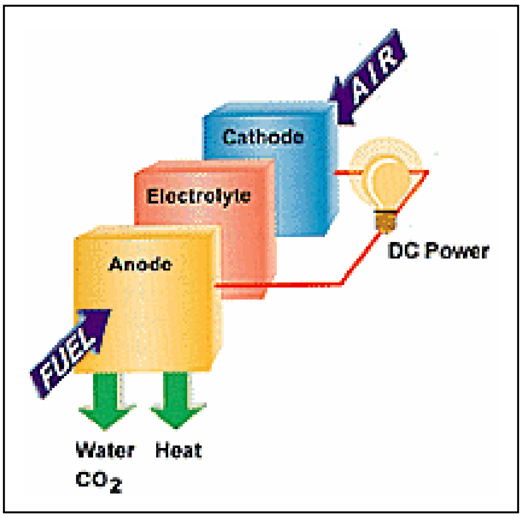

Figure 7: How fuel cells work
Sourced: www.fossil.energy.gov

A Fuel cell encompasses two electrodes - an anode and a cathode. Hydrogen is introduced to the anode causing a chemical reaction. This reaction releases hydrogen ions and electrons the transport of which is fundamentally crucial to energy production. The ions build up on the anode creating a positive potential, whilst the cathode has a negative potential and therefore attracts the ions through the electrolyte. How the ions migrate through the electrolyte depends on the many things such as the thickness of the membrane and the number of ions transported. The acid in the electrolyte is a barrier to the migration of electrons through the electrolyte and also provides it with some structure. Materials that are conductive are those in which the electrons are held loosely, but the acid chains hold their electrons tightly and effectively act as an electric insulator.

The processes and variations involved within a cell are illustrated in the following diagram.

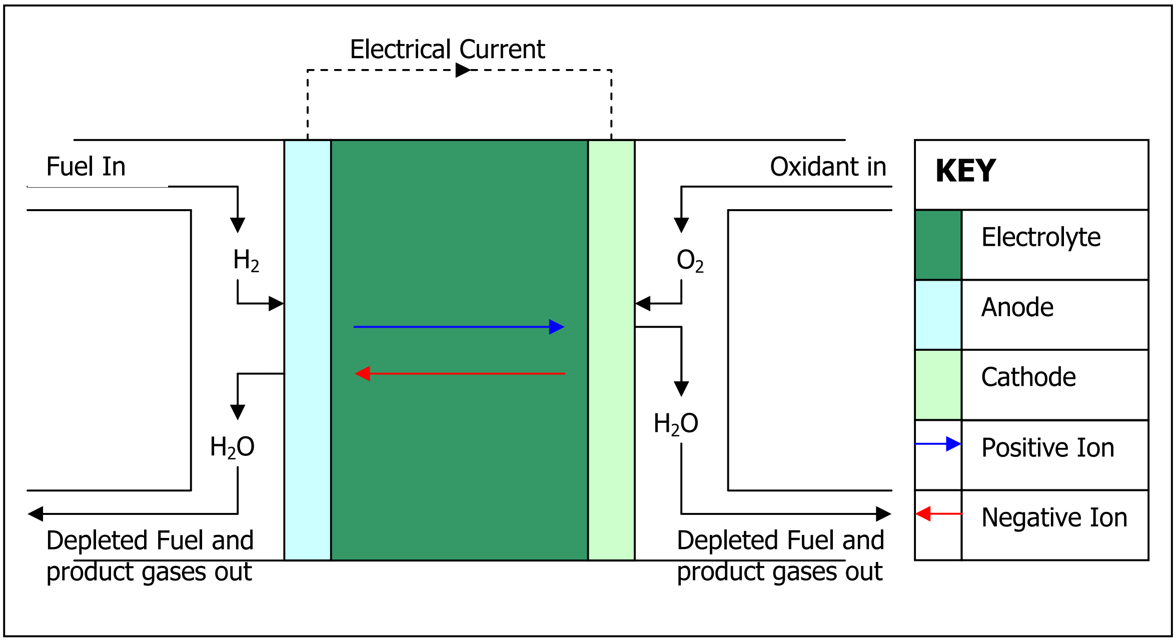

Figure 8: Fuel Cell Schematic Diagram

Fuel cells are now in place all over the world and are powering buses, cars, boats and scooters to name a few. Miniature devices for laptop computers, mobile phones and portable electronic devices are on their way to market. Practical cells typically generate a voltage of around 0.7-0.8V and power outputs of a few tens or hundreds of watts. To generate more power the cells are assembled in modules known as stacks, connected electrically in both series and parallel to provide a larger output. This can be seen in figure 9. Fuel cells generate DC power; therefore an Inverter is a necessary part of any system to change to AC power for use in our homes and industry.

The general chemical reactions that occur within a fuel cell that utilises hydrogen and oxygen are as follows:

At the Anode: $\mathbf{2H_2 \rightarrow 4H^+ + 4e^-}$

At the Cathode: $\mathbf{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O}$

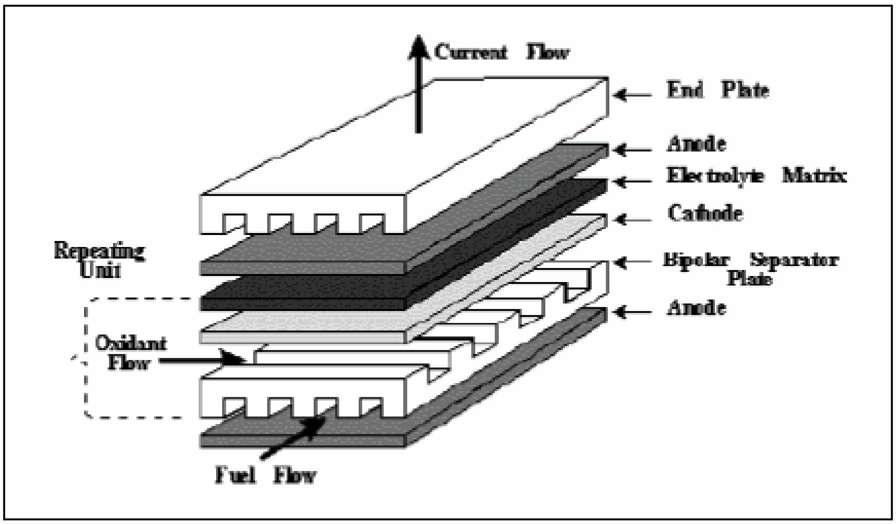

Figure 9: Components of a fuel cell stack[11]

Hydrogen is not always available and needs to be attained from a source to be used in a fuel cell. Hydrogen rich gases can be used but in most cases these have to be externally reformed in what is known as a Fuel Processor or Reformer. In those cells that operate at very high temperatures it is possible to reform the gas at the anode, depending on the chemistry of the cell and gas, and utilise the hydrogen.

Some fuel cells have the potential for combined heat and power (CHP); this is where heat and electricity are utilised from the cell, also known as cogeneration. This obviously has a positive effect on the efficiency of the cell. This holds potential for stationary generation and industrial applications of fuel cells. The performance of the cell can be controlled in order to fulfil either heat or power requirements. CHP systems are in use today from many different sources such as gas turbines or nuclear power plants. An example of a how a CHP system works is the Time Capsule swimming complex outside Glasgow. This employs a gas turbine running off mains gas. The turbine is run to satisfy the heating requirements of the complex, while any power generated is used to fulfil the electrical requirements, with any excess power needed being taken directly from the national grid. In the case of fuel cells, when reforming of the fuel is required this is a potential source of heat and is usually the basis of a CHP system, as shown in the following diagram.

[11] "Fuel Cells for Distributed Generation", Energy Centre of Wisconsin, 2000

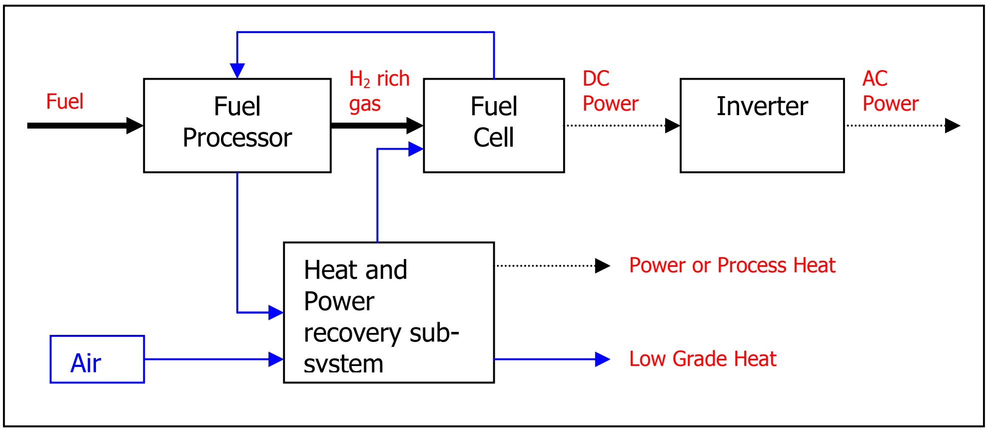

Figure 10: Components of a fuel cell cogeneration system with external reformer

If a cell has a high enough operating temperature then it has potential for cogeneration despite whether reforming takes place or not. This would be done with heat recovery directly from the fuel cell, as shown in the following diagram.

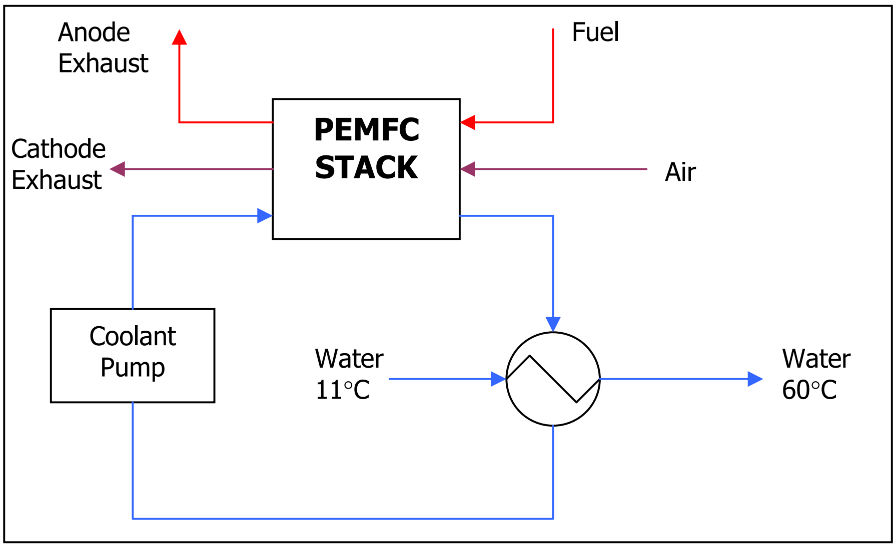

Figure 11: Example of a hot water cogeneration system

Electricity companies who are faced with the problem of upgrading the grid and improving transmission and distribution could potentially place fuel cell generators on their customer's property as a financially viable alternative. The electrical efficiency of a fuel cell depends on the type and also on the configuration of the system, normally ranging in the 36-60% region but with heat recovery can be in the region of 85%[12]. Fuel cells have many advantages over other forms

[12] "Fuel Cells for Distributed Generation", Energy Centre of Wisconsin, 2000

of generation; they are quiet and reliable, predictable, very flexible in terms of siting, and when hydrogen is produced from a renewable source are a completely emission free form of energy generation. Also, when used in conjunction with renewable energy and electrolysis, it is possible to use a regenerative fuel cell which utilises the water produced in the fuel cell for electrolysis, as shown in the following diagram.

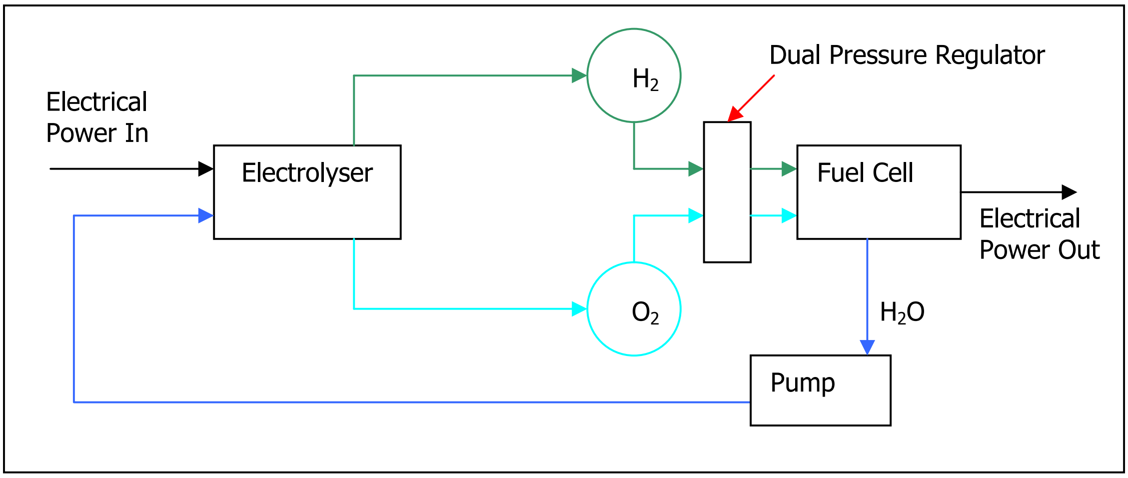

Figure 12: Regenerative fuel cell system

A development of the fuel cell technology is the reversible fuel cell. This is where the device is basically a combination of the electricity producing fuel cell and the hydrogen and oxygen producing electrolyse. The one unit can perform each of these functions at separate times on demand. At one time it can produce electricity at periods of high demand, and alternately can produce fuels during periods of low demand when it can receive power from the national grid. This device is in development at present but in the future could be seen to act like a rechargeable battery.

3.4.1 Fuel Cell Performance

The theoretical ideal performance of a fuel cell depends on the electrochemical reactions that occur with hydrogen and oxygen. The ideal performance is defined using the Nernst Equation, this equation provides a relationship between the ideal electrical potential, E^o, at standard conditions (Atmospheric pressure and 25°C), and the ideal equilibrium potential, E, at other temperatures and partial pressures of reactants and products. Once the ideal potential for standard conditions is known, the ideal voltage can be determined at other temperatures and pressures using the equation.

For a fuel cell operating using hydrogen and oxygen the Nernst equation will be as follows:

$$E = E^0 + \left(\frac{RT}{2F}\right)\ln\left[\frac{P_{H_2}}{P_{H_2O}}\right] + \left(\frac{RT}{2F}\right)\ln\left[P_{O_2}^{\frac{1}{2}}\right] \qquad (3)$$

Where, E = Equilibrium potential

R = Universal gas Constant

P = Gas Pressure

T = Temperature

The ideal potential of a fuel cell operating on pure hydrogen and oxygen is as follows:

$$E^0 = 1.229V(liquid)$$ [13]

$$E^0 = 1.18V(gas)$$

This ideal voltage which a fuel cell produces is affected by three inefficiencies:

1. Activation Polarisation
2. Ohmic Polarisation
3. Concentration Polarisation

Activation polarisation occurs due to the energy intensive activity of the making and breaking of chemical bonds at both electrodes. At the anode the ions form bonds with the surface, the electrons remain near the ions until another molecule reacts with the catalyst, which breaks their bond with the ion. Whether this separation is permanent is dependent on the energy put into the reaction. At the cathode the oxygen reacts and is broken into its components and then all electrons, ions and oxygen atoms are drawn together to form water which is removed from the cell. The energy required for this process comes from the fuel so therefore not all energy goes into generation and causes inefficiency. Increasing the temperature, increasing the active area of the electrode and the utilisation of the catalyst, can reduce the effects of this inefficiency.

[13] Fuel Cell Handbook, Fifth edition, USDOE, Office of Fossil Energy, 2000

Ohmic Polarisation is caused by the electrical losses in the cell. The electrolyte, electrodes and current collecting plates all have a level of resistance (R (Ohms)) that adds to energy loss. Other resistances can also be found in the material in the plates and in the use of different energy retrieval methods.

Concentration Polarisation is the result of the flow of fuel to the electrodes being hindered. This often occurs at high current values because the forming of product water and excess humidification blocks the reaction sites. This effect can be counteracted by increasing the pressure of the fuel supply, therefore driving the water out of the cell and increasing the fuel concentration. Also by using high surface area electrodes or employing thinner electrodes to shorten the journey of the fuel to the electrodes, acts to reduce the effect.

The combination of all three-polarisation effects can have a detrimental impact on the efficiency of the cell. But they also have a significant impact on their own and in general can all take effect at different instances. Ohmic polarisation is the only consistent effect, causing a near constant resistance regardless of situation. The following graph shows how the various inefficiencies take effect depending on cell voltage and current density.

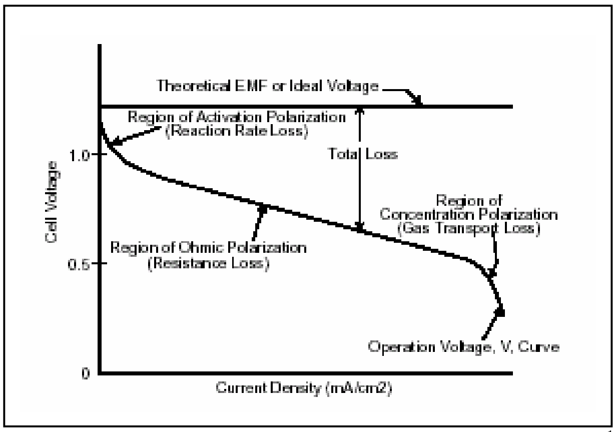

Figure 13: Ideal and Actual Fuel Cell Voltage/Current characteristic[14]

The performance of any fuel cell is affected by operating variables such as temperature, pressure and reactant utilisation to name a few, and other factors such as impurities and cell life. To meet requirements of any application normally means that compromises between parameters must be made to achieve the lowest cost and an acceptable cell life. Operating conditions are found by

[14] Fuel Cell Handbook, Fifth edition, USDOE, Office of Fossil Energy, 2000

defining specific system requirements such as power level or voltage. Using this and interrelated calculations the power, voltage and current of the stack and each individual cell is determined.

The higher the current density the better, but compromising this is the cell voltage due to the relationship between the two as shown in figure 13. Operating at a lower current density and higher cell voltage would mean a higher efficiency and a low operating cost and is suitable for stationary power generation. The opposite is true for transport applications where weight is a crucial factor.

The overall efficiency of a fuel cell is a combination of the thermal efficiency and the electrical efficiency:

$$\eta_{FC} = \eta_{TH} \cdot \eta_e \qquad (4)$$

The electrical efficiency takes into consideration the polarisation losses discussed previously and is as follows:

$$\eta_e = E^0 - IR - \varphi \qquad (5)$$ [15]

Where, I = current (amps)
R = Resistance (ohms)
φ = Over potential (V)

The thermal efficiency is the amount of useful energy produced divided by the change in the stored chemical energy (normally referred to as thermal energy) that is released when the fuel and oxidant react.

$$\eta = \frac{UsefulEnergy}{\Delta H} = \frac{\Delta G}{\Delta H} \qquad (6)$$

As the equation above shows, the useful work provided by the reaction has the symbol ΔG. This is the change in the Gibbs free energy. The maximum electrical potential at a constant

[15] "Fuel Cells as distributed energy generators", Karl Foger, Ceramic Fuel Cells LTD.

temperature and pressure can also be expressed as a change in the Gibbs free energy for the reaction between hydrogen and oxygen:

$$W = \Delta G = -nFE^0 \qquad (7)$$

Where, n = No. of electrons participating in reaction
F = Faradays constant = 96,490 Coulombs/g-mole electron
E^0 = Ideal potential of the cell

Also,

$$\Delta G = \Delta H - T\Delta S \qquad (8)$$

Where, T = temperature
ΔS = Change in entropy

Therefore the difference between the useful work and the thermal energy is proportional to the change in entropy. In other words, the maximum energy available = ΔG, the total thermal output = ΔH, and the amount of heat produced by the fuel cell is TΔS, if the entropy change is negative then the reaction produces heat.

The change in the Gibbs free energy can also be expressed in terms of the partial pressures of the reactants and products involved. The specific Gibbs free energy can be calculated using:

$$\Delta G = RT\left[-\ln K_p + \ln\left(\left(\frac{P_{H_2}}{No.moles.product}\right)\left(\frac{P_{O_2}}{No.moles.product}\right)\left(\frac{P_{H_2O}}{No.moles.product}\right)\right)\right] \qquad (9)$$

The above equation gives the change in Gibbs free energy in the units' *kJ/kmol*. To attain the value in *kJ/kgH$_2$* then the value is divided by the molar mass of hydrogen. To find the theoretical electrical potential the following equation is used:

$$E_{OC} = \frac{\Delta G}{q} \qquad (10)$$

3.4.2 Types of Fuel Cells

There are five main types of fuel cells all with varying characteristics and applications, these are:

- Proton Exchange Membrane (PEMFC)
- Alkaline (AFC)
- Solid Oxide (SOFC)
- Phosphoric Acid (PAFC)
- Molten Carbonate (MCFC)

The following table gives the characteristics of these fuel cells.

Fuel Cell Type	Operating Temperature (°C)	Applications	Maximum Electrical Efficiency (%)
PEMFC	70-90	CHP, Transport, Distributed Generation	50-60
AFC	50-200	Space, Transport	≈65
SOFC	750-1000	CHP, Power Generation	≈50
PAFC	190-210	CHP, Generation	≈40
MCFC	630-650	CHP, Generation	≈45

Table 1: Fuel Cell Characteristics

3.4.2.1 Proton Exchange Membrane Fuel Cell (PEMFC)

This type of fuel cell uses a sulphonic acid electrolyte that is incorporated within a polymer membrane, which makes the membrane become effectively solid. The electrolyte must be kept hydrated at all times, this obviously therefore limits the operating temperature of the fuel cell to 70-90°C[16]. The membrane uses inexpensive manufacturing materials, and the fuel cell can react

[16] "Analysis of Residential Fuel Cell Systems & PNGV Fuel Cell Vehicles", US DOE 2000

quickly to changes in demand and will not leak or corrode. A bipolar plate provides an electric connection between the cathode and anode, and acts as a barrier between the fuel and oxidant flows, a platinum-based catalyst is used at both cathode and anode.

The PEM fuel cell is at present the one which is attracting the most attention for transport applications due to its light weight, compact size, quick start up and ability to vary output in accordance with demand. The cell can be run on hydrogen or reformed hydrocarbon fuels such as methanol or natural gas. It is only a truly non-polluting process when run on pure hydrogen. A variation of the PEM fuel cell is the Direct Methanol fuel cell (DMFC). This also uses a solid polymer electrolyte but it oxidises methanol at the anode without reforming. This could become an important variation of the PEM but there is still much research and development required to improve the kinetics of the reaction at the anode and to reduce any methanol diffusion through the electrolyte.

The chemical reactions within a PEMFC are as follows.

At the anode: $\mathbf{2H_2 \rightarrow 4H^+ + 4e^-}$

At the Cathode: $\mathbf{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O}$

The chemical reactions within a DMFC are as follows.

At the anode: $\mathbf{CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2}$

At the Cathode: $\mathbf{3O_2 + 6H^+ + 6e^- \rightarrow 6H_2O}$

3.4.2.2 Alkaline Fuel Cell (AFC)

This type of fuel cell uses an alkaline electrolyte such as potassium hydroxide in water. This device was first used in the Gemini-Apollo space program to generate electrical power and also drinking water for the astronauts. It is a relatively simple device and was the first fuel cell to be fully developed. It has activated nickel or precious metal electrodes combined with the electrolyte that has excellent electrochemical properties but reacts with carbon oxides to reduce performance; therefore a soda lime scrubber often removes CO2.

Outputs of this type of fuel cell vary depending on application, generally in the range from 300W to 5kW. Their development led to low temperature operation being vastly improved in the 1980's, facilitating rapid start-up, which makes the device attractive for transport applications.

The chemical reactions within an AFC are as follows.

At the anode using a nickel, or platinum/palladium catalyst: $\mathbf{2H_2 + 4HO^- \rightarrow 4H_2O + 4e^-}$

At the cathode using a nickel oxide, silver or platinum/gold catalyst: $\mathbf{O_2 + 4e^- + 2H_2O \rightarrow 4HO^-}$

3.4.2.3 Solid Oxide Fuel Cell (SOFC)

This type of device uses a hard, ceramic compound of metal such as a solid Zirconia-based electrolyte, which is formed as a crystal lattice, and coated, on both sides with specialised porous electrode materials that conduct over the range of 750-1000°C. There are a number of different cell geometries; tubular, planar and monolithic designs are available each requiring different fabrication techniques but the same construction materials. As table one showed previously, this type of fuel cell has a very high operating temperature. Due to this high temperature, Solid Oxide Fuel Cells are often used in industrial and large-scale electrical generating stations. The fuel cell also has an in built reformer that can utilise carbon monoxide as a fuel. The high temperature also facilitates cogeneration, which can raise the efficiency of the process up to 90%[17].

The anode is a porous ceramic/metal complex of nickel oxide and Zirconia, while the cathode is lanthanum manganite doped with strontium. A separate bipolar plate, either metal or doped lanthanum chromite connects the anode and cathode.

[17] www.crest.org

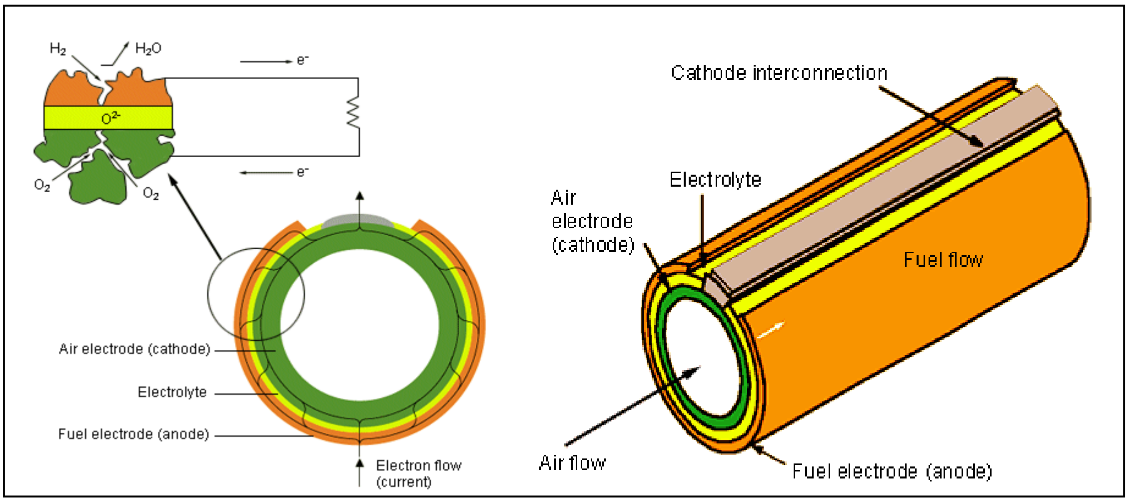

Figure 14: Siemens Tubular Solid Oxide Fuel Cell

The chemical reactions within a SOFC are as follows.

At the anode using a Zirconia cermet and nickel catalyst: $\mathbf{2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-}$

Or $\mathbf{2CO + 2O^{2-} \rightarrow 2CO_2 + 4e^-}$

At the cathode using a strontium doped lanthanum manganite catalyst: $\mathbf{O_2 + 4e^- \rightarrow 2O^{2-}}$

3.4.2.4 Phosphoric Acid Fuel Cell (PAFC)

This type of fuel cell uses an immobilised liquid form of phosphoric acid as its electrolyte, and platinum or platinum-ruthenium catalyst on carbon electrodes. The operating temperature being in the range of 150-200°C means that fuels cannot be internally reformed, therefore an external reformer retrieving hydrogen from hydrocarbon fuels is necessary unless pure hydrogen is available. But the operating temperature does leave the door open for cogeneration, but also limiting the device to stationary applications.

There have been installations of 11MW and 200kW devices which have operated very successfully and with high availability. The current electrical efficiency of this type of device is around 40% but is higher when cogeneration is used. The overall efficiency is expected to rise as the device is still being developed.

The chemical reactions within a PAFC are the same as those of the PEMFC, as follows.

At the anode: $\mathbf{2H_2 \rightarrow 4H^+ + 4e^-}$

At the Cathode: $\mathbf{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O}$

3.4.2.5 Molten Carbonate Fuel Cells (MCFC)

The electrolyte in this type of fuel cell is a liquid solution of lithium, sodium, and/or potassium carbonates soaked in a ceramic matrix. Both the electrodes are nickel based and a bipolar plate is used to collect the current. The way a MCFC operates is different to other fuel cells in that there is net carbonate ion transfer across the electrolyte; this gives the cell the unique ability to be tolerant to both CO and CO_2, but CO_2 must be reintroduced to the cell with the oxidant. Hydrocarbon fuels can be directly reformed at the anode, therefore no external reformer would be needed, but sulphur tolerance is a problem.

Devices up to 2MW have been constructed, and units up to 100MW are being considered. But the high temperature limits the materials and safe uses of this type of fuel cell, although this high temperature does support cogeneration that can raise the overall efficiency to around 85%[18].

The chemical reactions within a MCFC are as follows.

At the anode using a nickel-chromium/aluminium alloy catalyst:

$\mathbf{2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-}$

At the Cathode using a nickel oxide catalyst: $\mathbf{O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}}$

[18] www.fossil.energy.gov

4. The System

The system analysed is all encompassing from the incoming waves through to the amount of AC power that is made available from a fuel cell. The entire system is now introduced before each part is looked at more closely. The following is a schematic diagram of the entire system. The system is going to be investigated by performing a steady state analysis for predicted average monthly outputs from the LIMPET 500. The results of this will be considered against typical demand profiles for residential homes taken from the computer software tool MERIT, and with help from another software tool, esp-r. This analysis will display the real potential of this system and also the efficiency of the entire process.

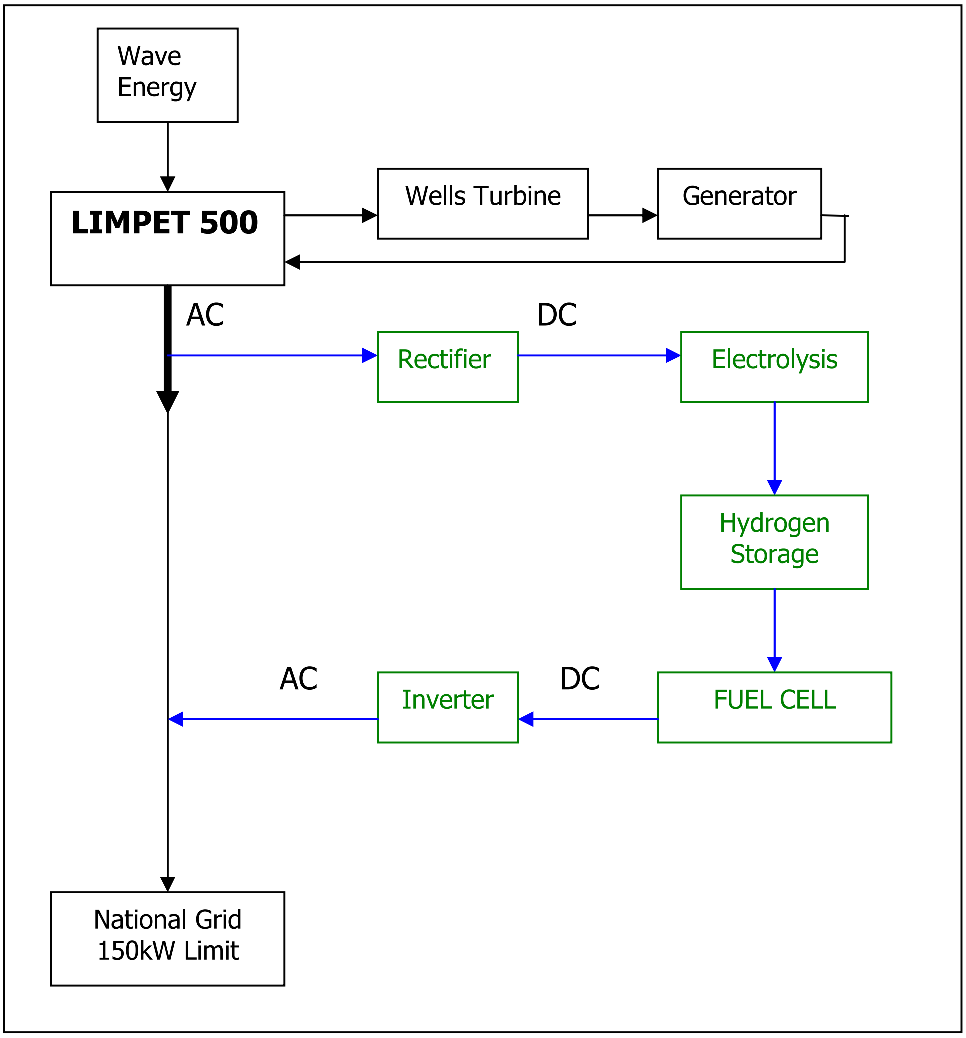

Figure 15: Simple Schematic of Entire System

4.1 Incoming Wave Energy

Unfortunately no site specific wave data for the coastline on Islay was available to the author. Wave data from the Marine Energy Test Centre in Stromness on the island of Orkney, by the Scottish Energy and Environment Foundation[19]. The monthly wave data was taken from this study and applied to the LIMPET 500 on Islay. The wave characteristics in both places were presumed to be similar and the results from the subsequent calculations implies this to be the case.

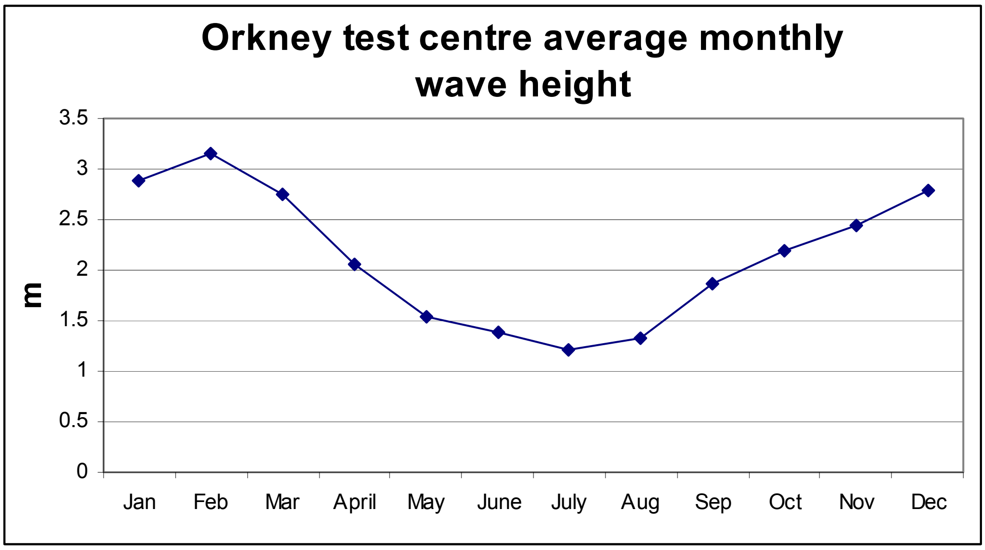

Figure 16: Orkney test site average wave heights

In order to calculate the power available from the waves entering the capture chamber either the wavelength or the period of the waves needs to be known, as can be seen in equations (1) and (2). Neither of these characteristics is given as a monthly average as the values can be extremely variable over that selected time period. British Maritime Technology have a published document named Global Wave Statistics. This gives wave statistics for certain sea areas around the world. These statistics are in the form of a probability of a certain wave height. This is given as a number in 1000 waves which will be of a certain height, within these statistics it also provides information of how many of these waves will be of a certain period. By totaling these periods for certain wave heights it was possible to calculate an average period for any wave height for the four different seasons of the year.

[19] www.seef.org.uk

This allowed the average monthly values to be used to calculate a power value for the wave in kW/m wave width. The calculated values for the average monthly wave periods were found to be as follows. These figures were agreed to be in the correct range after seeking academic consultancy.

MONTH	WAVE HEIGHT (m)	PERIOD (s)
January	2.89	8.98
February	3.15	9.52
March	2.75	8.73
April	2.05	8.73
May	1.53	8.16
June	1.38	8.16
July	1.22	7.4
August	1.32	7.4
September	1.86	8.26
October	2.19	8.89
November	2.45	8.89
December	2.78	8.98

Table 2: Average monthly wave height and period

These figures are confirmed to be in the correct range by a paper published in 1993 by Queens University Belfast[20]. Although the values do not correspond to those above they are in a similar range. It has to be expected that sites that are very close together such as the first test site for the 70kW device, which these values below correspond to, and the site of the LIMPET 500 will differ due to individual shoreline characteristics but be in a similar range.

The aforementioned paper provides data acquired from a 14 minute trace performed in June 1991. A summary of the data is as follows:

[20] "Shoreline Wave Power, Electrical Generation on Islay". S.J McIlwaine and T.J.T Whittaker, 1993

Date	06/06/1991
Time	15:49
Tide	+0.7m
Sig. Wave Height	2.6m
Period	9.6s
Elec Power	5.8kW
Wave Power	29.4Kw/m

Table 3: Data from a 14 minute trace in June 1991

The following figure shows the calculated average power per wave in any month using equation (2). Again these values are in a similar range to the data found for the 70kW test site.

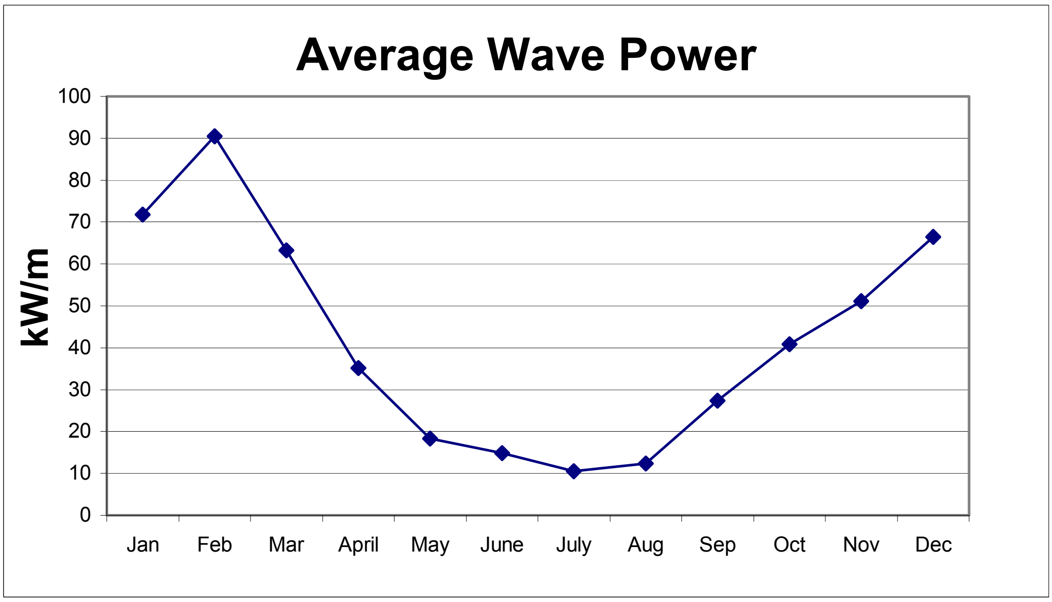

Figure 17: Average power in wave throughout the year

4.2 The LIMPET 500

In order to analyse the data calculated from the incoming waves it was necessary to know about the geometry of the capture chamber, its efficiency and also that of the wells turbine. The water depth at the entrance to the chamber is typically around 7 metres and the total water plane area which enters the chamber is 170m^2 [21] . Wavegen also state that the performance has been optimised for annual wave intensities of between 15 and 25kW/m. The width of the chamber, which is crucial to the power in the wave entering it, is 81 feet [22] or 24.705m.

The hydrodynamic conversion efficiency of the capture chamber varies widely depending on the sea conditions, from 15 to 100%[23]. Considering this and after seeking academic consultation an average value of 50% will be assumed for this.

The device consists of two wells turbines which convert the oscillary motion of the waves in the chamber into unidirectional rotational motion, each is mounted on a common shaft of a wound rotor induction machine rated at 250kW and 400V. There are two large flywheels that provide a means for temporary energy storage and ensure a constant supply from the device during a wave cycle.

The efficiency of the wells turbine, like the capture chamber, is variable depending on the wave conditions. Wavegen have said that the device operates at a peak efficiency of 80% but is generally in the 55-60% range[24]. After academic consultation the average efficiency of the device will be assumed to be 50%.

4.3 The Grid on Islay

The grid on Islay is mainly focused to the southern part of the island and the main populated areas of Port Ellen and Bowmore. The island has an electrical link with the mainland at Port Anne, where electrical overhead and sub-sea cables run to the 33kV substation in Bowmore. The area around the LIMPET 500, which includes the village of Portnahaven, is fed from the substation at Bowmore by 11kV overhead lines. The device feeds straight into this distribution

[21] www.wavegen.co.uk
[22] www.popsci.com
[23] “Shoreline Wave Power, Electrical Generation on Islay”. S.J McIlwaine and T.J.T Whittaker, 1993
[24] Wave Power Study, DTI, 2000

grid. This is known as embedded generation. To explain this concept we must understand how the national grid operates.

4.3.1 Embedded Generation

The National grid consists of three main parts:

1. Generation
2. Transmission
3. Distribution

Generation takes many shapes and form. We normally have centralised, large generating stations such as coal or nuclear power stations responsible for delivering large supplies of electrical power. This voltage is taken to other parts of the country via the transmission grid at very high voltages through a step-up transformer which increases the voltage to 400kV or 275kV, transmission is more efficient at these higher voltages. After transmission, this voltage is reduced using a step-down transformer at a sub station where it is reduced to 230V-132kV. It is then transported to to its area of use via the distribution grid. Embedded generation is where generating plant produces electricity which is supplied directly into the distribution network. Many renewable energy technologies fit into this category due to the resource being available in remote locations such as wave, tidal and wind energy.

4.4 Power Conditioning

Power conditioning is a necessary part of any energy system involving a fuel cell where AC electricity is required. The fuel cell produces Direct Current (DC) power but Alternating Current (AC) is required for use in our homes and appliances. DC power has a constant magnitude, whereas AC has a magnitude which varies with time following a sinusoidal waveform. Regarding the system being assessed in this paper, power conditioning is required twice as DC voltage is required for electrolysis but that produced by the LIMPET 500 is AC. AC to DC conversion is done using a Rectifier, and DC to AC is performed using an Inverter. Both these devices operate at an efficiency of 96%[25].

[25] "Assessment of Hydrogen-fuelled proton exchange membrane fuel cells for distributed generation and cogeneration", USDOE, 2000

4.5 Electrolysis

As mentioned previously, the electrolysis of water requires DC electricity. The amount of electricity which must be supplied to support the disassociation of the hydrogen and oxygen is the change in the Gibbs Free Energy.

$$\Delta G = \Delta H - T\Delta S = 285.38kJ - 48.7kJ = 237.1kJ$$

The environment can contribute to the process by increasing the size of $T\Delta S$; therefore less electricity is necessary if the temperature is increased. The change in Gibbs free energy is the amount of energy regardless of form which needs to be supplied in order to cause the reaction.

To calculate the average amount of hydrogen produced in cubic metres, in one month from the energy produced from the LIMPET 500 we will use an energy consumption of 4.5kWh/m^3 of hydrogen, with an efficiency of 67%[26].

4.6 Hydrogen Storage

Fuel Cells are not storage devices; the hydrogen gas is the storage device and fuel cells are a conversion device. When the hydrogen is not produced at the place or time when it is needed then an efficienct method of storage is necessary. So what are the options? The current methods and those that offer prospects for the future? These will be discussed in this section. The storage of hydrogen is fundamentally important; large scale, safe, practical and economically viable methods of storage are essential to the widespread use of the technology. The energy density, costs, technical and environmental conditions are the dominating criteria for the best method of storage for the future. This area is the subject of much R+D, there are five main areas at present[27].

1. Compressed Gas
2. Liquid
3. Hybrides
4. Carbon Nanotubes

[26] “Solar Hydrogen production by electrolysis”, Walt Pyle, Jim Healy, Reynaldo Cortez, 1994
[27] www.nrc.ca

4.6.1 Compressed Gas

To store significant amounts as a gas it is necessary to pressurise hydrogen. Then it can be pumped to its point of use via pipelines in the same way that natural gas reaches our homes today. One area where this technology is expected to be utilised is in Fuel Cell Vehicles, the target pressure to reach for an appreciable range for fuel cell vehicles is 10,000 psi (pounds per square inch). The most common storage containers hold 40 litres of hydrogen at a pressure of 150 bar.

4.6.2 Liquid

Hydrogen in its liquid form is very hard to obtain. The gas must be cooled to around -250°C in order for it to condense. Refridgerating it to this level uses the equivalent of 25-30% of its energy content and requires special materials and care; to cool 0.45kg of hydrogen requires 5kWh of electrical energy[28]. This method of storage is attractive for refueling stations. It has one of the highest storage efficiencies of 20% by weight hydrogen content. There are problems associated with easy evaporation posing problems for long term storage. There are also safety issues involved with working with the fluid at the temperature range specified and safety precautions would be necessary.

4.6.3 Hybrides

This method of storage is potentially more efficienct than the others. One problem is that their energy per unit weight is low and is the subject of present research. The hydrogen is chemically bonded to another compound and released when needed. There are two kinds of hybrides: Chemical Hybrides and Metal Hybrides.

[28] EREN, USDOE Consumer Energy Info: EREC briefs

4.6.3.1 Chemical Hybrides

Chemical hybrides involve the reaction of hydrogen with an alkali earth metal, an alkali metal, or a complex metal for storage purposes. The chemical reactions which follow go in both directions. They are endothermic from the left to the right, and highly exothermic in the opposite direction.

Calcium hybride (C_aH_2) reacts with water at atmospheric pressure:

$$2H_2 + C_a(OH)_2 \Leftrightarrow C_aH_2 + H_2O$$

The reaction with an alkali metal is common and cheap to use:

$$H_2 + N_aOH \Leftrightarrow N_aH + H_2O$$

Hydrogen reacting with a complex metal is also an endothermic reaction, in reverse the hydrolysis of Sodium Borohydride (N_aBH_4) is highly exothermic:

$$4H_2 + N_aOH + H_3BO_3 \Leftrightarrow N_aBH_4 + 4H_2O$$

All of these chemical hybride reactions take place in small containers; the hydrogen is released from these by reacting with water. The containers are expensive but safe, and the heat released by the reaction needs to be catered for.

4.6.3.2 Metal Hybrides

Hydrogen can react with a metal alloy, en example of which could be titanium or iron. The metal undergoes the following generic reaction:

$$M + H_2 \Leftrightarrow MH_2$$

The metal and hydrogen are combined by applying pressure in an exothermic reaction. The hydrogen is released by reducing the pressure or by increasing the temperature, causing an endothermic reaction. Storage is in a safe container and has a 7% by weight hydrogen capacity[29].

4.6.4 Carbon Nanotubes

One of the solid forms that carbon can be found in is known as Fullereness. Fullereness is made of many carbon atoms, usually 60 but more can exist, connected together. These atoms can form tubes known as nanotubes; these can store hydrogen. This is a promising area and is also the study of much R+D, so far it has been reported that 68g of hydrogen per 100g of total container mass is attainable[30].

4.7 Fuel cell

Two fuel cells are analysed using this sytem; the Proton Exchange Membrane Fuel Cell (PEMFC) and the Solid Oxide Fuel Cell (SOFC). One of the main reasons for this choice is that the PEMFC is a low temperature device whereas a SOFC is a high temperature device, as discussed previously in section 2.4. Analysing both the benefits of having a high electrically efficient cell (PEMFC) and one that has a heat ouput and a reduced electrical output (SOFC) will show the potential of the application of fuel cells in this situation, and the benefits associated with each type. Both of these fuel cells have solid electrolytes and therefore do not require a supply of liquid, such is the case with the AFC which requires a KOH (potassium hydroxide) electrolyte.

The PEMFC is the subject of much research and the most developed fuel cell after the AFC, the technology is advanced and the PEM is the most economically attractive fuel cell on the market at the present time. It has a quick start up time due to its low temperature and is capable of operating at high current densities compared to other cells.

The SOFC is also the subject of much interest and is very promising for cogeneration and also for use with Gas Turbines in a combined cycle. Due to the high temperatures the materials used are more costly, in the future the economics of the SOFC will have to be improved if commercialisation is to be achieved.

[29] www.nrc.ca
[30] www.nrc.ca

4.7.1 Proton Exchange Membrane Fuel Cell (PEMFC)

The low temperature of the PEMFC enables quick start up from ambient conditions. This is especially useful when pure hydrogen is the fuel as in this case there is no reformer to supply heat. The water produced from a PEMFC is as a liquid and not as steam. The ionic conductivity of the membrane is higher when fully saturated. Maintaining control over the water being used and produced is very important to ensure optimum performance. Cooling of the stack is usually accomplished using a heat transfer fluid , usually water, which flows through integrated coolers within the stack. The temperature rise across the cell is kept to less than 10˚C [31].

The focus of current research into this device is to lower costs further, improve the membranes, refine electrode design, and to handle CO occurrence in the fuel stream which is a contaminant to the cell. The handling of contaminants such as CO or CO_2 is especially important when the hydrogen is reformed from another source and not produced renewably from electrolysis.

Little information exists about the performance of hydrogen fueled PEMFCs and their operating characteristics. The values that follow which characterise the cell used in this analysis were attained through establishing the current state of the art in terms of efficiency and fuel utilisation.

PEMFC CHARACTERISTICS	
Electrical Efficiency(ηe)	≈50%[32]
Cell Voltage	≈0.8V[33]
Fuel Utilisation (η_F)	≈80%[34]
Operating Temperature / Pressure	80˚C / 1 bar

Table 4: PEMFC characteristics

[31] "Fuel Cell Handbook", Fifth edition, USDOE, Office of Fossil Energy, 2000
[32] "Fuel Cells for distributed generation: A technology and marketing summary", USDOE 2000
[33] "Fuel Cell Handbook", Fifth edition, USDOE, Office of Fossil Energy, 2000
[34] "Assessment of hydrogen fuelled proton exchange membrane fuel cells for distributed generation and cogeneration", USDOE 2000

Using these figures as targets for operating parameters for the fuel cell it is possible to determine other parameters. This was done for a power output of 150kW as this is potentially the maximum power that would be required from the fuel cell if all other power sources are not available, i.e. no power from the wave device and a shortage from the grid connection. In this case the fuel cell would be preferred to the diesel generator at Bowmore, due to the obvious environmental advantages, to supply as much power as the grid will allow. This is assuming that the hydrogen is produced near the LIMPET and that the fuel cell operates there to avoid considering the transportation of hydrogen or even the altering of the grid connection to allow electricity to be distributed to another area for electrolysis.

4.7.1.2 Calculating PEMFC characteristics

To calculate the characteristics of the fuel cell we must first know the change in Gibbs free energy. The following table considers all the reactants and products from the reaction which takes place at the temperature and pressure outlined in Table 4.

Reactants and Products	Number of Moles ($Products/H_2$)	Molar Mass (Kg/kmol)	Partail Pressure (bars)
H_2	-1	2	1
O	-0.5	16	1
H_2O	1	10	1
Reaction Total	-0.5		

Table 5: Properties of reactants and products

The electrons released at the anode, ne = 2

Ln K_p at the operating temperature = 77.19

Using equations (9) and (10) the following results are obtained:

Specific Gibbs Energy, ΔG	-1.1×10^5 kJ/kgH_2
Theoretical Potential, E^0	1.175V
Charge, q	96490000 C/kgH_2

Table 6: Specific gibbs energy and charge, and theoretical voltage - PEMFC

For a power output of 150kW AC, and using an inverter which is 96% efficienct, we require an output from the fuel cell of 156.25kW DC.

Assuming a cell voltage of 0.8V and knowing the power output as above, we can calculate the sum of all the cell currents in the stack:

$$I = \frac{P}{V} = \frac{156250}{0.8} = 1.95 \times 10^{5} A$$

The hydrogen which is utilised in the stack is found using this calculated current value and dividing it by Faradays constant:

$$\dot{H}_2 = \frac{1.95 \times 10^{5}}{96490000} = 2.52 \times 10^{-3} kg/s$$

Now that we know the flow rate of the hydrogen we can work out the change in Gibbs free energy for the reaction:

$$\Delta G = \left(2.52 \times 10^{-3}\right) \times \left(-1.1 \times 10^{5}\right) = -274.3kW$$

The heat from the fuel cell reaction is calculated using the following:

$$Q = \dot{H}_2 \times \eta_F \times \left(\Delta G - \frac{\left(\Delta \dot{H} \times no.moles\right)}{H_2 molarmass} \right) = 15.3kW$$

This heat value is very low but is expected from the low temperature PEMFC cell. It has been noted that how PEMFCs will meet any thermal loads is difficult to see unless external combustion takes place[35] as part of a reforming process which creates heat.

The overall heat efficiency is then given by:

[35] "Fuel Cells for distributed generation: A technology and marketing summary", USDOE 2000

$$\eta_h = \frac{Q}{\left(\dot{H}_2 - \Delta\dot{H}\right)} = 5.2\%$$

For a 150kW output, the electrical efficiency is: $\eta_e = 51.1\%$

Giving an overall efficiency of: $\eta_{FC} = 56.3\%$ and a heat to power ratio of **0.102**.

The following table is a review of the results of the fuel cell analysis.

Ideal Thermal Efficiency	**93.7%**	Operating Temperature	**80˚C**
Voltage Efficiency	**68.1%**	Operating Pressure	**1 Bar**
Fuel Utilisation	**80.3%**	Ideal Cell potential	**1.175V**
Gibbs Free Energy	**-274.3kW**	Actual cell Voltage	**0.8V**
Heat Efficiency	**5.2%**	Electrical Efficiency	**51.1%**
OVERALL EFFICIENCY OF 56.3%			

Table 7: Operating charcteristics of PEMFC used in analysis

4.7.2 The Solid Oxide Fuel Cell (SOFC)

The high temperature of the SOFC makes it very attractive for cogeneration. It also facilitates the internal reforming of fuels when not utilising pure hydrogen. The water that is produced from the fuel cell reaction will obviously be in a gaseous form due to the temperature of the cell. This higher temperature means that materials used must be able to withstand it. The solid electrolyte and solid state of all components means that this cell can be configured to meet a certain specification, ie. Tubular or planar. Siemens Westinghouse are the leaders of the tubular SOFC market and have demonstration plants in operation.

SOFCs have a lower theoretical efficiency due to the fact that the change in Gibbs Free Energy reduced as temperature of operation increases. But this higher temperature not only aids cogeneration but also is beneficial for reducing polarisation[36].

Little information exists about the performance of hydrogen fueled SOFCs and their operating characteristics. The values that follow which characterise the cell used in this analysis were attained through establishing the current state of the art in terms of efficiency and fuel utilisation.

SOFC CHARACTERISTICS	
Electrical Efficiency(ηe)	≈43%[37]
Cell Voltage	≈0.7V[38]
Fuel Utilisation (η_F)	≈70%[39]
Operating Temperature / Pressure	920˚C / 1 bar

Table 8: SOFC characteristics

Using these figures as targets for operating parameters for the fuel cell it is possible to determine other parameters. This was done, as previously, for a power output of 150kW as this is potentially the maximum power that would be required from the fuel cell if all other power sources are not available, i.e. no power from the wave device and a shortage from the grid connection. In this case the fuel cell would be preferred to the diesel generator at Bowmore, due to the obvious environmental advantages, to supply as much power as the grid will allow. This is assuming that the hydrogen is produced near the LIMPET and that the fuel cell operates there to avoid considering the transportation of hydrogen or even the altering of the grid connection to allow electricity to be distributed to another area for electrolysis. Proximity is also important for the potential use of the heat that is produced from the fuel cell.

[36] "Fuel Cell Handbook", Fifth edition, USDOE, Office of Fossil Energy, 2000
[37] "Design Optimisation of a hybrid Solid oxide fuel cell and Gas Turbine power generation system", DTI 2000
[38] "Fuel Cells as distributed energy generators" Karl Foger, Ceramic Fuel Cells LTD.
[39] "Design Optimisation of a hybrid Solid oxide fuel cell and Gas Turbine power generation system", DTI 2000

4.7.1.2 Calculating SOFC characteristics

To calculate the characteristics of the fuel cell we must first know the change in Gibbs free energy. The following table considers all the reactants and products from the reaction which takes place at the temperature and pressure outlined in Table 8.

Reactants and Products	**Number of Moles (Products/H_2)**	**Molar Mass (Kg/kmol)**	**Partail Pressure (bars)**
H_2	-1	2	1
O	-0.5	16	1
H_2O	1	10	1
Reaction Total	-0.5		

Table 9: Properties of reactants and products

The electrons released at the anode, ne = 2

Ln K_p at the operating temperature = 18.8

Using equations (9) and (10) the following results are obtained:

Specific Gibbs Energy, ΔG	-9×10^4 kJ/kgH_2
Theoretical Potential, E^0	0.935V
Charge, q	96490000 C/kgH_2

Table 10: Specific gibbs energy and charge, and theoretical voltage - SOFC

For a power output of 150kW AC, and using inverter which is 96% efficient, we require an output from the fuel cell of 156.25kW DC.

Assuming a cell voltage of 0.75V and knowing the power output as above, we can calculate the sum of all the cell currents in the stack:

$$I = \frac{P}{V} = \frac{156250}{0.75} = 2.08 \times 10^5\, A$$

The hydrogen which is utilised in the stack is found using this calculated current value and dividing it by Faradays constant:

$$\dot{H}_2 = \frac{2.08 \times 10^5}{96490000} = 2.16 \times 10^{-3} kg/s$$

Now that we know the flow rate of the hydrogen we can work out the change in Gibbs free energy for the reaction:

$$\Delta G = \left(2.16 \times 10^{-3}\right) \times \left(-1.1 \times 10^5\right) = -271.4kW$$

The heat from the fuel cell reaction is calculated using the following:

$$Q = \dot{H}_2 \times \eta_F \times \left(\Delta G - \frac{\left(\Delta \dot{H} \times no.moles\right)}{H_2 molarmass} \right) = 132kW$$

This heat value is much higher than that of the PEMFC as expected. The managing of this heat and the retrieval of it will affect the actual amount which can be utilised.

The overall heat efficiency is then given by:

$$\eta_h = \frac{Q}{\left(\dot{H}_2 - \Delta \dot{H}\right)} = 36.3\%$$

For a 150kW output, the electrical efficiency is: $\eta_e = 42.8\%$

Giving an overall efficiency of: $\eta_{FC} = 79.1\%$ and a heat to power ratio of **0.827**.

The following table is a review of the results of the fuel cell analysis.

Ideal Thermal Efficiency	**74.6%**	Operating Temperature	**920˚C**
Voltage Efficiency	**80%**	Operating Pressure	**1 Bar**
Fuel Utilisation	**71.7%**	Ideal Cell potential	**0.935V**
Gibbs Free Energy	**-271.4kW**	Actual cell Voltage	**0.75V**
Heat Efficiency	**36.3%**	Electrical Efficiency	**42.8%**
OVERALL EFFICIENCY OF 79.1%			

Table 11: Operating charcteristics of SOFC used in analysis

4.8 Demand Profiles

The real potential of the system is most easily demonstrated by analysing the number of homes that could be supplied by it. Like the supply from the LIMPET 500, the energy demands of a home vary over the course of a year. The demand of a residential property can be split into electrical and thermal loads.

The electrical loads used in this analysis were taken from the computer software MERIT at Strathclyde University. This gave the monthly electrical demand of a 1-2 bedroom house, and a 3 bedroom house. The following graph shows these results.

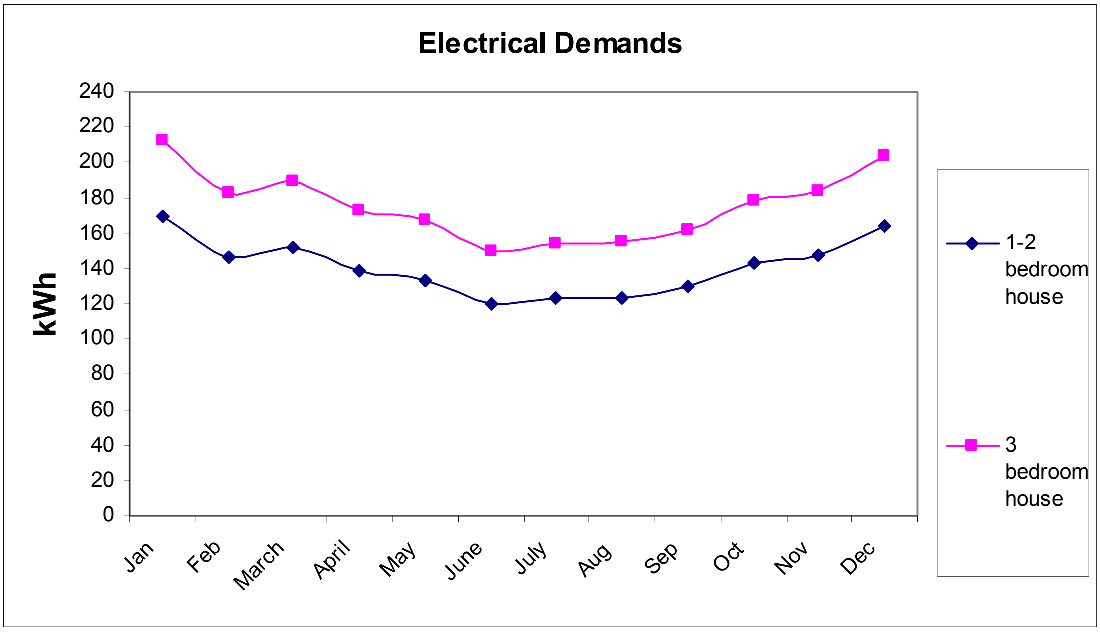

Figure 18: Monthly electrical demands from MERIT

The thermal load accounts for the largest proportion of the energy demands of a home in our Scottish climate. To predict the space heating requirements of an average home, Degree Days were used. What the value of degree days represents is how far the outside temperature is on average below 15.5°C (the control temperature)[40]. When the outside temperature is above this value it should not be necessary to heat the building. The higher the number of degree days then the colder the month.

To calculate the energy requirements for space heating it is necessary to know the fabric heat loss and the ventilation heat loss defined by the following equations.

Fabric Heat Loss:
$$Q = UA\Delta T \tag{11}$$

Where, U = Overall heat transfer coefficient (W/m^2K)

A = Area (m^2)

ΔT = Temperature change across fabric (K)

To change this to energy we must multiply it by a time component and divide by 1000 to give the result in kWh:

[40] www.energy-efficiency.gov.uk

$$E_f = \frac{UA(Degree.Days \times 24)}{1000} \quad (12)$$

The ventilation loss is calculated using the following equation:

$$Q = \frac{1}{3} NV\Delta T \quad (13)$$

Where, N = Volume Air changes per hour factor
V = Volume (m^3)

As before to calculate the energy:

$$E_v = \frac{NV(Degree.days \times 24)}{3 \times 1000} \quad (14)$$

Combining these two equations gives the total energy requirements for space heating within a building. The value of N above changes depending on how well sealed the building is, N=0.25-0.5 for a building with well sealed windows and doors, ie. a fairly modern/new house. N=0.5-1 for a poorly sealed building, ie. an older building. The entire equation is as follows:

$$E = (24 \times Degree.days)\left[\frac{UA}{1000} + \frac{NV}{3000}\right] \quad (15)$$

The computer software EXCEL was used to calculate the monthly space heating requirements for the corresponding degree days data. This was done for a well sealed house, N=0.25, and a badly sealed house, N=0.75, of an average size of 10m width, 7 metres length and 6 metres in height. Therefore the following values can be calculated:

Total surface area = 274m^2 Volume = 420m^3

The value of U, the overall heat transfer coefficient must be known for an external wall of a building. From the computer software Esp-r at Strathclyde University, we can find what an external wall consists of and calculate its U value. The external wall is made up as the following diagram shows:

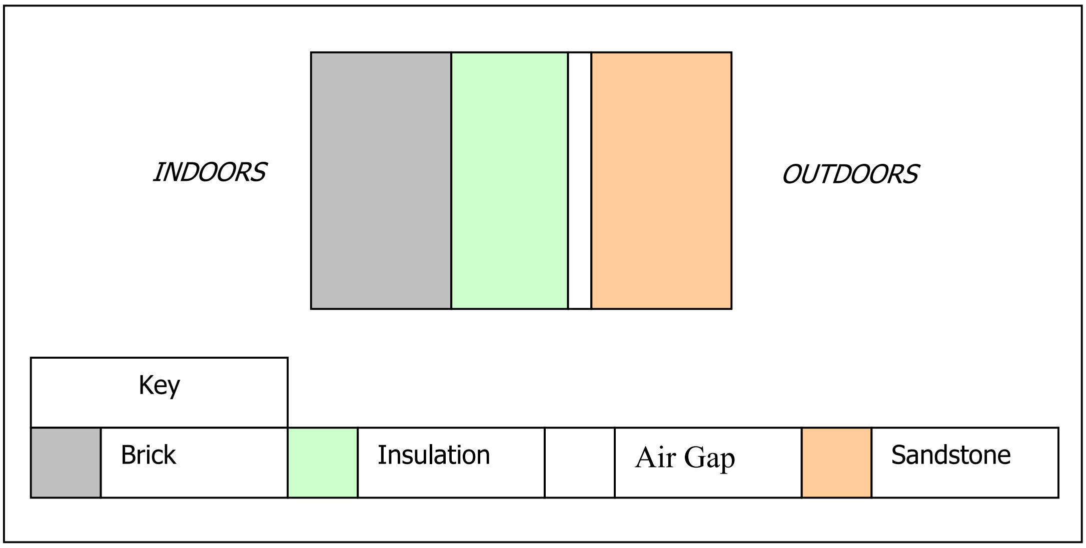

Figure 19: Components of typical external wall

To calculate the U value, the following equation is used:

$$\frac{1}{U} = R + \frac{L_1}{K_1} + \frac{L_2}{K_2} + R + \frac{L_4}{K_4} + R \tag{16}$$

The R in this equation represents the convective and radiative transfer between a material and air, R = 0.17. The other values $\frac{L}{K}$ represent the conductive transfer between materials. The other values which are necessary for the calculation are:

	Brick	**Insulation**	**Sandstone**
Thermal Conductivity, K (W/mK)	0.96	0.04	0.44
Thickness, L (m)	0.1	0.075	0.1

Table 12: Properties of components of external wall

Using equation (16), the U value is calculated to be = **0.3**

The monthly degree days values for the year 2000 are illustrated in the following graph:

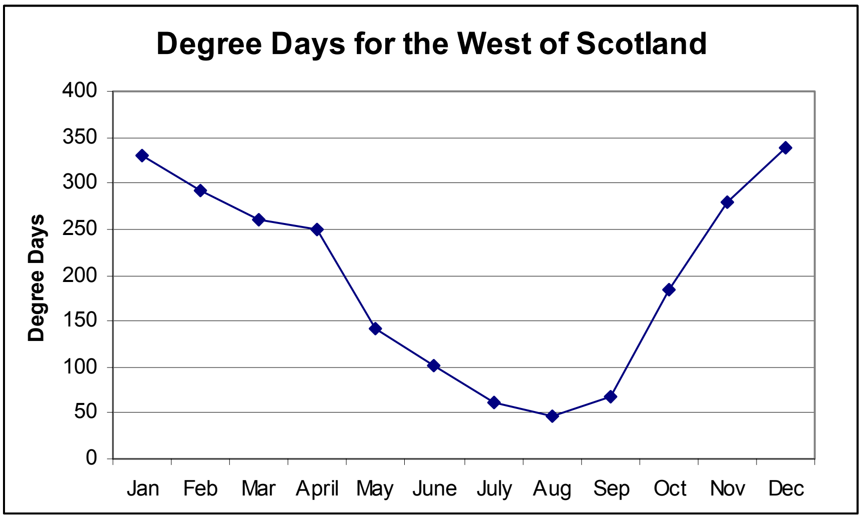

Figure 20: Degree days for the West of Scotland

For the different N values specified earlier and using equation (15), the space heating requirements are illustrated in the following graph:

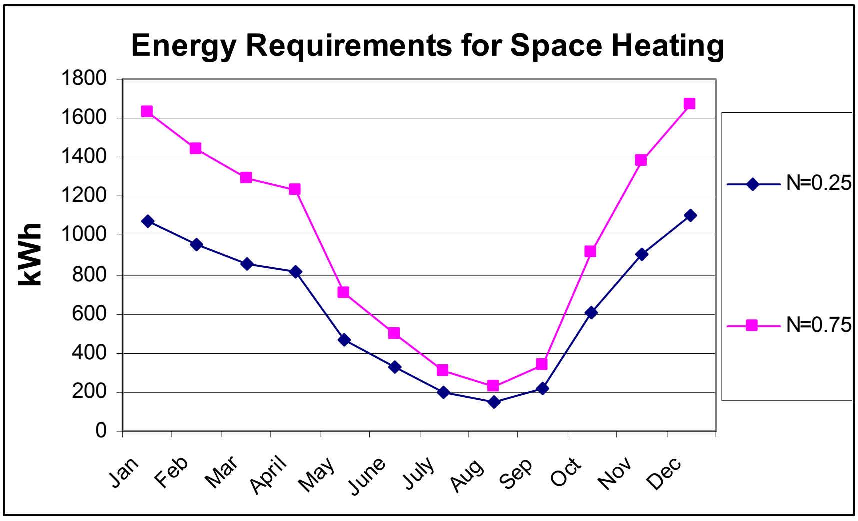

Figure 21: Energy requirements for space heating

The values that have been optained mean that the matching of supply and demand can be done for specific groups of housing and also quality of housing in terms of air leakage. This is appropriate as there is a diversity of buildings on Islay, from small old semi-detached homes to modern holiday cottages.

5. Results

The power output from the turbine was found to vary throughout the year as shown in the following graph. Therefore the excess power after supplying the grid with 150kW varies accordingly.

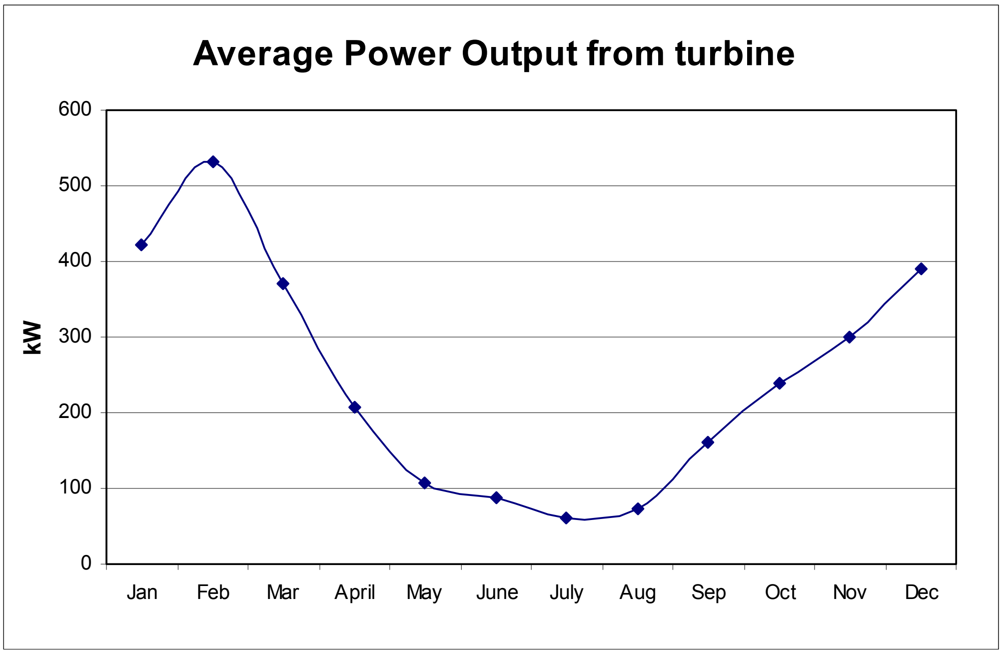

Figure 22: Average Monthly Power output from LIMPET 500

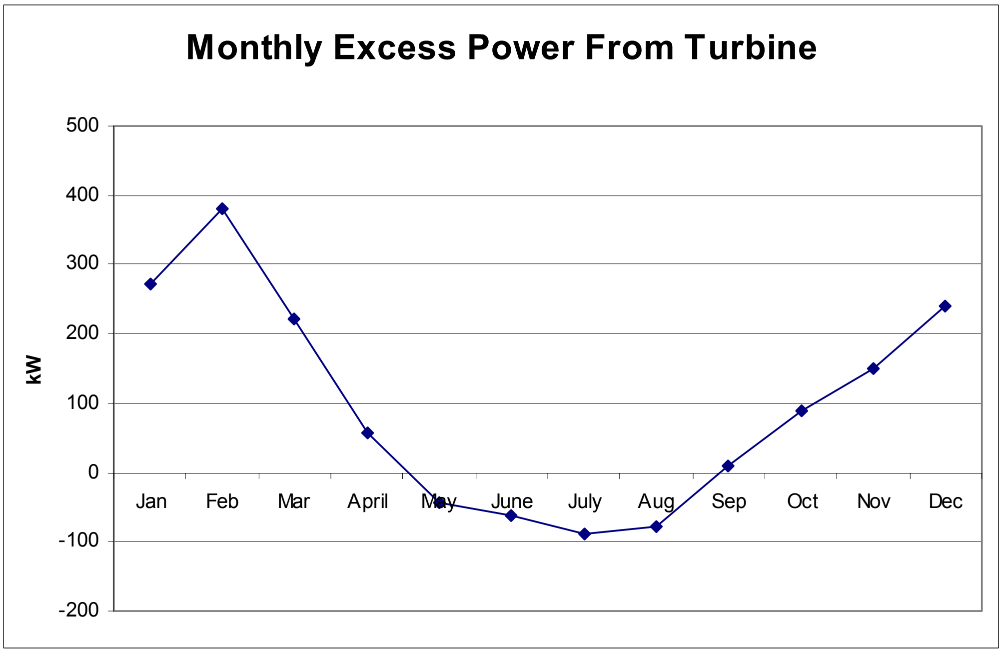

Figure 23: Average Monthly Excess power provided by the LIMPET 500

Where the previous graph became a negative value is when the storage system could work to ensure that the grid is fully supplied up to 150kW. For each month in a year that excess energy produced, it was calculated by multiplying the power by the number of days in the month multiplied by 24.

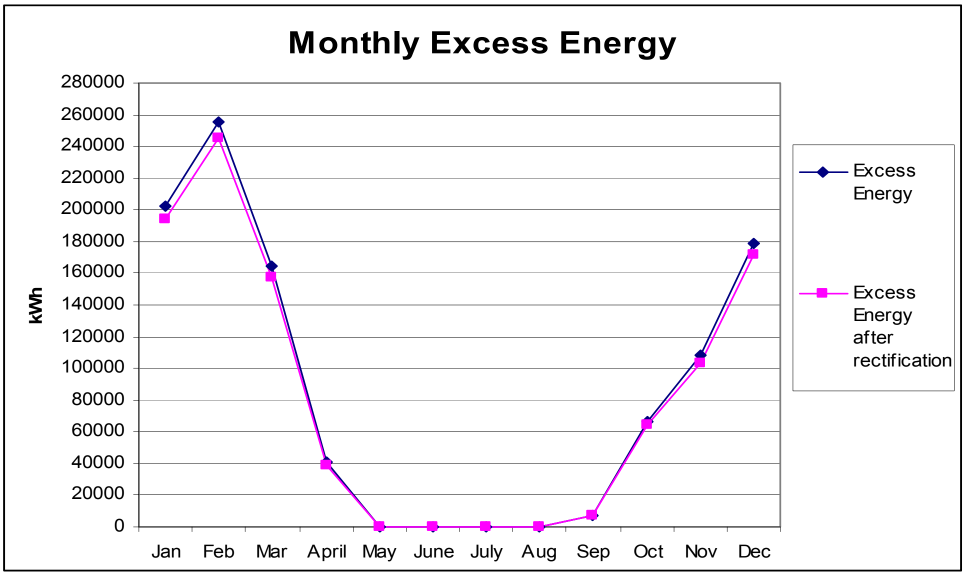

Figure 24: Excess energy per month before and after rectification

The amount of hydrogen produced throughout the year was dependent on the use of this excess electricity. There are periods of the year when the output from the LIMPET 500 is not large enough to warrant and energy being used for hydrogen production. Hydrogen produced earlier in the year could be stored to supplement the output of the LIMPET 500 to ensure that the grid is supplied at the maximum level.

The storage of hydrogen gas is a process which has been performed for over 100 years and is well developed. It is possible to store in containers which are impermeable. These are highly efficient methods of storage. Typical physical storage efficiency is 95%[41].

[41] "Technology status report: Hydrogen", DTI 2001

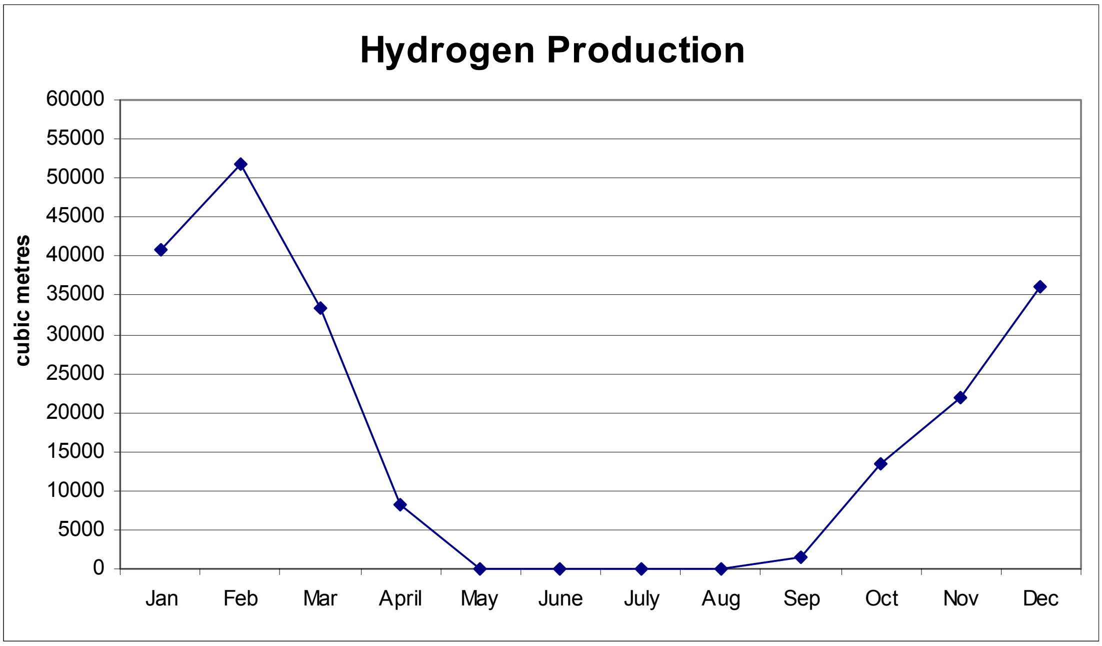

Figure 25: Monthly Hydrogen production in m^3

The density of hydrogen is 0.0899kg/m^3. This enables us to work out how much hydrogen is produced in kg. If we then know the Calorific value (kWh/kg) we can work out the energy available from the hydrogen. This depends on whether the product from the reaction is liquid or gas.

	Calorific Value (kWh/kg)	**Product State**
Higher Heating Value (HHV)	39.41	Liquid
Lower Heating Value (LHV)	33.3	Gas

Table 13: Calorific value of hydrogen for HHV and LHV

The PEMFC will produce liquid water as it operates at a temperature of 80°C, below the boiling point. The SOFC will produce steam as it operates above the boiling point of water. The graph shows the energy available from the hydrogen for both calorific values.

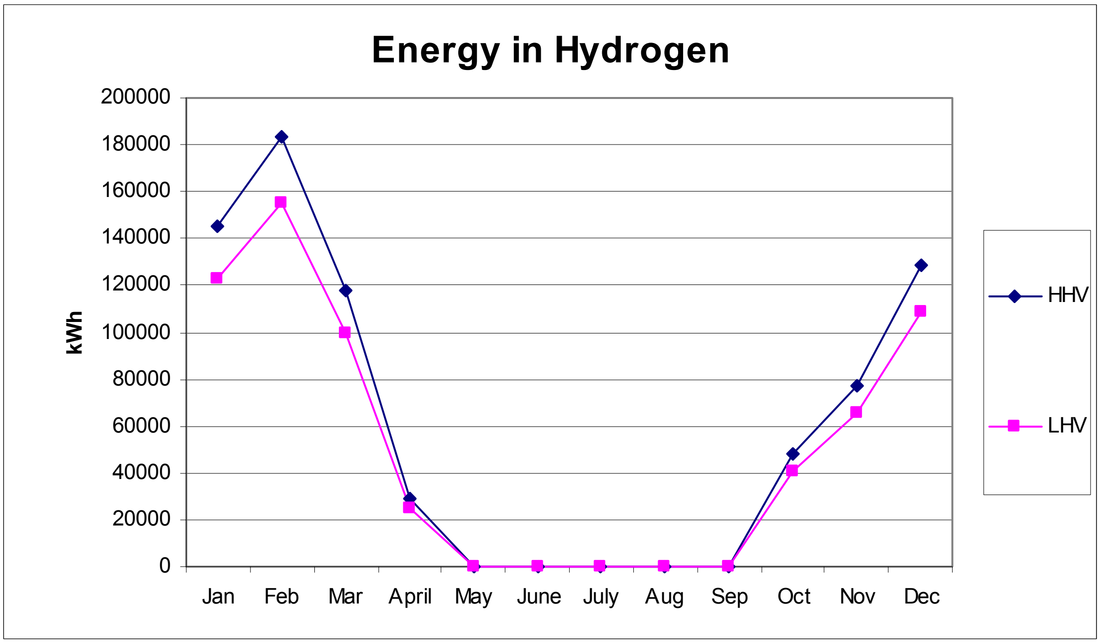

Figure 26: Energy available in hydrogen for higher and lower heating values

The fuel cell characteristics in tables 7 and 11 were used to calculate the amount of electricity generated by the fuel cells each month if utilising the hydrogen produced in that particular month. The results for electrical supply take into consideration the efficiency of the Inverter, and the values are AC.

The following figure shows the monthly outputs from the fuel cells presuming that all hydrogen created in a particular month is used in that same month for electricity generation.

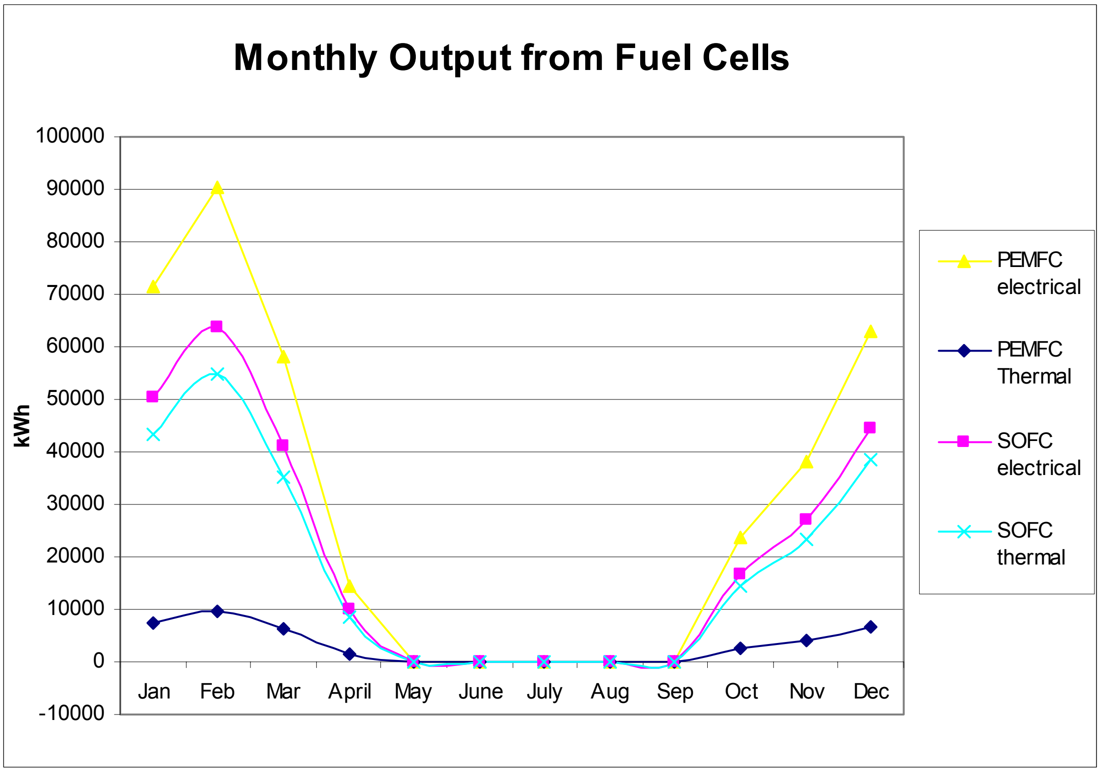

Figure 27: Potential monthly heat and electrical output from Fuel Cells

These values above enable the matching of supply and demand for electrical and thermal loads as specified in figures 18 and 21 for each month of the year.

The number of homes which will have their electrical loads satisfied are shown for each house size considered in the following figure. These results represent how many homes would be supplied if all the electrical energy created by the fuel cell was used to meet electrical loads for that individual house type only.

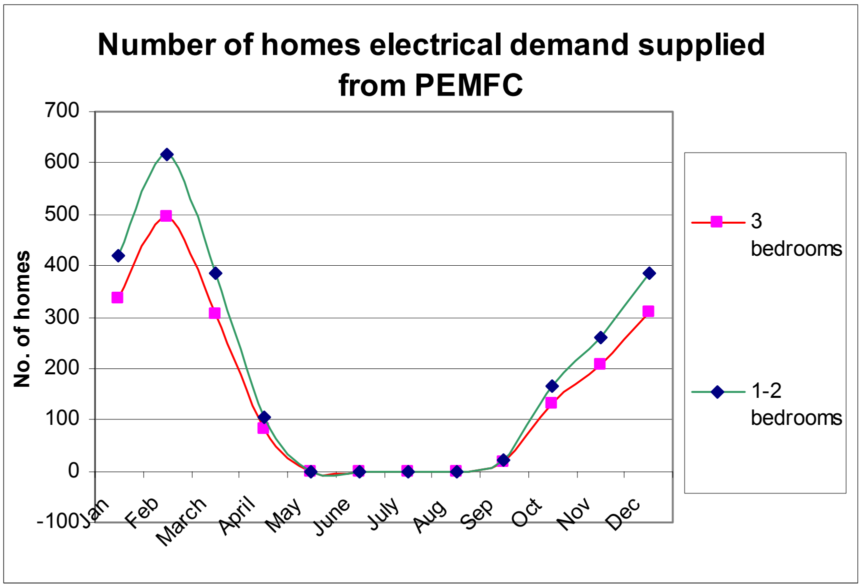

Figure 28: Number of homes whose electrical demands are met by PEMFC

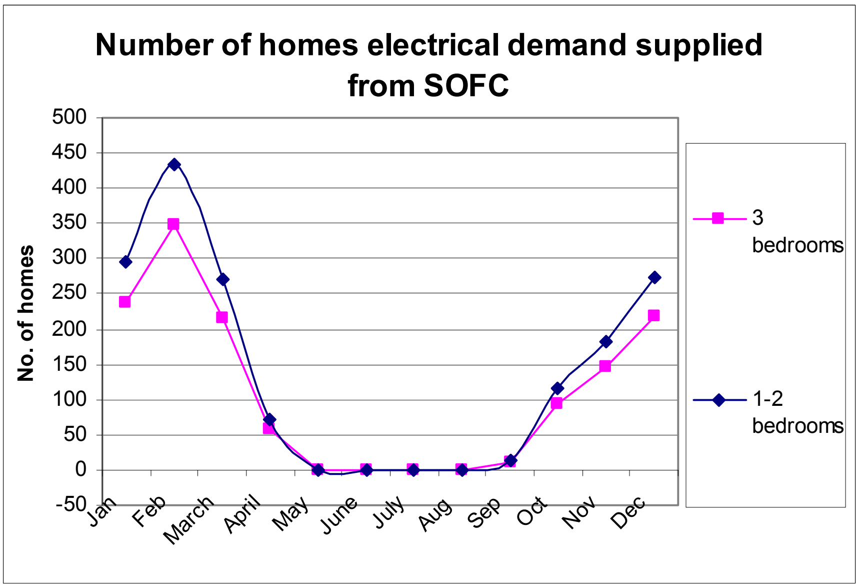

Figure 29: Number of homes whose electrical demands are met by SOFC

As stated previously the thermal outputs from the fuel cells will be considered against the monthly energy requirements for space heating for a residential building on the west coast of Scotland. The following graphs demonstrate the number of homes whose space heating requirements could be met using the heat output from the fuel cells.

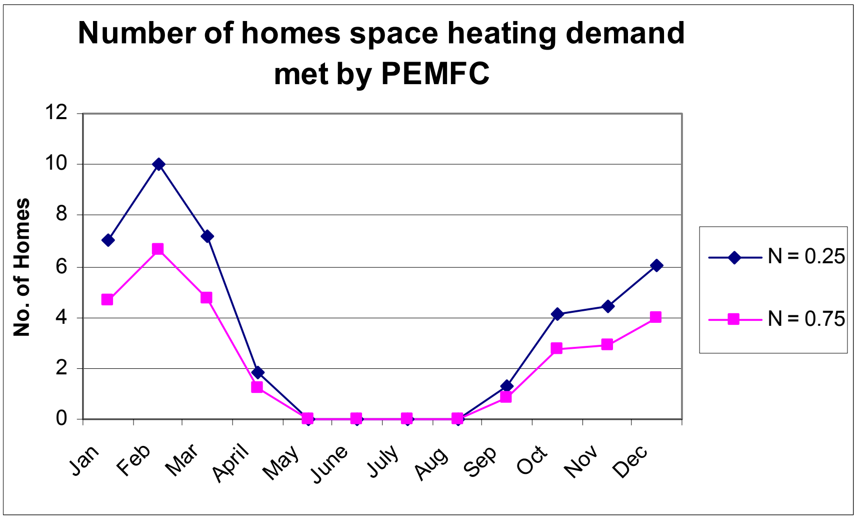

Figure 30: No of homes space heating demands met by PEMFC for N = 0.25, 0.75

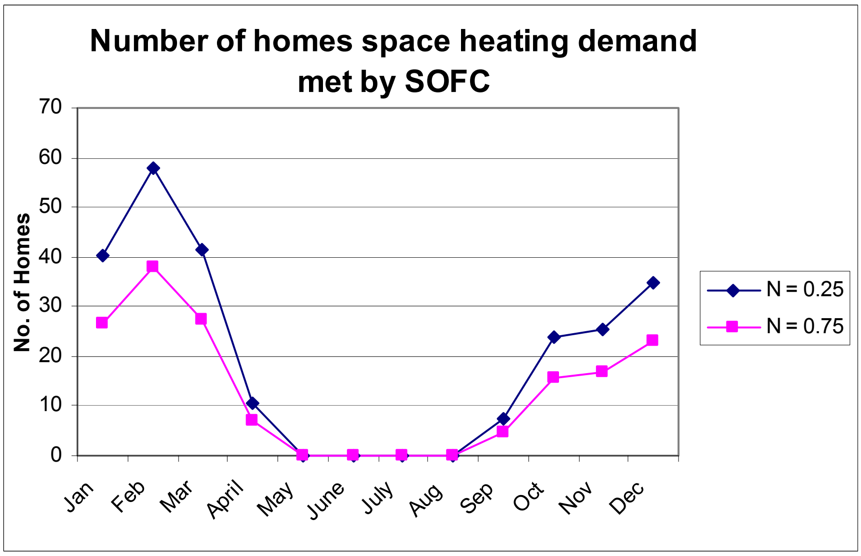

Figure 31: No of homes space heating demands met by SOFC for N = 0.25, 0.75

The overall system efficiency was calculated using an energy balance of the energy in to the system in the form of waves, and the energy out. The energy out comes in two forms, first of all the maximum power from the turbine up to 150kW is always given priority, then the energy generated by the fuel cells is added. At present we will presume that what the fuel cells generate in a certain month they also supply in that month. This means that for four months of the year when the turbine output is below 150kW, there is no energy being supplied by the fuel cell. The overall efficiency was calculated by adding all the monthly values from each fuel cell considered and the output from the LIMPET 500, to get the kWh generated in a year by the entire system.

This value was divided by the total energy input in the form of waves for one year. The following table gives the results of this.

System defined by fuel cell used	Efficiency
PEMFC	16.8%
SOFC	17.65%

Table 14: System efficiency depending on fuel cell used

When the output from the turbine is less than 150kW there is also the option of storing hydrogen to use in the fuel cells to supplement the grid to ensure a full supply. Presuming this is the case, as small a storage time as possible is desirable so as to reduce the necessary capacity as much as possible. The deficit of energy from the maximum permissible by the grid from May to August is shown in the following table.

Month	**May**	**June**	**July**	**August**
Energy generated by LIMPET 500 (kWh)	79864	62876	46050	53908
Deficit (kWh)	31735	45123	65549	57691

Table 15: Monthly deficit of LIMPET 500 under 150kW, May to August

Total energy needed to supplement the LIMPET 500 from May to August = **200,100 kWh**

The hydrogen generated previously to this in the year and available after storage is shown in the following table.

Month	**January**	**February**	**March**	**April**
Hydrogen (kg)	3680	4622	2995	736

Table 16: Hydrogen produced by excess energy, January to April

Giving a total potential amount of hydrogen of = **12075 kgH_2 or 134324.1m^3**

6. Analysis of Results

The analysis of the results of this investigation will be split into three categories:

1. Matching Supply and Demand
2. System Efficiencies
3. Energy Storage Options Comparison

6.1 Matching Supply and Demand

The most efficient way to utilise the wave energy would be by directly supplying customers. By looking at the numbers of homes that would be supplied if there were no grid restrictions and comparing those figures to the ones resulting from a hydrogen Fuel Cell storage system we can see how the system performs against the ideal situation. The following graph displays this information, the data for the two types of fuel cells incorporates not only their electrical output but also that from the LIMPET 500 whether it be fully supplying the grid or not.

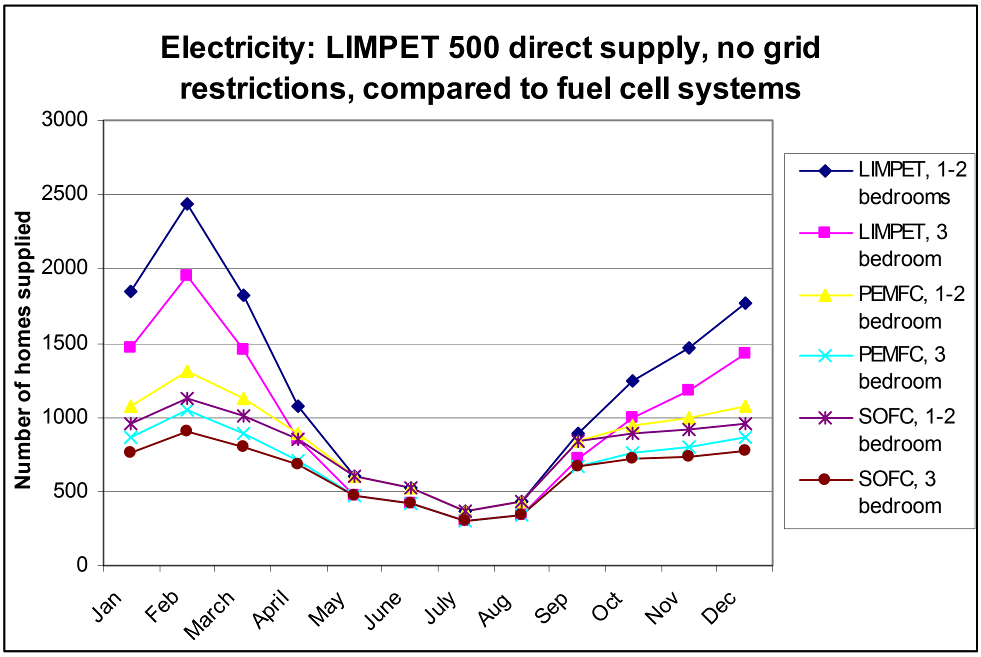

Figure 32: Homes supplied: LIMPET 500 direct supply, no grid restrictions, compared to fuel cell systems

As this graph shows there is a large drop in the number of homes that could be supplied by the LIMPET 500 device when the hydrogen and fuel cell storage system is necessary. Despite being inefficient, it does enhance the performance of the LIMPET 500 by reducing the effect of the grid restrictions. The system allows excess energy to be stored, and to be used to supplement the output from the LIMPET 500 when necessary.

The following graph gives the output from the LIMPET 500 and illustrates the output falling below the capacity of the grid. The storage of hydrogen could allow a fuel cell to supplement the power and maximise the grid. The electrical performance of the fuel cell is what is important and any heat generated during the process can be seen as a bonus.

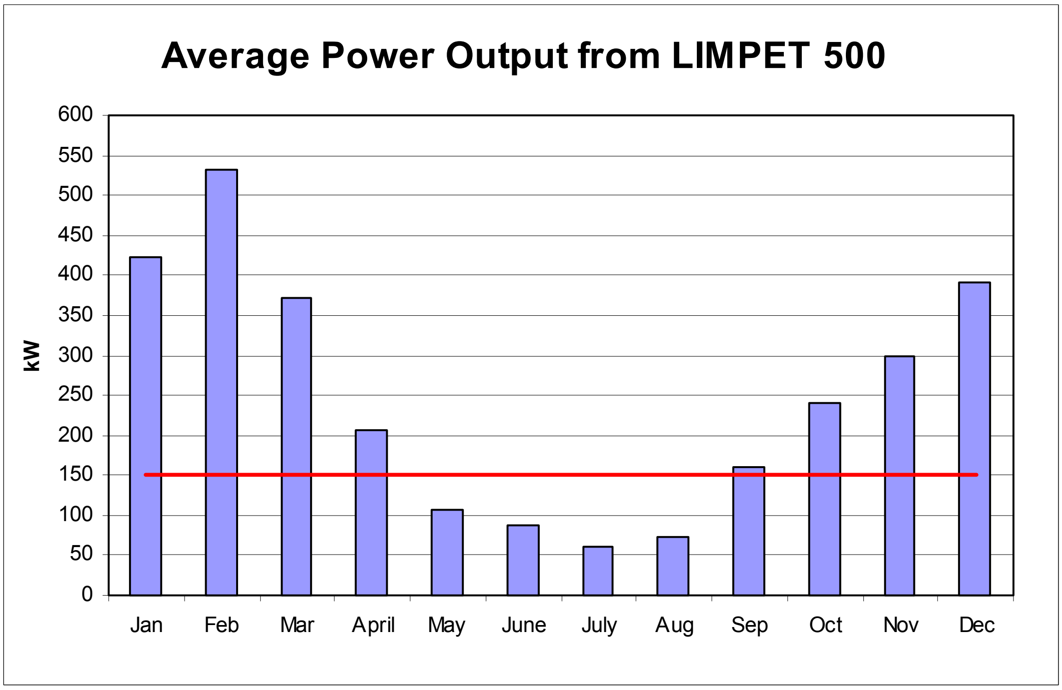

Figure 33: The average monthly output from the LIMPET 500 and the level of grid restriction

On an electrical basis, the PEMFC would be the obvious choice as the power generator to supplement the power required to fulfil the grid due to its higher electrical generating efficiency. An amount of hydrogen which would be stored for this purpose would have to have an element of safety about it, in that more would need to be stored than was predicted to be needed for the sake of error in demand prediction. The hydrogen that is not being stored for this purpose could be used to generate power as it is produced, to supply electricity. Islay has many distilleries which have high electrical needs and the electricity could be generated in a fuel cell on site to offset the strain the distillery puts on the grid. The transportation of the hydrogen would then have to be assessed. United Distillers have initiated an economic study of Islay in the past which covered environmental and energy issues. It is groups like these which could be looked to for financing the formation of a hydrogen system on Islay by utilising the technology to power the distilleries. This would gain publicity and would be a very good demonstration of the potential of the technology and a hydrogen economy on the Island.

Meeting the demand to supplement the LIMPET 500 would mean the following energy output from a fuel cell.

Month	**May**	**June**	**July**	**August**
Energy kWh	31735	45123	65549	57691

Table 17: Energy required from fuel cells to supplement LIMPET 500, from May to August

As shown previously, the amount of hydrogen required to do this would be different depending on the fuel cell used. The PEMFC is more electrically efficient, but the SOFC has the possibility of heat recovery dependent on the electrical load. The PEMFC also has a small heat output but it is much lower than that of the SOFC.

	May	**June**	**July**	**August**
Hydrogen required for PEMFC, kg	1569	2231	3242	2853
Heat Produced PEMFC, kWh	3216	4573	6644	5847
Hydrogen required for SOFC, kg	2226	3166	4599	4047
Heat produced SOFC, kWh	11520	16379	23794	20941

Table 18: Hydrogen required to meet demands by both fuel cells and associated heat production

If heat produced from the fuel cell can be utilised then the SOFC is the obvious choice and will also reduce the amount of hydrogen in storage. If a purely electrical output is required then the PEMFC is the obvious choice as it is a more efficient producer of electricity.

The amount of homes that this heat would supply in terms of space heating requirements is shown for both the fuel cell types, for the period when they could be used to maximise the grid.

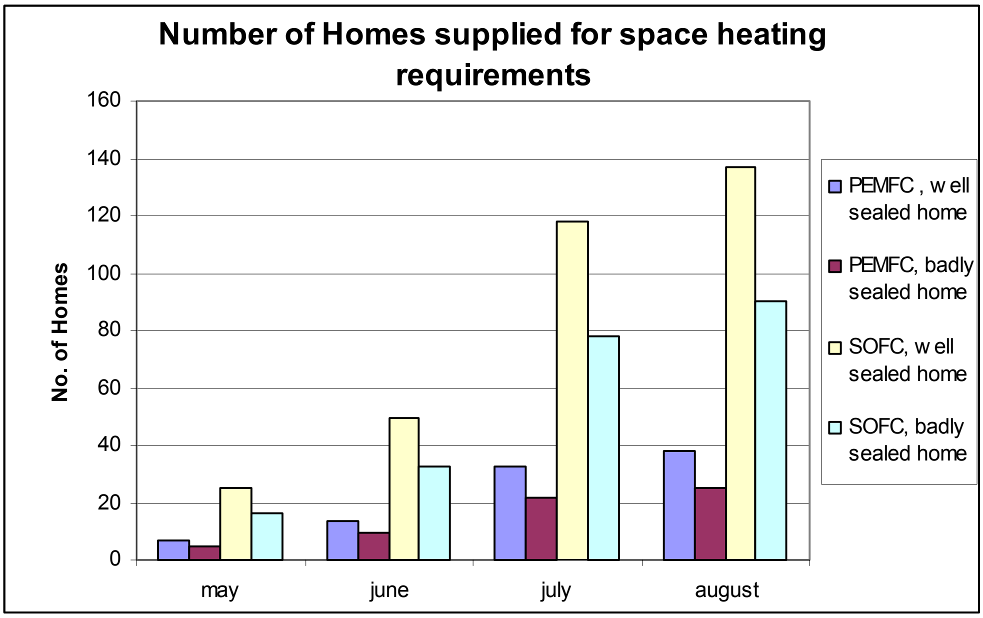

Figure 34: Number of homes supplied for space heating requirements

This would alter the homes that could be supplied in the earlier months of the year as more hydrogen would be stored rather than used. This would be from February until May which is still a cold time of the year for Scotland, and the electrical and thermal demands of homes are still high especially at the beginning of this period. The nearby village of Portnahaven has 68 houses in it. Its proximity to the site of the LIMPET means that if fuel cell generation was to take place there and heat could be recovered and used in peoples homes then it could supply a significant amount of the local population's energy requirement for space heating. Also, if we look at figure 27 in the previous chapter we can see that the heat produced throughout the colder months of the year could meet the demand of a significant number of homes if hydrogen is used for generation as it is produced, mainly when considering the SOFC.

To supply customers with electricity on top of that supplied by the grid using fuel cells would mean the design of a centralised supply system which would be expensive to initiate. Initially, the most economically favourable decision would more than likely be the implementation of the fuel cell system to supplement electricity from the LIMPET 500 to ensure full supply at either times of low wave energy or when the device is unavailable. This investigation is illustrating the true potential of such a system. This would also allow monitoring and testing of the system when not in use.

It can be seen in figures 28 and 29 in the previous section, that if operated on hydrogen when produced throughout the year, both fuel cells hold promise for being able to supply a significant proportion of the consumers of electricity on the Island, this supply combined with the supply from the LIMPET 500 ensures a large renewable resource for the Island as shown in figure 32 at the beginning of this chapter.

Wind energy is also being proposed for Islay and an existing hydrogen infrastructure could help to optimise this also intermittent form of renewable energy. How this electricity could be distributed to its point of use is a possible avenue for future study.

6.2 System Efficiencies

The overall system efficiencies take into consideration both the electrical and thermal outputs from the fuel cells. The outputs from the system do not necessarily display the exact energy which can be utilised; the reasons for this will be covered in the discussions chapter of this paper. The following numbers are the result of adding the energy out from the LIMPET and the fuel cells in the year and dividing it by the energy input from the original source; the waves off the west coast of Islay. The efficiency is shown with and without heat recovery to illustrate the effect of heat utilisation on the efficiency of the whole system.

Fuel Cell used in system	**PEMFC**	**SOFC**
System efficiency utilising electrical energy only.	**16.39%**	**15.21%**
System efficiency utilising electrical and heat energy.	**16.82%**	**17.65%**

Table 19: Overall system efficiencies

The previous table shows that the system efficiency using either fuel cell is low. Cogeneration makes a difference to the overall efficiency when heat is utilised from the SOFC. The technology is still developing and improvements in performance are expected in the near future.

6.3 Energy Storage Options Comparison

Energy storage is not a new challenge and batteries and flywheels are two methods which have been around for many years. The hydrogen system analysed in this paper is a futuristic one, how this compares to the more traditional methods will now be looked at. First of all, lead acid batteries and flywheels will be introduced and then compared to the hydrogen system. A future use of hydrogen in combustion engines and turbines is also attracting interest. What potential this holds for the future will also be investigated.

6.3.1 Lead Acid Batteries

This form of electricity storage is purely electrical. The lead acid battery is the most widely used storage battery; it was invented in 1860 by Planté. It works under a similar principle to that of electrolysis and fuel cells, two solid plates are immersed in an electrolyte. The plates are grids holding pastes of lead and lead dioxide. The electrolyte is a solution of Sulphuric Acid and deionised water, 35% and 65% respectively. The electrolyte ionises as follows:

$$H_2SO_4 \rightarrow H^+ + HSO_4^-$$

During the discharge of the battery, the reaction at the cathode or negative electrode is:

$$P_b + HSO_4^- \rightarrow P_bSO_4 + H^+ + 2e^-$$

The lead (P_b) is oxidised and deposited as the sulphate P_bSO_4, this sulphate replaces the lead paste in the new cell. The electrons liberated in the reaction travel through the external circuit which connects the two electrodes to the anode. The reaction at the anode or positive electrode is as follows:

$$P_bO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow P_bSO_4 + 2H_2O$$

The electrical current in the circuit is carried by the H^+ and HSO_4^- ions from the sulphuric acid. These also take part in the reactions at both the anode and cathode.

Batteries do not last forever and require maintenance and regular cleaning. Intermittent use and charging of a battery can affect its performance for the worst. Long periods of idleness are not good for the battery and damaging sulphation builds up on the plates. This problem affects the lifetime of the battery and only 30% of batteries sold today reach the 48 month mark[42]. The cause of this build up of sulphation is numerous:

- Too long between charges
- Battery Storage without some form of energy input.
- Undercharging will allow left over battery chemistry capacity to cause sulphation.
- As the temperature rises so does internal discharge, a new fully charged battery left sitting 24 hours a day at 110°F for 30 days would most likely not start an engine[43].
- A low electrolyte level can expose the plates to air which will immediately cause sulphation.
- A deeply discharged battery will freeze in sub zero temperatures.

Batteries perform at their best when regular maintenance and inspection are carried out and recharging takes place immediately after discharging. The efficiency of a lead acid battery is around 50%[44] when looked after properly.

The disposal of lead acid batteries has been an environmental problem worldwide. Lead is known to cause environmental and health related problems. The disposal must be performed properly within guidelines set out by government policy. This can be expensive and many measures must be taken to ensure that during operation and disposal no leakage to the environment occurs and that the habitat around the battery remains intact.

6.3.2 Flywheels

This method of energy storage is based on a mass rotating about an axis. This has been a popular choice for the smoothing of operation of engines for many years. An electrical input accelerates the rotor to speed by using a built in motor. The electricity is returned by using the

[42] Hawker Energy Products Inc, 1997
[43] Hawker Energy Products Inc, 1997
[44] "Energy Resources and Policy", Lecture Notes of Dr Andrew Grant, Strathclyde University, 2001

same motor as a generator. The rotor is normally enclosed within a vacuum to eliminate air resistance on the rotating mass which would slow it down and result in a loss of energy.

Traditionally, flywheels are made of steel but advances in the mechanical properties of composites have renewed interest in the technology as they enable higher rpm to be achieved. This technology is attracting interest for electric vehicles and load levelling in particular.

They offer high energy density and have advantages over chemical storage. Energy can be put into or taken out of the battery very quickly; the only limitation is the motor-generator design. It is possible to extract large amounts of electricity from flywheels in a far shorter time than conventional batteries. Flywheels are mainly unaffected by temperature extremes, have a very high output and a long life. The stored energy within a flywheel is the sum of the kinetic energy of all the individual mass elements that comprise it:

$$E_k = \frac{1}{2} I\omega^2 \tag{17}$$

Where ω = Rotational velocity (rpm)
I = Moment of Inertia (kgm^2)

The moment of Inertia can be calculated using the following:

$$I = K \cdot M \cdot R^2 \tag{18}$$

Where K = Inertial constant (dependent on shape)
R = Radius (m)
M = Mass (kg)

The value of the Inertial constant K, is at a maximum for a wheel loaded at the rim such as a bike tyre, for this situation k=1.

Flywheels are around 75% efficient[45].

[45] "Energy resources and Policy", Lecture Notes of Dr Andrew Grant, Strathclyde University, 2001

Assuming these efficiencies to be accurate we can assess how flywheels and lead acid batteries compare to the hydrogen storage system we have studied already. It is worth noting that no heat will be extractable from either of the previous two storage methods discussed. All this analysis will show is the true electrical potential of each method and there are other factors which need to be considered. These are the social, economical and environmental factors involved in each method. The hydrogen system is more environmentally friendly than the lead acid battery which requires disposal of chemicals after use. In this situation the lead acid battery would not perform well due to the sporadic charging it would undergo, and long periods of idleness in the summer months when excess electricity to charge any batteries used would be unavailable. This could lead to sulphation and affect the life of the battery. Utilising large amounts of energy would also require large batteries and therefore maintenance would need to be available regularly. This could be a problem in a remote community such as Islay, and the shipping of such large units to such a remote area would be expensive.

The noise from a flywheel could be a problem for nearby residences. There is a flywheel already in place at the LIMPET 500 to ensure a smooth output from the turbine. A study would have to be undertaken to predict the size and number of flywheels that would be necessary to store the excess energy output from the LIMPET 500, affecting the efficiency of the process.

If the only need is for electrical storage then both these technologies hold promise for this application, but a fuel cell and hydrogen system which provides electricity and heat would provide a different service which possibly is more important in this situation where there is not a high electricity demand nearby. This could offset some of the demand for electric heating on the Island which is becoming more popular as local alternatives, such as peat and coal, are more expensive[46]. This system is a more sustainable way of meeting the overall needs of a small, isolated community providing the heat that is produced can be utilised.

The electrical efficiency of the storage system alone (i.e. excluding the efficiency of the LIMPET 500 and all its components), the fuel cell and hydrogen system analysed in this paper, gives the following results:

[46] "The Islay Energy Study", ETSU 1996

Hydrogen Storage system, Fuel Cell used	Electrical Efficiency
PEMFC	35.3%
SOFC	24.9%

Table 20: Electrical efficiency of storage system

It can be seen that these are below the electrical efficiencies of flywheels and lead acid batteries. But this is a futuristic system and a developing technology; if hydrogen is to become the fuel of the future then this system could be an important part of a sustainable energy program based around hydrogen on the island of Islay. It would also serve as an environmentally friendly way of optimising renewable energy, and would be an international demonstration of the technology. Indeed, if heat is utilised from the fuel cells then the overall efficiency rises again as the following table shows.

Hydrogen Storage system, Fuel Cell used	Overall Efficiency
PEMFC	39%
SOFC	46.4%

Table 21: Overall storage efficiency, utilising heat

This is an important aspect of fuel cells, especially the higher temperature cells such as the SOFC. They have the capability for higher overall system efficiencies providing the heat they produce can be utilised. These efficiencies are not as high as the other methods discussed for storage but this technology is still under development and advances in system efficiencies will come.

The efficiency of the LIMPET 500 alone is calculated by an energy balance and gives the following result.

LIMPET 500 Efficiency	23.75%

Table 22: Efficiency of LIMPET 500

Hydrogen combustion in conventional engines could be an important part of building up a hydrogen infrastructure. On Islay there is a 6.2MW standby diesel generator located at Bowmore. It has been shown elsewhere that in the future it is thought that these engines will be adaptable for hydrogen fuel by the development of a hydrogen injector and ignitor. It is thought that this will lead to an electrical efficiency of 45-50%[47] LHV and a perfectly clean system. This would be another attractive method of generation from hydrogen on the island. The injection of hydrogen is the main problem for adapting these types of engines; this is because a high velocity of hydrogen is required (2.65 – 3.25m/s for hydrogen compared to 0.4m/s for methane)[48]. This obviously means that high pressures are involved and that makes the flame harder to control.

Combustion in a gas turbine was also the focus of a previous study[49], the results of which showed that this holds potential for large scale and centralised power generation. The study proved the electrical efficiency to be around 61% HHV, with a gas inlet temperature of 1700˚C. This is a very attractive result and also holds potential for cogeneration due to the high temperatures involved.

These studies were undertaken in Japan which has very high energy costs and few natural energy resources. For these reasons it is looking to hydrogen as an important part of a sustainable future.

47 "Hydrogen/Oxygen fuelled diesel cogeneration systems", WE-NET: The national H_2 program of Japan, vision and status
48 http://www.esru.strath.ac.uk/EandE/Web_sites/99-00/hybrid_PV_FC/burninghydrogen.html
49 "Hydrogen/Oxygen fuelled diesel cogeneration systems", WE-NET: The national H_2 program of Japan, vision and status

7. Discussions

The study undertaken was completed and the results obtained. These results are based on calculations using average values and should not be taken as exact figures for the system in question. What these results do is illustrate the potential of such a system and let us see how it compares to other options that are available today.

The electrical outputs from the fuel cells will be lower then those calculated. This will be due to the pumps, fans and compressors which are a part of any fuel cell system and are a load which the electricity from the fuel cell must meet. This should be taken into account when considering these values. The heat output from the fuel cells is similar in that it can also be expected to be lower as heat extraction form the cell will not be 100% efficient. How efficient it will be depends on the proximity to point of use and the design of the heat exchanger used to extract it. To compress hydrogen for storage would also require energy. This would depend on the pressure of storage, how much hydrogen requires storage, and on the goal of the system, i.e. whether it would supply electricity from the hydrogen quickly after storage or would keep it for longer.

In reality the system is much more dynamic, supply and demand both change rapidly. A fuel cell systems ability to meet these demands would be hampered by start up time, especially in the case of the SOFC. The PEMFC is renowned for its quicker start up as it operates at a lower temperature. Performance can be affected by rapidly varying loads.

The reversible fuel cell holds potential for this type of application where production of hydrogen and generation using the hydrogen takes place in the same location.

The figures for the wave data are from the Orkney test centre and this explains why it appears that more power is available from the turbine than it is able to produce in the month of February. In a more detailed analysis with proper wave data this would not happen, as the turbines will have been sized according to the results of a study into the wave characteristics of this site. These results were unavailable to the author.

7.1 Social, Environmental and Economic factors

What affects an energy system or plant has, can be summarised using three main categories:

- ***Social***
- ***Environmental***
- ***Economical***

This system would have social implications. There would be employment in the area in question which would be beneficial to attracting more people to stay on the island which suffers during the winter from the absence of workers who only stay for the busy summer period. The traffic to the area would increase, meaning noise and air pollution levels would be higher which could affect the local population.

The local environment would be changed but the LIMPET 500 is in a remote part of the island with few houses nearby. Nevertheless new plant would be built on the landscape and if a district heating scheme were employed to utilise the heat from the fuel cells then this would require major work in the area. A storage system, involving hydrogen and fuel cells, benefits the environment in that it is emission free and offsets the need for fossil fuels and other environmentally harmful methods of energy production. It would be a further display of the environmental awareness of the area to utilise renewable energy.

The local area would benefit financially from new jobs and also the influx of people who have many needs to be met, such as accommodation. This would also give an economic boost to the area and encourage tourism. Any system such as this would be very expensive and an economic analysis would be an important part the investigation and is recommended for future work. The type of system considered is not financially feasible at present but could be a target for funding due its futuristic outlook and demonstration of what is such a promising and safe technology for the future.

8. Recommendations for future work

This paper has illustrated the potential of a hydrogen and fuel cell storage system for electricity from wave energy on the island of Islay. The results are not exact and the system has a much more dynamic performance than the steady state one analysed, each component's own dynamic behaviour would need to be modelled. This would be best achieved using computer modelling; a simulation programme such as SIMULINK could facilitate this type of analysis.

Any further work would have to involve site specific wave data for the LIMPET 500. An economic analysis would also be required to assess the start up capital and the cost of electricity from such a system. Hydrogen storage is an important issue for consideration and a more detailed investigation into methods of storage, in terms of performance, economics and practicality would be necessary.

9. Conclusions

The objective of this thesis has been achieved. The system that was analysed has given a picture of the potential of using hydrogen and fuel cells for optimising wave energy on Islay. The fuel cells that were analysed have shown that there is potential for a substantial portion of the electrical and thermal loads of the island to be met. This is an environmentally friendly way to harness the electricity which the LIMPET 500 cannot supply due to grid restrictions.

The results have shown the number of homes whose electrical and thermal loads can be supplied by the fuel cell systems. This was done for a variety of housing categories and gives an indication of how many homes of a certain type can be supplied by each system. Hydrogen and fuel cells are developing technologies and the creation of a hydrogen system on Islay could lead to further uses of hydrogen on the island and also more hydrogen production from other renewable sources, potentially playing an important part in the development of the technology with a view to improving performance and increasing system efficiencies.

This is a promising technology for the future as it becomes more important to fully harness renewable energy wherever possible. This system allows storage of that energy in an environmentally friendly, emission free manner. As renewable energy becomes more economically feasible, the possibility of such a system will become a more realistic option.

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