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Hydrogen production from biogas:

A model for the H2 SEED Project

by

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“I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable.”
Jules Verne, *The Mysterious Island (1874)*

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Abstract

The release of greenhouse gases generated by humankind since the Industrial Revolution seems to be irreversibly affecting the equilibrium of the whole planet. Considering this scenario, many initiatives are under analysis to curb the emissions of Greenhouse gases and at least try to mitigate the "dangerous anthropogenic interference with the climate system", as stated in Kyoto Protocol.

Among many options, hydrogen is one of the most attractive choices.

The main objective of this project is to simulate the H2 SEED project that will be installed in Stornoway, Isle of Lewis. Stornoway is the main city of the Outer Hebrides, a set of islands located in North-West of Scotland. This region is well known by its unrivalled natural resources, especially for wind and marine power.

In this project, hydrogen will be produced from biogas, for supply to a small filling station and also to fill cylinders for a variety of applications and demonstration projects in the region.

A model in TRNSYS was developed to simulate different operational conditions of the plant and to explore alternative configurations.

The model showed that the system is feasible and can produce enough hydrogen to meet the demands of the local council. The model also showed that alternative configurations could be implemented.

1 Introduction

1.1 Motivation

Global warming and climate change have become topics of quotidian discussion. Once mere speculation of some scientists, the latest wave of extreme climate across the world possibly indicate that humankind is facing the biggest environmental challenge in its history.

The release of greenhouse gases generated by humankind since Industrial Revolution seems to be irreversibly affecting the equilibrium of the whole planet.

Considering this scenario, many initiatives are under analysis to curb the emissions of Greenhouse gases and at least try to mitigate the "dangerous anthropogenic interference with the climate system", as stated in Kyoto Protocol.

The most important measure to reduce the levels of CO_2 and other harmful gases in atmosphere is the substitution of fossil fuels. Taking into account the public objection against nuclear power and its inherent risks, the only alternative to traditional fuels are renewables.

The majority of renewable energy technologies are still under development but some recent research shows promising results: among the many options, hydrogen is one of the most attractive choices in long term, since it can be obtained from an abundant resource and it almost does not generate any emission.

Nevertheless, some challenges must to be overcome before hydrogen can be used without restrictions. Most of hydrogen technologies are in the early stages of development; thus, lifetime, efficiency and reliability are issues for commercial applications.

The biggest barrier for hydrogen is cost. Not only the cost of a new distribution infrastructure but also the cost of electricity generation are too prohibitive when compared to traditional sources in a business as usual scenario.

Recent studies show that hydrogen can achieve remarkable penetration in some sectors within 20 or 30 years given appropriate regulatory incentives and considering economies stemming from mass production and technology learning.

1.2 Project outline

This project is supported by Greenspace Research Institute from Lews Castle College in cooperation with University of Strathclyde. This project is one small element of significant hydrogen research being undertaken in the Outer Hebrides and seeks to contribute to further developments and future projects in the region.

1.3 Main objectives

The focus of this project is to analyse the H2 SEED project and propose alternative configurations for this kind of system. This system will produce hydrogen from biogas produced from organic municipal waste in Outer Hebrides.

Within the scope of this project is included:

- modelling of the H2 SEED Project as a reference case
- proposition of alternative configurations to the system
- comparison of different technologies
- suggestion of several technological pathways to the establishment of hydrogen infrastructure in Outer Hebrides.

It is intended that this project can provide support for several future initiatives under development in Outer Hebrides.

1.4 Organisation of this dissertation

This dissertation is organised as follows. **Chapter 2** presents a broad review of hydrogen technology, addressing status, potential for further development and economic aspects. It also lists some demonstration projects around the world. **Chapter 3** outlines the background of the project, especially the conditions in the Outer Hebrides that motivated several initiatives under development in the region. **Chapter 4** present the technological pathways to hydrogen from biogas, detailing a demonstration project. **Chapter 5** details the objectives of the project, defines the methodology and describes the tools that were used to develop the model. On **Chapter 6,** the details of system are presented and the simulation is described. The main assumptions, basic data and results obtained for the reference case and alternative scenarios are also presented in this section. **Chapter 7** presents the overall analysis of the results, addressing main conclusions, alternative configurations for the system, recommendation for further research and suggestions of new projects for the region. **Chapter 8** presents the references that supported this study. In the last section, some support material is included as **Appendixes**.

2 Hydrogen Technology

2.1 Overview: Hydrogen as an energy carrier and the "hydrogen economy"

Hydrogen was first recognised as a distinct substance in 1766 by Henry Cavendish. Since then and especially over the last 50 years, industry has used large amounts of hydrogen as an industrial chemical and as an aerospace fuel. However, among the general public, hydrogen has a misleading reputation stemmed from the spectacular fire that destroyed the German dirigible Hindenburg in 1937. Nevertheless, an investigation in 1990 blamed the doped material covering the outer layer of the airship's envelope as the main cause of the accident.[1]

Recently, environmental awareness and climate change has increased the interest in hydrogen as an energy source. It is considered by many as the fuel of the future. Hydrogen, however, is not a primary source of energy, since it does not t occur free in natural in considerable quantities. Therefore, it is referred as an energy carrier or energy vector, just like electricity.

Combustion of hydrogen with oxygen produces only water; with air and some nitrogen oxides. Hydrogen, thus, is virtually carbon free, depending on the primary resource used for its production.

The following table shows the properties of hydrogen compared to some other fuels.

Table 1: Comparative properties of Hydrogen and fuels (Adapted from [2])

Properties	Units	Hydrogen	Methane	Propane	Methanol	Ethanol	Gasoline [2]
Chemical Formula		H_2	CH_4	C_3H_8	CH_3OH	C_2H_5OH	C_xH_y (x = 4 - 12)
Molecular Weight		2.02	16.04	44.1	32.04	46.07	100 - 105
Density (NTP) [1]	kg/m^3	0.08375	0.6682	1.865	791	789	751
Viscosity (NTP) [1]	Pa.s	8.81×10^{-4}	1.10×10^{-3}	8.012×10^{-4}	9.18×10^{-2}	0.119	0.037 - 0.044
Normal Boiling Point	ºC	-252.8	-161.5	-42.1	64.5	78.5	27 - 225
Flash Point	ºC	< -253	-188	-104	11	13	-43
Flammability Range in Air	vol%	4.0 - 75.0	5.0 - 15.0	2.1 - 10.1	6.7 - 36.0	4.3 - 19	1.4 - 7.6
Auto Ignition Temperature in Air	ºC	585	540	490	385	423	230 - 480
Higher Heating Value (at 25 ºC and 1 atm)	MJ/kg	141.86	55.53	50.36	19.96	29.84	47.50
Lower Heating Value (at 25 ºC and 1 atm)	MJ/kg	119.93	50.02	45.60	18.05	26.95	44.50

(1) NTP = 20 ºC and 1 atm
(2) Properties of a range of commercial grades

Although hydrogen has the highest energy to weight ratio (energy density per mass) when compared to traditional fuels, its low energy to volume ratio (volumetric energy density) constitutes a major setback for further development. For example, to deliver the same amount of energy of 1 litre of gasoline, it would be necessary approximately 20 litres of compressed hydrogen or 3.6 litres of liquid hydrogen. Many researches are currently looking at alternative technologies to store hydrogen in a more efficient way. More details about hydrogen storage will be explored in section 2.3.

The prognosis of a clean source of energy produced from an omnipresent resource – water - coined the term “hydrogen economy”. The hydrogen economy is a hypothetical scenario where hydrogen plays a major role in the energy systems, substituting all fossil fuels by renewables, hydrogen and electrical systems.

More than a vision of Jules Verne, this term is derived from the potential represented by the widespread use of hydrogen technologies. Hydrogen technologies have the following main benefits:

- reduction of carbon emissions: hydrogen can be carbon neutral when produced form renewables
- energy diversity and security of supply, with reduction of dependence on oil or biofuels, whose production is inexorably concentrated in few countries
- increased efficiency: besides less pollutant than the traditional internal combustion engines (ICE) running on fossil fuels, fuel cells can be much more efficient. That is the reason why all big automotive companies are investing considerable amount of resources on fuel cells development
- boost to renewables: hydrogen storage can minimise the intermittency and unreliability of renewable sources
- growing interest for portable power: small hydrogen systems can provide electricity, heat and water even for portable applications.

2.2 Hydrogen production

The vast majority of current world production of hydrogen, around 500 billion cubic meters, is generated from fossil sources, mainly natural gas and oil, or obtained as by-product from chemical industries.

The method of production of hydrogen dictates the life cycle emissions of a hydrogen system: hydrogen is truly carbon free only if it is produced form a renewable primary source of energy.

2.2.1 Thermal Processes

2.2.1.1 Steam Reforming

Steam reforming is an endothermic catalytic conversion of light hydrocarbons in the presence of steam. The main reactions in this process are:

Step 1: $CH_4 + H_2O \underset{cat.}{\overset{\Delta}{\Longrightarrow}} CO + 3H_2$

Step 2: $CO + H_2O \Rightarrow CO_2 + H_2$

The resulting mixture from the reaction is separated by adsorption, producing high-purity hydrogen.

Most of the hydrogen nowadays in the world is produced through this process. This is the most energy-efficient and cost-effective commercial technology, when applied to large, constant loads.

Steam reforming can also be used to produce hydrogen from ethanol and bio-oils obtained from biomass. The following reaction represents the steam reforming of ethanol:

$$C_2H_5OH + H_2O \underset{cat.}{\overset{\Delta}{\Longrightarrow}} 2CO + 4H_2$$

In stationary fuel cells, the process responsible for the generation of electricity from methane is also reforming.

Methane can be obtained from natural gas or produced by anaerobic digestion of sewage, waste or biomass. In this process, micro-organisms decompose organic matter, producing a gas mixture called biogas, composed mainly by methane and carbon dioxide. Even though this gas has small concentration of hydrogen, it can be used directly in advance High Temperature Fuel Cell (MCFC) or Solid Oxide Fuel Cells (SOFC) to produce electricity directly. In this case, the reforming of methane occurs directly at the electrode due to the high operational temperature. The presence of CO_2 is beneficial since it accelerates the reforming of methane.

2.2.1.2 Partial oxidation

Partial oxidation is the thermal conversion of hydrocarbons and alcohols with or without the presence of catalyst into hydrogen. This reaction is exothermic and requires lower temperatures, which makes the process less energy and cost intensive than steam reforming. Researches in progress are trying to develop catalysts that are more efficient, with higher selectivity and more resistance to high temperatures. [3]
The reaction of partial oxidation of methane is:

$$CH_4 + \frac{1}{2}O_2 \overset{\text{cat.}}{\Longrightarrow} CO + 3H_2$$

2.2.1.3 Plasma-arc process

The Norwegian company Kvaerner has been developing since 80's the plasma arc process which at temperatures of 1,600°C, splits hydrocarbons into pure carbon and hydrogen. The process has high efficiencies, produces no significant emissions and requires along with the primary energy source, cooling water and electricity.
A pilot plant is operating since 1992 and a large-scale plant is planned to be built, with a capacity of 100,000Nm^3/h of hydrogen. [4]

2.2.1.4 Biomass and Coal Gasification

The gasification process is carried out under high temperature and pressure in the presence of steam and a controlled amount of oxygen.
The reaction for coal gasification can be represented as:

$$10CH_{0.8} + \frac{17}{2}O_2 + 2H_2O \Rightarrow 5CO + 5CO_2 + 6H_2$$

A similar process is used to gasify biomass. Since biomass has highly variable composition and complexity, the complete gasification process takes one more step, in order to reform the gaseous hydrocarbons generated in the first stage.

2.2.1.5 Solar and Nuclear Thermal Splitting

High temperature can be used to produce hydrogen. Temperatures between 500 to 2000 ºC drive a series of chemical reactions in which the reactants are recycled, in a closed loop that consumes only water.

Next generation nuclear reactors under development, reaching up to 1000 º C, or solar concentrators, reaching up to 2000 º C, could supply the heat needed to drive this kind of reaction.

Researchers have identified more than 200 possible cycles with different substances. These are two examples:

- Zinc Oxide in a solar concentration at 1900ºC

$$2ZnO \overset{\Delta}{\Rightarrow} 2Zn + O_2$$

$$2Zn + 2H_2O \Rightarrow 2ZnO + 2H_2$$

- Sulphur-iodine cycle with the help of a nuclear reactor

$$2H_2SO_4 \overset{\Delta = 850^o C}{\Rightarrow} 2H_2O + 2SO_2 + O_2$$

$$4H_2O + 2SO_2 + 2I_2 \Rightarrow 2H_2SO_4 + 4HI$$

$$4HI \overset{\Delta = 300^o C}{\Rightarrow} 2I_2 + 2H_2$$

2.2.2 Electrolytic Processes

Electrolysis is the process of splitting molecules of water into molecules of hydrogen and oxygen using electricity. This technology was mainly used for industrial production of chlorine through electrolysis of sodium chloride (NaCl), generating as by-products sodium hydroxide (NaOH) and hydrogen.

The diagram below illustrates the process

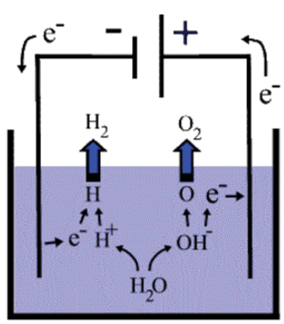


Figure 1: Schematic representation of an eletrolyser

These are the main technologies for electrolysis:

- **PEM Electrolysers**: The Polymer Electrolyte Membrane (PEM) electrolysers use a solid plastic membrane as electrolyte;
- **Alkaline Electrolyser**: similar to PEM electrolysers, these equipment use an alkaline solution as the electrolyte;
- **Solid Oxide Electrolyser**: use a solid ceramic material that selectively transmits negative charged oxygen ions at around 500 to 800 ºC.

The following table present the characteristics of regular and advanced electrolysers.

Table 2: Characteristics of existing and advanced electrolysers [5]

Technology	**Conventional electrolyser**	**Advanced Alkaline Electrolyser**	**Inorganic Membrane Electrolyser**	**PEM electrolyser**	**SOFC High temp. steam electrolyser**
Development stage	Commercial large scale units	Prototypes and commercial units	Commercial units	Prototypes and commercial units	Lab stage and commercial units
Cell voltage (V)	1.8-2.2	1.5-2.5	1.6-1.9	1.4-2.0	0.95-1.3
Current density (A/cm^2)	0.13-0.25	0.20-2.0	0.2-1.0	1.0-4.0	0.3-1.0
Temperature (°C)	70-90	80-145	90-120	80-150	900-1 000
Pressure (bar)	1-2	Up to 120	Up to 40	Up to 400	Up to 30
Cathode	Stainless steel or Ni	Catalytic or or non-catalytic active Ni catalystic	Spinel oxide based on CO	C- fibre and Pt	Ni
Anode	Ni	Catalytic or or non-catalytic active Ni	Spinel oxide based on CO	Porous Ti and proprietary catalyst	Ni-NiO or Perovskite
Gas separator	Asbestos 1.2-1.7 Ohm/cm^2	Asbestos < 100°C; Teflon bonded PBI- K-titanate >100°C; 0.5-0.7 Ohm/cm^2	Patented polyantimonic acid membrane 0.2-0.3 Ohm/cm^2	Multilayer expanded metal screens	None
Electrolyte 25-35%	25-40% KOH	14-15% KOH	Perfluorosulfonic KOH	Solid Y_2O_3 acid membrane 10-12 mils thick 0.46 Ohm/cm^2	stabilised ZrO_{380}
Cell efficiency (GJ H2/GJ el)	66-69	69-77	73-81	73-84	81-86
Power need (kWh/Nm^3H^2)	4.3-4.9	3.8-4.3	4.8	3.6-4.0	2.5-3.5

2.2.2.1 Synergy between electrolysis and other renewables

With electrolytic systems, hydrogen can also be produced from several renewable sources such as wind, marine, geothermal and tidal power.

In this pathway, hydrogen is produced and stored as a way to minimise the intermittency and unavailability of the renewable energies. In a connected system, a renewable power plant would dispatch electricity to the grid in normal operation; in periods of excess of electricity available in the grid, the electricity would be redirected to an electrolyser, producing hydrogen for storage. This hydrogen then can be used to generate electricity in a fuel cell in periods of unavailability or shortage of the renewable resource.

It is worth mentioning that the control of this system is complex and further development is needed to achieve commercial operation.

2.2.3 Photolytic Processes

Some researches are looking at biological hydrogen production, where special kinds of bacteria or algae produce hydrogen directly as a by-product of their metabolic processes. This can constitute in the future one of the most important resources for hydrogen production, but there is need for great progress. By now, the main challenges to be addressed are the low hydrogen yield per gram of organic matter, long recovery time between cycles of production and high cost of construction materials. [6-7]

Photoelectrochemical water splitting is also under research, in which hydrogen is produced from water using light and special semiconductors called photoelectrochemical materials.

2.3 Storage

Hydrogen storage is a key enabling technology. Not only as the potential application as an energy buffer substituting large scale battery systems but also to make transport application commercially feasible.

The key challenge is to develop storage methods with higher energy densities, which can provide considerable amounts of energy in a safer and cheaper way. The main current technologies are compressed gas, liquid hydrogen and materials-based storage.

The following chart illustrates a comprehensive view of the status in terms of weight, volume and cost of various hydrogen storage technologies.

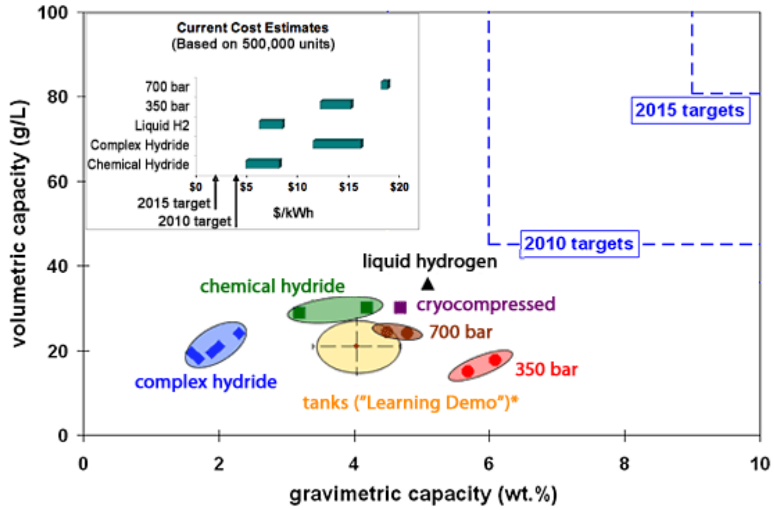


Figure 2: Status of hydrogen storage technologies. **Presented costs expressed in US$. [8]**

2.3.1 Compressed gas

The storage as a compressed gas is the most mature technology. Mobile application requires high-pressure tanks, typically from 300 to 700bar, due to lack of space aboard a vehicle. Some carbon fibre reinforced tanks are under development but the cost of material and conformability are issues that still need to be addressed. [8]

2.3.2 Liquid hydrogen

The liquid hydrogen storage is a well-understood technology. It presents higher density than compressed gas but requires cryogenic tanks, since the boiling point of hydrogen is -252.8ºC (around 20K).

The main barriers are large evaporative losses, volume, weight and tank cost, and especially the energy intensity of liquefaction: typically, 30% of the heating value of hydrogen is consumed in the process.

Hybrid tanks, called cryo-compressed tanks, combine high pressure and cryogenic technology. These vessels are lighter than hydrides and more compact than compressed tanks. Furthermore, the process is less energy intensive than liquefaction and present less evaporative losses. [5]

2.3.3 Materials-based storage

Hydrogen can be stored in materials by absorption, adsorption or chemical reaction.

The main methods of materials-based storage are metal hydrides, chemical hydrides and carbon based materials

- **Metal hydrides:** they present on-board reversibility and can release hydrogen at low temperatures and pressures**.** Current hydrides present gravimetric capacity from 1.3 to 4 wt% but some complex hydrides can potentially achieve 10wt%. [8] Although not providing much higher storage density than compressed gases (around 200bar), metal hydrides are particularly interesting by conformability and safety, since they operate under low temperatures and pressures, but currently present problems with degradability, weight and cost. Some manufacturers are already using this technology in the tanks of their hydrogen hybrid vehicles.

Table 3: Key properties of main metal hydrides [5]

	Max. theoretical storage density wt%	**H_2 release temperature °C**
Alanates		
$LiAlH_4$	10.6	190
$NaAlH_4$	7.5	100
$MgAlH_4$	9.3	140
$CaAlH_4$	7.8	>230
Borohydrides		
$LiBH_4$	18.5	300
$NaBH_4$	10.6	350
KBH_4	7.4	125
$Be(BH_4)_2$	20.8	125
$Mg(BH_4)_2$	14.9	320
$Ca(BH_4)_2$	11.6	260

- **Chemical hydrides:** also called chemical hydrogen storage, is the generic term that describe processes in which hydrogen is generated through chemical reactions, most commonly using chemical hydrides with water or alcohols. In most cases, the reactions are not easily reversible and the regeneration must be carried out off-board. The following reaction is one example of this kind of process:

$$NaBH_4 + 2H_2O = NaBO_2 + 4H_2$$

This sodium tetrahydridoborate system has gravimetric capacity of about 4% but presents the common problems of this technological route: necessity of regeneration off-board, regeneration energy requirements, system volume and weight, complexity and water availability and storage.

Similar systems under development use MgH_2 with water, conversion of decalin ($C_{10}H_{18}$) under moderate temperatures to naphthalene, or ammonia borane materials (Na_3BH_3).

- **Carbon based materials:** carbon nanotubes and fullerenes promise to revolutionise the hydrogen storage technology in the future. Although some initial experiments had some problems of replicability, there is potential that this technology would lead to a capacity from 3 to 6 wt% at room temperature. [8]

2.4 Hydrogen Transport and Distribution

Hydrogen can be transported and distributed as a compressed gas or as a cryogenic liquid. The chosen method for transport and distribution depends on the consumption of hydrogen and the area to be covered. The following chart shows the appropriate demand for each method of transport and distribution:

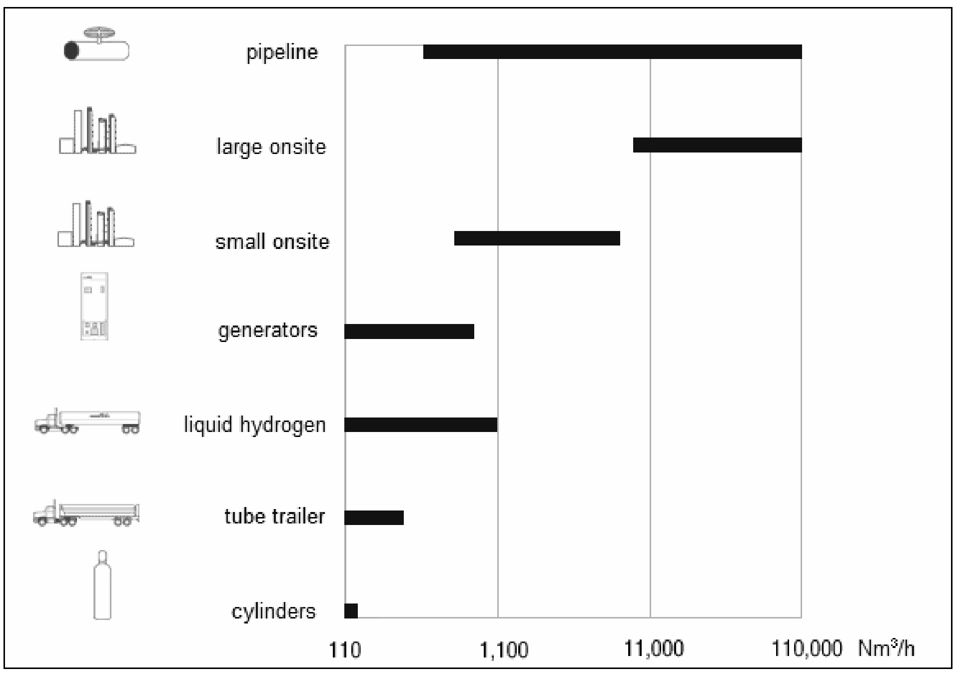


Figure 3: Methods for hydrogen distribution [9]

Pipelines are the least expensive way to deliver large amounts of hydrogen. They have been used for more than 50 years and there are currently in the world several thousands of kilometres of hydrogen pipelines. These pipelines do not constitute a network, in the sense that they were built solely to supply hydrogen for refineries and chemical plants. Current hydrogen pipelines operate at a pressure of 10-20 bar, but pressures up to 100 bar can be used.

Hydrogen pipelines must be made of non-porous materials, such as stainless steel. The hydrogen molecules are so small that they would be able to permeate porous materials, resulting in gas losses and making the pipeline materials brittle. The main consequence of this problem is that most of the natural gas network cannot be used for hydrogen.

Transporting compressed hydrogen gas over the road in high-pressure tube trailers is expensive and used primarily for short distances; it becomes cost prohibitive when transporting farther than about 200 miles from the point of production. As long as liquid hydrogen has a higher energy density, cryogenic tankers are the preferred method for delivering hydrogen over long distances.

Since hydrogen pipeline transport has limited availability and high capital cost for development, hydrogen is often transported in cryogenic tankers and then vaporised at the point of consumption.

2.5 Fuel Cells

A fuel cell is a device that uses hydrogen and oxygen to produce electricity, generating as by-products heat and water. Fuel cells can potentially substitute with advantages several applications that use combustion-based technologies, mainly in transport. In this way, a myriad of applications are envisaged, from systems as large as utilities power stations to small appliances as a computer. Fuel cells are basically classified by the electrolyte employed.

2.5.1 Polymer Electrolyte Membrane Fuel Cells (PEM)

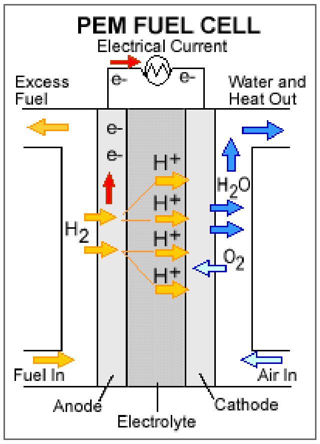


Figure 4:Schematic diagram of a PEM Fuel Cell [3]

This model is also called proton exchange fuel cells. They deliver high power density and present lower weight and volume when compared to other fuel cells. These fuel cells use a solid polymer as the electrolyte and porous carbon electrodes containing platinum catalyst.

They operate in low temperatures (around 80 ºC) and use pure hydrogen. The catalyst is especially sensitive to CO poisoning, requiring hydrogen with high degrees of purity. [3]

For vehicles application, their lifetime is around 2,000 hours. For stationary applications, they may reach 30,000 hours. [10]

2.5.2 Direct Methanol Fuel Cells (DMFC)

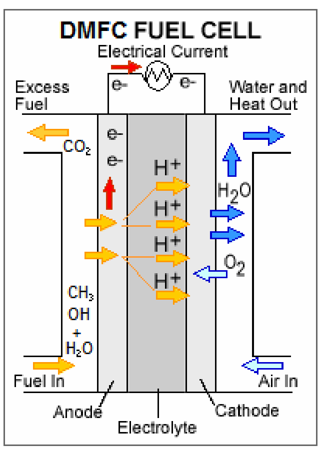


Figure 5:Schematic diagram of a DMFC

This kind of fuel cell is directly fuelled with methanol, mixed with steam and fed directly to the fuel cell anode.

This technology is similar to the one applied in PEM fuel cells, but it is in an early stage of development. The main setbacks of this kind of fuel cell is the higher amount of catalyst needed to oxidize methanol at low temperatures and the high permeation of methanol through the membrane, not mentioning methanol's toxicity and flammability.

With low efficiency and low power density, they are not suitable for mobile or stationary applications, but represent a good option to replace batteries in portable devices.

2.5.3 Alkaline Fuel Cells

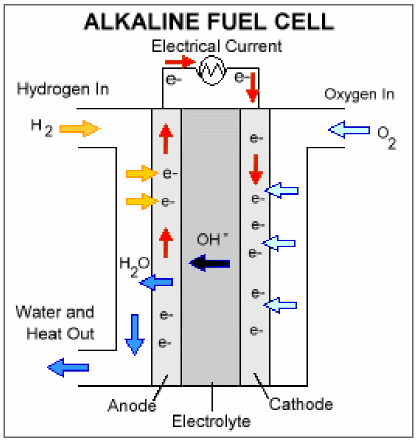


Figure 6:Schematic diagram of an alkaline fuel cell [3]

Alkaline fuel cells were one of the first fuel cells developed, widely used in spaceships. They use a solution of potassium hydroxide and operate at temperatures between 100 ºC and 250 ºC.

They present high performance and potentially can achieve 60% of efficiency. However, they are easily poisoned by carbon dioxide, demanding purification for both the hydrogen and oxygen used, increasing cost and affecting cell's lifetime.

They present approximate lifetime of 8000 hours. [5]

2.5.4 Phosphoric Acid Fuel Cells (PAFC)

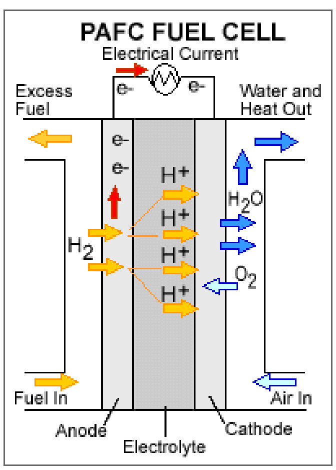


Figure 7:Schematic diagram of a alkaline fuel cell [3]

These fuel cells use liquid phosphoric acid as electrolyte, which is contained in a Teflon®-bonded silicon carbide matrix. It also uses porous carbon electrodes containing platinum catalyst. It is one of the most mature technologies and it is mainly used in stationary power generation.

PAFCs are more tolerant to impurities and present high efficiency: 85% when used when used as combined heat and power (CHP) and around 40% generating only electricity. These fuel cells are larger and heavier than other models since they generate less power given the same weight and volume.

2.5.5 Molten Carbonate Fuel Cells (MCFC)

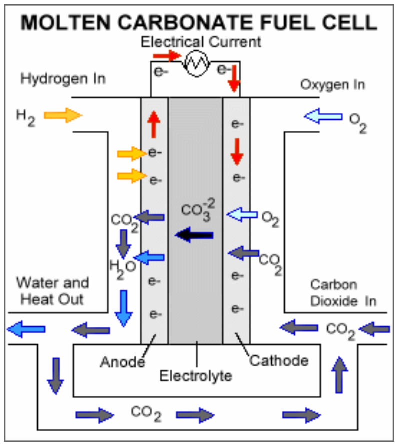


Figure 8:Schematic diagram of a molten carbonate fuel cell [3]

MCFCs are high temperature fuel cells that use as electrolyte a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium oxide ($LiAlO_2$). Operating in temperatures around 650ºC, these devices convert hydrogen within the fuel cell itself, in a process called internal reforming.

These fuel cells can reach efficiencies around 60% and when waste heat is covered, up to 85%.

MCFCs do not have problems with catalyst poisoning, but short cell's lifetime due to high temperatures and corrosive electrolyte are problems being addressed in current researches.

Their current lifetime is 8,000 hours for vehicles and 20,000 hours for stationary applications. Targeted lifetime is between 40,000 to 60,000 hours. [10]

2.5.6 Solid Oxide Fuel Cells (SOFC)

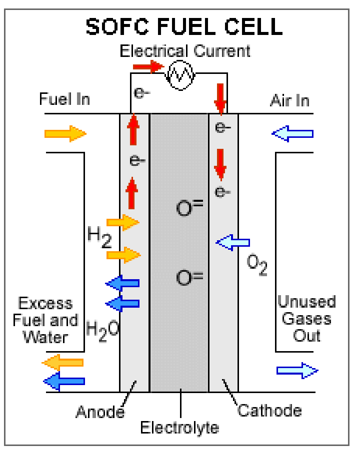


Figure 9:Schematic diagram of a molten carbonate fuel cell [3]

SOFCs use hard, non-porous ceramic compounds as electrolyte. They operate very high temperatures (up to 1000 ºC, removing the need for precious metal catalysts or external reforming.

Unlike the other fuel cells described previously, these cells are not poisoned by carbon monoxide nor carbon dioxide; moreover, they can tolerate higher levels of sulphur content, allowing to be used with gases made from coal and biogas. These cells present 50 to 60% of efficiency generating electricity and 80 when 85% for CHP.

They present lifetime of 6,000 hours for vehicles and 20,000 hours for stationary applications. Targeted lifetime is between 40,000 to 60,000 hours. [10]

The following table shows a comparison among different fuel cell technologies prepared by the United States Department of Energy:

Table 4: Comparison chart of fuel cell technologies [11]

Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Efficiency Electrical	Lifetime	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	Solid organic polymer poly-perfluorosulfonic acid	50 - 100°C	<1kW – 250kW	53-58% (transport) 25-35% (stationary)	• 2,000 hours (transport) • 30,000 hours (stationary)	• Backup power • Portable power • Small distributed generation • Transportation	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up	• Requires expensive catalysts • High sensitivity to fuel impurities • Low temperature waste heat • Waste heat temperature not suitable for combined heat and power (CHP)
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90 - 100°C	10kW – 100kW	60%	• 8,000 hours	• Military • Space	• Cathode reaction faster in alkaline electrolyte, higher performance	• Expensive removal of CO2 from fuel and air streams required (CO2 degrades the electrolyte)
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	150 - 200°C	50kW – 1MW (250kW module typical)	32-38%		• Distributed generation	• Higher overall efficiency with CHP • Increased tolerance to impurities in hydrogen	• Requires expensive platinum catalysts • Low current and power • Large size/weight
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates, soaked in a matrix	600 - 700°C	<1kW – 1MW (250kW module typical)	45-47%	• 8,000 hours (transport) • 20,000 hours (stationary)	• Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature speeds corrosion and breakdown of cell components • Complex electrolyte management • Slow start-up
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of Yttria is added	650 - 1000°C	5kW – 3MW	35-43%	• 6,000 hours (transport) • 20,000 hours (stationary)	• Auxiliary power • Electric utility • Large distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte reduces electrolyte management problems • Suitable for CHP • Hybrid/GT cycle	• High temperature enhances corrosion and breakdown of cell components • Slow start-up • Brittleness of ceramic electrolyte with thermal cycling
Direct Methanol (DMCF)	Polimeric proton conducting electrolyte, similar to PEM	80 - 100°C	up to 5kW	15-30%	• 5,000 hours	• Portable devices	• Methanol is easily transportable and have good energy density	• Low efficiency • Low power density

2.5.7 Main fuel cell applications

The possibility to generate clean energy with high efficiency and in a sustainable way made fuel cell development the focus of research of many industries.

Fuel cells have broad application potential in both transport and electrical power generation.

All multinational vehicle manufacturers are investing considerable amounts of money in hydrogen-fuelled vehicles, perceiving low emissions, high efficiency, low level and vibration noises as perfect features for vehicle applications.

Many manufacturers consider a period of 5 to 10 years as a reasonable timescale for a commercial availability of fuel cell fuelled cars. Nevertheless, some prototypes of passenger cars and buses are already available.

The main setbacks for vehicle applications are reliability, mileage range, hazard due to hydrogen leakages in enclosed spaces and vehicle lifetime.

Marine propulsion is also considered as an application for fuel cells. The efficiency of electric generation and the stealth capabilities of future fuel cell powered ships have called the attention of navies. Nevertheless, the same barriers encountered in fuel cells for vehicles are also present here.

Fuel cells can also play an interesting role in stationary power generation. They can be used in backup power units, grid management (to produce electricity from stored hydrogen, for example), to generate power for remote locations and stand-alone systems, cogeneration for buildings and public premises.

The most promising fuel cell technologies for larger systems are molten carbonate and solid oxide fuel cells; phosphoric acid ones are already in use for large scale applications but have been losing market during the last few years. Small domestic CHP systems seem to be one of the most feasible applications for fuel cells, considering that steady supply can be provided properly.

Considering portable power generation, fuel cells have the potential to deliver electrical power for much longer periods than batteries. Small portable electronic and electrical equipment can be a niche for further development. Nowadays for example, some electric wheelchairs already use PEM fuel cells.

2.6 Internal combustion engines and other hydrogen combustion applications

Internal combustion hydrogen engines are considered a stepping-stone towards fuel cell powered vehicles. This technology can be developed faster and with more reliability that fuel cells, since it only requires modifications to an existing well-developed technology.

As long as hydrogen has wider flammability range and lower ignition energy, some modifications in the engine must be made in order to prevent pre-ignition.

Vehicles using internal combustion engines are now in demonstration phase and present good efficiency and low emissions.

Although the fact that hydrogen combustion does not produce any CO_2, when burning hydrogen with air some NOx compounds are produced. These nitrogen oxides are created due to the high temperatures encountered in the combustion chamber during combustion. These emissions are controlled by the increase of air/fuel ratio in these engines, with a consequent power loss. [12]

Another approach to internal combustion engines is the use of hydrogen as an additive to hydrocarbon fuels. The addition of hydrogen in general has a disproportionate effect on emissions and overall efficiency. "Hydrogen's low ignition energy limit and high burning speed makes the hydro-gen/hydrocarbon mixture easier to ignite, reducing misfire and thereby improving emissions, performance and fuel economy. Regarding power output, hydrogen augments the mixture's energy density at lean mixtures by increasing the hydrogen-to-carbon ratio, and thereby improves torque at wide-open throttle conditions." [12]

The most common blend of hydrogen is with compressed natural gas, since they can be stored in the same vessel. If used with different fuels, in most cases hydrogen has to be stored separated and mixed in gaseous state immediately before ignition.

One commercially available blend is a gas mixture called Hytane®, containing 20% of hydrogen and 80% of natural gas. The most interesting aspect of this blend is that no modifications are required to the engine.

Hydrogen can potentially be used as a combustion fuel for industrial furnaces and domestic cooking or heating. Considering its different properties, an adaptation for hydrogen would require at least a complete new burner unit. Although theoretically possible, there is no commercial experience of hydrogen as cooking fuel or for domestic boiler operation

2.7 Economic aspects

Even with the high efficiencies and low emissions of its technologies, hydrogen economy will turn into reality when the production and operation costs match the cost levels of current and competing technologies.

In many articles, authors refer to the "chicken-or-egg" dilemma of hydrogen infrastructure: technologies would achieve commercial feasibility with a good and low cost distribution network but a distribution network would only be feasible with available market and demand.

Recent studies show that hydrogen applications can take more than 30 years to achieve expressive penetration, considering favourable conditions. The main assumptions for this forecast are the adoption of CO_2 restriction policies and significant cost reduction in basic technologies. [5]

2.7.1 Hydrogen Production

The following chart illustrates the cost of hydrogen from a range of different technologies. All costs presented are adjusted to 2007 pounds (£).

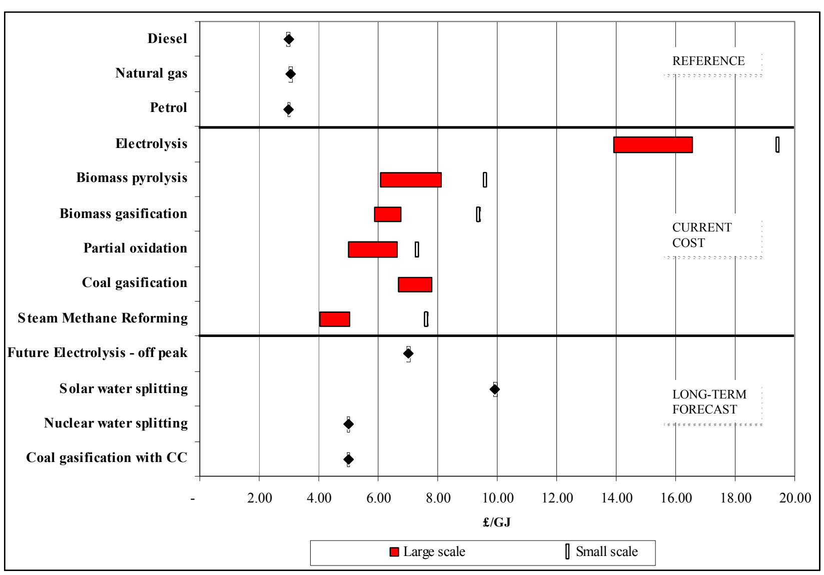


Figure 10: Cost of hydrogen from different technologies, compared to traditional fossil fuels. Values in pounds (£) per GJ of annual capacity [13-14-5-15-16]

As can be seen in the graph, large plants can reach cheaper production due to economies of scale, not reaching the cost levels of traditional fossil fuels though.
For both Steam Reforming and Partial oxidation, the main cost driver is the feedstock: the cost of methane or natural gas accounts for over than 50% of the total cost.
With reference to coal gasification, cost of feedstock and solid waste disposal are the most significant costs. This cost can increase if carbon dioxide capture is considered.
Biomass based technologies present the same dependence upon the cost of feedstock.
Finally, electrolysis presents the higher cost both for large and small scale. The cost of production is heavily influenced by electrical efficiency of the conversion and the cost of electricity.

2.7.2 Hydrogen storage

For each technology considered, cost of processing (compression or liquefaction, for instance) and vessels must be considered.

2.7.2.1 Compressed gas

Compression is an energy intensive process whose cost varies greatly with the size of the equipment, inlet pressure and outlet pressure and flow rate. The following chart shows the cost curve for compression and typical unit powers for hydrogen compressors.

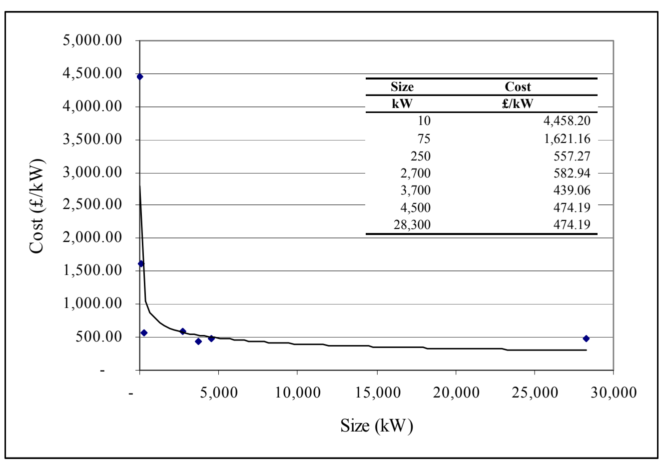


Figure 11: Variation of cost against size of compressor (Costs in 2007 £) [17]

The table below presents the efficiency of typical units

Table 5: Efficiency of typical compression units [18]

Inlet-Outlet (psig)	Inlet-Outlet (bar)	Adiabatic Efficiency	Compression Energy
300 - 1,000	20 - 70	70-80%	0.6 -0.7 kWhe/kg
100 - 7,000	7 - 480	50-70%	2.6 -3.6 kWhe/kg

The cost of vessels is proportional to the quantity of material and typical values are around £1100/kg H_2 to £1600/kg H_2. [5]

2.7.2.2 Liquid hydrogen

By far the compression is the largest operating expense for liquefaction. It is an energy intensive process, demanding from 11kWh/kg, around 30% of its energy content. [17]
Cost of liquefaction varies greatly in the literature. These costs are high, but significant economies of scale can be achieved.
Liquefaction investment cost is assumed in 2005 as £73.5/GJ of annual capacity. However, very large systems (over 30PJ/yr) can achieve £3.45/GJ. [5]
Although operating under low pressures, liquid hydrogen vessels have high capital costs due to the insulation required to minimise boil-off. Small vessels can be quite expensive, besides having greater hydrogen losses. The cost of cryogenic storage can vary from 13 to 500 £/kg of hydrogen of capacity, depending on the size of the vessel. [17]

2.7.3 Transport and distribution

The investment cost for hydrogen pipelines of a given diameter is about twice that of natural gas pipelines. Considering the difference of energy density between hydrogen and natural gas, a hydrogen pipeline would cost six times the cost of a natural gas pipeline with the same energy capacity.
The following chart illustrates a comparison between natural gas and hydrogen pipelines.

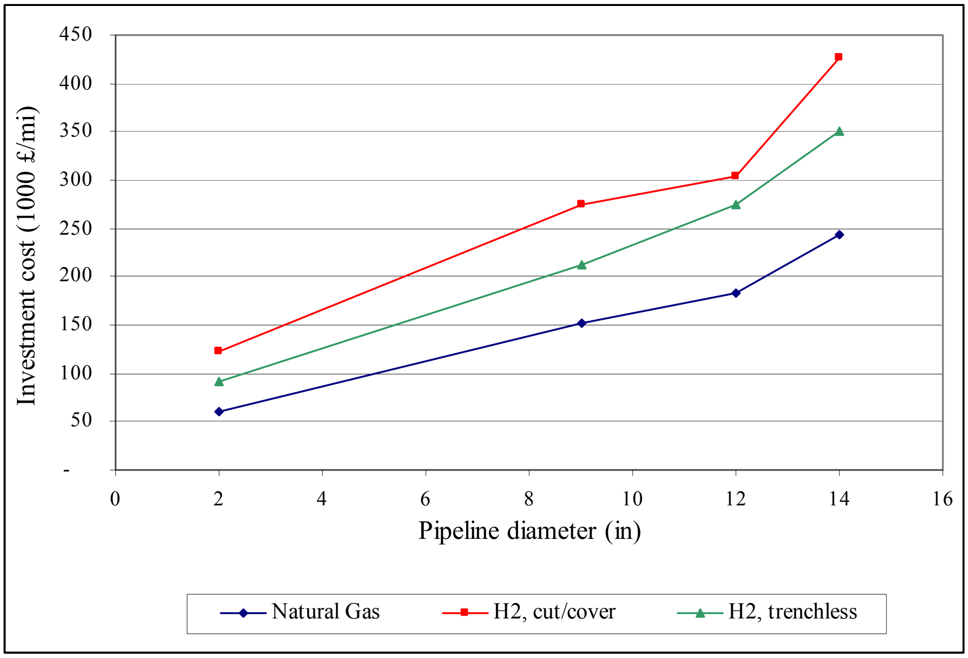


Figure 12: Comparison between cost of hydrogen and natural gas pipelines [19]

As a reference, the cost to develop a hydrogen network as big as the natural gas network in the United States is estimated to reach around US$ 620 billion. [5] Considering the same figures, the worldwide investment to develop a hydrogen network would be in the order of US$2.5 trillion.

Additionally, the energy required to move hydrogen through a pipeline is on average 4.6 times higher per unit of energy than for natural gas, i.e. the same amount of energy needed to move hydrogen over a distance over 1200km would move natural gas over a distance of 5000km. [5]

Regarding liquid hydrogen, although highly dependent on volume and distance, the cost of distributing hydrogen by truck is assumed to be £1.25/GJ, based on liquid nitrogen industry. [5]

Transportation by ships require fast ships in order to reduce boil-off losses, that amount to 0.2% -0.4% per day. For shipments of a few thousand kilometres, the cost of transport is around £1/GJ. [5]

2.7.4 Fuel Cells

According to the latest report from the International Energy Agency [5], to achieve commercial feasibility, fuel cell for vehicles must achieve 10 to 50 times cost reduction, while stationary fuel cells need 5 to 10 times cost reduction. This ambitious target can be achieved, if possible, by economies of scale and mass production, technology learning and development of new materials and concepts. For vehicle applications, current prototypes reached the cost of £1000/kW, which would potentially lead to a cost of £50/kW to £100/kW in mass production.[5] These figures, however, are far from cost target: the current cost of ICE engines, approximately £25/kW.

The main cost of maintenance is the replacement of fuel cell stack after its lifetime. As a rule of thumb, a fuel cell stack costs one third of a complete fuel cell. [20]

2.7.4.1 PEM fuel cell

In general, the cost of a PEM fuel cell can be split into fuel cell stack and auxiliary equipment that is necessary for fuel cell operation.

The cost of the stack is the sum of the individual costs of its main components. The total cost of a manually produced stack is around £895/kW, which is dominated mainly by the cost of the bipolar plates and the electrodes. The following graph shoes the cost breakdown of the PEM fuel cell stack.

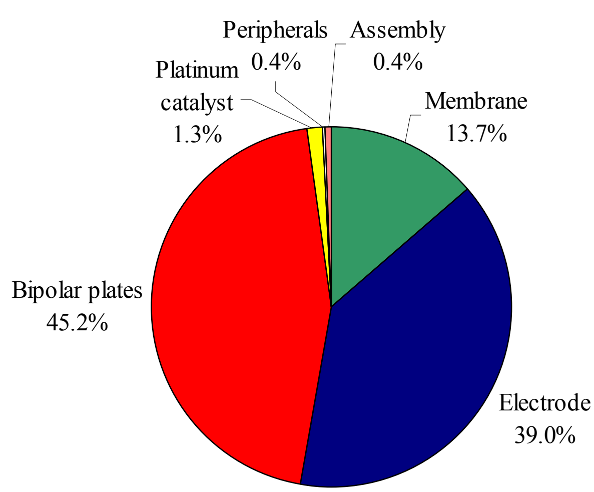


Figure 13: Cost breakdown of current cost estimate of manually produced PEM fuel cells [5]

Mass production and further improvements can lower this value for approximately £50/kW. [5]

The auxiliary system comprises the power electronics required for operation of the fuel cell: AC/DC converters, inverters, control electronics, etc. The cost of this system is estimated from £500/kW to £750kW, but dramatic reductions are expected with mass production. [5]

2.7.4.2 Stationary fuel cells: MCFC and SOFC

The main cost driver for these kinds of fuel cells is also the stack. Mass production can lead to remarkable cost reductions, but not enough to achieve the level of competing technologies as large-scale gas-fired combined-cycle power plant (arounf £245/kW). [5]

A MCFC system of 300kW currently cost £6400/kW, with a target to achieve £800/kW with mass production. [5]

A SOFC system of 200kW currently cost £7800kW, with a target to achieve the same £800/kW with mass production. [5]

These figures can be decreased with designs of higher capacity.

The following table shows the cost breakdown for current systems and expected cost for mass production:

Table 6: Cost breakdown of MCFCs and SOFCs [5]

	MCFC (300 kW)		SOFC (200 kW)	
	Demo (£/kW)	Target (£/kW)	Demo (£/kW)	Target (£/kW)
Operating system	563.00	82.00	844.00	71.00
Inverter	60.00	48.00	103.00	45.00
Heat exchanger	196.00	41.00	188.00	45.00
Reformer	373.00	30.00	36.00	36.00
Boiler	1,472.00	214.00	3,205.00	262.00
Burner	177.00	32.00	74.00	26.00
Stack	3,197.00	287.00	3,234.00	271.00
Frame	343.00	69.00	-	29.00
Air supply	22.00	6.00	81.00	26.00
Total cost	**6,403.00**	**809.00**	**7,765.00**	**811.00**

2.8 Current demonstration projects

2.8.1 Utsira Island and HyNor, Norway

Utsira is an island 10 nautical miles away off the west coast of Norway. The island has no autochthonous electricity generation but it is cable connected to the mainland. The project had a cost of £3.4m and was developed by the Norwegian company Hydro. It comprises two wind turbines, an electrolyser and a compressor, storage tank, a flywheel, fuel cell and one hydrogen engine.

The system supply electricity and heat for 240 people living in the island. Hydrogen is produced with surplus of electricity generated from wind. During wind outages, hydrogen is used in the fuel cell and in the engine to provide electricity and heat. The storage of hydrogen is designed to supply energy for 2 days. In case of longer outages, electricity is supplied by the grid connection.

The demonstration project started operating in summer 2004 and was scheduled to work for only two years, but it had its operation extended until spring 2008.

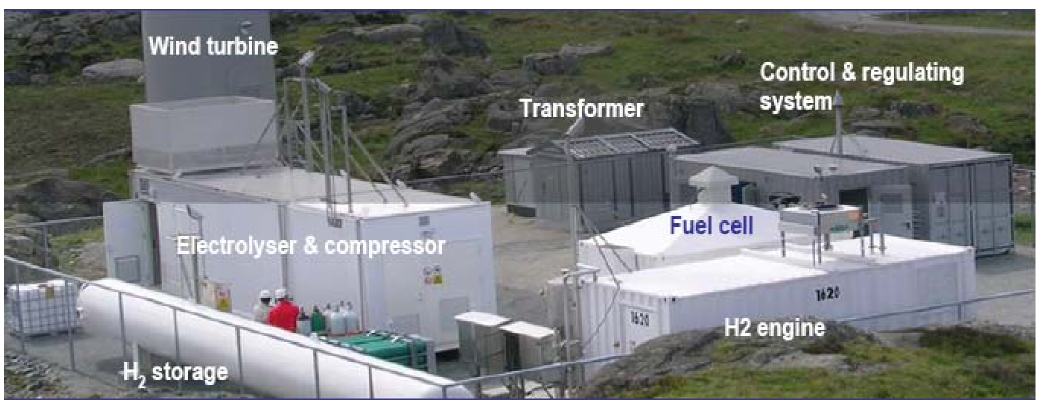


Figure 14: Equipments of Utsira demonstration project [21]

HyNor is a hydrogen highway connecting Bergen to Oslo passing through seven hydrogen production nodes in the South of Norway. This hydrogen distribution infrastructure is planned to be operating in the end of 2008, enabling the development of several hydrogen applications, especially hydrogen fuelled vehicles.

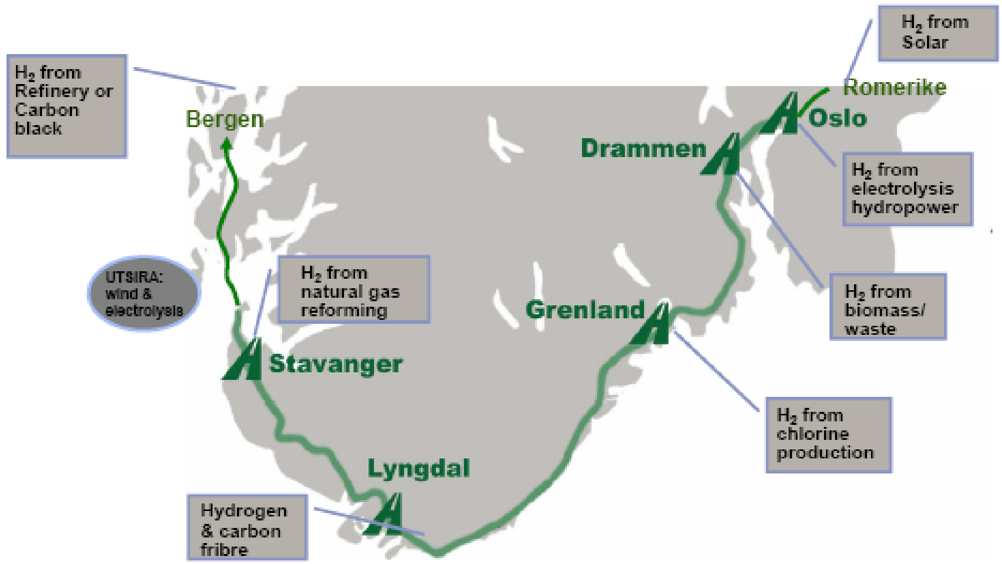


Figure 15: Seven nodes in a southern necklace constituting the projected Norwegian hydrogen highway [22]

2.8.2 Prince Edward Island Hydrogen Village, Canada

Prince Edward Island Energy Corporation and Hydrogenics are the leaders of this project which combine a commercial-scale wind farm, hydrogen production, fuel cells and hydrogen-powered internal combustion engines. The project started in 2005 and is expected to be finished over the course of three years. The estimate cost of the project is CAD$ 10.3m (around £4.8m). [23]

The system will supply energy to 3 research facilities and 10 houses.

The project is divided in the following phases:

- **Phase 1a – Grid Dependent Village:** installation of 65kW wind turbines, a hydrogen generation station, a hydrogen storage depot, stationary fuel cell with wind and PV input, fuel cell powered truck and work vehicle and .
- **Phase 1b – Grid Independent Village:** wind-hydrogen and wind-diesel integrated control system to be installed, with grid as back-up.
- **Phase 2 – Transportation Corridor:** installation of a hydrogen refueler in Charlotetown and 3 hydrogen ICE shuttle buses in full service

- **Phase 3 – Expanded Village:** additional hydrogen powered buildings, including 10 additional houses, 1 commercial building and 1 farm, plus additional hydrogen powered vehicles.
- **Phase 4 – North Cape boat:** introduction of a hydrogen powered tour boatm which will be retrofitted with an engine that has the ability to run on pure hydrogen, but with a diesel fall-back system.

This project aim at development and test of hydrogen applications in a "microcosm model of the hydrogen economy". [23]

2.8.3 West Beacon Farm (Crest, Loughborough University)

This project was developed by the Centre for Renewable Energy Systems Technology (CREST) from Loughborough University. The system was installed in end of 2003 in order to give self-sufficiency to a farm and residential dwellings. Wind and solar energy are used to generate hydrogen with an electrolyser. A compressed gas storage system and a stationary PEM fuel cell are available. Future planned additions include metal hydrides, a refuelling station and other stationary fuel cells.
The following diagram illustrates the systems installed in the project:

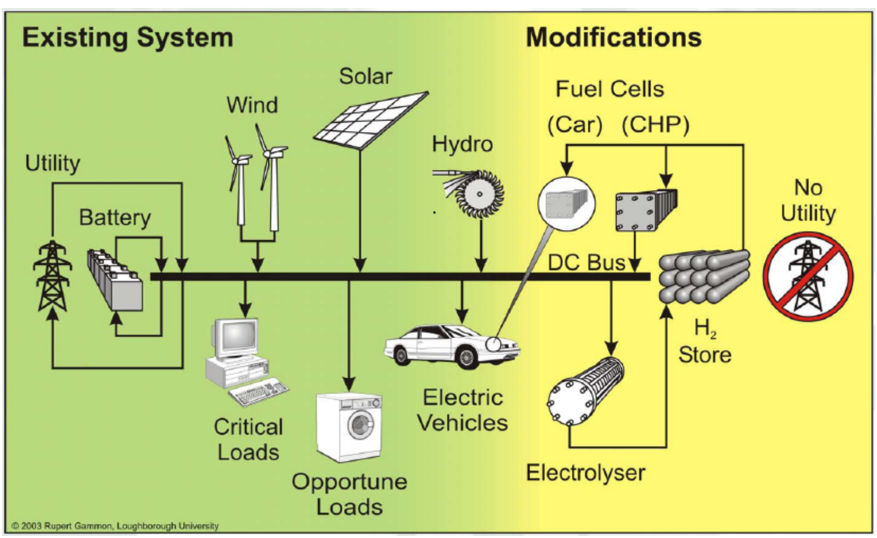


Figure 16: Integrated system of West Beacon Farm [24]

2.8.4 Iceland

Icelandic New Energy Ltd. is a consortium formed by Shell, Daimler-Chrysler, Norsk Hydro and VistOrka. The consortium is committed to develop several projects to transform Iceland into a hydrogen economy and society by 2030-2040.
Hydrogen will be produced mainly by geothermal and hydro power, the main energy sources available in Iceland.
The phases of the project include gradual replacement of the Reykjavik city bus fleet, introduction of fuel cell vehicles for private transport and gradual replacement of present fishing fleet by fuel cell powered vessels. [25]

2.8.5 PURE (Promoting Unst Renewable Energy)

The Pure Project is located in Isle of Ust, the most northern island in the UK, in Shetlands. The aim of the project was to demonstrate how wind power and hydrogen technology can be combined to provide renewable and sustainable energy.
The project delivered in 2005 zero emissions, off-grid renewable hydrogen hybrid power supply for five business units in a remote industrial state.
The system comprises two 15kW wind turbines, one electrolyser, hydrogen and thermal storage and an innovative load management system that controls supply of renewable electricity to the electrolyser, for hydrogen generation, and to thermal storage units.

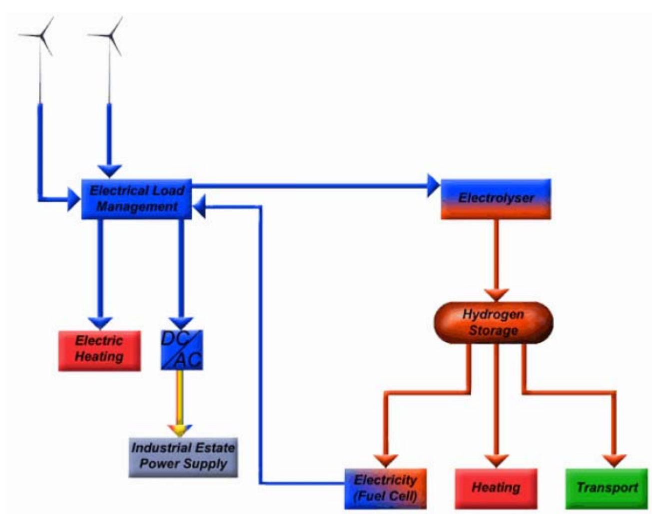


Figure 17: Schematic diagram of PURE Project [26]

The PURE project has been developed with remarkable small budget of approximately £350,000, including equipment and installation, engineering and consultancy.
This project was the first community owned renewable energy project of its kind in the world.

2.8.6 Chewonki Renewable Hydrogen Project

The Chewonki Renewable Hydrogen Project is located in the Centre for Environmental Education in Maine and it is considered as the America's first publicly-accessible project that integrates renewable direct high-pressure hydrogen production with hydrogen fuel cell technology.
The system was unveiled in August 2006 after three years of implementation, which consumed US$ 250,000 (around £122,500).
The 3kW hydrogen system comprises a solar system (a 4.5kW PV array installed in on the roof of the building), an electrolyser that produces high pressure hydrogen, without the need of a compressor, hydrogen cylinder storage system, a stationary PEM fuel cell, batteries and an inverter.

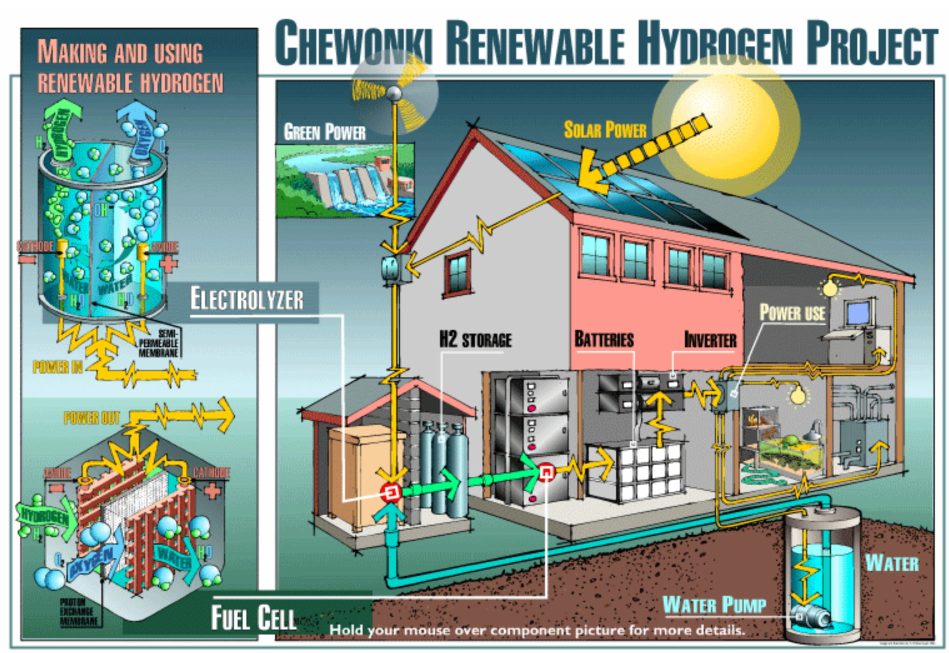


Figure 18: Artistic view of Chewonki Hydrogen Project [27]

2.8.7 Xcel –NREL Wind2H2 Project

The U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and Xcel Energy are working in partnership on project to analyze and compare hydrogen production from wind power and the electric grid.
The project started in September 2003 and has a budget of US$2.3m (around £1.2m). The project objectives are to explore synergies for hydrogen as an energy storage medium and a transportation fuel and study the potential of hydrogen storage as a way to overcome wind energy intermittency.
The following picture illustrates the system configuration:

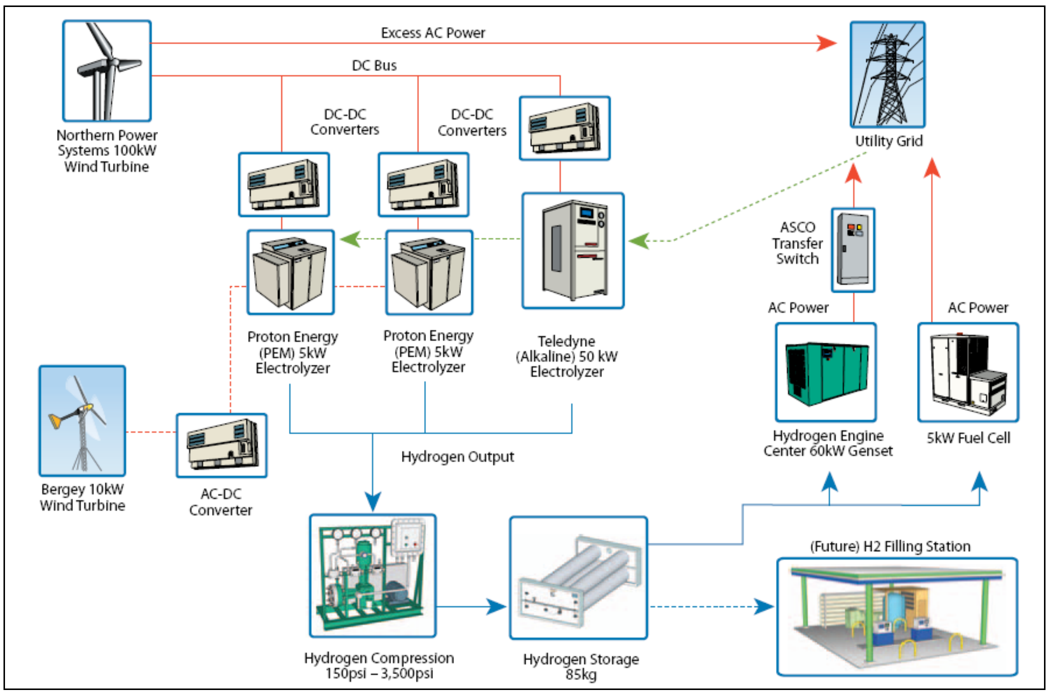


Figure 19: Configuration of Xcel-NREL Wind2H2 Project [28]

3 Project background

3.1 The Outer Hebrides

The Outer Hebrides are the set of islands located off the Northwest coast of Scotland. The main islands of this region, also called Western Isles or "Na h-Eileanan Siar", are Lewis, Harris, North Uist, South Uist and Barra, occupying an area of 3.100 km^2. The population is near 27.000 inhabitants. The main city, Stornoway, located on the Isle of Lewis, is home of 9.000 inhabitants. [29]

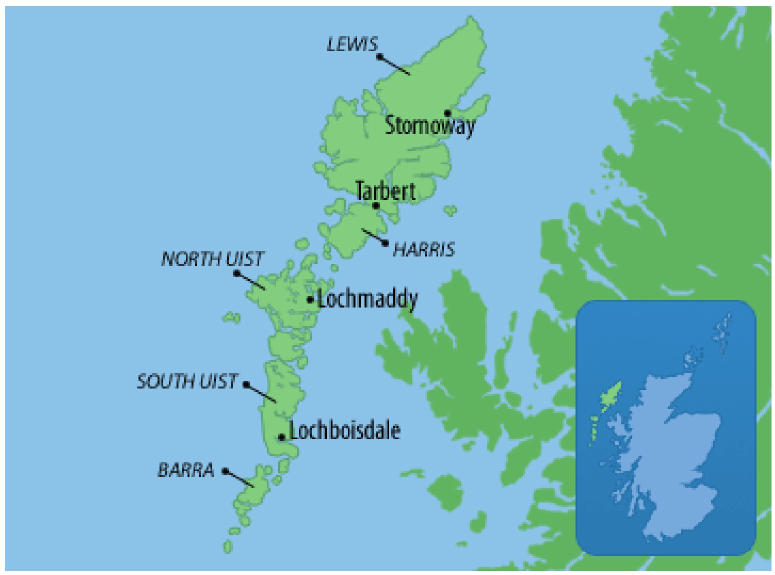


Figure 20: Map of Western isles

The main industry of the region has been fishing. During last century, the Hebrides supplied fish for England and many other countries of Europe. Nevertheless, the region lost its main economic activity with declining of fish stocks caused by predatory and uncontrolled fishing.

Consequently, with the lack of opportunities and limited economic activity, the region is suffering from a decreasing and ageing of population.

The following graph shows the projection of population from 1995 to 2006, estimated by the General Register Office for Scotland (GROS).

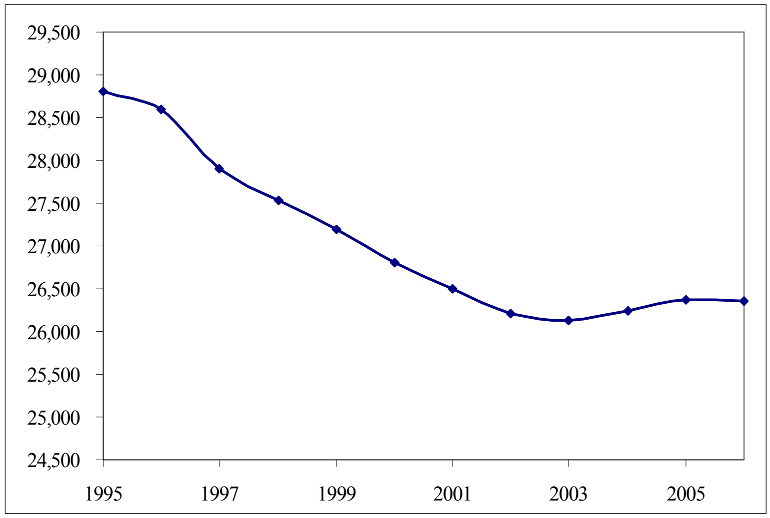


Figure 21: Population projection for the Hebrides [29]

The main employer is the public sector, as can be depicted by the following chart:

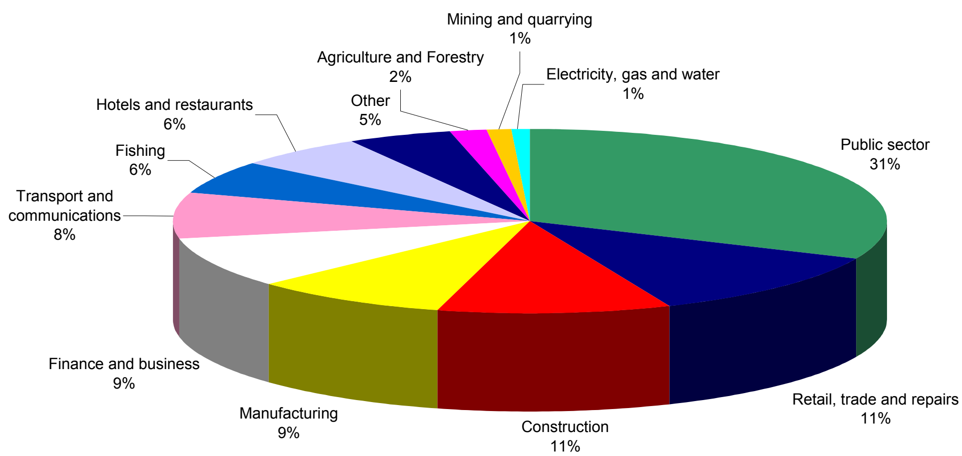


Figure 22: Employment by economic sector [30]

Additionally, the region presents the following characteristics:

- GDP per capita of £10,708, corresponding to 57% of the average in the UK (figures from 2003) [31]
- Trade deficit of £163.4m, due to lack of indigenous resources and a reliance on importing. [31]
- Highest unemployment among the Highland and Islands but still below Scottish average (3.8% in 2003) [30]

- 34% of households in fuel poverty (more than 10% of household income spent on fuel costs) [34]

97% of the energy needs of the region are imported and the average energy cost is over 13% higher than in the main land. In 2005, the estimated consumption was approximately 865GWh. [35]
The following charts show the energy demand of the Outer Hebrides for 2005.

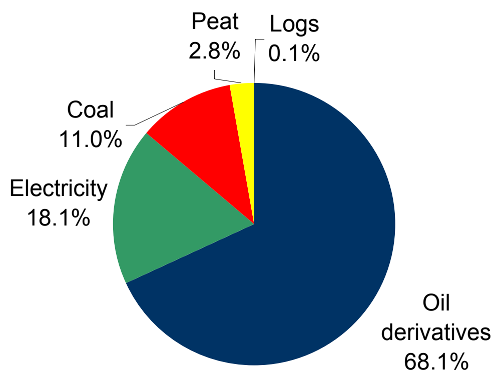


Figure 23: Energy demand by fuel [35]

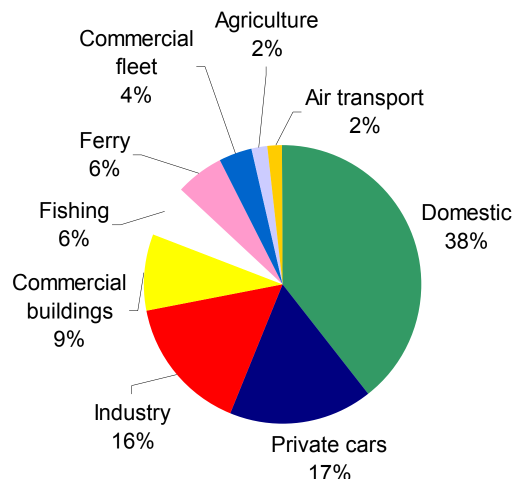


Figure 24: Energy demand by economic sector [29]

Oil represents 68% of the energy imports, while coal accounts for 18%, electricity for 11% and peat for 3%.
The carbon footprint in the Outer Hebrides is 10% larger than the UK average.

One 32kV line connects the island the rest of the grid in Scotland. The dependence on imported electricity cause significant instability and lack of reliability of electrical supply.
The following map illustrates the main systems installed in the islands and the future projects under analysis.

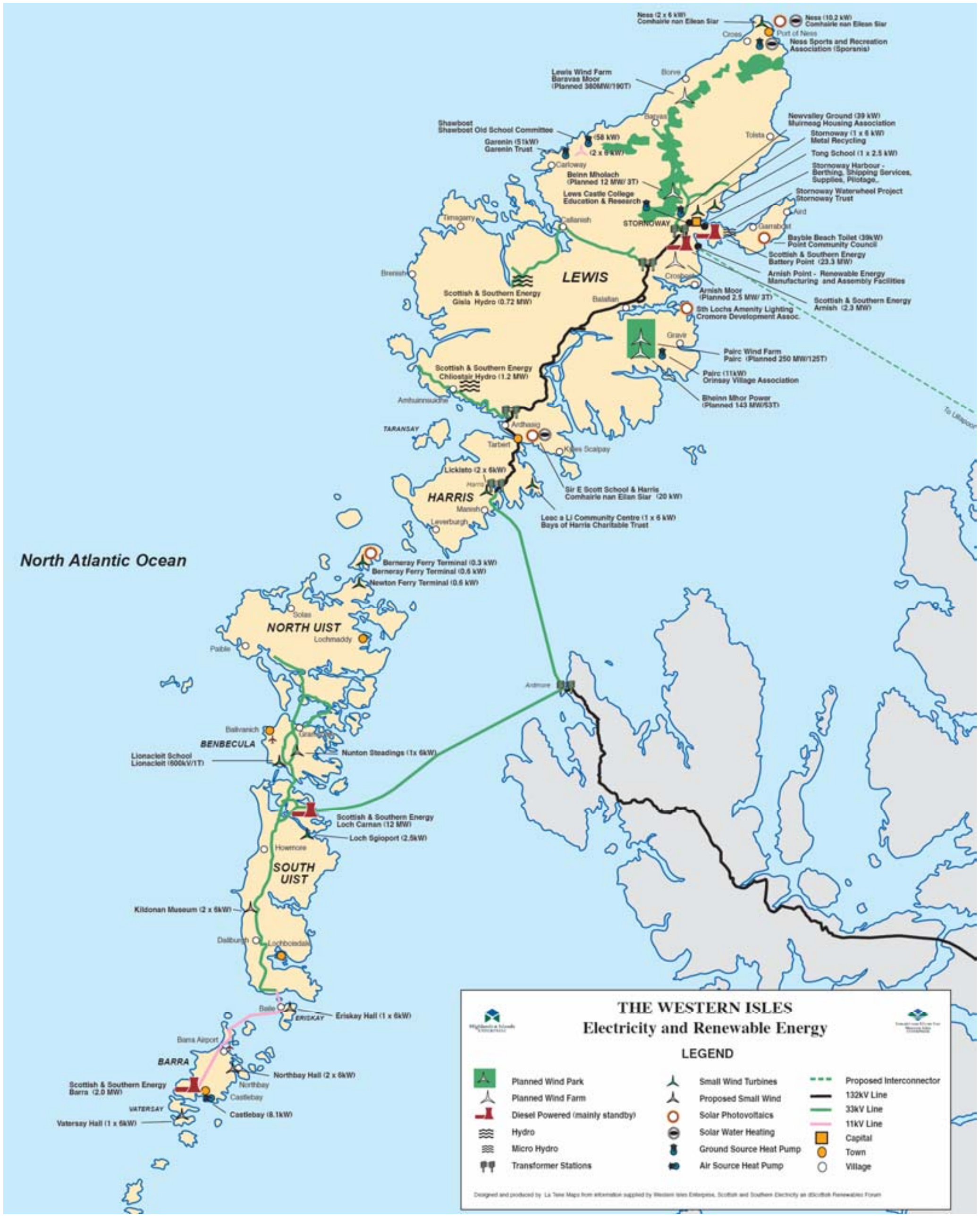


Figure 25: Electricity and Renewable Energy map of Western Isles

In the map, some of the large-scale wind farms proposed for the region were indicated as green-shaded areas. Those controversial projects try to take advantage of the huge renewable energy potential present in Outer Hebrides.

Even though the Outer Hebrides has negligible indigenous energy generation, the region is endowed with significant renewable resources.
As can be seen by the charts included in the Appendix, which illustrate the renewable energy resources availability across Scotland, the region has considerable potential for Onshore Wind power and huge resources for Offshore Wind and Wave power.
The three ambitious large-scale wind systems proposed would generate, together more than 1GW of renewable energy from wind resource, constituting one of the biggest wind power parks in the world. The projects have the following details:

Name	Lewis Wind Power
Location	Barvas Moor, Isle of Lewis
Installed Capacity	651.6 MW 181 turbines
Expected cost	£411m

Name	Pairc Wind Farm
Location	South Lochs area, Isle of Lewis
Installed Capacity	205 MW 57 turbines
Expected cost	£200

Name	Bhein Mhor Power
Location	Eishken Estate, Isle of Lewis
Installed Capacity	159 MW 53 turbines
Expected cost	£120

On one hand, these projects may potentially boost the local economy and bring prosperity to the region, injecting millions of pounds as rental income, providing business opportunities and jobs and opening the window for development of different renewable energy technologies, such as marine power and hydrogen.

On the other hand, these projects have been facing severe barriers since the first proposals. Local communities are afraid of landscape degradation and loss of cultural identity and environmentalists created objections due to the impact on moorlands and bird life, especially golden eagles.
Moreover, these projects can only be implemented if a major grid interconnection to the mainland is installed, most likely via sub sea cable, demanding further massive investment.

3.2 Hebridean Hydrogen Park

The Hebridean Hydrogen Park is a structural program that plans to provide solid foundation for the development of a hydrogen economy, positioning the Outer Hebrides at a good position to take advantage of opportunities in the emerging hydrogen market. This program is complimentary to the Energy Innovation Zone Initiative.
The fundamental idea of the Energy Zone Initiative is to take advantage of nature resources available in the region to develop an international centre of excellence for renewable energy research and innovation. The vision of this programme is to transform the Western Isles in the renewable energy capital of Europe.
The Hebridean Hydrogen Park is organised in three distinct but inter-related phases:

- Phase 1: Capacity building and skills development
- Phase 2: Infrastructure and development projects
- Phase 3: Development of hydrogen markets

The phase 1 aim at the promotion of hydrogen technologies and the development of necessary skills as a background to support other initiatives. The main initiatives included in this phase are:

- Hydrogen Schools Education Project: the main objective of this initiative is to provide schools with equipment for practical demonstration of hydrogen basic technology and to promote the inclusion of hydrogen in the normal curriculum.
- Hydrogen teaching and research facility: installation of a complete hydrogen laboratory at Lews Castle College. The main objective of the facility is to enable research and development of hydrogen technologies. As can be seen in the following

picture, the laboratory is equipped with several hydrogen demonstration units, including fuel cells, CHP systems and hydrogen fuelled portable devices.

Figure 26: Hydrogen Lab at Lews Castle College [36]

- Broadband Project: this project will develop a hydrogen UPS that will offer superior performance compared to traditional battery based UPS systems.

The Phase 2 of the project will develop hydrogen infrastructure and support several demonstration projects. The initiatives of this phase are organised and managed in the H2 SEED project.

The H2 SEED project is a complete and self-sustained hydrogen system that will generate hydrogen from biogas, which is produced in an anaerobic digester from organic waste. The installation will have an electrolyser, one compressor, hydrogen storage, a vehicle filling station and a cylinder refuelling system. This project will supply hydrogen to fuel two demonstration vehicles and several hydrogen demonstration projects, including the hydrogen lab at Lews Castle College.

The following diagram shows the main units of the system:

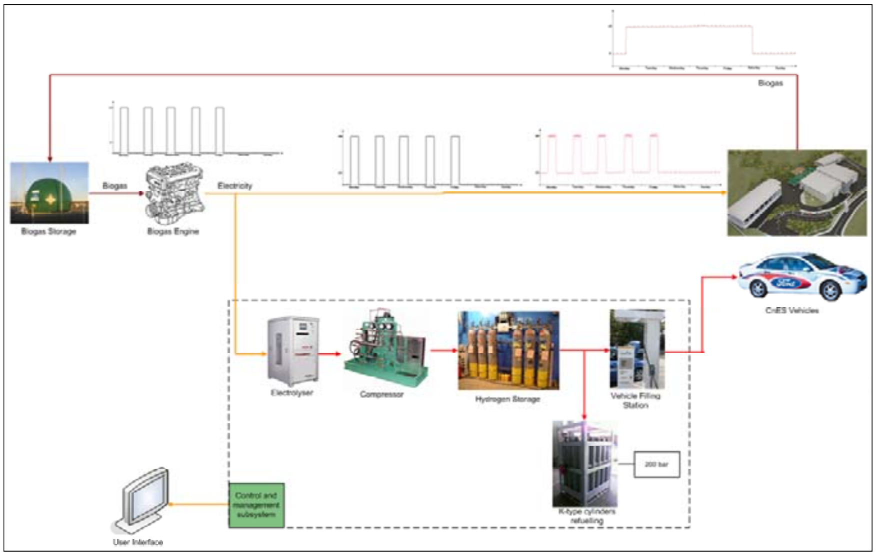


Figure 27: Schematic diagram of the H2 SEED project

The Phase 3 is the consequential expansion derived by the successful delivery of other phases. In this phase, the main indicative activities are development of hydrogen export markets, establishment of hydrogen vehicle fleets and adaptation of hydrogen fuelled marine vessels.

The project also includes a program for Emergency Services training.

The Hebridean Hydrogen Project has initiated in 2006 and has an expected cost of £2.7m.

4 Biogas and hydrogen technologies

Several pathways are available connecting biogas and hydrogen technologies. The following diagram summarises these technological routes:

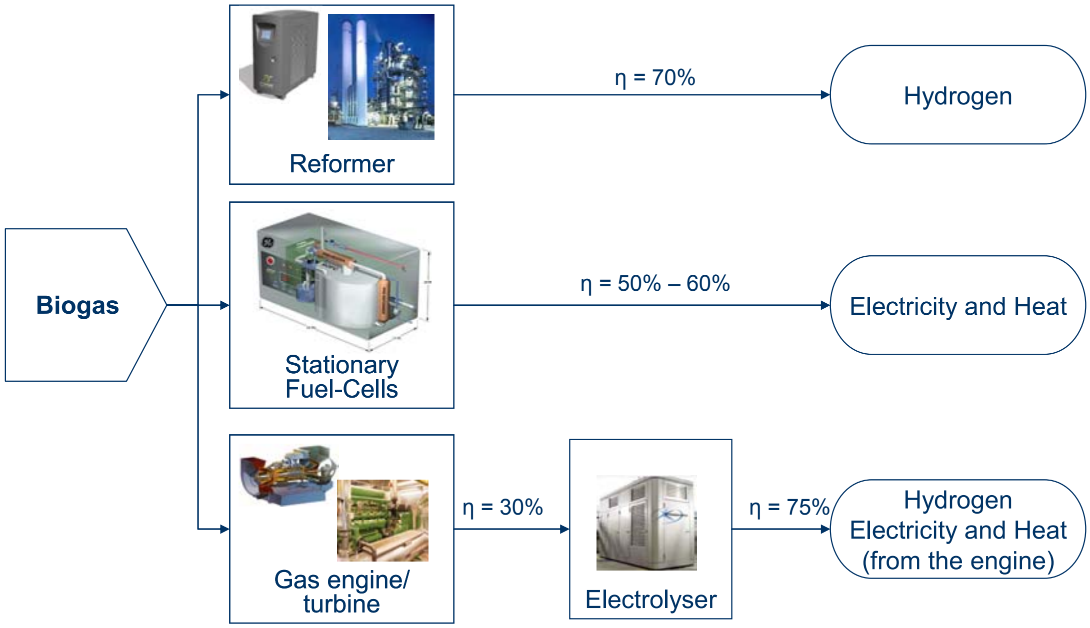


Figure 28: Technological pathways with biogas and hydrogen technologies

The composition of biogas is particularly interesting for reforming. The high content of carbon dioxide helps the reforming of methane and increase the rate of shift reactions.

Based on the same chemical kinetics, Solid Oxide and Molten Carbonate Fuels cell can be used to generate electricity directly from biogas, as an alternative to combustion. These fuel cells operate under high temperatures and the reforming is performed directly in the electrodes.

The best example application of these technologies is a sewage treatment plant located in Renton, Washington. In this plant, 154,000 cubic feet of biogas are consumed per day to produce up to 1 MW of electricity in the world largest biogas-powered fuel cell. The total cost of the project is US$22.5 million, but the fuel cell electric output saves $400,000. [37]

These figures show that the plant is not economically feasible with current costs but the project is a milestone as a demonstration project. The following pictures show the installation:

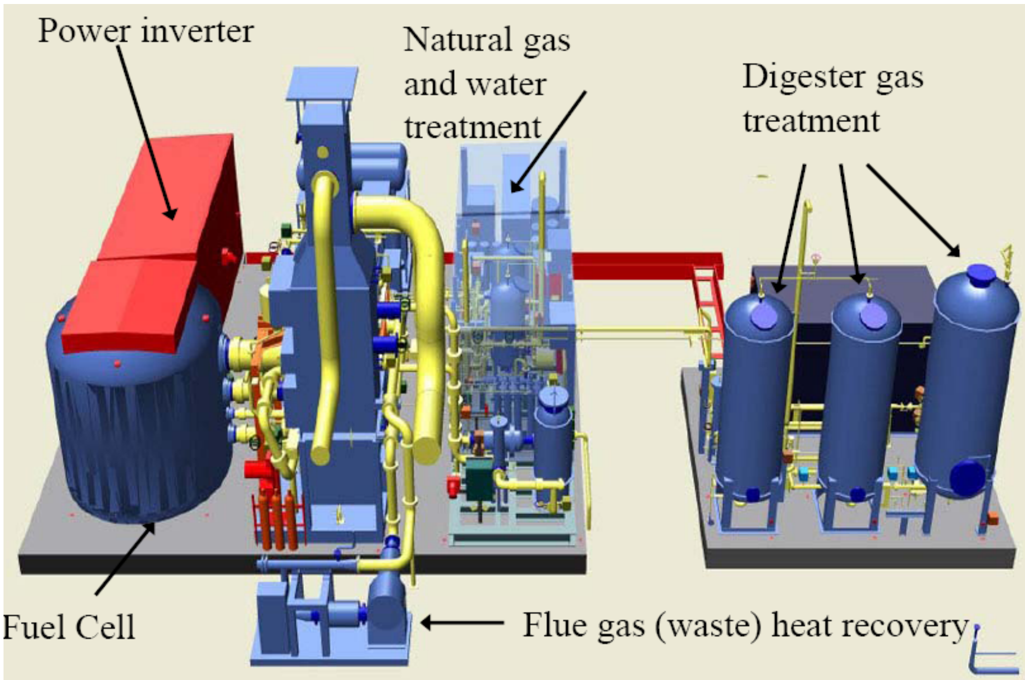


Figure 29: 3D model of 1MW biogas-powered fuel cell installation [37]

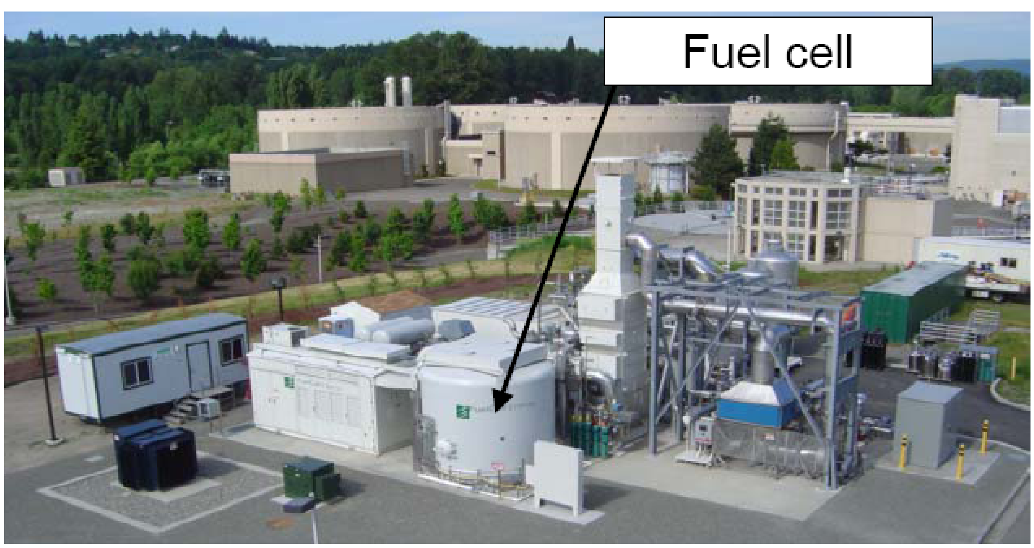


Figure 30: Picture of the installation located in Renton, WA [37]

5 Project Description

5.1 Methodology

The methodology applied in this project included a broad literature review of all suitable hydrogen technologies, review of available simulation tools, discussion with local authorities and local stakeholders, data collection and preparation, set-up of models, analysis and comparison of results.

Two tools are used in the development of the models for the different configurations for the system: **Homer**, developed by National Renewable Energy Laboratory from the United States Department of Energy, and **TRNSYS**, developed by University of Wisconsin, Madison.

5.2 Simulation

5.2.1 The importance of simulation

Simulation and modelling play a key role in the design of energy systems. With the help of simulation tools, system performance can be assessed, different configurations can be tested and alternative technologies can be compared.

The following graph shows the impact of changes across the stages of development of a project.

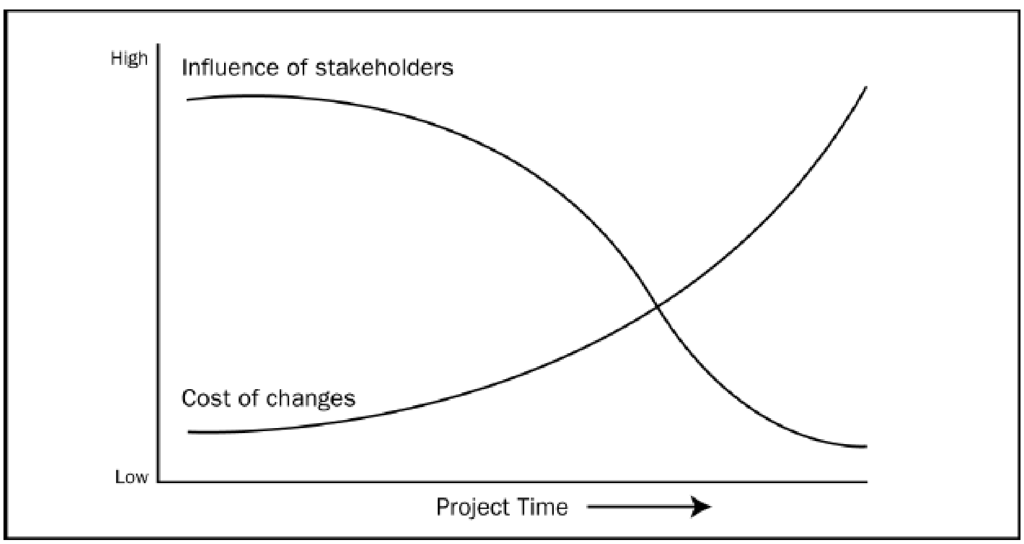


Figure 31: Impact of changes across project development [38]

In this project, simulation is vital in order to study the possible impacts of specific operational conditions on equipment performance, to define the optimal size of equipment considering potential production and forecasted demand, and to compare different technologies.

5.2.2 Homer

Homer is a computer model used to analyse micropower system options. This software offers a comprehensive range of conventional and renewable technologies, allowing the evaluation of design options for both off-grid ad grid-connected small power systems.
It is especially designed for technical and economical feasibility of different system options.
The model simulates the behaviour of a given system in a hourly basis throughout the course of one year, evaluating the possibility to match demand and supply among the options included by the user.
The software operates in the level of balances of mass and energy, following the concept of "big boiler" energy system model, as represented by the following picture.

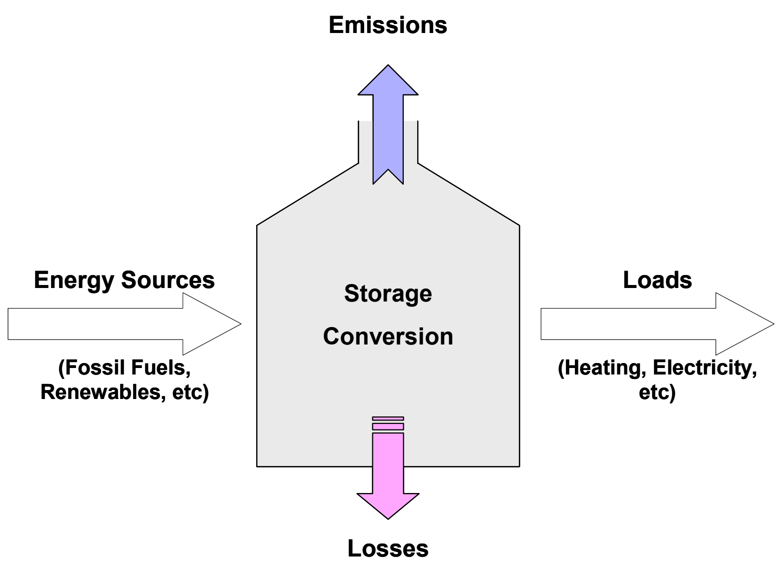


Figure 32: The "big boiler" energy system model [39]

Homer also has an optimization and sensitivity analysis tool, with a variety of reports and outputs. Detailed technical analysis and simple economic performance can be evaluated for every option simulated.

5.2.3 TRNSYS

TRNSYS stands for Transient System simulation. "It recognizes a system description language in which the user specifies the components that constitute the system and the manner in which they are connected. The TRNSYS library includes many of the components commonly found in thermal and electrical energy systems, as well as component routines to handle input of weather data or other time-dependent forcing functions and output of simulation results. The modular nature of TRNSYS facilitates the addition to the program of mathematical models not included in the standard TRNSYS library." [40]

In this project, it was used version 16.01 of TRNSYS, which has the Hydrogen components integrated in the main libraries.

6 System description and Modelling

6.1 System Description – Creed Park Waste Management Facility

The Creed Waste Management plant was commissioned in the end of 2006. The plant can process up to 9,500,000 tonnes per annum of organic waste, which represents 30% of the waste generated in the Western Isles. The organic matter is processed in an anaerobic digester, producing up to 1.382.400 Nm^3/year of biogas, which contains at least 60% of methane.

Biogas is used to feed an engine that produce electricity and heat to supply the plant needs. The plant is connected to the grid and it can export surplus electricity generated by the biogas engine. When the engine is not running, the grid connection supplies electricity to the plant.

The system had German design and the anaerobic digester can be considered an operational success. The compost produced has high standard, with no traces of micro-organisms or heavy metals, allowing to be used in landfill recuperation and as fertiliser. The quality and composition of the biogas produced are steady and present negligible variation along the year.

Nevertheless, the current engine is overrated, due to overestimate of organic waste collection during design phase.

Educational programs are under development to increase the public awareness of the importance of proper selection of organic waste. Regular garbage, which also arrives at the plant, still contains considerable amount of organic matter that would boost biogas production.

It is technically possible to feed into the digester the regular waste, but this would lower the standard of the compost produced. There are strict regulations regarding use of compost and any kind of contamination (micro-organisms, heavy metals, etc) would prevent its application for landfill recuperation and for food production, restricting its market and depleting its commercial value.

Consequently, the engine consumes more biogas than the plant can currently produce. The solution adopted by the management of the plant was to operate the engine during some hours along the day at 100% capacity and then ramp it down according to the level of the biogas storage. This operational condition was considered "less harmful" than a longer operation in low capacity.

As long as this kind of engine is designed to operate at maximum capacity 24 hours a day, this operation profile will certainly bring some maintenance problems in the near future and it will decrease its lifetime.

A survey was performed in the plant to investigate technical specification of the equipment and operational conditions. The following data were obtained:

Biogas plant

Technology licenser: Linde AG

Main Contractor: Earth Tech

Operation: only weekdays, from 8:00 to 18:00

Production: on average, approximately 50Nm^3/h (ranging from 35 to 75 Nm^3/h).

During weekends, waste is not fed into the digester and biogas production declines to 10 Nm^3/h.

Biogas composition: 60% of methane at least

Currently connected to the grid and allowed to dispatch excess power

Biogas Generator

Generator Set Manufacturer: Ener G

Model: ENER·G 290B

Rated Power: 290kW (de-rated to 240kW)

Recoverable heat: 385kW (370kW after engine modification)

Consumption: 125Nm^3/h (at full capacity and with methane content in the biogas of 60%)

Biogas Storage (Gas bag)

Capacity: 400m^3

Biogas production profile

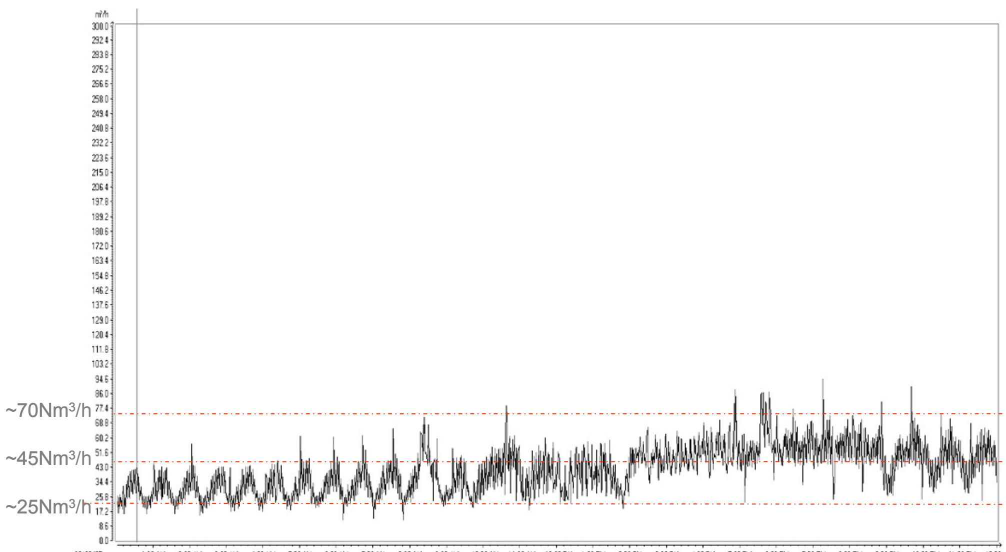


Figure 33: Daily biogas production profile

Power Consumption profile

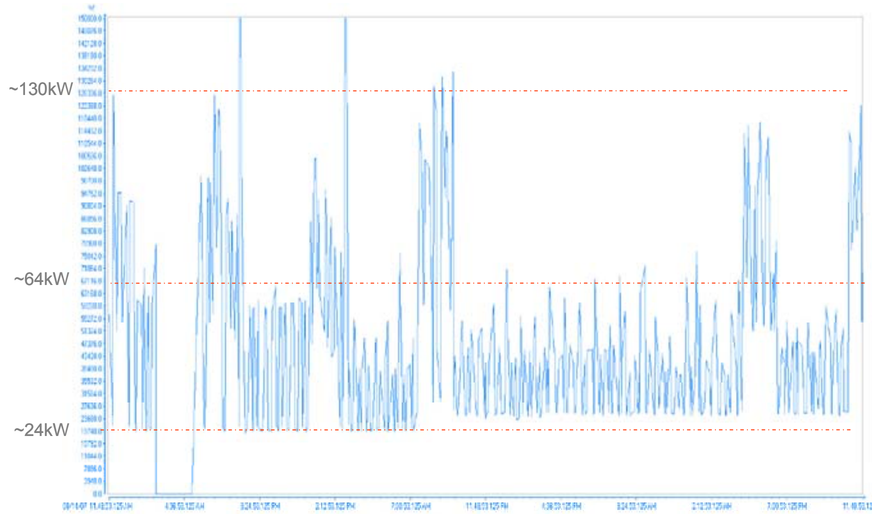


Figure 34: Weekly electricity consumption profile

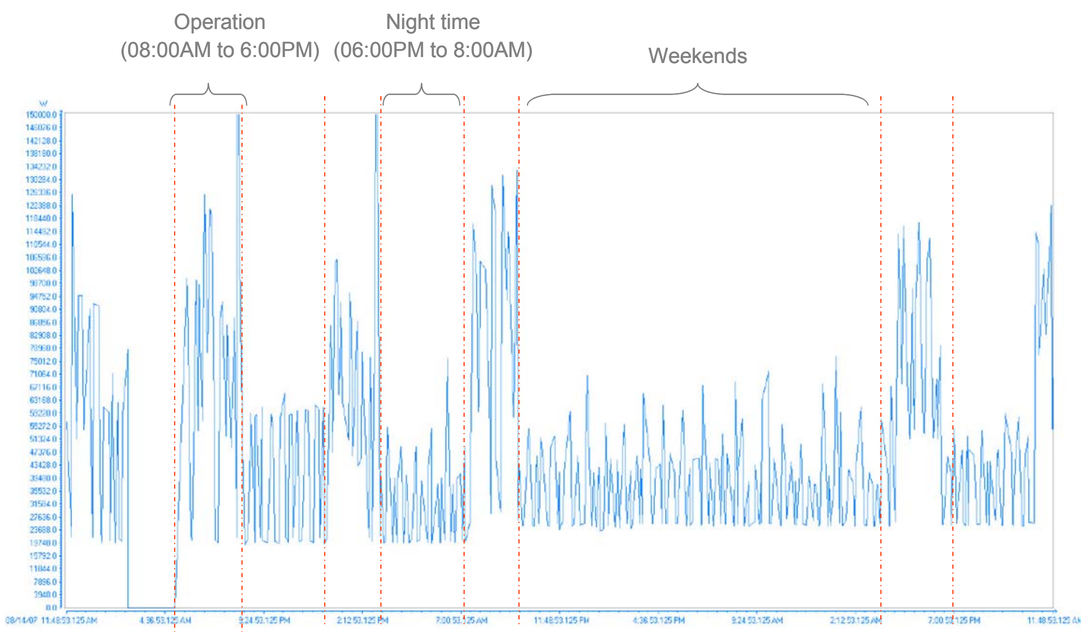


Figure 35: Weekly electricity consumption profile, with daily variation in detail

Operation

As already mentioned, the engine operates in a special operational condition, according to the level of the biogas storage:

Table 7: Set points for engine operation

Biogas Storage Level	Biogas Engine Operation
95-60%	100%
60-40%	75%
40-20%	50%

The engine operation follows the logic diagram presented below:

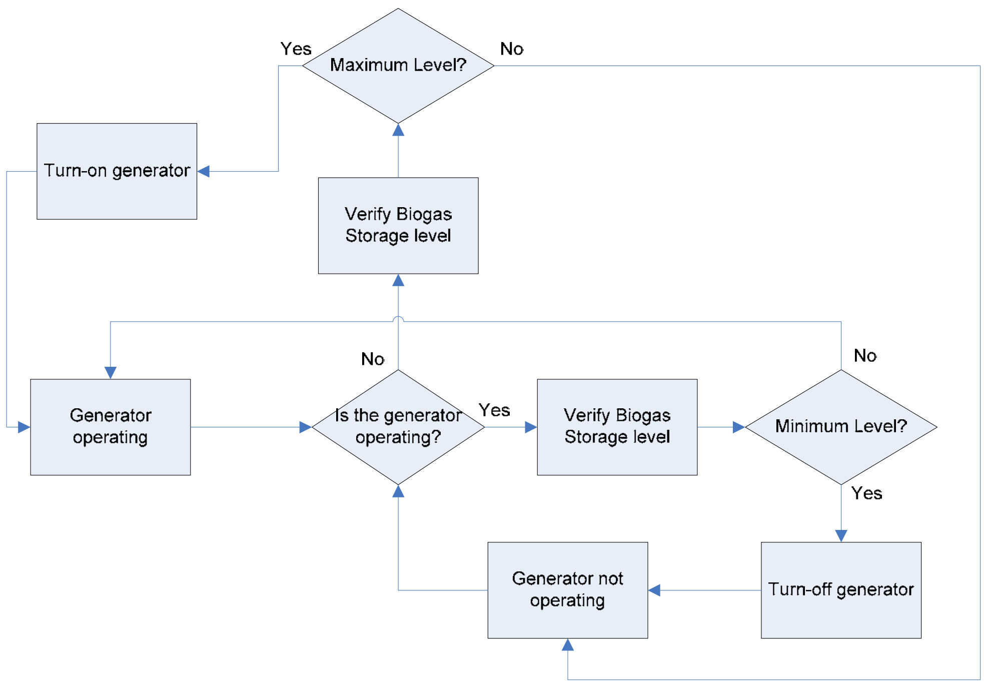


Figure 36: Logic diagram for biogas engine operation

6.2 System Description – H2 SEED project

The H2 SEED project will use the surplus of energy to generate hydrogen in an electrolyser. Hydrogen will be compressed and stored, feeding a vehicle filling station and a cylinder filling system.

The hydrogen supplied by the plant will fuel two hybrid ICE vehicles that will be used by the local council. The hydrogen cylinders will be used in the Hydrogen Lab at Lews Castle College and in other demonstration projects.

The design of the system started in the beginning of 2007 and the hydrogen production facility must be finished by the end of 2008.

The following diagram depicts the main components of the system:

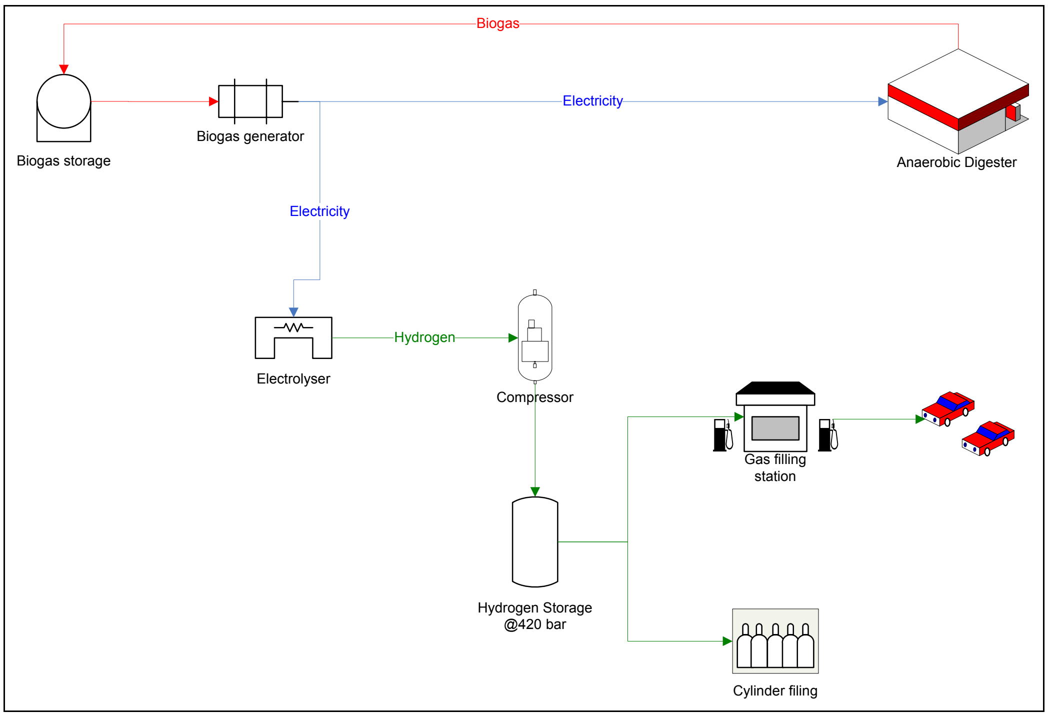


Figure 37: Schematic diagram of the H2 SEED Project

Preliminary design of the system pre-dimensioned the electrolyser. It will be used an Advanced Alkaline Electrolyser with capacity of $5Nm^3/h$. This electrolyser would be able to generate enough hydrogen to the vehicle filling station and to the cylinder filling system.

The electrolyser will be operated according a control loop that is similar to the one that the engine follows. The electrolyser must operate whenever any surplus from the biogas engine is available, given that the hydrogen storage has not reached the maximum level.

The resulting logic diagram for this system is as follows:

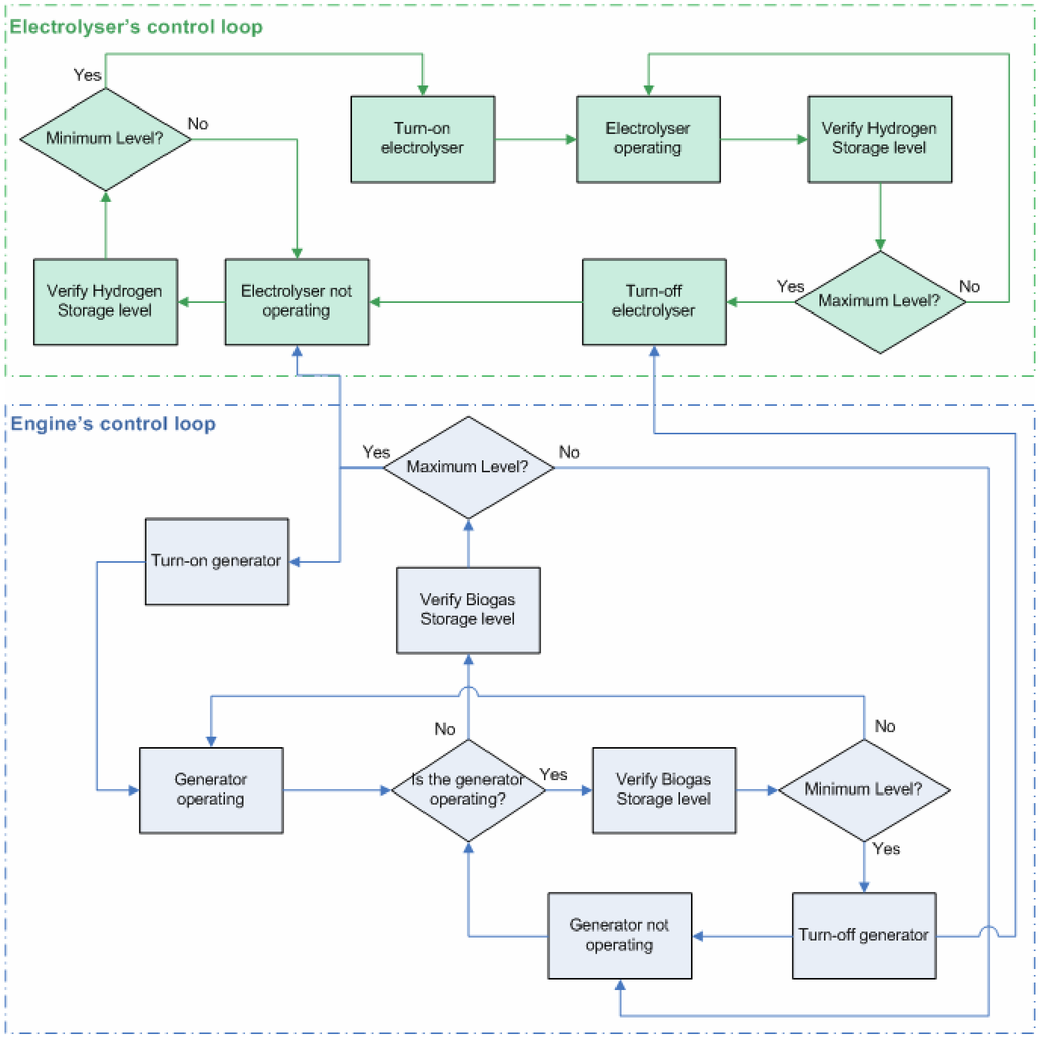


Figure 38: Logic diagram for the H2 SEED project

6.3 Model Development

6.3.1 Energy balance

Considering the information collected and the demand profiles generated, a simple, annual energy balance can be calculated prior to any simulation.

	Biogas Production	286,000	Nm^3	Electricity Load	550,055	kWh
x	Energy content	22.36	MJ/m^3			
	Energy available	6,393,635	MJ			
=	Energy available	1,776,010	kWh			
x	Engine efficiency (approx.)	30%				
	Total Energy Recoverable	532,802.93	kWh	Electricity Load	550,055	kWh

Balance	- 17,252	KWh
Deficit	3.1%	

As can be seen in the energy balance, the energy available in the biogas produced converted into electricity in the generator almost matches the annual energy demand of the plant. The problem is that the generator cannot follow the load variation. Therefore, during some periods there is shortage of electricity, covered by the grid, and in other periods there is excess electricity.

In Homer it is possible to perform an hourly energy balance and verify the performance of the system hour by hour during the year.

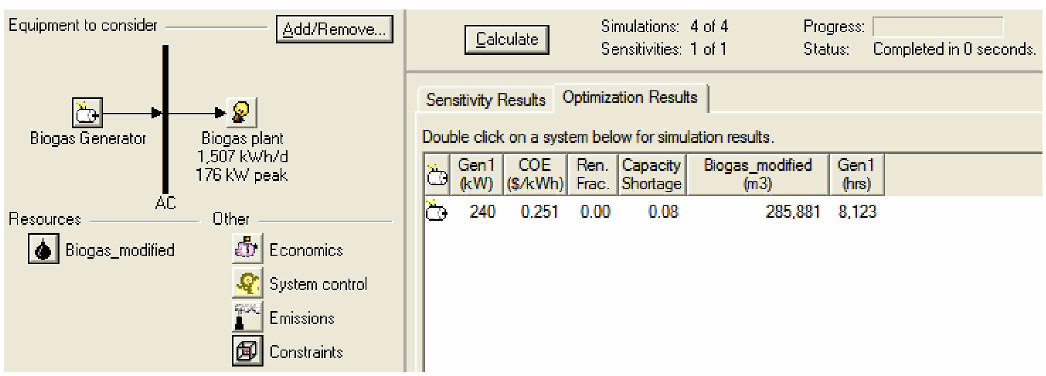


Figure 39: Simplified energy balance in Homer

As expected, this simple simulation resulted in a large deficit, since Homer applies an efficiency curve for the generator performance. However, the detailed results show that this scenario is not feasible, since the generator operates around 20% of rated power most of the time.

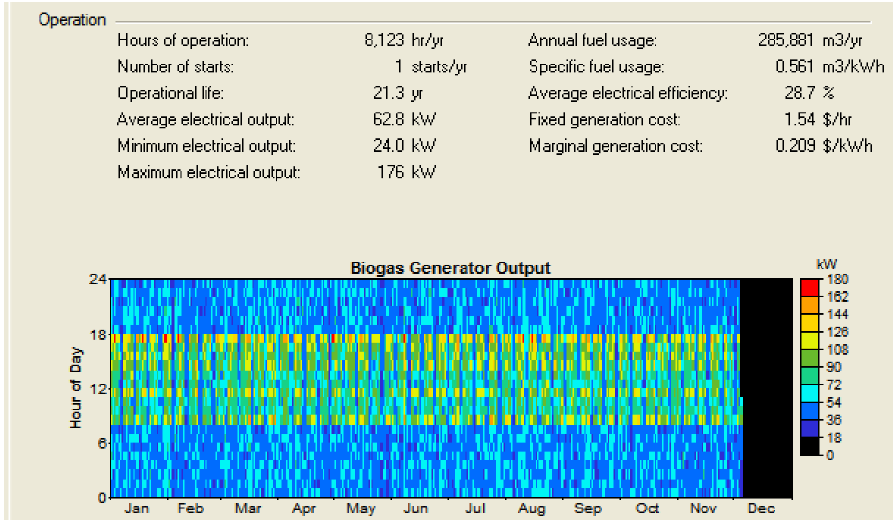


Figure 40: Detailed results for a simplified energy balance in Homer

The main conclusion is that with this level of production of biogas and mainly with the size of the generator available, the plant is not self-sustainable and needs imports from the grid.

6.3.2 Model in Homer

The first step on the development of the model for the project was the simulation of the system in Homer, for its simplicity and optimization capabilities. A simple model was developed, including the biogas engine, the electricity demand and the hydrogen system, as can be depicted from the picture below.

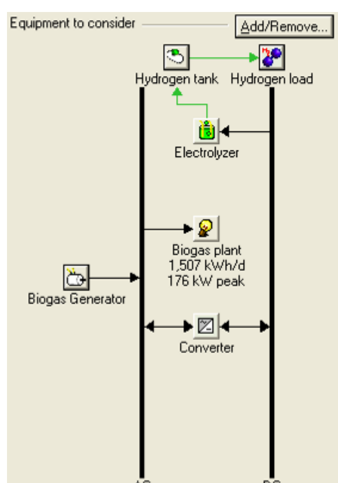


Figure 41: Components considered in Homer model

The load profile generator was used to represent the load profile as presented in Figure 34. With this tool, an hourly data file was generated to serve as input for the models.

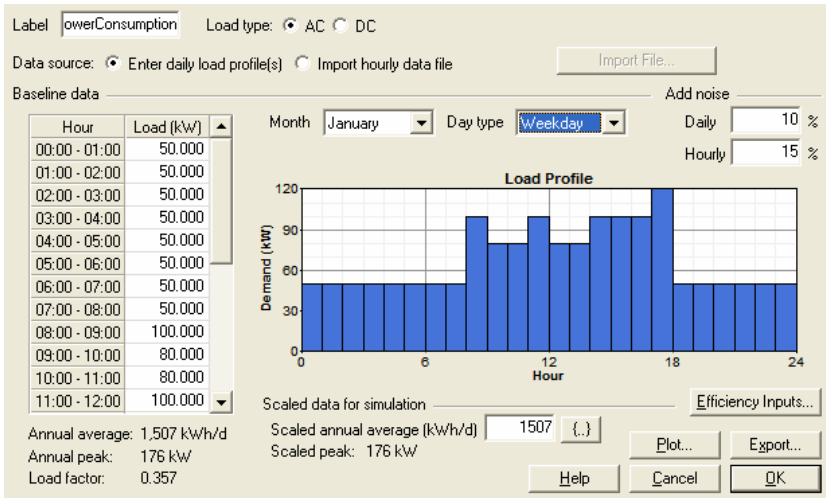


Figure 42: Load profile generator in Homer

Similar procedure was adopted for generation of the biogas consumption profile and hydrogen demand profile.

Nevertheless, the limited control over the behaviour of the main components operation showed the inadequacy of the software to simulate the special operational conditions of the system.

First, in Homer it is not possible to control the operation of the generator according to the availability of fuel. The only possible parameter that can be controlled in this matter is the annual limit of usage of fuel.

Besides that, the engine operates in any point between the minimum load ratio and the maximum rated power to meet a given electrical load. No surplus of electricity is generated, unless an artificially high minimum load is inserted, which decreases the performance of the system, in the sense that too much excess electricity is produced.

The nature of the connection to the grid is another limitation for the model in Homer. In the actual system, the generator operates whenever the biogas storage reaches a pre-defined level. Energy is supplied from the grid whenever the generator is not working. In Homer, the generator operates whenever the load exceeds a pre-defined maximum grid demand and this behaviour cannot be adjusted.

Taking into account these limitations and recognising that the actual behaviour of the system cannot be properly addressed with Homer, further modelling effort focused on TRNSYS.

6.3.3 Model in TRNSYS

TRNSYS is a more robust, complex and flexible simulation tool than Homer. The main libraries available in the software are able to represent each component of the real system.

The resulting TRNSYS model is indicated in the diagram below, according to the characteristics of the plant already described:

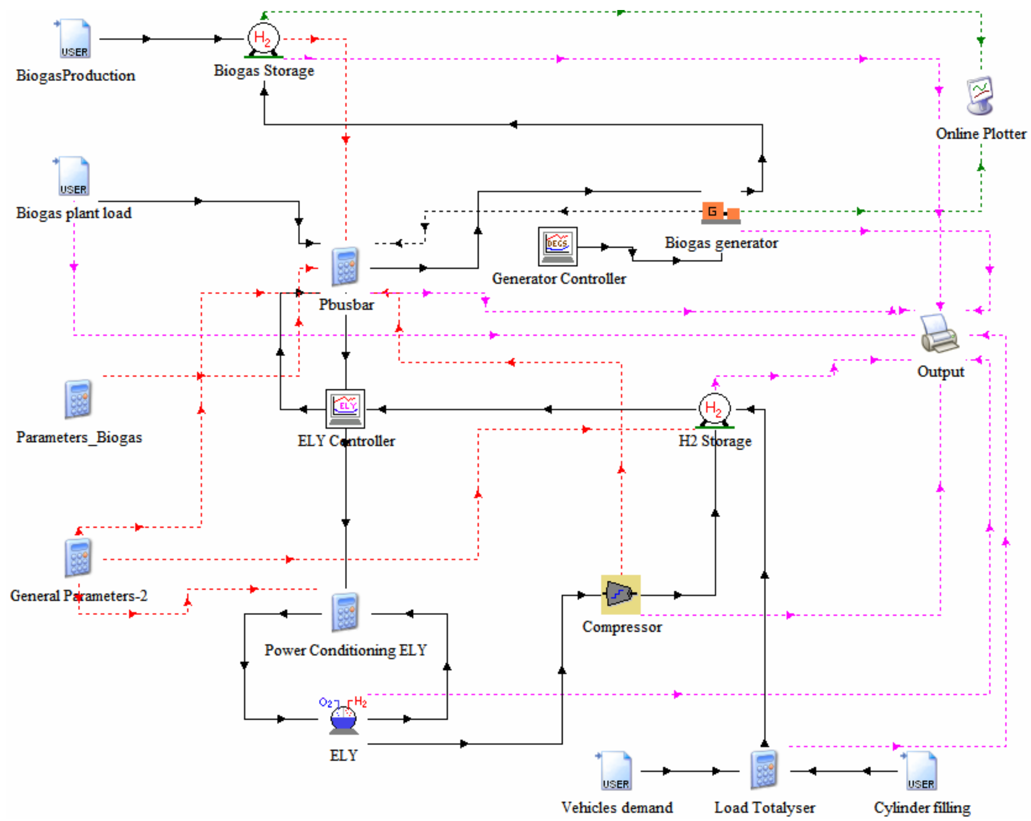
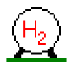
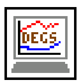
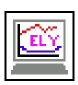
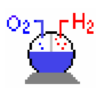
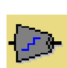


Figure 43: TRNSYS model of the H2 SEED project

The components on the top of the picture describe the engine control loop, while the set of equipments on the bottom of the picture describe the hydrogen system.

The following table presents the description of each component:

Table 8: Description of components of TRNSYS model

Component	Object	Description
	Data Reader For Generic Data Files	Input data files. Files generated with the help of Homer's profile generator based on real data acquired in the plant
	Compressed Gas Storage	This instance of the model calculates the pressure in the storage based on the van der Waals equation of state for real gases. It is used in the simulation to represent the biogas storage (methane, in fact) and the hydrogen tank.
	Control functions for Diesel Engine Generator Sets	This component contains the control functions for one or several engine generator sets.
	Diesel Engine Generator System (DEGS)	This component is a mathematical model for an engine generator set. Default fuel is diesel, but a database is available for more 5 alternative fuels. In this case, methane was selected as the fuel.
	Control functions for an electrolyser	In this case, the electrolyser is designed to operate in a variable power mode. This controller peform the control loop for the hydrogen system indicated in green in Figure 37.
	Advanced Alkaline Electrolyzer	This is a is a mathematical model for a high pressure alkaline water electrolyser. The model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships.
	Compressor, Polytropic / multistage compressor	The compressor is modelled as an multi-stage polytropic compression process with between one and five intermediate stages.
	Equations Processor	The EQUATIONS statement allows variables to be defined as algebraic functions of constants, previously defined variables, and outputs from TRNSYS components. The equation processor indicated as Pbusbar in the model contains all definitions of the control loop for the engine described in Figure 36.
	Online graphical plotter	This component displays selected system variables while the simulation is progressing.
	Printer - No units printed to output file	This component generates output file of selected variables.

PBusbar and the Electrolyser controller are the two key components that define the instructions of the control loops and, eventually, the behaviour of the system.
The electrolyser controller is a standard component of last versions of TRNSYS. It contains a control strategy that links the electrolyser operation and the level of the storage device.
If the electrolyser is ON, the electrolyser Setpoint Power is equal to the maximum between power available and the idling power, until the maximum level of the hydrogen storage is reached and the electrolyser is switched off.
If the electrolyser is OFF, the Electrolyzer Setpoint Power is equal to the idling power, unless the minimum level of the hydrogen storage is reached and the electrolyser is switched on.

The core of the control of the engine is performed by a set of equations in the equation processor Pbusbar. In the same way as the Electrolyser controller does, these equations link the operation of the engine with the level of the biogas storage. It also calculates the available power for the electrolyser, the amount of power that has to be imported from the grid and the amount of power to be exported. These equations are presented in the table below:

Table 9: Equations used in the control loop of the biogas engine

Equations	
HighLevelControl	*GT(BiogasTankLevel,BiogasLevelMax)*
LowLevelControl	*GT(BiogasTankLevel,BiogasLevelMin)*
State	*GT(Ptotal,0)*
CheckHigh	*EQL(State,1)*
Switch	*CheckHigh*HighLevelControl+CheckLow*LowLevelControl*
Grid_export	*abs(min(Load+PSP_ely+Pcompressor-Ptotal,0))*
Grid_import	*abs(max(Load-Ptotal,0))*
Pely	*Switch*Pelymax*

Table 10: Variables for the equations used in the control loop of the biogas engine

Variables	
BiogasTankLevel	Level of biogas storage or SOC (State of charge)
BiogasLevelMax l	High-level set-point for biogas storage
BiogasLevelMin	Low-level set-point for biogas storage
Ptotal	Output of biogas generator
PSP_ely	Output of the electrolyser
Pcompressor	Consumption of the compressor
Load	Electricity load of the plant
Pelymax	Rated power of the electrolyser

The intermediate operational set points for the engine were not reproduced in the simulation in order to make the model simpler. This assumption does not affect the results, since in the real system the engine operates short times below full load. Moreover, this approach is conservative, since the generator will operate a shorter period of time, even though generating the same amount of power.

The engine in the model uses only methane. In this way, the biogas production that feeds the tank is multiplied by 60%, which is the minimum content of methane.

As already mentioned, the electrolyser was pre-dimensioned with the capacity of 5Nm^3/h. Assuming a consumption of around 4.8kWh/Nm^3, the rated power of the electrolyser used in the simulation is around 24kW.

The size of the hydrogen tank and the hydrogen demand derived from the vehicle filling station and from the cylinder filling system are defined after definition of the amount of hydrogen produced by the system. The hydrogen tank will operate at a pressure of 420bar.

6.4 Results for reference case

The results for the reference case are presented in this section.

The set points used in each control loop are as follows:

	Maximum Level	Minimum Level
Biogas Storage	0.95	0.2

Hydrogen tank	0.95	0.8

As can be seen in the picture below, the results obtained in the simulation are similar to the real operational condition of the plant. The red line shows the level of biogas storage, in the left axis while the purple line shows the operation of the generator in the right axis.

The generator operates whenever the biogas storage reaches the maximum level. The biogas production rate is almost half of the consumption rate, as can be seen by the inclination of the red curves.

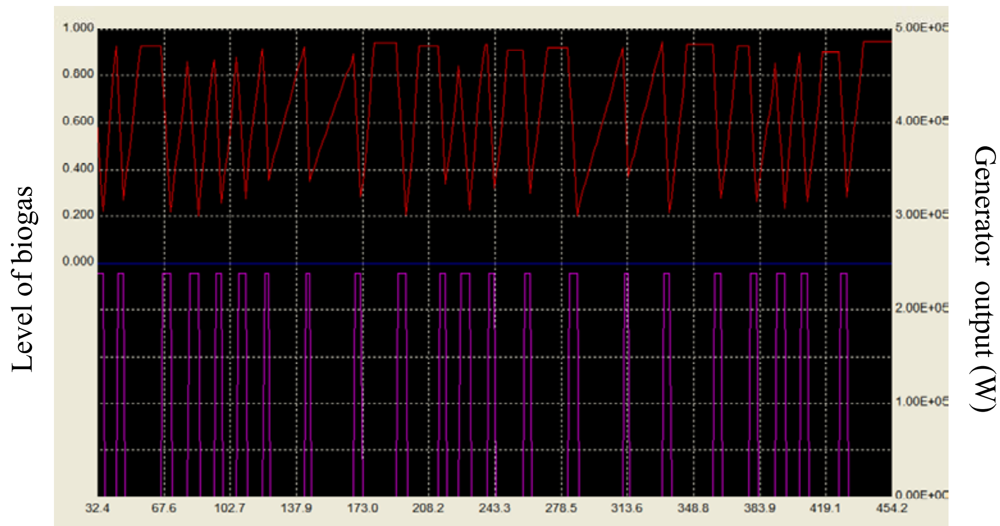


Figure 44: Engine operation and biogas storage level

The electrolyser only operates when the generator is producing electricity. The electrolyser operation is also controlled by the level of the hydrogen tank.

The grid balances surpluses and shortages of electricity.

The following graph shows the total energy produced by the engine along one year, and also the grid imports and exports.

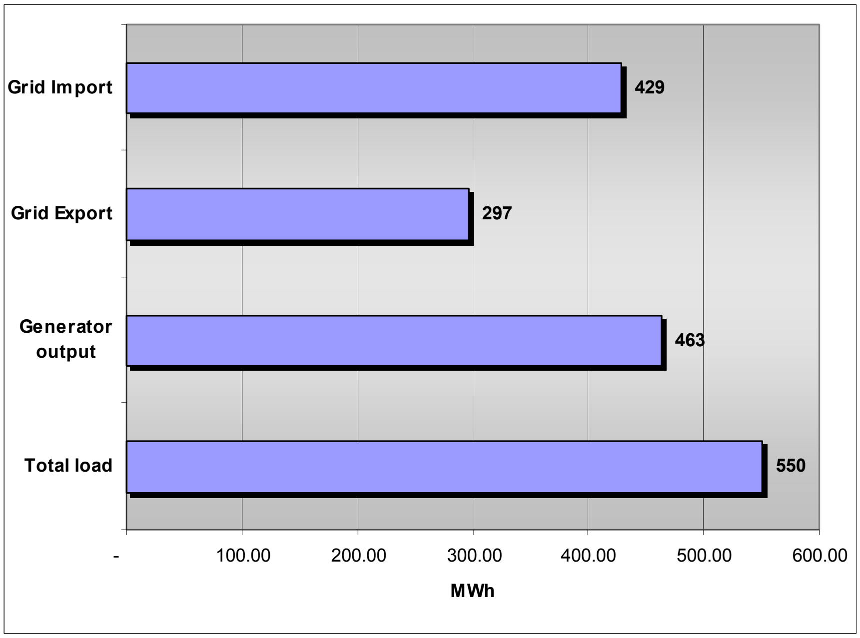


Figure 45: Results for reference case

The generator not only meets the load of the whole plant when it is operating but also supplies electricity to the electrolyser and the compressor and export the surplus to the grid .

The following equations detail the energy balance of the system:

Supply = Demand
Generator output – Grid Export + Grid import = Total Load + Pelectrolyser + Pcompressor + Losses
463.44 – 296.54 + 429.06 = 550.08 + 36.20 +1.02+ Losses
Losses = 8.66 MWh

The Losses in this equation account for the losses in the power conditioning to the electrolyser.

The model also determines the total production of hydrogen by the electrolyser. With this information, not only the demand for vehicles and for cylinders can be established, but also the appropriate size of the hydrogen tank was defined.

In this operational condition, using a hydrogen storage tank of approximately 24 kg (1 m^3 @ 420bar), the annual production of hydrogen reaches almost 8,500Nm^3.

This production is enough to meet the following demand for vehicles and cylinders:

Table 11: Definition of hydrogen demand that can be met by the system

2 vehicles	**2 cylinders a day**
Assumptions - Vehicle: hybrid ICE engine - Tank: solid storage - Capacity: 3.3kg of H_2. - Daily mileage: 60 miles - Consumption: 0.0166 kg/mile - One filling a day per vehicle (one vehicle in the morning and the other one in the evening) - Vehicles do not operate during weekends	**Assumptions** - Cylinders size: 200/K - Capacity: 0.463 kg - Pressure: 136 bar - Filling is not simultaneous to filling of vehicles. - Cylinder filling system does not operate during weekends

The following graph shows the curves for consumption and production of hydrogen, considering the assumptions indicated in the previous table.

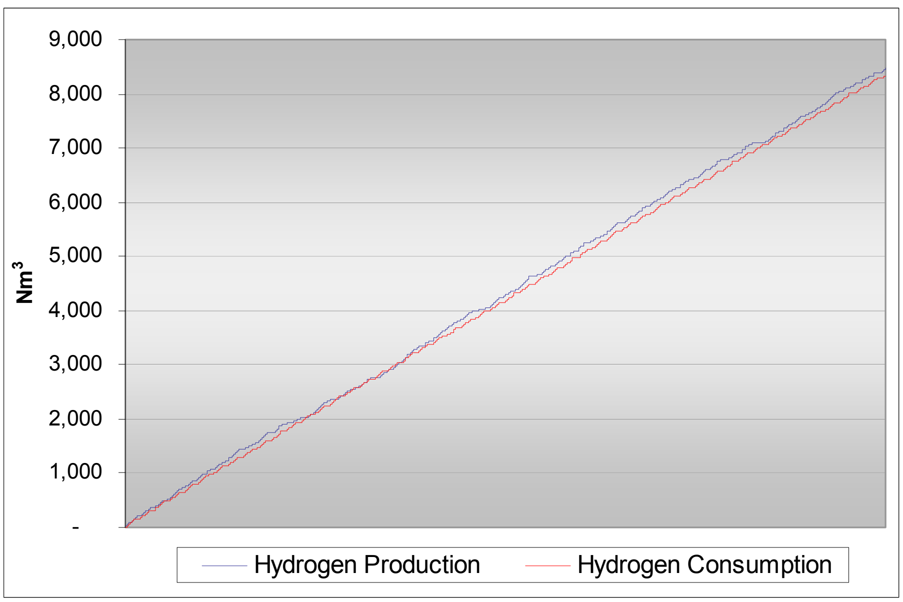


Figure 46: Curves for hydrogen production and consumption

The system is designed for optimised operation. Therefore, it considered the smallest hydrogen storage tank possible. On one hand, a bigger tank would allow increased production of hydrogen and give slightly bigger flexibility to the system. On the other hand, this would result in a bigger capital cost.

As can be seen by Figure 44, with this operational condition and with this level of biogas production the engine does not operate most of the time.
The following graphs show the operation performance of the generator and the electrolyser:

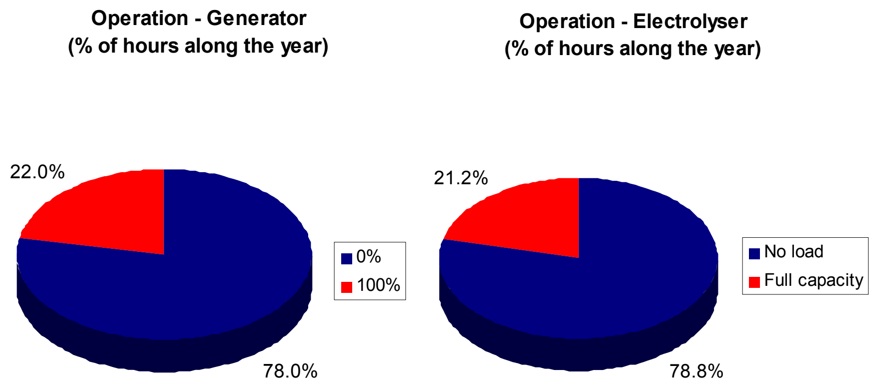


Figure 47: Number of hours of generator and electrolyser operation

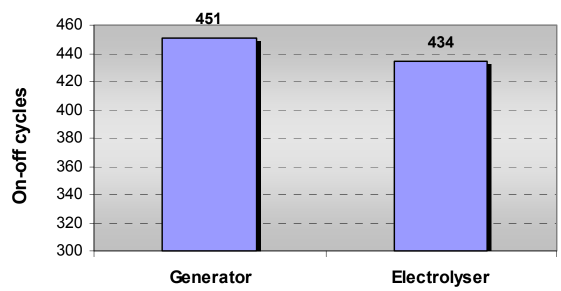


Figure 48: Number of on-off of generator and electrolyser

The electrolyser had less start-ups along the year because in some circumstances the hydrogen storage tank was already full, and in this case the electrolyser does not operate even with available energy from the generator. This behaviour is defined by the electrolyser control loop. (See Figure 38)

This configuration respects the conditions stated in the early stages of conceptual design of the system, which among other parameters defined that the electrolyser would only operate when the engine is operating, preventing the system to import electricity to produce hydrogen.

This would ensure that all the hydrogen produced would be generated directly from a "green energy source". However, this would cause a great stress on the electrolyser and a steep decrease in lifetime.

6.4.1 Results for modified reference case

Therefore, a modified reference scenario was simulated. In this case, the electrolyser operates in idling power most of the time; when the engine is operating, the electrolyser operates in full capacity.

The results obtained in this case are shown in the following figures:

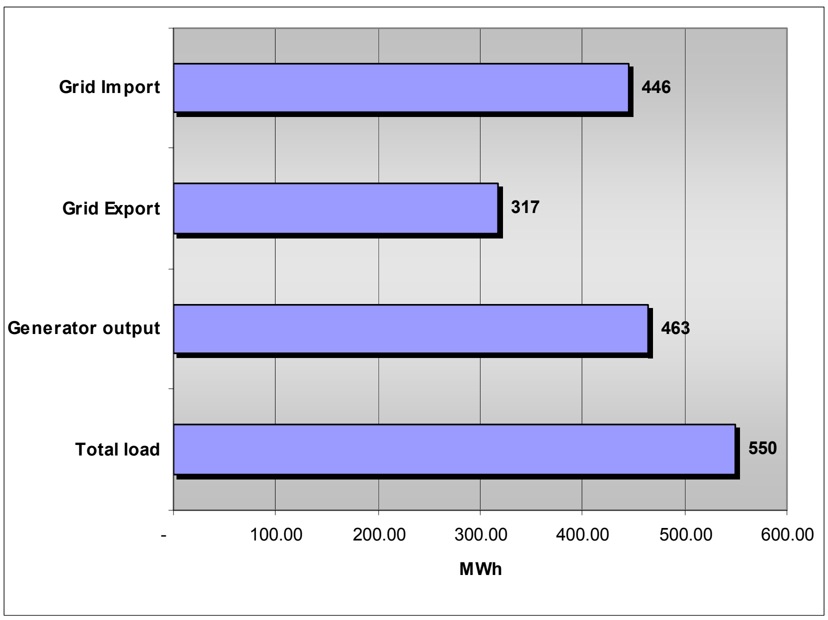


Figure 49: Results for modified reference case, with electrolyser operating in idling power

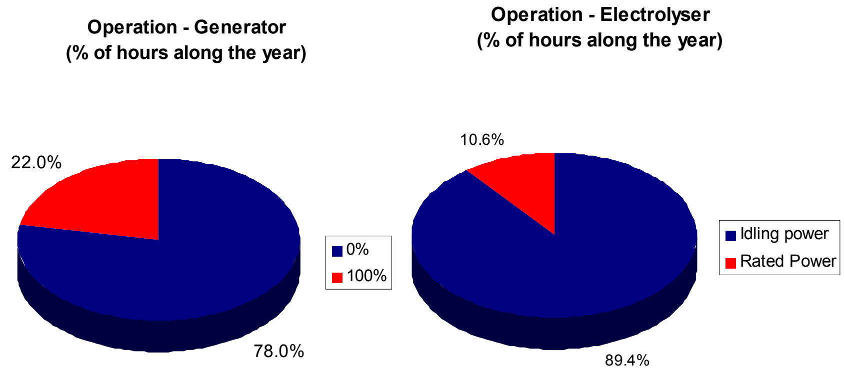


Figure 50: Number of hours of generator and electrolyser operation in the modified reference case

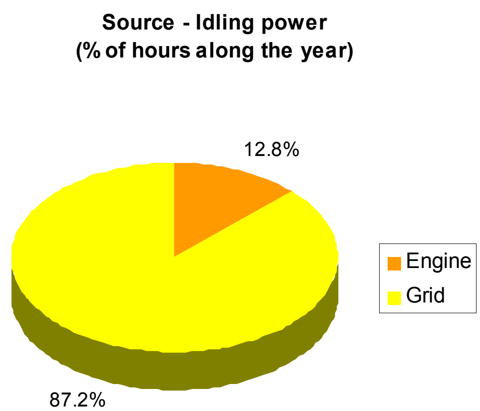


Figure 51: Source of energy supplying idling power to the electrolyser

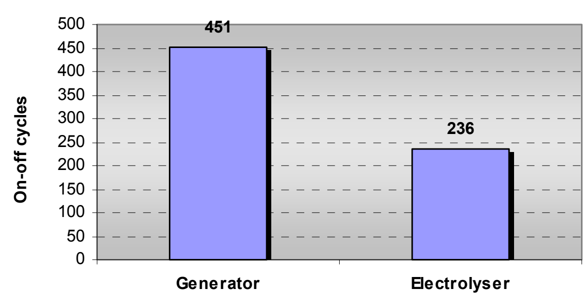


Figure 52: Number of on-off cycles of generator and electrolyser in the modified reference case

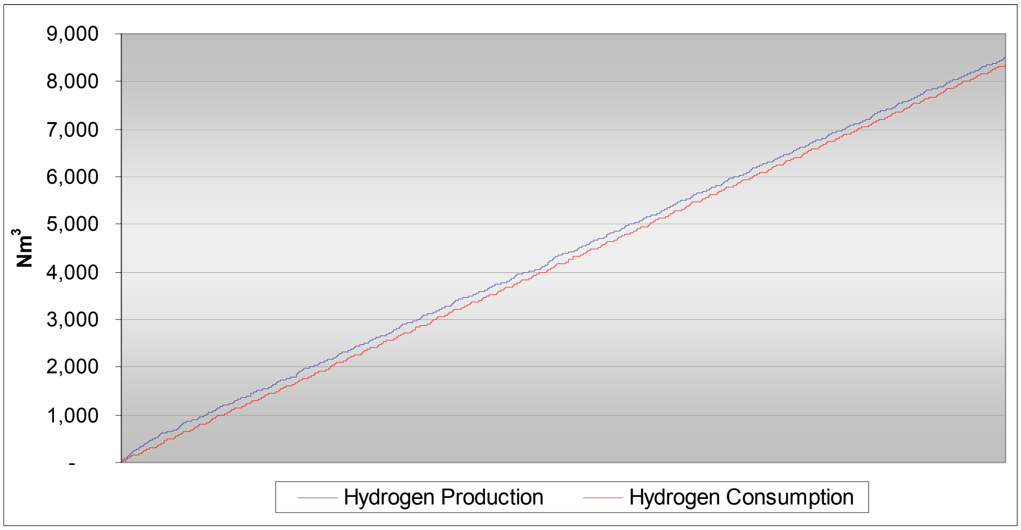


Figure 53: Curves for hydrogen production and consumption for the modified reference case

As can be seen in the previous charts, the grid import in this case is negligibly higher. However, the electrolyser operates in steadier condition, since the operation in idling power minimises the fatigue in the electrodes.

It is worth mentioning that this configuration is a theoretical exercise and it does not represent a feasible practical configuration. For this operational condition, a buffer tank would be needed after the electrolyser, allowing the compressor to operate for longer and in a higher capacity load. However, this simulation shows that this approach is not “less green” than the reference case, with the advantage of protecting the electrolyser integrity.

6.5 Analysis of different operational conditions

The board of the Waste Management plant is working intensively to solve the problem of shortage of organic waste and increase the production of biogas of the plant. In this way, an interesting exercise is the impact of the increase in the amount of organic waste processed by the plant and consequently the augment of biogas production.

6.5.1 Increase in biogas production following current operation profile

In this scenario, the behaviour of the system was assessed in steps of 10% of increase in biogas production. It was also assumed that the consumption would increase 5% for every 10% of increase in biogas production, limited to 30%. These assumptions were arbitrary and different configurations would be easily simulated. All other conditions remained the same, including the operation period (operation only during weekdays, from 8:00 to 18:00).

As long as all physical parameters were maintained constant, a different set point had to be chosen for the biogas storage. With the increase of inflow of biogas, the maximum level of 0.95 showed to be too high and in some peaks of production the engine was not activated and the gas was vented directly. This problem would be unlikely happen in a real system, as long as the PLC would follow and control the system online and instantaneously, instead of using 1 hour time steps.

In this way, a different setpoint is adopted for this simulation exercise as follows:

	Maximum Level	Minimum Level
Biogas Storage	0.95	0.2

A large hydrogen storage tank was used in these simulations, in such a way as to not to interfere into or limit the electrolyser operation.

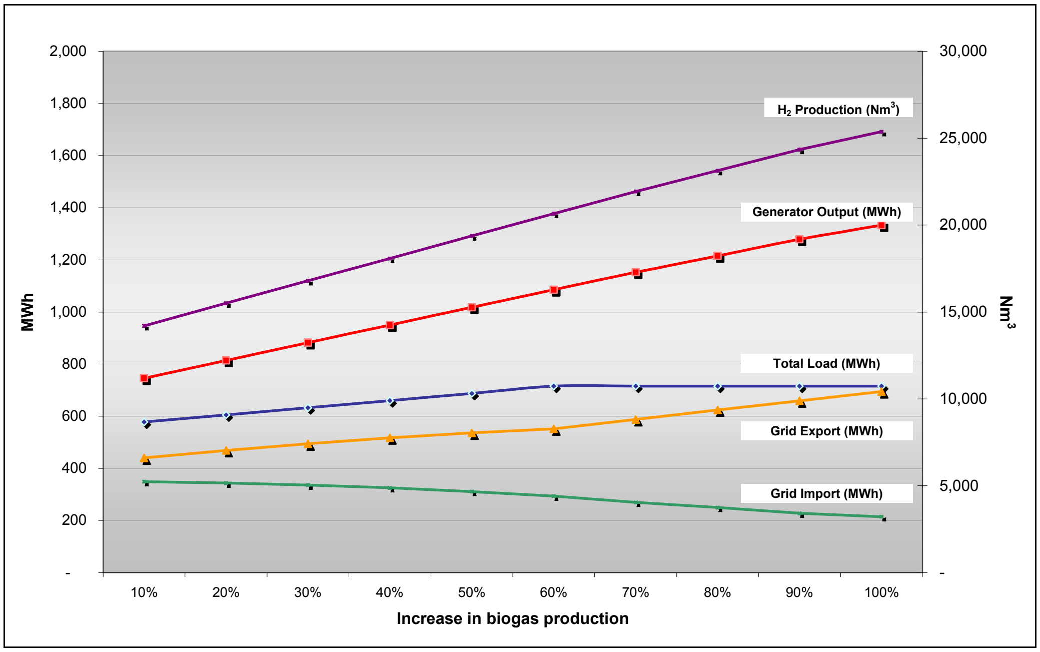


Figure 54: Results for the constant increase in biogas production

The results obtained show that the model behaves as expected.

With the increase in biogas production, not only higher production of hydrogen is achieved but also higher generator output, higher export to the grid and decreasing import of electricity. The generator and the electrolyser presented similar number of on-off cycles, but both equipments operated for longer periods.

6.5.2 Increase in biogas production reaching maximum capacity of the plant

Another interesting scenario is the production of biogas with full capacity of waste processing in the plant. This is a desirable target not only for the possibility of bigger amount of electricity to be exported but also for the optimal operation of the equipment.

Different biogas production and electricity consumption profiles were developed for this case.

Biogas production is adjusted around 100Nm^3/h, ranging from 80 to more than 120 Nm^3/h. This hypothetical curve is shown as follows:

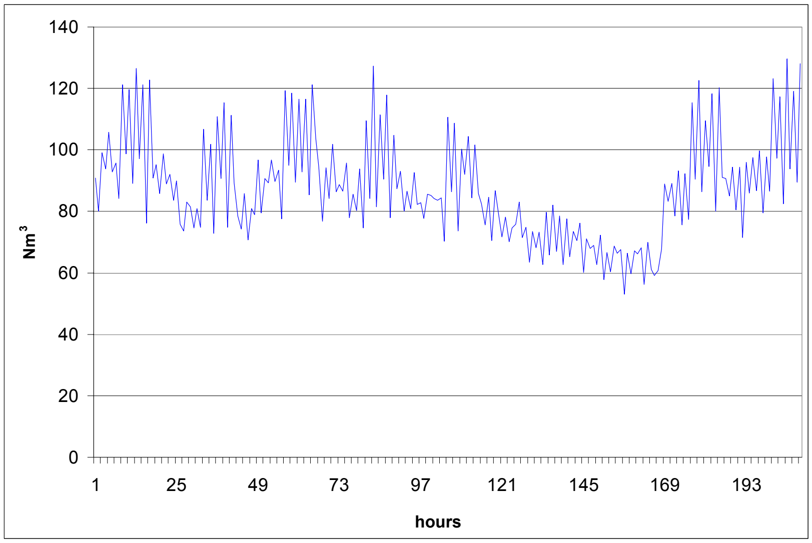


Figure 55: Assumed curve of biogas production in full capacity

It is assumed that the plant operates for 24 hours a day only in the weekdays, as can be shown by the valley in the graph.

Similar approach was adopted to the generation of the electricity consumption in this scenario.

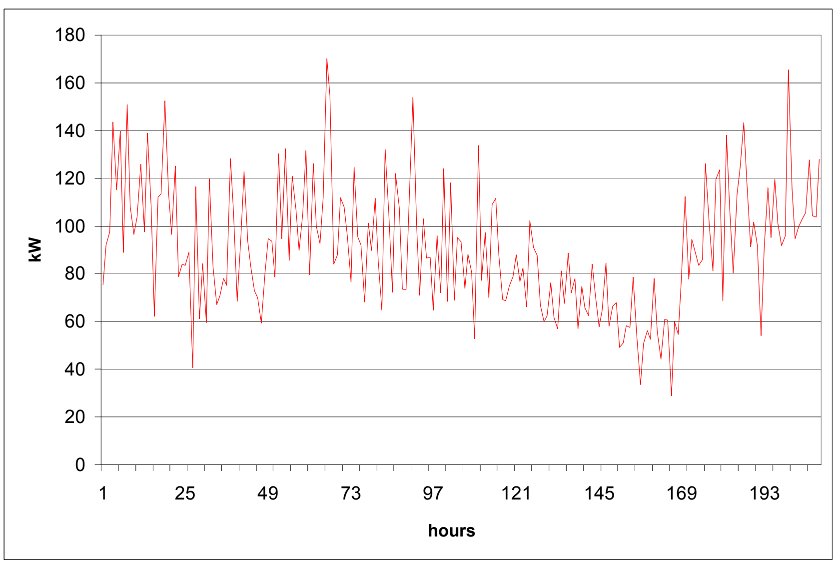


Figure 56: Assumed curve of electricity consumption of the plan in full capacity

For this case, an intermediate level of control was implemented in order to maximise the operation of the engine according to the level of the biogas storage.

In this case, if the intermediary set point for the biogas tank is reached, the generator operates in an intermediary load. The generator will shut down if the tank reaches minimum level or it will come back to 100% load if the tank reaches the maximum level. The set points used in this case are indicated in the following table:

Table 12: Set points for full capacity of biogas production

Level of the biogas storage	Action on the generator
80%	Turn on
80% to 50%	100% of Rated Power
50% to 20%	70% of Rated Power
20%	Shut-down

In this case, the engine can operate most of the time, reducing the number of on-off cycles to a minimum level.

The following chart shows the behaviour of the system under those constraints:

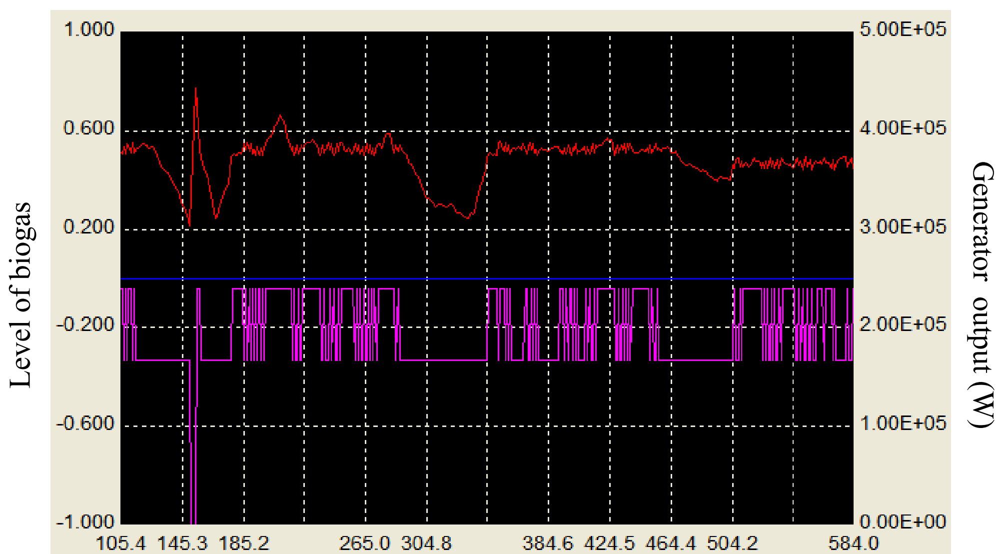


Figure 57: Biogas level and generator behaviour for plant operating in full capacity

The red curve represents the biogas storage level. The pink curve represents the output of the generator.

With this operational condition, the plant becomes auto-sufficient and import electricity to the grid only whenever the generator is not available. The following graph shows the summary of electricity generation and consumption:

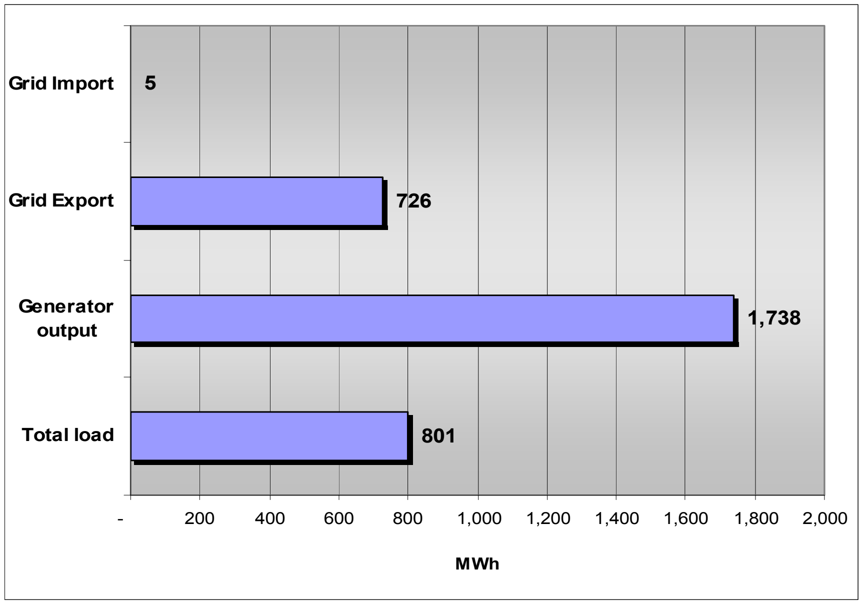


Figure 58: Results for plant operating in full capacity

The following charts show the performance of the generator and the electrolyser operating under those conditions:

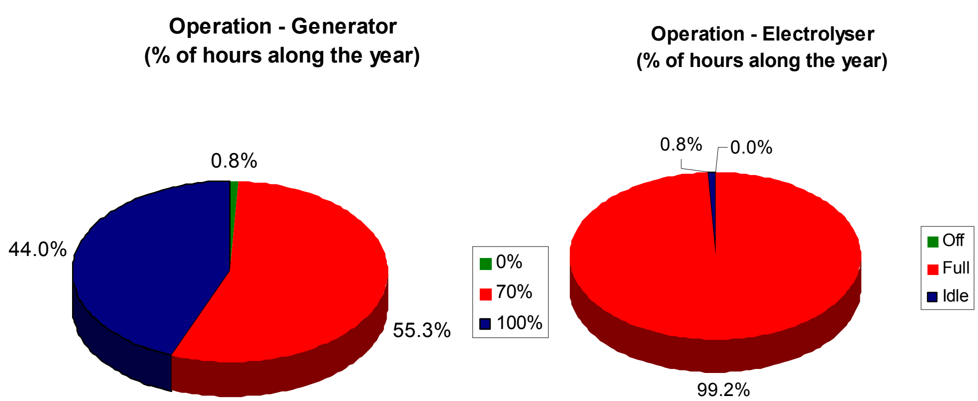


Figure 59: Performance of generator and electrolyser for plant operating in full capacity

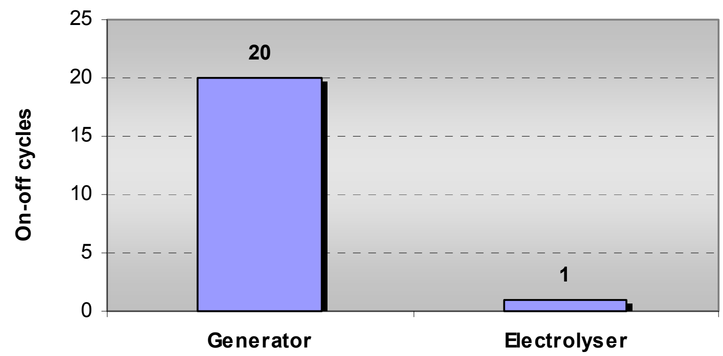


Figure 60: Number of on-off cycles for plant operating in full capacity

In this scenario, the plant can produce around 40,000 Nm^3 per year of hydrogen. This production would be high enough to provide fuel to 8 vehicles (considering the same assumptions indicated as the reference case) and 4 cylinders a day.

6.6 Alternative configuration

6.6.1 Introduction

The previous sections showed that the system proposed for the H2 SEED project can work and produce the amount of hydrogen needed. Nevertheless, the production of hydrogen from biogas through electrolysis has very low efficiency, mainly because of the electricity conversion in the generator.

Electrolysis is the technology of choice whenever cheap or renewable electricity is available. However, in this case, hydrogen can be obtained directly from the renewable primary source, skipping the step of conversion to electricity: from natural gas (or biogas), hydrogen can be produced directly via reforming.

The main setback of this process was the size of reforming units, mainly designed for medium to large-scale production.

With the development of hydrogen systems and the growth of demand for hydrogen, many efforts have been made to decrease the size of units. In the early stages of development of a hydrogen economy, mini and micro reformers can decrease the investment cost of development of a distribution network, by producing it directly in the point of consumption.

This year, a company based in The Netherlands called HyGear released and tested a micro-scale reformer with capacity of 5Nm^3/h of hydrogen. The first commercial unit will be installed in the end of 2007. The standard system operates with natural gas and is targeted to produce hydrogen in filling stations.

Based on this new technology, another configuration for the H2SEED is possible, converting hydrogen directly from the biogas stream. An additional purification unit is needed to remove the CO_2; SO_2 is currently removed by a scrubbing system in the plant.

The following picture shows the resulting diagram of the system:

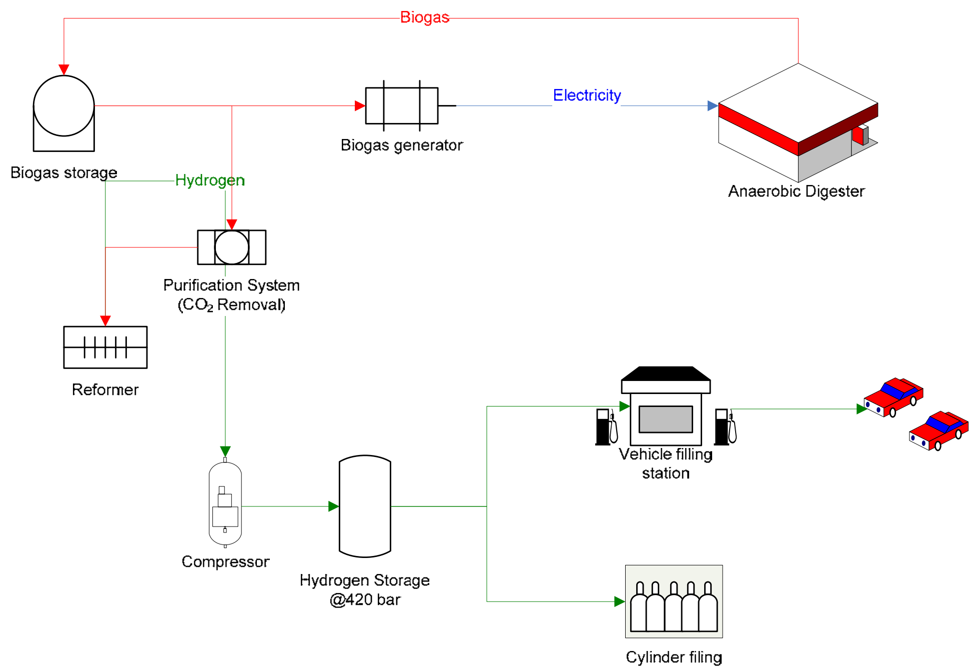


Figure 61: Diagram of alternative configuration

As showed in section 2.2.1.1, in a reformer hydrogen is produced by the reaction of methane with steam, under high temperatures and in the presence of a catalyst. Considering the chemical reactions involved in this process, some estimates can be made.

For every 2 moles of hydrogen produced, 1 mole of water is needed (1 mole in each reaction). In this way, in stoichiometric conditions, for every kilo of hydrogen produced, 4.42 kg of steam would be needed.

Considering the difference of enthalpy between water and steam, the energy required for a given flow rate of hydrogen can be easily determined, as showed in the following mass and energy balance:

Enthalpy - H_2O @ 20°C	506,609.00	J/kg	(a)
Enthalpy - H_2O @ 800°C	4,157,410.00	J/kg	(b)
(b) - (a)	3,650,801.00	J/kg	
Consumption of steam	4.42	kg of H_2O/kg H_2	
Heat required	16,124,371.08	J/kg H_2	
or			
Heat required	1,449,580.96	J/m^3 of H_2	

Considering the capacity of the reformer as 5Nm^3/h, the power needed for the steam generator is expressed as follows:

Hydrogen Flow rate	5	Nm^3/h
Power	7,247,904.80	J/h
Power (kW)	2.01	kW
Efficiency - steam generator	50%	
Heat consumed	4.03	kW

Waste heat from the generator can be used to generate steam to run the reaction, since excess heat is currently available.

6.6.2 Model description and assumptions

In order to verify the feasibility of the alternative configuration, a simple model was prepared in TRNSYS. A set of equations were inserted representing the new reformer in the level of mass and energy balance. A future improvement of this model is the development of a component for reformer units in TRNSYS, as will be discussed in section 7.3.

All the results obtained are presented in comparison to the reference configuration, using the same parameters.

The main assumptions in this model are:

- The reformer only works during normal operating hours of the plant

- The reformer operates 8 hours a day, regardless the operation of the biogas generator
- Heat is always available to generate steam to run the reaction
- The reformer operates at 95% of nominal capacity
- Power consumption for purification unit and possible ancillary systems is assumed as 10kW (which is reasonably high and thus ultra conservative)
- The efficiency of the reformer is 75%
- The set-point for high level in the biogas storage is considered in this case as 90%
- The hydrogen storage is big enough not to interfere in the electrolyser or reformer operation (this assumption is used only to evaluate the maximum capability of each configuration to produce hydrogen; in normal procedure the reformer and the electrolyser operation is limited by the level of the storage.

The following diagram represents the system in TRNSYS:

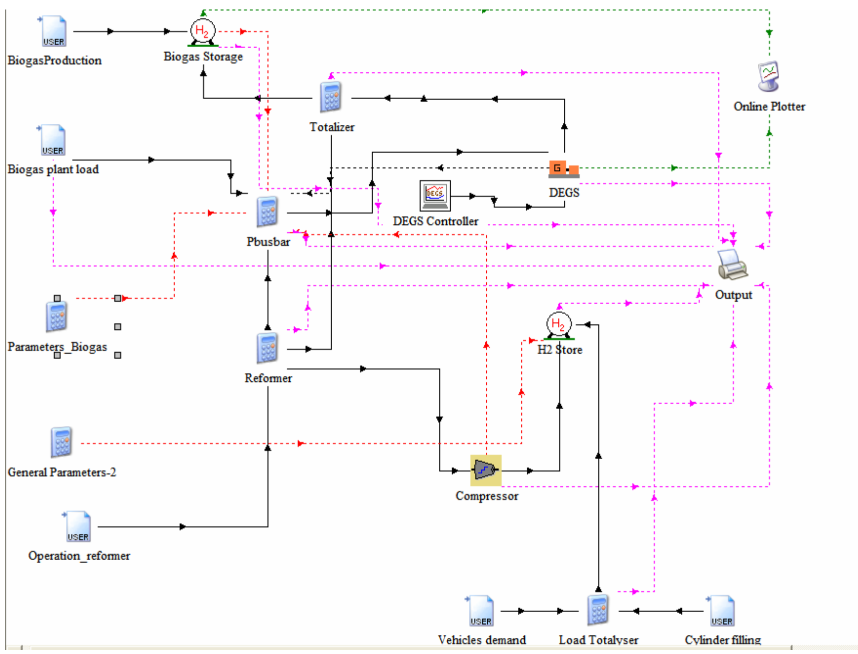


Figure 62: TRNSYS model for the H2SEED project using an alternative configuration with a reformer

The following equations govern the behaviour of the reformer, considering the assumptions previously presented:

Table 13: Equations used in the simulation of the reformer

Equations	
Hydrogen	*Operation*Capacity_load*Capacity*
Methane	*Hydrogen/Efficiency*
Load_Purif	*Operation*Purif_consump*Capacity_load*
Heat_steam	*(Hydrogen*1449580.96)/3600*
Steam_generator	*Heat_steam/Steam_gen_effic*

Table 14: Variables for the equations used in the simulation of the reformer

Equations	
Hydrogen	Amount of hydrogen produced (in Nm^3/h)
Operation	Defines the operation profile of the reformer (runs only when the plant is operating)
Capacity_load	Percentage of nominal capacity of the reformer
Capacity	Nominal capacity of the reformer
Methane	Amount of methane produced (in Nm^3/h)
Efficiency	Efficiency of reformer unit
Load_Purif	Electrical load of the purification plant and ancillary systems
Purif_consumption	Consumption of the purification plant and ancillary systems
Heat_steam	Heat needed to generate required steam
Steam_gen_effic	Efficiency of steam generator
Steam_generator	Consumption of steam generator

With those equations, the model is able to determine the amount of hydrogen produced, the methane (and consequently, the biogas) consumed, the demands of the steam generator and the same outputs as presented for the reference case.

6.6.3 Results

All results in this section will be presented for the reference case and the alternative case in order to compare the two configurations.

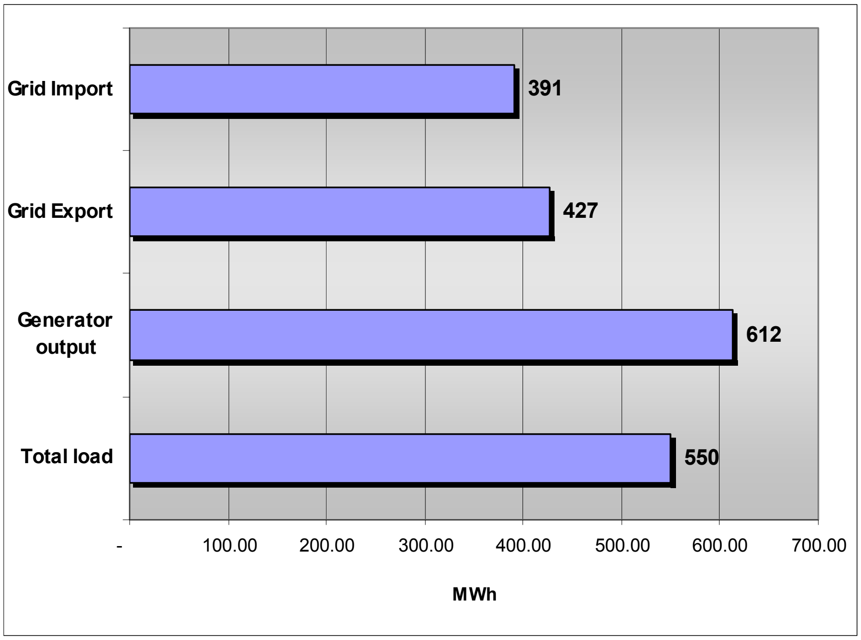


Figure 63: Results obtained for the alternative configuration with reformer

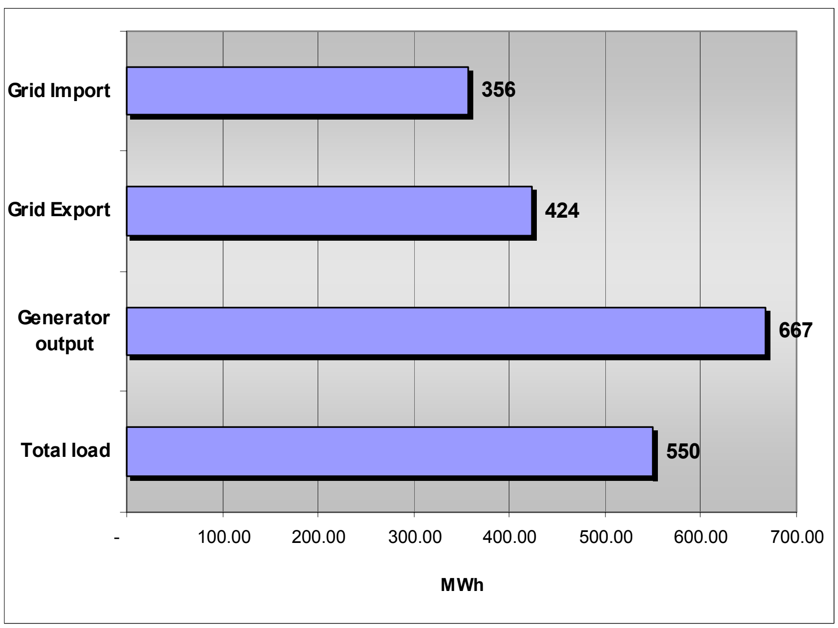


Figure 64: Results for reference case with the same parameters as the alternative configuration

As can be seen by the charts, the results obtained are very similar. The configuration with a reformer presented slightly higher grid export and import and slightly shorter generator output. These changes, on one hand, stem from the fact that the total electrical consumption for the assumed ancillary systems for the alternative configuration is less than electrical consumption of the electrolyser; on the other hand, the output of the generator is slightly less because of the consumption of biogas by the reformer.

The following set of charts show the number of on-off cycles for both cases:

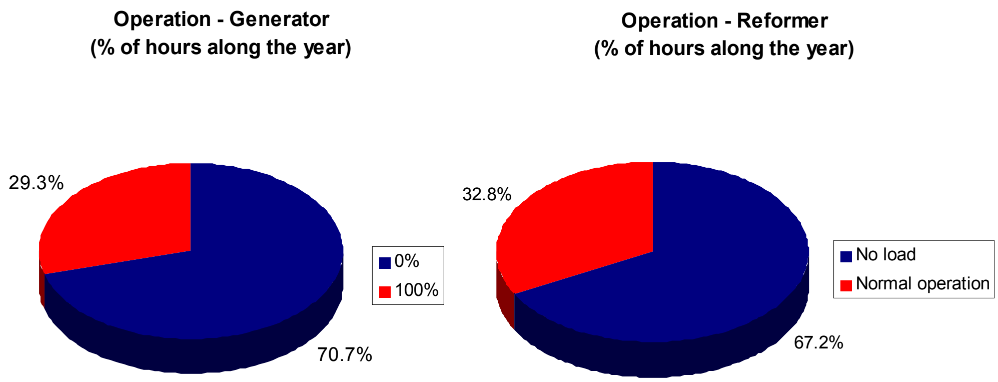


Figure 65: Performance of generator and reformer

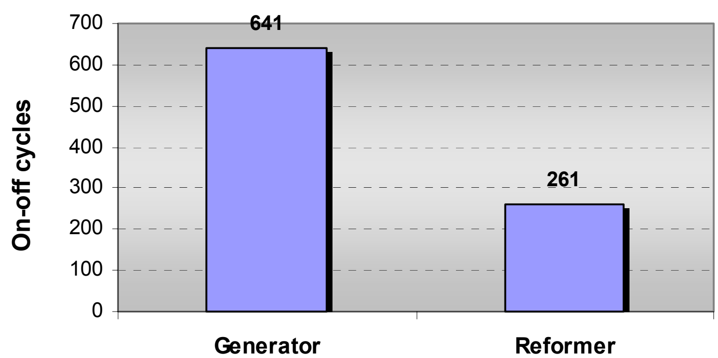


Figure 66: Number of on-off cycles for alternative configuration with reformer

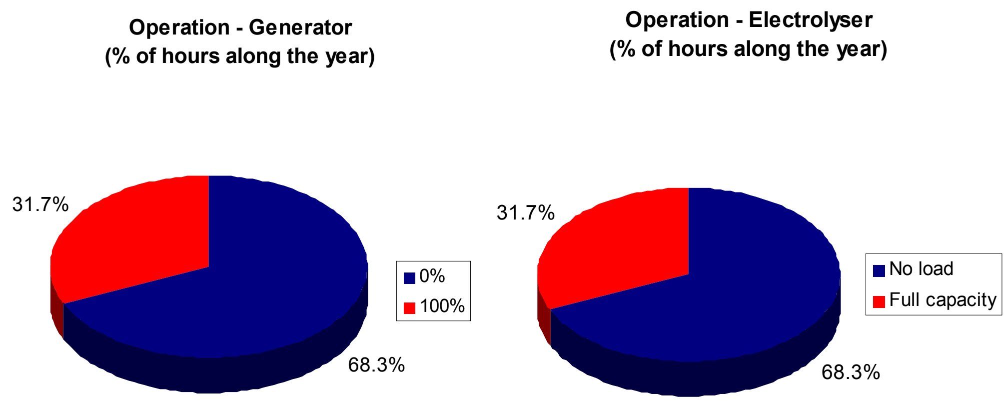


Figure 67: Figure 68: Performance of generator and electrolyser with the same parameters as the alternative configuration

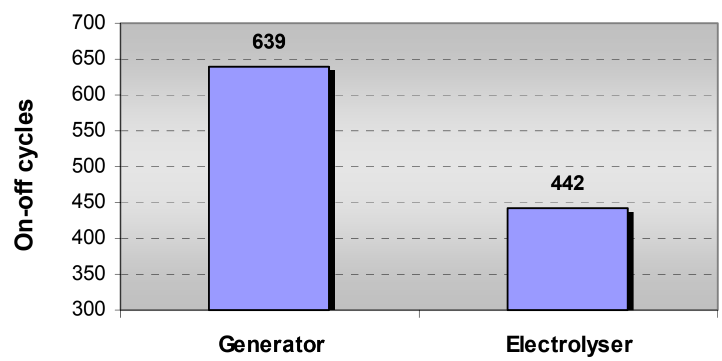


Figure 69: Number of on-off cyles for reference case using the same parameters as the alternative configuration

As can be depicted by the graphs, the reformer operation is independent on the generator and presented less on-off cycles. The higher consumption of biogas stemming from the addition of the reformer did not change considerably the behaviour and the operational profile of the generator.

As expected, the electrolyser followed the operation profile of the generator (since the size of the hydrogen storage is so big that does not affect the operation of the electrolyser).

The following chart shows the production of hydrogen in both cases:

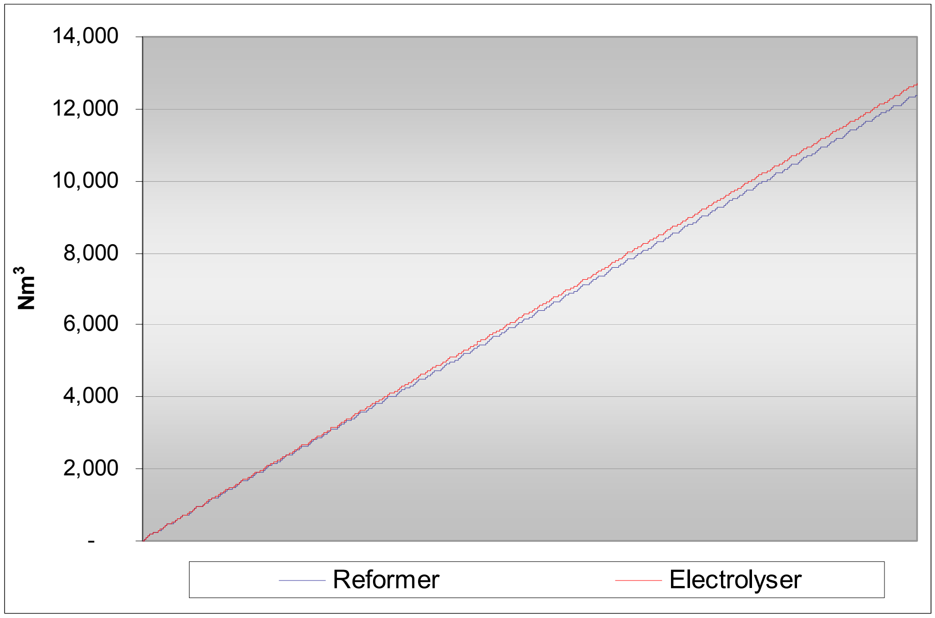


Figure 70: Hydrogen production of reformer and electrolyser

Again, results obtained are very similar and it can be assumed that both systems produce the same amount of hydrogen along the year.

The following graph shows the biogas consumption along the year for both systems:

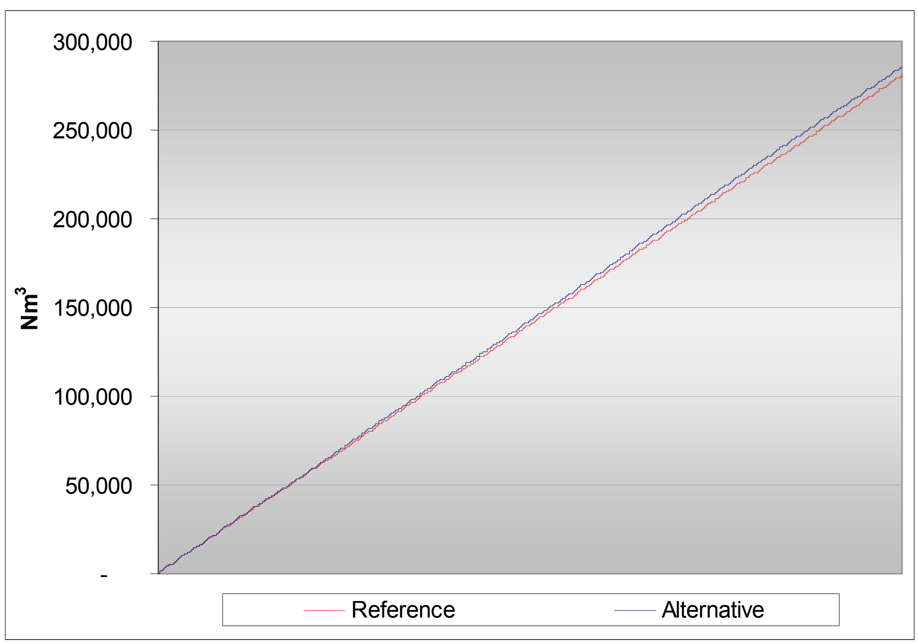


Figure 71: Biogas consumption for reference and alternative cases

The inclusion of the reformer did not affect considerably the consumption of biogas.

7 Overall analysis

7.1 Conclusions

The results presented in the previous section showed the potential of the model. TRNSYS is not limited to a mere balance of mass and energy in the system. It takes into account physical parameters of each component, describing the behaviour of a equipment through algorithms and empirical correlations.

As far as the reference case is concerned, the results showed that even with the intermittent production of electricity, the system would be able to produce as much hydrogen as needed by the initiatives and demonstration projects in the region. However, some issues cannot be assessed by the model but are crucial for feasible operation of the system. The elevated number of on-off cycles is one of the biggest problems. This operation is harmful not only to the engine, but also for the electrolyser and the compressor.

The modification of the configuration of the system, including a low pressure tank right after the electrolyser and the operation of the electrolyser – at least in idle power – regardless the availability of electricity from the engine would probably mitigate some damage to the system. In this configuration, the compressor would also be protected, since it would operate for longer periods and according to the level of the buffer tank.

The analyses presented in section 6.4 showed that the continuous operation of the electrolyser without preventing the import of electricity to the grid to supply idle power while the generator is not operating would not increment considerably the amount of electricity imported. Moreover, this operational condition would produce almost the same amount of hydrogen, with the benefit of protection of the main components of the equipment. Therefore, as already mentioned, the use of electricity from the grid would not affect the sustainability or increase the overall emissions of the system, since a higher amount of renewable generated electricity is exported.

As far as the alternative configuration is concerned, the simulation showed that a micro-reformer would also be suitable for the H2 SEED project. Even with the ultra-conservative assumptions adopted, the system with a reformer produced satisfactory amount of hydrogen in order to meet the forecasted demand.
The higher efficiency of the conversion in the reformer did no affect considerably the results, since the hydrogen production unit and the load involved in its operation for both cases are too small when compared to the generator output and the load of the plant.
The benefits brought by the reformer rely on lifetime and investment cost.
The reformer unit seems to be less sensitive to the number of on-off cycles than an electrolyser, even thus this operation is not ideal for the equipment either. The demand for CO_2 removal on biogas stream does not seem to be a setback, since a scrubbing system for sulphur removal is already installed and operating.
Considering the investment costs, the preliminary estimates for both systems presented similar values.

Therefore, the simulation did not show any remarkable advantage in any of the systems studied. In order to select the preferred system, a more accurate and detailed design would be needed.

Given that the engine is available, installed and working, the cheaper and most effective approach to increase the performance of the system is the increase of organic waste and consequently the increase in biogas production. A set of smaller engines that would operate in higher capacity load for longer periods of time would be more suitable for the profile of fuel availability and load variation, not mentioning the benefits from redundancy and back-up operation. Nevertheless, the investment commitment to implement this modification would be too high, even considering the possible damage that this operational profile can cause in the current engine.
Several alternative sources of organic matter are under analysis in order to increase biogas production. Among several possibilities, possible sources are:

- Increase of segregation of organic waste from the community, arising from educational program and environmental awareness
- organic waste from neighbour regions that do not have digester or incineration facilities
- sludge from wastewater treatment from the local council
- residues from fish farming and fish industry
- vegetable waste from food processing

The main reasoning for the project at first was the fact that in early stages of operation electricity was not exported to the grid. With the availability of a free surplus of electricity, the production of hydrogen was one of the obvious answers. However, the research and development prospects with a project like this are benefits that cannot be measured in terms of pay-back period and investment cost. This project can be a landmark on hydrogen technologies in the region, putting the Western Isles in the avant-garde of renewable energy development.

7.2 Alternative configurations

Considering the current technological development, several options are available to this system. The rationale behind the choice of a gas engine to provide electricity and heat relies on economical factors and maturity of technology.

A good alternative to the engine would be a stationary fuel cell. Solid oxide and molten carbonate fuel cells can produce electricity directly from biogas. The high content of carbon dioxide helps the internal reforming of methane. The overall efficiency of the system is higher and the emissions considerably lower.

However, these technologies are under development yet.

As a result, the capital investment of a system of this size would exceed many times the cost of the engine. Moreover, short lifetime is still an issue. Purification of the biogas would be also be required.

7.3 Recommendations for further research

This study can be easily expanded due to the flexibility of the model and the different alternatives that can be tested not only for the hydrogen plant but also for the anaerobic digester. The following topics are considered motivating challenges for future research:

- Development of TRNSYS components for reforming systems and stationary fuel cells
- Study in detail the constraints and equipment characteristics of the system and propose the optimal design for systems with the same features of H2 SEED.
- Analysis of the impact of different feedstocks into the digester performance
- Comparison of efficiency and life cycle costs of reforming, fuel cell and electrolyser systems from biogas
- Logistics and economic study of alternative sources of organic waste that would improve the production of biogas.

7.4 Recommendations for further development in the region

The unrivalled renewable resources in Western Isles allow the development of several initiatives with no parallel across the UK. Natural resources allied to the energy and enthusiasm of young researchers and entrepreneurs can transform the region into the centre of excellence of renewable technology in the UK.

Besides the wind energy projects and prospects for wave and tidal energy, the Hebridean Hydrogen Park can lay the groundwork for the development of one of the most promising hydrogen industries in Europe.

In this section, some complimentary projects are indicated in order to contribute to this vision. This is not an exhaustive and ultimate review; the technologies described here, however, can accelerate the development of hydrogen market predicted in the third phase of the Hebridean Hydrogen Park Program.

Small CHP systems

This is the most prominent contribution of hydrogen to the built environment. Currently, the maturity of technology allows the usage of small CHP systems in domestic sectors. The barriers for development is hydrogen availability and establishment of a distribution network of hydrogen and cost.

Systems like this can achieve great efficiencies with no emissions and can substitute gas or diesel based systems with several advantages.

Once established the initial hydrogen production, incentives can be created for application of small hydrogen CHP systems in new developments and refurbishments in domestic, industrial and commercial sectors.

Hybrid stand-alone systems

Some remote areas across the Western Isles would benefit from the construction of small stand-alone systems that would be able to provide all the energy needs of small communities.

The PURE project developed in Shetlands is an example of the feasibility of these systems. The availability of plentiful wind resources and hydrogen storage would allow the implementation of similar system that would decrease the dependence on fossil fuels from small isolated communities and potentially could decrease the energy poverty in the region.

Development of hydrogen fuelled public fleet

The size of the public fleet in the Hebrides can be considered small enough to be completely supplied by renewable technologies. Hydrogen or blends of hydrogen and gas can be used to fuel buses and taxis in the region.

Research on marine propulsion devices

The Western Isles is connected to the mainland mainly by marine transport. The constant supply of goods from mainland and people transportation is primarily done by ferry. Annual energy demand for this sector is not negligible.

In this way, the region has the potential to be a testbed for development of renewable marine technologies. Partnerships can be formed with bigger research institutions to use the Hebrides as case study.

8 Bibliography

1. Hydrogen fact sheets – Hydrogen Safety. The National Hydrogen Association. [homepage on the Internet]. Available from: http://www.hydrogenassociation.org/general/factSheet_safety.pdf (Accessed 26 July 2007).
2. Comparative Properties of Hydrogen and Fuels. Hydrogen Analysis Resource Center. [homepage on the Internet]. Last update: 18 January 2006. Available from: http://hydrogen.pnl.gov/cocoon/morf/hydrogen/article/716 (Accessed 26 July 2007)
3. U.S. Department of Energy. Hydrogen, Fuel Cells and Infrastructure Technologies Program. Fuel Cells. Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/current_technology.html (Accessed 27 July 2007)
4. Cross industry developments , Energy Focus, Issue 3, 2004
5. International Energy Agency. Prospects for Hydrogen and Fuel Cells. Energy Technology Analysis. Paris. December 2005
6. Ghirardi ML, Amos WD. Renewable hydrogen from green algae. BioCycle; May 2004; 45, 5; ABI/INFORM Global pg. 59
7. U.S. Department of Energy. Hydrogen Program. A Prospectus for Biological H_2 Production
8. U.S. Department of Energy. HFCIT Hydrogen Storage: Status of Hydrogen Storage Technologies. Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/tech_status.html (Acessed 08 August 2007)
9. Distribution Options. Air Products and Chemicals, Inc. Available from: http://www.airproducts.com/Products/LiquidBulkGases/Hydrogen/Distribution/DistributionOptions.htm. (Acessed 31 July 2007)
10. International Energy Agency. Energy Technology Essentials – Fuel Cells. April 2007

11. U.S. Department of Energy. Hydrogen, Fuel Cells and Infrastructure Technologies Program. Types of Fuel Cells. Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf (Accessed 27 July 2007)
12. Lanz, A et all. Module 3: Hydrogen use in internal combustion engines. Hydrogen, Fuel Cells and Infrastructure Technologies Program: Technology Validation. Revision 0 - December 2001, Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf (Accessed 26 July 2007)
13. Padró CEG, Putsche V. Survey of the economics of hydrogen technologies, NREL Technical Report NREL/TP-570-27079, 1999
14. Dutton AG. A review of potential hydrogen production and delivery costs. H2NET - Hydrogen Energy Systems. May 2002
15. Ivy J. Summary of Electrolytic Hydrogen Production - Milestone Completion Report. NREL/MP-560-36734. National Renewable Energy Laboratory (NREL). September 2004.
16. Kauffman M. Electrolysis Development and Hydrogen Infrastructure. U.S. Department of Energy. Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/euiw_a10_electricity_mtg.pdf (Acessed 31 July 2007)
17. Amos WA. Costs of Storing and Transporting Hydrogen. NREL/TP-570-25106. National Renewable Energy Laboratory (NREL). November 1998
18. Drnevich R. Hydrogen Delivery - Liquefaction & Compression. Strategic Initiatives for Hydrogen Delivery Workshop. May 2003.Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/liquefaction_comp_pres_praxair.pdf (Acessed 31 July 2007)
19. Minz M, Folga S, Molburg J, Gillete J, Cost of some Hydrogen Fuel Infrastructure Options. Transportation Research Board paper. Argonne National Laboratory. Transportation Technology R&D Center,16 January 2002.
20. Stationary and portable fuel cells information resource - Information Resource for Highlands & Islands Enterprise. Hi-Energy: Renewable Energy &

Alternative Energy in Scotland. Available from: http://www.hi-energy.org.uk/hydrogen/2-Stationary-and-portable-fuel-cells-information-resource.pdf. (Acessed 31 July 2007)

21. Hexeberg I. Utsira Wind-Hydrogen System. Hydro – Oil & Energy. May 2005. Available from: https://www.hfpeurope.org/uploads/699/808/UTSIRA.pdf . (Acessed 31 July 2007)
22. HyNor – The Norwegian Hydrogen Highway. June 2007. Available from: http://www.hynor.no/pdf/engelsk-hynor-presentation.pdf . (Acessed 31 July 2007)
23. Island to be Microcosm Model of the Hydrogen Economy. North Cape, Prince Edward Island. May 17, 2005. Available from: http://www.renewable energyaccess.com. (Acessed 08 August 2007)
24. Gammon R. The Hydrogen and Renewables Integration (HARI) Project. H2NET Summer Conference, RAL, 14 July 2004.
25. Skúlason JB. The Icelandic hydrogen society. H2Net Seminar. 2001.
26. Gazey R. Promoting Unst Renewable Energy Project in Scotland's Northern Isles. Available from: http://www.hydrogenassociation.org/newsletter/ad93sref.asp . (Acessed 08 August 2007)
27. Chewonki Renewable Hydrogen Project. Available from http://www.chewonkih2.org/. (Acessed 08 August 2007)
28. Wind-to-Hydrogen Demonstration Project. Xcel Energy. Available from: http://www.xcelenergy.com/docs/W2H23FactSheetFINAL.pdf (Acessed 08 August 2007)
29. Comhairle nan Eilean Siar. Population Fact File. Available from: http://www.cne-siar.gov.uk/factfile/population/index.htm (Acessed 08 August 2007)
30. Comhairle nan Eilean Siar. Economy Fact File. Available from http://www.cne-siar.gov.uk/factfile/economy/index.htm . (Acessed 08 August 2007)
31. Comhairle nan Eilean Siar. Hebridean H2 SEED: Hebridean Hydrogen SEED. Project Description. July 2007

32. Comhairle Nan Eilean Siar . Regional Accounts 2003. Available from: http://www.cne-siar.gov.uk/factfile/economy/mluri2/coreRegionalAnalysis.htm. (Acessed 31 July 2007)
33. Highlands and Island Enterprise. Economic Update. October 2003. Available from http://www.hie.co.uk/HIE-western-isles-area-profile-2003.pdf (Acessed 31 July 2007).
34. Comhairle Nan Eilean Siar. Western Isles Fuel Poverty Strategy. Final Draft. 30 June 2005
35. Comhairle nan Eilean Siar. Alternative / Renewable Energy Schemes. Available from: http://www.cne-siar.gov.uk/cxdir/altenergy/hebH2Park.htm . (Acessed 08 August 2007)
36. Comhairle nan Eilean Siar. Hebridean Hydrogen Park - Business Plan: 2006-2008. Draft V.2.4. 14 August 2006
37. Bush, G. Lessons Learned from the World's Largest Digester Gas Fuel Cell. Washington State Recycling Association –Spokane. May, 2006
38. A guide to the project management body of knowledge: PMBOK® guide. – 3rd ed. ANSI/PMI 99-001-2004. Project Management Institute. 2004. USA
39. Bakken BH, Wolfgang O, Røynstrand J, Frydenlund F, Skjelbred HI. eTransport - A novel tool for energy system planning - Preliminary version. December 2005.
40. TRNSYS Primary. Available from http://sel.me.wisc.edu/trnsys . (Acessed 08 August 2007)
41. Scottish Executive. Matching Renewable Electricity Generation with Demand - Full Report. University of Edinburgh. February 2006
42. Avadikyan A, Cohendet P, Hèraud JA. The Economic Dynamics of Fuel Cell Technologies. Berlin: Springer. 2003.
43. Cloonan M. Energy from Waste on the Isle of Mull: A Feasibility Study of an Anaerobic Digestion Plant. University of Strathclyde. September 2003
44. Comhairle nan Eilean Siar. Hebridean H2 SEED: Hebridean Hydrogen SEED. Project Summary. March 2007

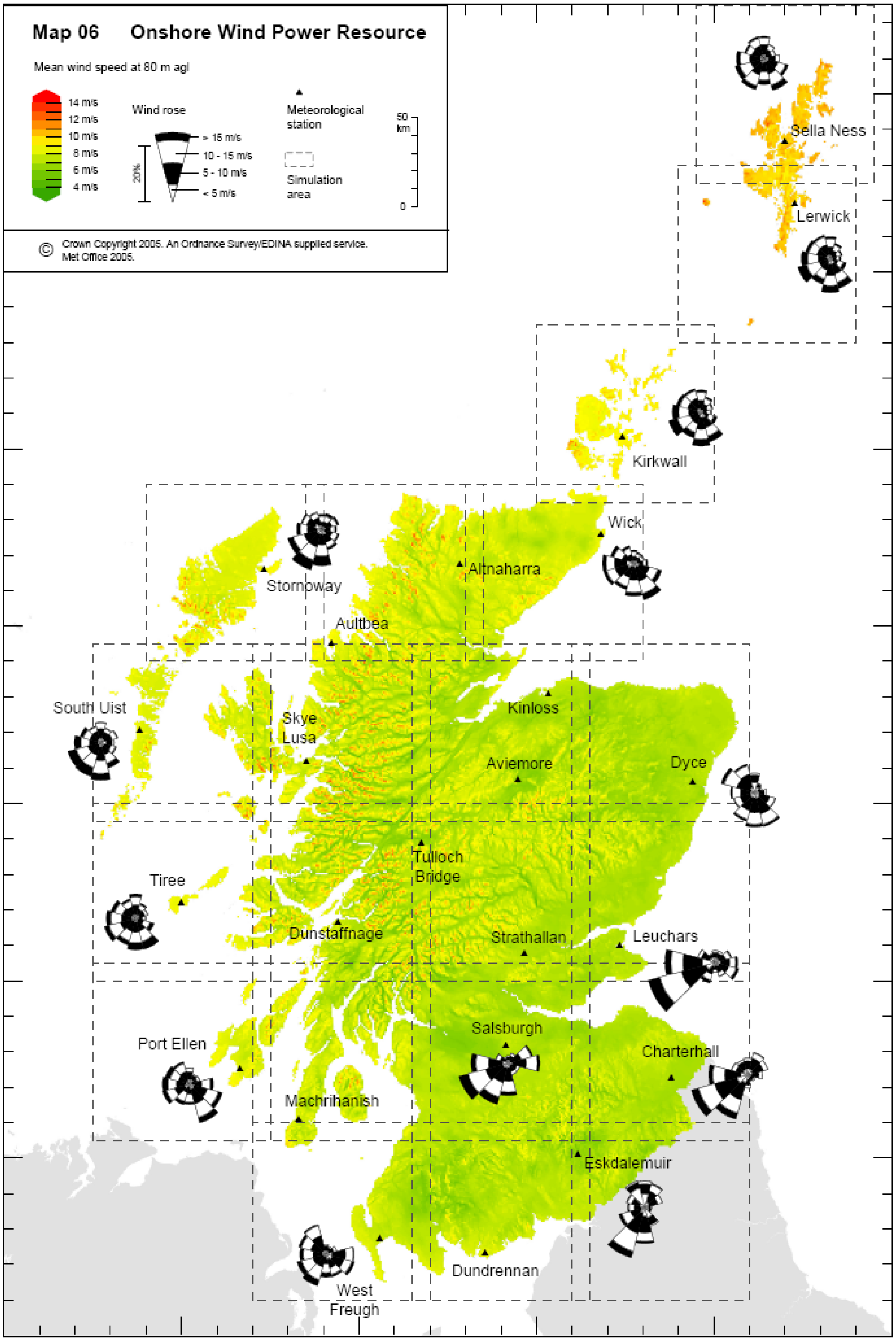
45. Comhairle nan Eilean Siar. Windpower Applications. Available from: http://www.w-isles.gov.uk/lewiswindpower/index.htm . (Acessed 08 August 2007)
46. Department for Business, Enterprise and Regulatory Reform.. A strategic framework for hydrogen energy in the UK - Final report. December 2004.
47. Ete A. Optimization of the HARI stand-alone energy system with TRNSYS. University of Strathclyde. September 2006.
48. European Commission. Hydrogen Energy and Fuel Cells - A vision of our future. Final Report of the High Level Group. EUR 20719 EN. 2003
49. Hance WA. The Fishing Industry of the Outer Hebrides. Economic Geography. 1953 Apr. Vol. 29, No. 2, pp. 168-182
50. Highlands and Islands Enterprise. The Western Isles – Electricity and Renewable Energy map. 2006
51. Homer – Analysis of micropower system options. Available from: http://www.nrel.gov/homer/default.asp . (Acessed 08 August 2007)
52. Hydrogen Refuelling and Storage - Information Resource for Highlands & Islands Enterprise. Hi-Energy: Renewable Energy &Alternative Energy in Scotland. Available from: http://www.hi-energy.org.uk/hydrogen/3b-Hydrogen%20refuelling%20and%20storage%20infrastructure.pdf (Accessed 26 July 2007)
53. Introduction to hydrogen energy projects - Information Resource for Highlands & Islands Enterprise. Hi-Energy: Renewable Energy &Alternative Energy in Scotland. Available from: http://www.hi-energy.org.uk/hydrogen/1-Introduction-to-hydrogen-energy-projects.pdf (Accessed 26 July 2007)
54. Kroposki B. Renewable Electrolysis Integrated System Development and Testing. 16 May 2006. 2006 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review.
55. Lanz, A et all. Module 0: Hydrogen Properties. Hydrogen, Fuel Cells and Infrastructure Technologies Program: Technology Validation. Revision 0 - December 2001. College of the Desert, USA. Available from:

http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm01r0.pdf (Accessed 26 July 2007)

56. Leposky, G. Fuel Cell Uses – Biogas from Sewage to Generate Electricity. Available from: http://www.gradingandexcavation.com/de_0511_fuel.html (Acessed 08 August 2007)
57. PEI Wind-Hydrogen Village – Initial Public forum. North Cape. 22 April 2005. Available from: http://www.hydrogenics.com/pdf/PEI_Wind_Hydrogen_Village.pdf . (Acessed 31 July 2007)
58. Scottish Executive - The Hydrogen Energy Group. Hydrogen and Fuel Cell Opportunities for Scotland. August, 2006.
59. Stationary and portable fuel cells information resource - Information Resource for Highlands & Islands Enterprise. Hi-Energy: Renewable Energy &Alternative Energy in Scotland. Available from: http://www.hi-energy.org.uk/hydrogen/2-Stationary-and-portable-fuel-cells-information-resource.pdf (Accessed 26 July 2007)
60. Syed MT, Sherif SA, Veziroblu TN and Sheffield J W. Economic analysis of three hydrogen liquefaction systems. Int. J. Hydrogen Energy, Vol. 23, No. I: pp. 565-576, 1998.
61. The European Hydrogen and Fuel Cell Technology (HFP). HFP Infotools. Available from: http://www.infotools.hfpeurope.org/ (Accessed 26 July 2007)
62. U.S. Department of Energy. Hydrogen, Fuel Cells and Infrastructure Technologies Program. Available from: http://www1.eere.energy.gov/hydrogenandfuelcells/ (Accessed 26 July 2007)
63. U.S. Department of Energy. National Hydrogen Energy Roadmap - Production • Delivery • Storage • Conversion • Applications • Public Education and Outreach. November 2002

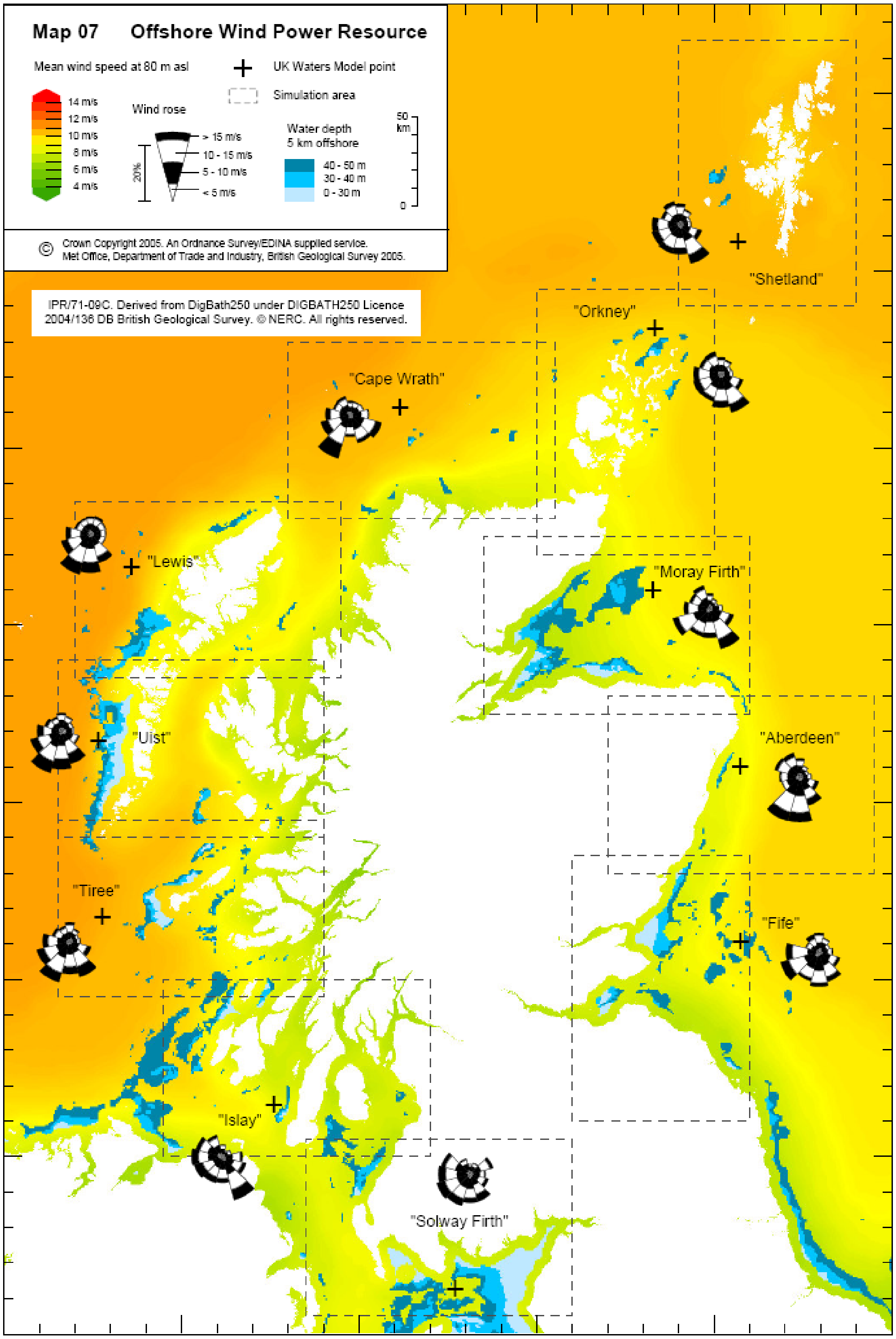
Appendixes

Appendix 1
Scotland's Onshore Wind Power Resource



[41]

Appendix 2
Scotland’s Offshore Wind Power Resource



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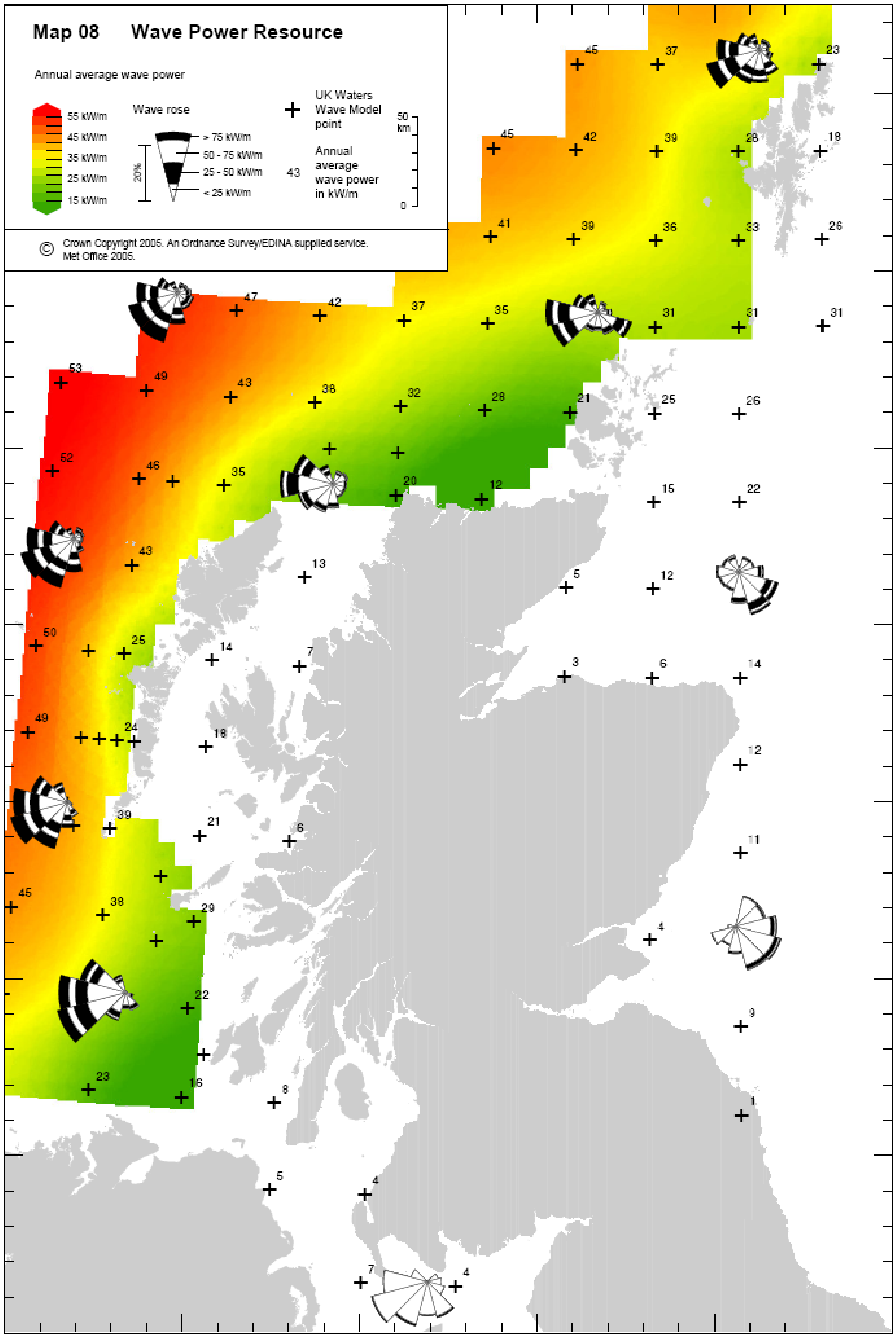
Appendix 3
Scotland's Wave Power Resource



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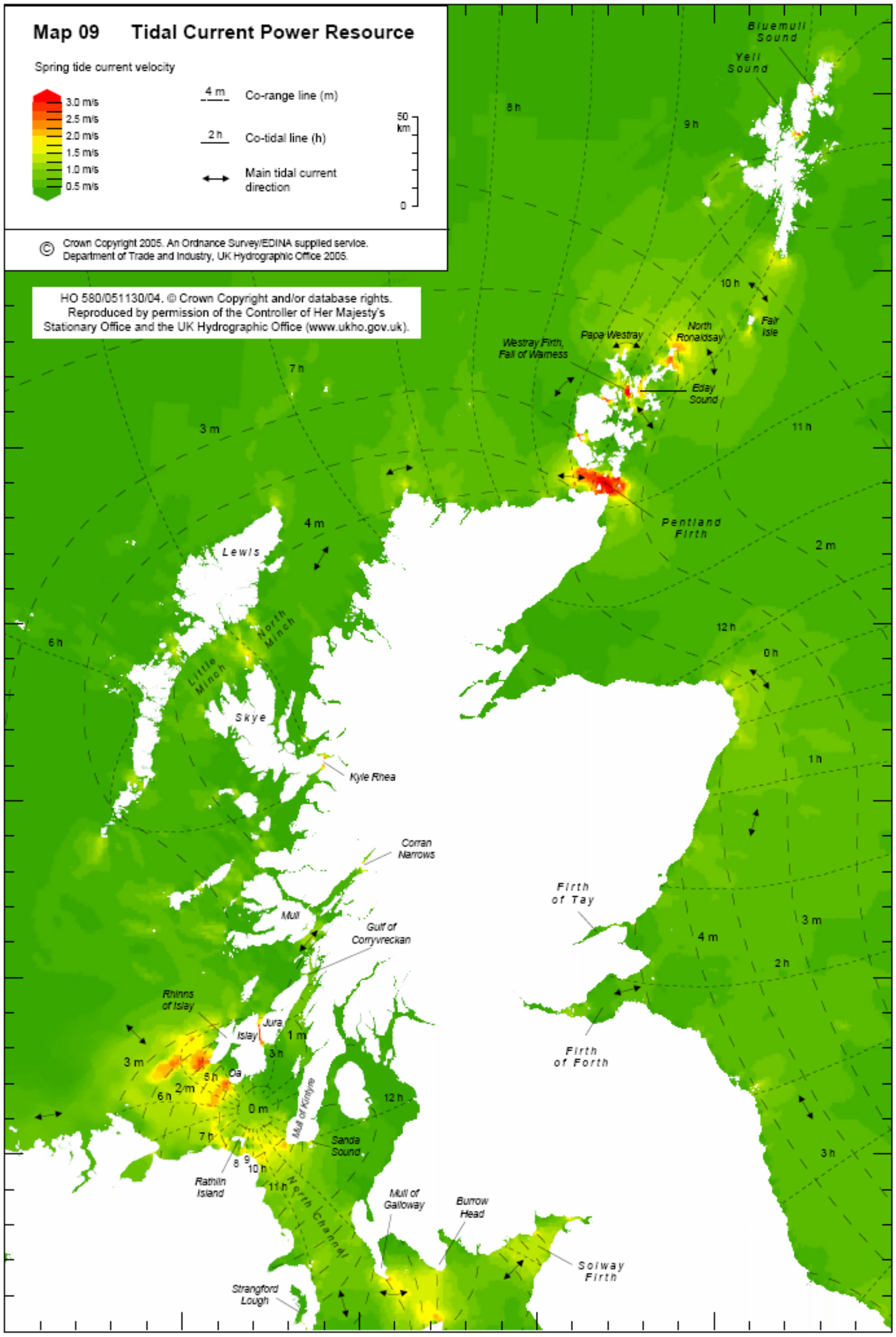
Appendix 4
Scotland's Tidal Power Resource



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