Implementation of hydrogen storage on the wind-powered islanded grid on the Isle of Muck.

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Copyright Declaration

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2. Abstract

Renewable power supply schemes on islands are becoming increasingly popular around the world. The autonomy permitted by such schemes is limited by the requirement for fossil fuel imports to permit backup generation and transportation. Implementation of a hydrogen storage system in such isolated systems can enable the final leap to full autonomy. Hydrogen storage can maximise the exploitation of renewable resources where before they were limited by the supply-demand balance of the islanded system. Excess energy can be stored in the long term to enable a more reliable system operation.

This project addresses the potential for addition of a hydrogen storage system to the wind powered mini-grid on the Isle of Muck, off the West Coast of Scotland. Two 25kW wind turbines are used in a diesel-hybrid system to supply the island's power. In the light of surprising output readings for wind turbine performance on the island, a detailed analysis of wind turbine behaviour was undertaken using historical data and gradually adapting a wind turbine model based upon the manufacturer's power curve to react to various system states. The aim was to reach a level of understanding of the turbine operation such that a model could be built to closely emulate the turbine's performance.

This analysis of the existing system provided insights into its current operation, highlighting load availability as being one of the major reasons for poor turbine performance and suggesting potential for a more extensive storage implementation which would add additional load to the system. In order to investigate the potential of a hydrogen storage system, historical data and wind turbine models were combined with high-level electrolyser and fuel cell models.

Few high level models of hydrogen storage systems have been developed. The majority of studies approach hydrogen systems at a very detailed molar level. Implementation of high level models with simple manufacturer-based input parameters enabled a quick and easy evaluation of the best storage sizing strategy for the existing system. A 15kW PEM fuel cell and 10kW advanced alkaline

electrolyser with combined metal hydride and pressurised hydrogen storage were recommended. Valuable insights into the more general issues of sizing hydrogen components were also gained.

Costs of such systems are still very high, but it is important to evaluate the economics taking into account funding availability for ground-breaking projects, fuel savings and other potential benefits. The analysis of the hydrogen system model indicated that diesel imports could be completely replaced by hydrogen generation on the island, with 6 to 86 %[1] additional energy in the form of fuel being available to the islanders. The island could achieve full autonomy, experiencing environmental and economic benefits in the long-term and improving considerably upon security of supply.

[1] Dependent on turbine performance and electrolyser sizing.

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3. Glossary of Terms

AFC	Alkaline fuel cell
AEL	Alkaline electrolyser
AC	Alternating current
CF	Correction factor
DAFC	Direct alcohol fuel cell
DC	Direct current
DM	Deutsche Marks
DMFC	Direct methanol fuel cell
EL	Electrolyser
FC	Fuel cell
HV	High voltage
MCFC	Molten carbonate fuel cell
NOK	Norwegian Kroner
PLC	Programmable logic control
PLU	Programmable logic unit
SCADA	Supervisory Control and Data Acquisition system, used in engineering applications to control distributed systems.
SAPS	Standalone power systems
SPE	Solid polymer electrolyte
SPFC	Solid polymer fuel cell (another term for PEM)
PAFC	Phosphoric acid fuel cell
PEFC	Polymer electrolyte fuel cell (another term for PEM)
PF	Power factor
PEMFC	Proton exchange membrane fuel cell
PV	Photovoltaic or solar power technology
SPE	Solid polymer electrolyte, a type of electrolyser
WTG	Wind turbine generator

4. Introduction

The Isle of Muck, the smallest of the "Small Isles," has a population of approximately 38. The island is not grid connected, and power currently comes from a hybrid wind-diesel scheme via an islanded / mini grid. The aim of this project is to investigate the potential of installing a hydrogen-based storage and electricity generation system to improve the performance of the existing system and give it more flexibility.

Sections 5 and 6 of this report are an investigation of the existing operation of the system. Section 7 features some modelling of the existing system, using detailed historical data from 2000, when data recording on the project was at its most detailed. In Section 8, the choice of hydrogen technologies is discussed and particular technologies for the Muck scheme are recommended, and Section 9 addresses modelling of the hydrogen components of the proposed system and the recommended system configuration for an implementation on the Isle of Muck.

4.1. Hybrid Systems

Hybrid systems are those where a renewable energy system is combined with other conventional generation – usually diesel, batteries or both. Renewables in such a system might be PV, hydro or wind turbines or a combination of all three. A typical wind-diesel hybrid system is shown in Figure 1 below:

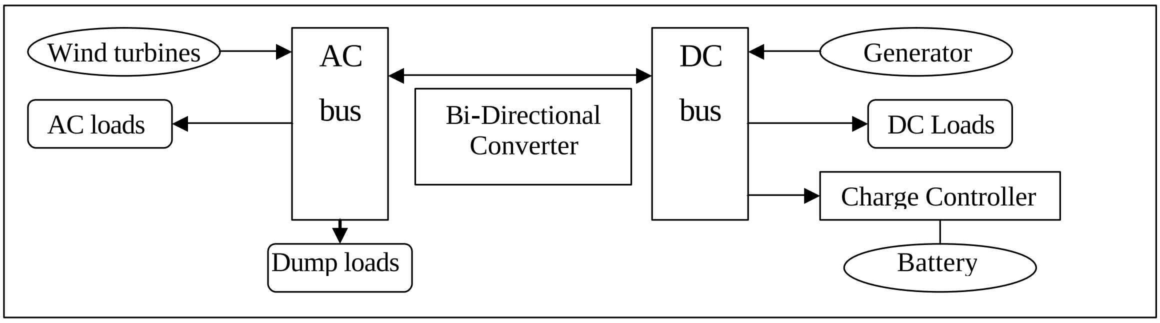

Figure 1 - Layout of a typical hybrid system with diesel generator (Mills & Al-Hallaj, 2004)

Often peak renewable supply fails to coincide with peak demand. Because of this intermittency and unpredictability of supply, the battery banks or diesel generators are necessary to act as backup to the renewable systems. However, batteries are said to typically lose 1 – 5% of their energy content per hour, and are therefore only suitable for short term storage (Agbossou et al., 2001). The addition of diesel generation rather than reliance on a large battery bank is preferred because of the high costs of large battery banks compared to the favourable cost per unit power for large diesel generators (Mills & Al-Hallaj, 2004).

Hybrid systems can be superior to conventional schemes in terms of energy efficiency, reduction in environmental degradation and cost reduction (Isherwood et al., 2000). It is widely stated that hybrid renewable energy systems are especially suitable for remote off-grid locations with good resource such as islands. This is because the reduction in the use of fossil fuels increases the level of autonomy of the island by reducing the need to replenish the fuel supply from external sources (Mills & Al-Hallaj, 2004; Dutton et al., 2000; Vujcic & Josipovic, 1996; Agbossou et al., 2001; Taylor, 2001).

4.2. Hydrogen Systems

There is much focus on hydrogen storage as the solution to both local and regional environmental problems as well as climate change – however, its economic viability is questionable except in remote areas, due to the energy losses in storage and various economic considerations. Some sources believe that for a number of years tools such as intelligent management of electricity demand and combined heat and power schemes will be more cost effective (Dutton et al., 2000).

More recently however, hydrogen has been considered a useful component specifically in standalone power systems (SAPS). If in a remote location with good resource, hydrogen can be used successfully to replace diesel generation (Mills & Al-Hallaj, 2004; Marschoff, 1998). A survey of renewable island SAPS found that wind penetration on islands with turbine systems installed was very low (Jensen, 2000) – indicating a potential for intelligent demand management and hydrogen storage possibilities. Hydrogen can improve on current storage capabilities, therefore making better use of existing assets (Crockett et al., 1995). In one study, the use of advanced storage in a diesel-hybrid system resulted in a reduction in diesel use to almost zero – a significant reduction in fossil fuel consumption, fuel costs and life-cycle costs (Isherwood et al., 2000).

Figure 2 below shows the replacement of a diesel generator by a fuel cell.

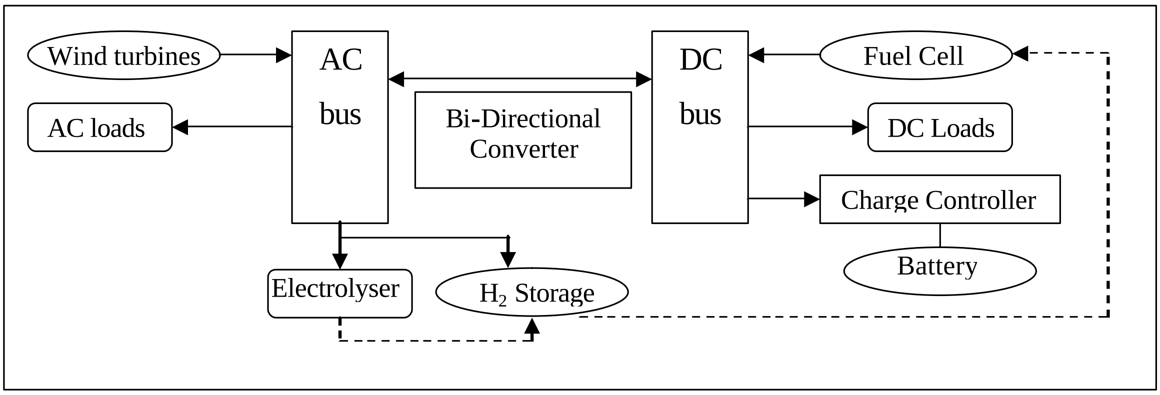

Figure 2 - Layout of a hydrogen-based hybrid system (Mills & Al-Hallaj, 2004)

The excess energy that is not required to meet demand is consumed by an electrolyser which will produce hydrogen. The hydrogen will then be stored and supplied to the fuel cell when additional electricity is required. In an ideal system the size of each component is engineered so that the hydrogen store is never depleted even during non-windy periods (Mills & Al-Hallaj, 2004).

The hydrogen generated by an electrolyser need not only be used for electricity generation via the fuel cell. If can also be used for heating, cooking and transport needs, shown in Figure 3. Hydrogen can be used as a fuel in a conventional internal combustion engine at high efficiency. If the engine's fuel/air mixture is set to an equivalence ratio of 2.5 engine efficiency often is above 40% (Hagen, 2002). This fuel flexibility is an especially useful feature in an island situation where fuel importation costs are high.

Several issues require attention when implementing a hybrid hydrogen system, including type of storage technology, economic viability (capital and operational cost), capacity and rating of storage relative to generation capacity, and the operation and management of the system as a whole (Cruden & Dudgeon, 2000). These considerations will be discussed in detail wherever possible in Sections 8 and 9.

4.3. Why Hydrogen?

Hydrogen has a very low boiling point and a low density at standard state (0.08245 kg m^{-3}) so at ambient conditions it exists only as a gas. It has a wide flammability range, meaning that it can burn when it occupies anywhere from 4% to 74% of the air by volume. It mixes well with air to allow efficient combustion, burns with an invisible flame and is odourless. Safety is always a concern when dealing with hydrogen due to its flammability, although as a fuel it is in fact considered to have the same overall level of risk as petrol. Hydrogen is not inherently explosive and its self-ignition temperature is higher than that of petrol. If used according to standards, hydrogen can actually be safer than petrol, diesel or natural gas (BOC, 2004).

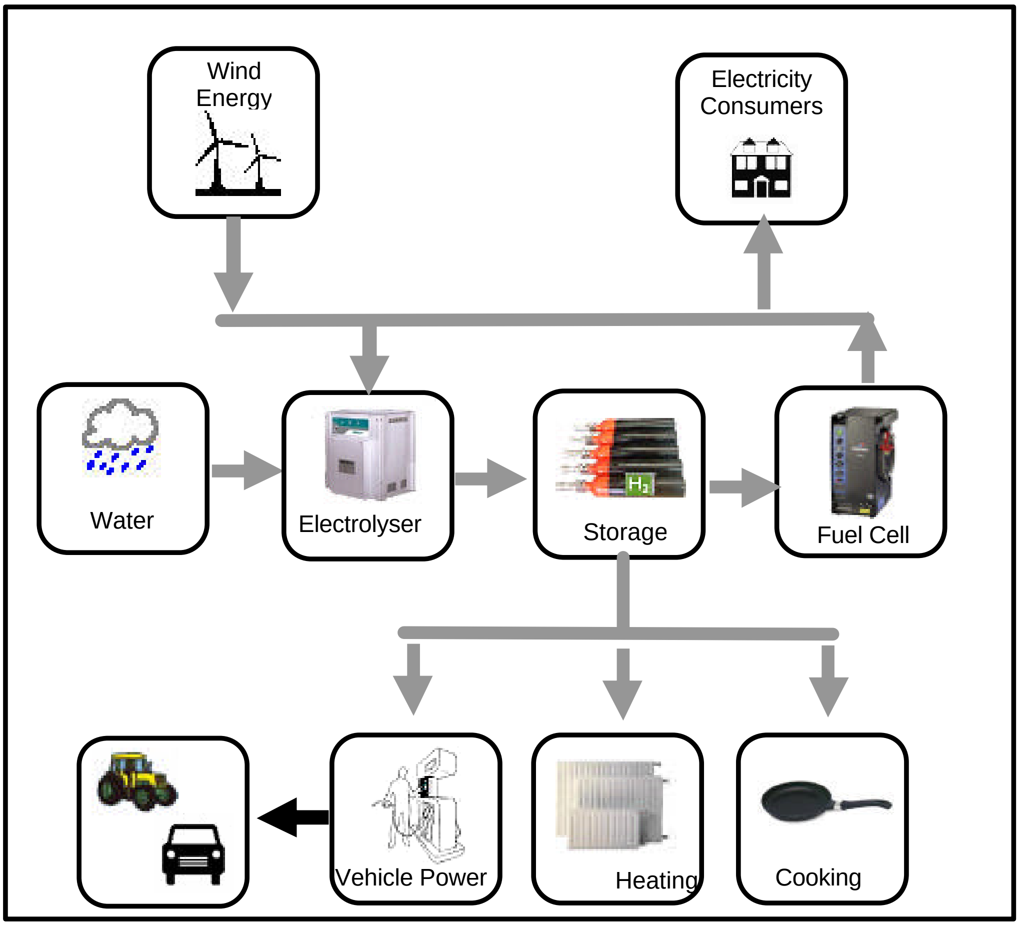

Figure 3 - Hydrogen use possibilities

Hydrogen, when produced from water and electricity from renewable resources, represents a zero-emission fuel alternative. The use of hydrogen with a fuel cell results in emission only of water, and hydrogen has more energy per unit mass than any other fuel (Hagen, 2002). The key drivers and potential barriers for such a project are shown in Figure 4.

Although hydrogen fuel cells have been used in space travel for some time due to their weight advantages their application in other areas remains in an early stage of development. There are some commercial devices now available, but due to the immaturity of the technology, costs of these devices remain high. Figure 5 shows the potential developme nt timescale of hydrogen technologies, indicating that by 2010 the technology will have established itself in the mainstream.

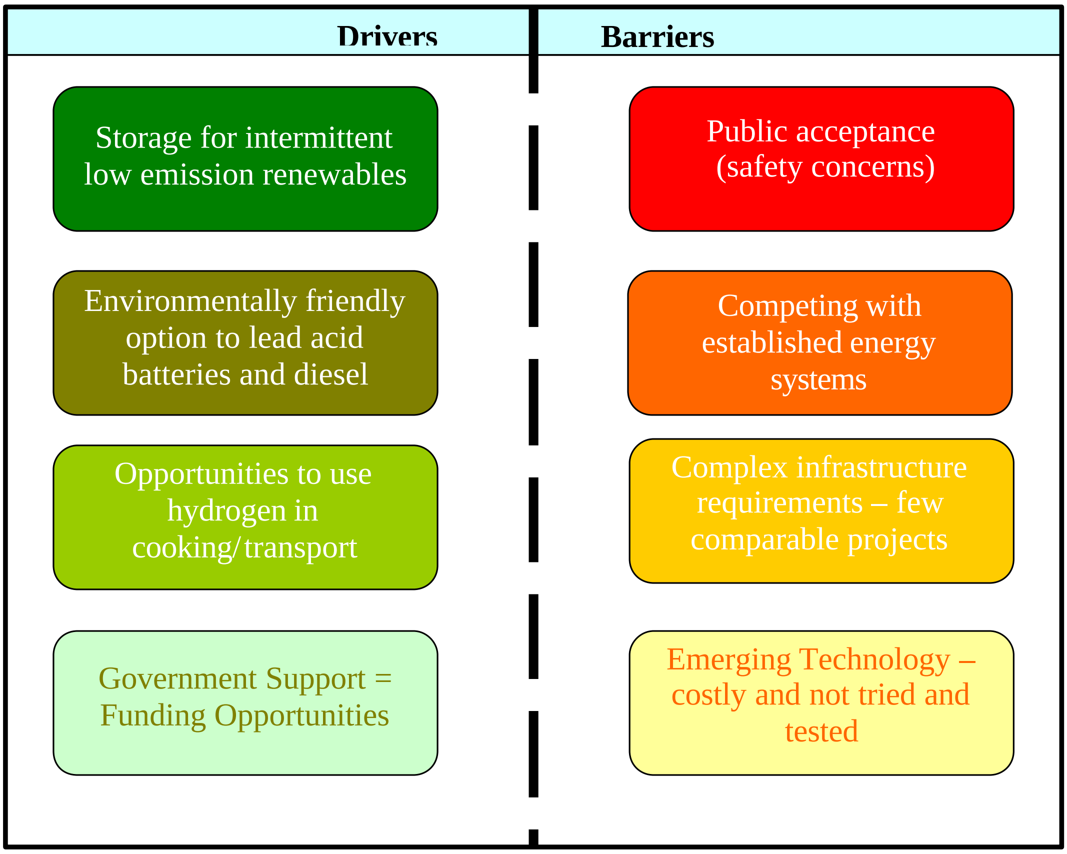

Figure 4 - Drivers and barriers for hydrogen usage

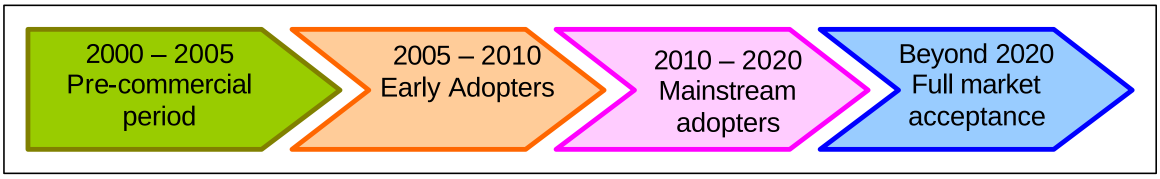

Figure 5 - Timescales for hydrogen technology development (adapted from Hagen, 2002)

4.4. Funding for Hydrogen System Development

Hydrogen systems are still very much in the early stages of commercial development, and require government support to become an economically viable option in the near future (Figure 6). The US government currently is heavily committed to hydrogen research, particularly in terms of storage, although the focus of this is for vehicular use. Nearly one third of President Bush's 2004 $1.2 billion budget for research funding is going towards bringing hydrogen and fuel cell technology "from the laboratory to the showroom" (Energy World, 2004).

> *"A number of serious techno-economic issues remain to be overcome before mass market applications in the field of…stationary power generation will be possible. Commercialisation for niche applications is widely expected within the next 2 – 5 years"*

Figure 6 - Science and Technology Committee view on fuel cells (2003)

Three main barriers to commercialisation of fuel cells have been identified by the UK government's Science & Technology Committee (2003) as:

1. The current regulatory environment makes it difficult to install fuel cell technologies.
2. Extensive demonstration and field trials are required to achieve commercialisation.
3. Market entry support is needed to help push the technology in the early years.

In the UK, "Fuel Cells UK" has been created to "foster the development of a UK industry and to raise the profile of fuel cell activity in the UK" (Science & Technology Committee, 2003). Big business has also been investing in hydrogen, with Shell spending £18 million annually on their transport focused research programme, and BP spending £8 million a year on their broader hydrogen research programme. The nuclear industry is also interested in hydrogen, as electrolysis would be made more efficient under their high operating temperature and steady loads (Science & Technology Committee, 2003).

There are a number of possibilities being considered for future hydrogen scheme funding. These include a potential system of tax incentives to support the development of new technologies. Also, complementing of carbon trading with direct support for innovation in the form of tax credits, public procurement and major research and development programmes is a possibility (Anderson & Leach, 2004).

4.5. Existing Renewables Projects on Islands in Scotland

The Scottish islands have some of the best resources for the generation of renewable energy in the world, but these areas often support very small populations. The existing grid system in these areas is usually inadequate for export of power on a major scale. The majority of large-scale developments proposed for the Western Isles, Orkney and Shetland are dependent upon the installation of sub-sea cables to link to the mainland grid system (Scottish Islands Network, 2003). However, there are also smaller community-serving projects which have been successful in meeting the power requirements of the local residents in non grid-connected situations. Community ownership of renewable projects can secure income for the community and existing industries in the area can also benefit due to reduced electricity costs.

4.5.1. Shetland

Homes on Fair Isle, one of Scotland's most remote islands have been powered by wind since 1982. The Fair Isle wind turbine project was the first in Europe to be commercially operated in place of diesel generation. A second turbine was installed in 1996 and in 1999 the Fair Isle Electricity Company was established as a community owned enterprise. Wind power now supplies 85% of winter and 50% of summer energy requirements to Fair Isle's 80 residents. (Fair Isle Website, 2004)

Planned for operation in 2004/2005, the PURE Project is a test and demonstration project investigating the production of hydrogen from renewables in the remote location of Unst, the most northerly island in the UK. The project is being developed jointly by the Unst Partnership and the Aberdeen based company, siGEN. This project pilots an off-grid renewable / hydrogen system, which works to minimise grid connection of an industrial estate (Unst is connected to the mainland grid). The installation will consist of two 15 kW Proven wind turbines, an electrolyser, metal hydride bottle hydrogen storage, and a 5 kW Plug Power hydrogen fuel cell system. These will supply five industrial units at Unst's Hagdale industrial estate. Considerable funding has been provided by ERDF, Highlands & Islands Enterprise, Shetland Enteprise and Shetland Islands Council (Gazey & Macauley, 2004).

An additional wind installation on Shetland is the Burra Dale farm managed by Shetland Aerogenerators, consisting of 5 turbines, and rated at 3.7MW, with extensions of 1.7MW approved (yes2wind, 2004).

4.5.2. Orkney

Construction of 65m tall wind turbines began at Burgar Hill on mainland Orkney in March 2000. The two turbines have the potential to meet one quarter of the islands needs, capable of generating 3.5 megawatts. Additional proposals of 5MW at the same site have been approved (yes2wind, 2004).

Orkney-based company Fairwind recently announced their plans for the development of up to 4 windfarms with 30-50 turbines. Landowners and communities are being encouraged to come forward with potential sites for the developments. Fairwind believe that a project of this scale would justify the creation of a subsea power link between Orkney and the mainland. However, it has been announced that any renewable projects in Orkney not already constructed will have existing offers of connection to the national grid withdrawn because of current capacity problems (Scottish Islands Network, 2003).

4.5.3. Western Isles

The Stornoway Trust recently announced plans to locate the world's largest windfarm at Barvas moor on Lewis. The proposed farm would consist of 300 turbines, cost £600 million, create up to 900 jobs and be capable of producing up to 6% of Scotland's 33 TWh[2] total energy needs. However, much of the island is designated as conservation area, so proposals have faced considerable opposition (Scottish Islands Network, 2003).

4.5.4. Skye

A £30 million windfarm near Edinbane on the Isle of Skye has been approved. The windfarm will consist of twenty-seven 100m tall turbines is rated at 47.25MW - enough power for 30,000 homes (yes2wind, 2004). According to crofting law, Ruairidh Hilleary who owns more than half of the land on which the windfarm is to

[2] Scottish Executive figure for 2003

be built, must share half of the profits he receives from the development with the twenty-six crofters who occupy his land. A second 14 turbine windfarm near Dunvegan has been proposed which could potentially provide an income of up to £40 000 a year for the next 25 years to local crofters and the local community council. An additional third windfarm in the south of the island is also under discussion (Scottish Islands Network, 2003).

4.5.5. Small Isles

On Eigg, the Eigg Heritage Trust is building a water-powered generator to serve 5 of the community-owned island's households. Most of the energy needs for the shops and tearoom on the island are met by hydro power (Glebe Barn, 2004).
On Rum, a small hydro-diesel hybrid scheme provides 45kW rated hydro power to the 30 residents living and working on the Rum National Nature Reserve (total system rated at 70kW). Fuzzy logic control units are installed on various loads to allow for the fluctuating nature of supply and demand (Taylor, 2001).

4.5.6. Mull

There is a proposal for a community windfarm near the village of Dervaig on the Isle of Mull (grid connected). The mini wind farm would consist of 12 x 850kW turbines, costing around £7 - 8 million. The energy produced would not serve Dervaig direct, but will be sold to the Grid. Dervaig would continue to buy from the Grid. The development could produce the equivalent annual power consumption of Mull (Dervaig, 2004).

4.5.7. Islay

Islay boasts the first commercial wave power project capable of producing up to 500 kW of power. There are also plans for community wind projects to be initiated on the island (Scottish Islands Network, 2003).

4.5.8. Slate Islands

The island of Luing has been feeding electricity into the national grid since 2001 with a prototype wind turbine. The turbine can produce 70 kW of power and generates an income of £7 000 - £8 000 per year (Scottish Islands Network, 2003).

4.5.9. Further a field

A number of islands around the world have set themselves the target of becoming 100% self-sufficient using renewable energies, including Samsoe and Aeroe (Denmark), Pellworm (Germany), Gotland (Sweden), El Hierro (Spain) and St Lucia (Jensen, 2000).

4.6. Existing Hydrogen-Wind Projects

One of the first major autonomous hydrogen-wind projects is being implemented on the remote island of Utsira, off the west coast of Norway with 240 inhabitants. Due to the windy conditions in Utsira, the two 600kW wind turbines (Figure 7) produce a significant amount of excess power, which is stored as hydrogen generated via an electrolyser. This is turned back to electricity via a hydrogen engine and fuel cells. Ten houses receive their electricity from this completely renewable system, and excess power is sold on the electricity market. Peak load is 55 kW and the hydrogen plant has been sized to produce enough electricity for two days in the rare event that there is no wind at all.

Figure 7 - Utsira Scheme in Norway with two 600kW turbines (Norsk Hydro, 2004)

The H_2 generation system consists of two 600kW wind turbines, a 5kW flywheel, a 55kW hydrogen engine, 10kW fuel cell, 10 Nm^3/h 48kW electrolyser and 5.5kW compressor with 2400 Nm^3 storage. Power production from the plant started in March 2004 and energy production is expected to be approximately 5.1 GWh annually (Norsk Hydro, 2004). The project budget is approximately NOK 40 million (£3.3 million), implemented with Norwegian company Norsk Hydro, Norsk Hydro Electrolysers and German turbine company ENERCON, with support from

Enova (a government body), the Norwegian Pollution Control Authority (SFT) and the Research Council of Norway.

There is additional work around the world being carried out into hybrid hydrogen systems, and these projects are summarised in Table 1.

As can be observed in the table, hydrogen-renewable projects are being implemented all over the world, in projects ranging from 3 KW to 110MW of installed wind, sometimes coupled with PV, often combined with battery banks of varying sizes. Storage methods are either high pressure storage tanks or metal hydrides at pressures ranging from 5 to 120 bar. Mainly alkaline electrolysers have been used, although solid polymer electrolyte electrolysers are becoming more viable options. Discussion of possible hydrogen system configurations can be found in Sections 9.5.

Table 1 - Hydrogen Projects and Research

		1	2	3	4	5	6	7	8	9
Project		Hunterston Hydrogen ltd & Wind Hydrogen Ltd (proposed) (Pritchard, 2000)	Anglesey Wind & Energy Ltd (proposed) (Anglesey Wind, 2004)	Statkraft, (Dutton, 2002)	Mawson Station, (Dutton, 2002)	(Jacobson, Purcell, & Wermers, 2001)	(Ulleberg, 2003), PHEOBUS	Utsira (Norsk Hydro, ENERCON) (Norsk Hydro, 2004)	Pure Project (Unst Partnership & siGEN (Gazey & Macauley, 2004)	Econnect (Altener Programme, 2001)
Location		Ladyland Moor, West Kilbride.	Anglesey	Smola wind farm, Norway	Antartica	Reno, Nevada	Germany	Norway	Unst, Shetland.	England
Turbine		25MW (15 x 1.75MW)	3MW of wind turbines	Phase 1 40MW, Phase 2 110 MW	900kW Enercon E30 turbines	3kW	--	2 600kW Enercon wind turbines	two 15 kW Proven wind turbines	20kW Gazelle wind turbine
PV		--	--	--	--	2kW	30kW	--	--	
Battery		--	--	--	--	--	300kWh 220V	5kW flywheel,	--	
Electrolyser	Rating	4MW electrolysis project	300kW hydrogen electrolysis plant	--	2KW electrolyser	5kW	26kW	48kW electrolyser	electrolyser	8kW, 48V PEM
	Pressure	--	--	--	--	--	7bar	10 Nm^3/h	--	--
	Manufacturer	--	--	--	--	Stuart energy	--	Norsk Hydro Electrolysers	--	--
Storage		600,000Nm^3 hydrogen per yr.	--	--	--	Hydrogen tank 100psi 80 ft3, psi to FC	120 bar 26.8m3 H_2 70 bar 20 m3 O2	5.5kW compressor with 2400 Nm^3 storage.	metal hydride bottle hydrogen storage	--
Fuel Cell	Type	Conventional internal combustion hydrogen generators	Plans to install a fuel cell for back-up power and grid support.	By 2007 excess wind energy will be used to generate hydrogen. Fuel cells will replace diesel generators.	--	--	--	hydrogen engine and fuel cell.	Plug Power hydrogen fuel cell system.	--
	Rating	up to 10MWe.	--	--	--	2kW	6kW	55kW engine10kW FC	5 kW	6kW
	Manufacturer		--	--	--	Dais-Analytic	--	--	--	--
Comments		Plan for H_2 plants and fuelling stations along electricity nets. Electrolysis plant "despatchable load" and hydrogen gensets "despatchable peaking plant".	Study of hydrogen energy storage as an alternative to grid reinforcement. Hydrogen and oxygen to be used in local fish farm.	Turbines supplying 80% of the station's energy needs.	Poor performance due to "one-off" design of electrolyser	Overall efficiency 20 – 30% depending on conditions	--	--	Power generated will supply five industrial units at Unst's Hagdale industrial estate	+ 40kVA synchronous compensator and 10kVA PF correction capacitor.

		9	10	11	12	13	14	15	16
Project		Abbossou, Chahine, Hemeline et al. (2001) and Kolhe, Agbossou, Hamelin et al. (2003)	Shatter et al., (2001)	Isherwood, Smith, Aceves et al. (2000)	Datta, Velayutham, & Goud (2002)	(Galli & Stefanoni, 1997)	(Vanhannen, Lund, & Tolonen, 1998)	(Mills & Al-Hallaj, 2004)	(Dutton, Bleijs, Dienhart et al., 2000)
Location		Canada	Egypt	Alaska (hypothetical)	India	Rome Casaccia Research centre ENEA	Helsinki	Chicago	Rome Casaccia Research centre ENEA
Turbine		10kW	--	70kW	--	--	--	12kW	5.2kW
PV		1kW	2.24 kW	--	--	5.6kWp	--	6.5kWp	
Battery		42.24kWh	--	--	--	--	--	350Ah, 6Vdc per battery	330Ah
Electrolyser	Rating	Alkaline 5kW, 65% to 71% without compression (-5%)	--	--	--	Alkaline bipolar ALyser-0100 17 cell 29 Vdc 5kW	Alkaline then 30W SPEL 5 bar, prefer in future 100 - 200W,	5.76kW//8kW, 70%, idling power25% rated	1kW pre but 2.25kW used, 50V,
	Pressure	7 bar, 1 N m^3 h^{-1}	--	--	--	20 bar max	operating 5 – 10 bar	--	20 bar
	Manufacturer	Stuart	Stuart	--	--	Metkon-Alyser,	--	--	Hoerner System electrolyser
Storage		10 bar, 3.8m^3 = 125kWh *and* 207 bar (4.5 1 N m^3 h^{-1}) 154 m^3 = 507kWh	3 bar tank	Low pressure compressed H_2 storage. 4.1MPa, 600psi	--	Metal hydride tank based on automotive manuf HWT, Germany 18Nm3, 15bar + standard gas cylinders	Pressure Vessel, then metal hydride min 5bar – 10bar	Low pressure 0.6barto 3kW compressor to 22m3 high pressure tank	--
Fuel Cell	Type	PEM	PEM	--	PEM	SPFC	PAFC / SPFC	PEM	commercial Otto engine.
	Rating	5kW, 19 – 35V > 45% when gen over 4kW.	Current density 400mA/cm2, stack of 90 cells	--	500W, 12V,	22 – 30Vdc, max P 30psigH_2	100W	1/2kW	8kW
	Manufacturer	Ballard	--	--	--	Ballard	--	NTT labs	--
Comments		--	--	--	--	--	30% round trip efficiency	--	--

4.7. Summary

This section has given an overview of the areas of research relevant to this project, in terms of; the reasons for hybrid and hydrogen systems, current funding for hydrogen research, existing renewable projects on Scottish islands and cutting edge hydrogen-renewable projects around the world.

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5. Isle of Muck System Stage 1 - Windharvester

5.1. Project Overview

The installation of a hybrid power system on the Isle of Muck was initiated in 1992 with funding from Highlands & Islands Enterprise, Highland Regional Council and the European Community via a Thermie grant. The scheme designer and main contractor at this time was Windharvester Limited, who proposed a 100kW wind turbine and 37kW diesel generator. Windharvester went bankrupt in 1994. At this time the HV 3.3kV/415V electrical distribution network was incomplete and key components of the wind turbine had not been delivered. The residents of the island still relied on imported diesel for power, at an electricity cost of 26p/kWh.

6. Isle of Muck System Stage 2 – Scottish Power Technology

6.1. Project Overview

The project remained in this state until 1997, when a revised scheme was proposed by Scottish Power Technology[3] using two 25kW Vergnet wind turbines and a Lister Petter diesel generator. A successful application was made to the National Lotteries Charities Board with matched funding being offered by Highlands & Islands Enterprise and Lochaber Limited, and the project was embarked upon anew in March 1998. Scottish Power Technology acted on behalf Isle of Muck Community Enterprise Limited to design, procure, install and commission the revised wind/diesel scheme.

[3] Scottish Power Technology in the course of the project became Ingenco, and have since split into Sgurr Energy and SKM.

6.2. Implementation

6.2.1. Overview

The system implemented, pictured in Figure 8, consisted of:

? 2 x 25kW Vergnet Wind Turbines on 18m high masts

? 23.5kW Lister Petter Diesel Generator

? 550kW Ainelec Rectifier/Inverter

? 52kWh Fulmen Battery Bank

? 3300V/415V Distribution Network with Graded Protection

? PLC Control system for inverters, diesel generator and circuit breakers

? Radio Telemetry linked control system to all houses, allowing a two-tier tariff (wind/diesel), grid status indication and external control of storage heaters in houses.

Figure 8 – Stage 2 Muck Scheme

To the left the power-house, and to the right the two turbines.

6.2.2. Wind Turbine Selection

A review of diesel fuel consumption and electricity generation on the island revealed that a maximum of 45MWh of electricity could be generated annually by diesel generators presently installed on the island (Ba-maung et al., 2000).

Assuming a mean wind speed on site of 7.5m/s, it was thought that a 25kW rated turbine could yield at least 60MWh annually (more than previously obtained from diesel generation). However, studies based on the Foula wind energy scheme showed that only 80% of the wind energy can be used due to wind speed variations, allowing for 48MWh (Ba-maung et al., 2000). To allow for expansion, intermittency and storage, 50kW of wind power was proposed.

At the time of the implementation there were only a few machines on the market rated at 50kW, most being either larger, in the 80 to 100kW range, or smaller at 30kW and below. Several manufacturers were reviewed, and two were identified as possible contenders – an Atlantic Orient Corporation design and a Vergnet design, shown in Table 2.

	Atlantic Orient Corporation AOC 15/50	**Vergnet GEV 10/25**
Rated output:	50kW at 12m/s	25kW at 12m/s
Rotor:	15m diameter, down wind.	10m diameter, down wind.
Tower:	25m Latice.	18m Latice.
Energy Yield:	160MWh	140MWh
Number of installations:	20	100
Country of Manufacture:	USA	France

Table 2 - Turbine property comparison

The French Vergnet GEV 10/25 turbine was chosen. This strategy of using two 25kW rated turbines gave reliability advantages - if one was out of service the other could still be functioning. In addition, the design had the advantage that it could be lowered for ground maintenance easily using a hand operated winch – preferred in exposed locations such as Muck.

6.2.3. Energy Storage Selection

Fluctuating power production from wind, varying load profiles and relatively low system inertia can result in technical difficulties, system instability and poor efficiency in island grids (Taylor, 2001). Energy storage assists in riding through moments of generation deficit. The unpredictability of short-term wind speeds and the variability of the electricity demand profile for Muck, means that the wind turbines will inevitably generate electricity when there is no demand. Conversely, there will be situations when there is demand but no wind. Using a storage facility, energy can be stored during periods of high-energy production and low-demand, and used during periods of low-energy production and high-demand.

The tried and tested method of a battery bank and inverter was opted for in this case. This had benefits when running with the diesel generator. Without the batteries, a diesel generator sized to meet peak demand, which only lasts for short periods, will run for much of the time at lower percentage load, and therefore lower efficiency. A battery bank providing 10kW of power for 6 hours means that the diesel generator peak output can be reduced by 10kW, operating more efficiently as it runs closer to full load.

The bank of 20 Fulmen lead acid batteries, pictured in Figure 9, was sized by balancing the cost of using diesel against the capital cost of the bank. It was initially guaranteed for 3 years, with an expected 10 year lifespan, meaning that replacement would be expected in 2007/2008.

Figure 9 - Battery bank installed on Muck

Additional requirements of the batteries were to:

? Smooth variations of raw wind turbine electric signal fluctuations due to sudden wind changes.

? Have sufficient capacity to allow energy supply to grid for several hours without wind, reducing number of diesel start-ups (intended 12 hrs at 15kW, though normal operation has been much lower than this).

? Act as a load for the diesel generator to improve efficiency.

? Provide back-up power for the primary school.

6.2.4. Diesel Generator Selection

With an established reputation for supplying and servicing diesel generators in the Western Isles, the company Lister Petter (based north of Glasgow) was selected as the supplier of the diesel generator. The original feasibility study identified a requirement for a 35kW diesel generator to ensure that peak demand could be met. As mentioned previously, this could be reduced to 25kW by running the system in parallel with the battery bank.

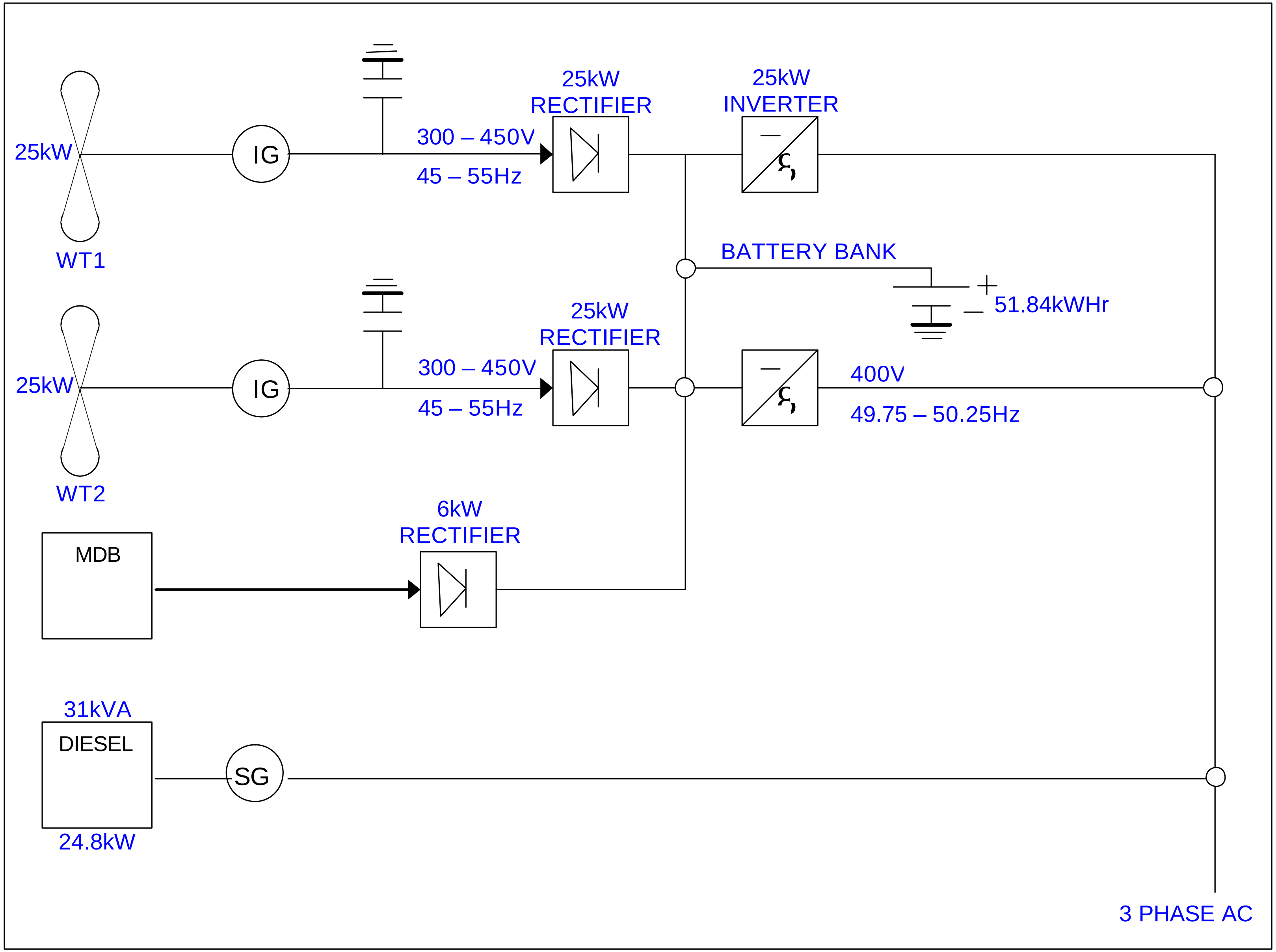
The power output from the diesel generators is self-governed to balance the supply to the network such that the demand on the network is matched. In order to avoid excessive wear and tear on the engine, operations below a set percentage load (40%) are avoided and a minimum run-time (3 hours) is applied. Although not implemented in Muck, another possibility for reducing wear is the application of a minimum off time between starts (Bonanno, Consoli, Salvatore et al., 1998).

6.2.5. Electrical Infrastructure - Network

An overview diagram of the system configuration is shown on the following page in Figure 10. Power is supplied at 415 Volts from the wind turbines to the site distribution board. From this board, power is supplied to the main distribution board in the power-house via the Stage 1 transmission system.

Domestic and workshop inductive loads above 500W are fitted with appropriately sized capacitors such that the distribution network can be operated with unity power factor.

Figure 10 - System design



The low voltage distribution network supply characteristics are required to remain within the limits listed below:

- ? 50Hz ?4? 95? of the time
- ? 50Hz ?15? 100? of the time
- ? 230V ?10? 100? of the time

In the main period of study (September 2000), these limits were more or less met, with the exception of the voltage requirement – the voltage being found to dip to as low as -15%. This is discussed in more detail in Section 7.3.7.

6.2.6. Electrical Infrastructure - Control

The two 25kW wind turbines must self-synchronize. Matching wind turbine output with consumer demand is achieved by consumer cooperation in initiating/dropping higher rated loads (such as washing machines), and automatic switching of resistive loads (immersion heaters and storage heaters) at each consumer.

Resistive loads are switched using signals sent from the power house in order to maintain grid voltage and grid frequency within the above limits based on voltage variation across the main distribution board as a whole. Loads are in the range of 1 to 3 kW, with an intended switching response time of 2 seconds.

Using this control philosophy, the consumer will observe the following when power availability exceeds demand:

- ? Consumers are advised by an “excess wind energy” indication light in the premises. Figure 11 shows the consumer panel with indication lights.
- ? If consumers don’t react and power continues to exceed demand, storage heaters/water heaters are switched on automatically according to a list of priorities (see Section 6.5.4)
- ? The converse is true for a low energy situation.

Each consumer has an isolator switch in each house enabling them to generate power from a private diesel generator if preferred.

Figure 11 - Consumer indicator panel

6.2.7. Operation

6.2.7.1. Priority Periods and Use of Private Generation

The system follows the priority periods defined as shown in Table 3.

Year	Morning	Afternoon
2000	08:00 to 11:00	18:00 to 00:00
2004 Summer	08:00 to 11:00	15:00 to 00:00
2004 Winter	08:00 to 11:00	16:00 to 00:00

Table 3 - Priority periods

During these hours, if low wind and low battery occurs, the diesel generator will be run. In the times outside these priority periods, the diesel generator will not run and the system will be dependent upon batteries if there is insufficient wind. As indicated previously, there is a requirement for co-operation from the community out-with priority periods to avoid use of heavy loads such as washing machines if wind energy is low. However, the demand itself is not restricted. In low generation, low battery situations out-with priority periods, large demand can result in grid shut down.

6.2.7.2. Basic Operation of Wind Turbines, Batteries and Diesel Generator

The operational strategy of the system is explained in the Table 4 below:

Case	**System Activity**
Not enough wind to cover demand.	Complementing energy is supplied by the battery set. The output from the batteries and the DC from the turbines is inverted by one or both of the inverters to feed the grid.
Wind speed is above cut-in, sufficient supply to meet demand.	Wind turbines supply energy to the grid through the inverter. The battery will charge from the wind turbines whenever they are running at sufficient speed. Both turbines can charge the batteries at the same time.
High wind, supply exceeds demand.	Excess energy is stored in the battery set, sent to dump loads or in extreme circumstances the turbine is disconnected.
Diesel-based battery charge complete.	The diesel cannot synchronise with the inverters, although the inverters can synchronise with it (this was to reduce costs). Therefore, to connect the battery inverter to the grid, the diesel disconnects. Each permutation from wind to diesel or back requires a very brief power cut out for a few seconds on the grid – the duration is dependent on the radio system.
Wind-battery charge complete	The chargers automatically disconnect when the battery voltage is sufficiently high to indicate that the bank is fully charged. When the batteries reach full charge, the load on the wind generator charging them reduces to the point where it cuts-out, the turbine start to over-speed and the mechanical governor limits their speed.
Discharged battery and low wind, priority period.	When the battery is discharged and wind is low, the Programmable Logic Control (PLC) unit sends a signal to diesel plant. The diesel generator starts up to supply the grid, and the inverter switches off to let the diesel generator take over and stop the battery from discharging. The diesel and inverters need to run in parallel for charging purposes, so the inverters shut down and disconnect from the grid, the diesel starts up and reaches steady state and then one of the inverters will synchronise and connect in parallel. Again, a brief blackout is experienced during this process.

Table 4 - Basic system operation

6.2.8. Historical System Performance

Figures for system performance are shown in Table 5:[4]

	Average Wind Speed	Total Power Delivered	Potential wind power delivery	Nominal Tariff
Jan 2000 – 2001	8m/s	71MWh 78% wind, 22% diesel	97MWh (27% shortfall)	10p/kWh (26p/kWh previously)
2002	--	85% wind, 15% diesel	--	--

Table 5 - System performance

Wind energy comprises a good percentage of the power on the island, although there is a greater potential of wind energy than that which is delivered (27% shortfall). The implementation of the scheme resulted in a substantial reduction in the cost of electricity of over 60%.

[4] These figures have been taken from Sgurr Energy documentation, and have not been confirmed from actual data calculations.

6.3. Economics

6.3.1. Funding

The £236,000 cost of the project was funded with contributions from the following sources:

? National Lottery Charities Board - £95k,

? Lochaber Ltd - £90k

? Highland Council - £18k

? Community Enterprise Company and Private Donations - £10k +

Additional funding sources considered included Highlands and Islands Enterprise, the Department of Trade and Industry and Scottish Enterprise.

6.3.2. Cost to the end user

The cost of electricity is structured as follows:

? £25 per quarter standing charge.

? Wind power = 5p per unit for the first 250 units each quarter and 4p/unit above[5].

? Diesel power = 12p per unit for the first 150 units and 14p per unit above.

The average household has been found to pay approximately £50/quarter.

6.3.3. Maintenance, Insurance etc

Scottish power technology assumed a 3% overall capital cost for maintenance. Salt water corrosion to the turbines in such a location is a concern, but this is managed by blade replacement every 5 years. In order to reduce maintenance costs, Vergnet trained residents of the island in turbine maintenance. A total of £2,000 is put aside each year for the purpose of maintenance.

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[5] Wind is cheaper after 250 units have been used as the customer has no control over the storage heater usage (dump loads) except to switch them off completely.

6.4. Operational Issues

6.4.1. Batteries

The lead acid battery bank was designed to deliver 54 kWh, this size being considered the minimum requirement for the system. This was opted for due to budget constraints, but if more money had been available a battery bank in the range of 10 or 20 times this size would have been preferred. However, the batteries have been found to produce only around 20 kWh. In fact, in 2001 it was estimated that the useful battery storage was around 12 kWh.

In a renewable system, the battery generally follows the “opportunity charging” methodology, often receiving partial or incomplete charge for long periods. There are deep charge settings and trickle charge settings which can be set in the charger/ inverter equipment governing the battery charging regime. A poor charging strategy can result in damage to the batteries and reduction in the battery capacity (Ulleberg, 1998). There were some problems with the charging regime for the batteries on Muck. The deep charge setting is now only allowed to occur once during a preset time period as it was 'boiling' the batteries and the electrolyte was gassing excessively. This could be one of the reasons for their disappointing performance.

A disadvantage of flooded and vented lead-acid batteries is the decomposition of water into hydrogen and oxygen. In order to prevent dry out of the electrode, water needs to be refilled at regular intervals. (Ulleberg, 1998) This is currently the case in Muck, where the batteries regularly require to be topped up with de-ionised water. In addition, another indication as to why the batteries are performing so poorly is the formation of small pools of acid on top of the batteries, around the vent plugs. The fumes of acid that escape with the gases produced in the battery dilute the electrode over time and therefore reduce the capacity of the battery (Ulleberg, 1998).

6.4.2. Rectifier and Inverter Issues

When the two inverters were running in parallel, the best balance that could be achieved at one point was an accuracy of 7kW. If load on grid was less than 7kW, then there may have been negative power, so at this time it was necessary for the two inverters to be run in parallel only above a minimum load.

There were some problems with the operation of the two inverters in low-wind situations when both inverters became enabled, resulting in one of the inverters tripping. Grid voltage was found to vary more when supply came from one inverter than the other, and overall the grid was more stable when powered by diesel. Voltage variations in early days of operation were found to be high, with flicker occurring and some private equipment being damaged due to the fluctuating AC supply.

6.4.3. Diesel battery charging

There were some problems with the operation of the diesel generator and the inverter after a diesel battery charge was complete. The inverter failed to disconnect, so that the battery voltage dropped rapidly. The system was changed from a 2 to a 3 hour diesel on-time, with immediate diesel disconnection when the battery was able to take over at the end of the run.

6.5. System Data Analysis

6.5.1. Environmental Conditions

The ambient environmental conditions for the site are shown in Table 6 below:

Property	Units	Value
Average Air Temperature	^oC	9
Minimum Air Temperature	^oC	-10
Maximum Air Temperature	^oC	35
Relative Humidity	%	100

Table 6 - Environmental conditions on-site (Ba-maung et al., 2000)

6.5.2. Wind Resource

Wind monitoring was carried out on the site from August 1997 to March 2002 using an anemometer mounted on a redundant 18m high telecommunications mast. The initially predicted long-term mean wind speed at the wind turbine locations was 7.5m/s, with a frequency distribution and wind rose as given in Figure 12.

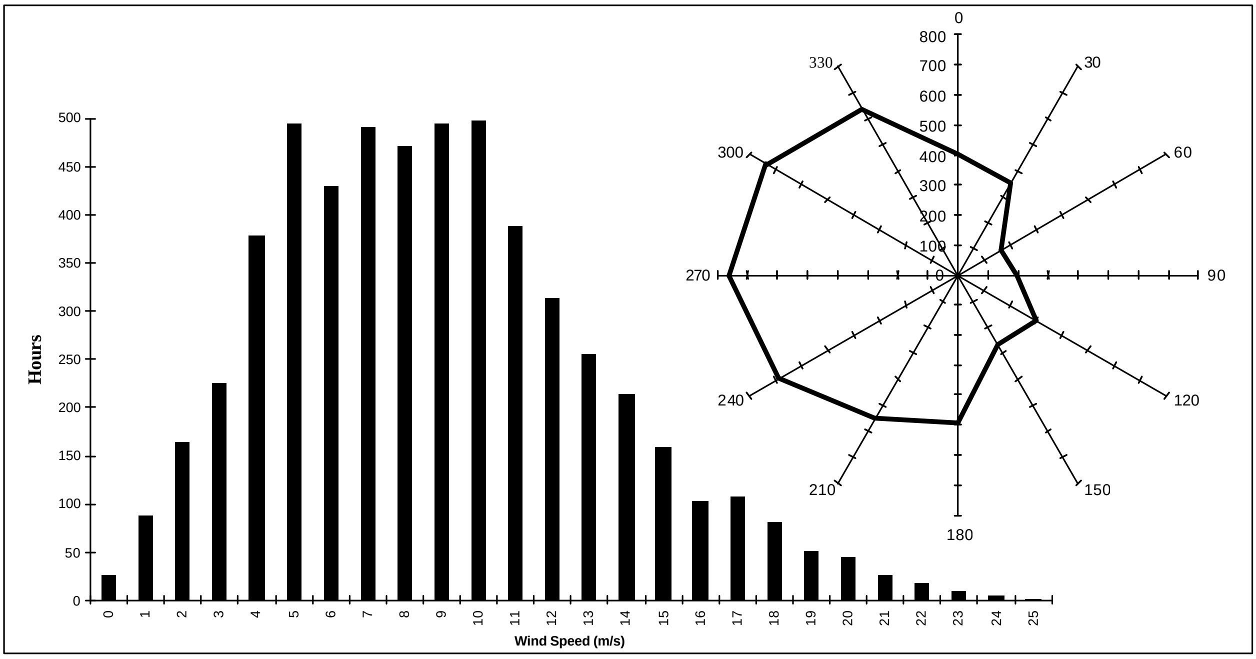

Figure 12 - Wind distribution and wind rose for Muck site (Ba-maung et al., 2000)

The design was intended to allow for variations in annual mean wind speed due to climatic variations of up to ?15%. A further analysis of the wind resource was undertaken as part of this thesis. This analysis calculated the average wind speed over a number of years using data from 1997 to 2002 (Figure 13), arriving at a figure of 8.4m/s. The variation from winter to summer was +14.2% to -15.4% in this period, matching positively with the previously calculated figures.

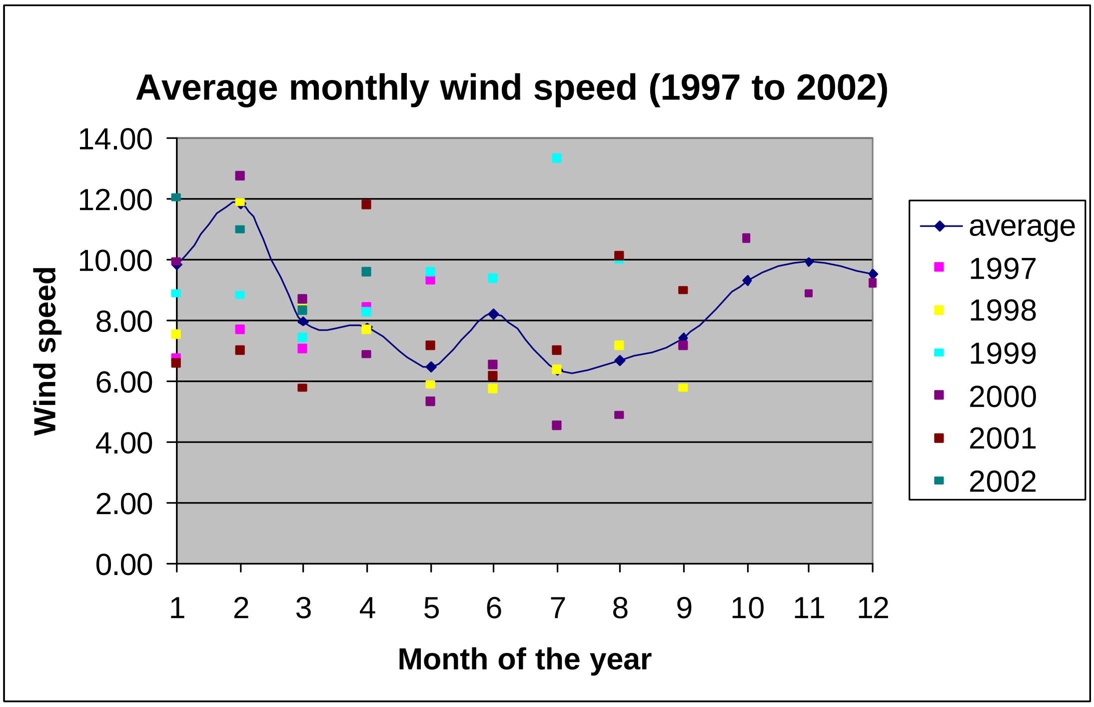

Figure 13 - Average monthly wind speed

6.5.3. Demand

Buildings on the island include 19 houses, 4 workshops, a primary school and a telephone exchange. For the initial project implementation, questionnaires were used to calculate the electricity demand, and low-energy light bulbs were introduced to lower the peak load by 14%. A predicted daily consumption graph was drawn showing a range in use of 7 to 30 KW throughout the day. This was reduced to 26kW with the use of energy saving bulbs, shown in Figure 14.

Additional data from a similar scheme in Canna suggested that when the wind scheme was in place, demand would be approximately:

? 6kW during the day

? 12-15kW in the evening.

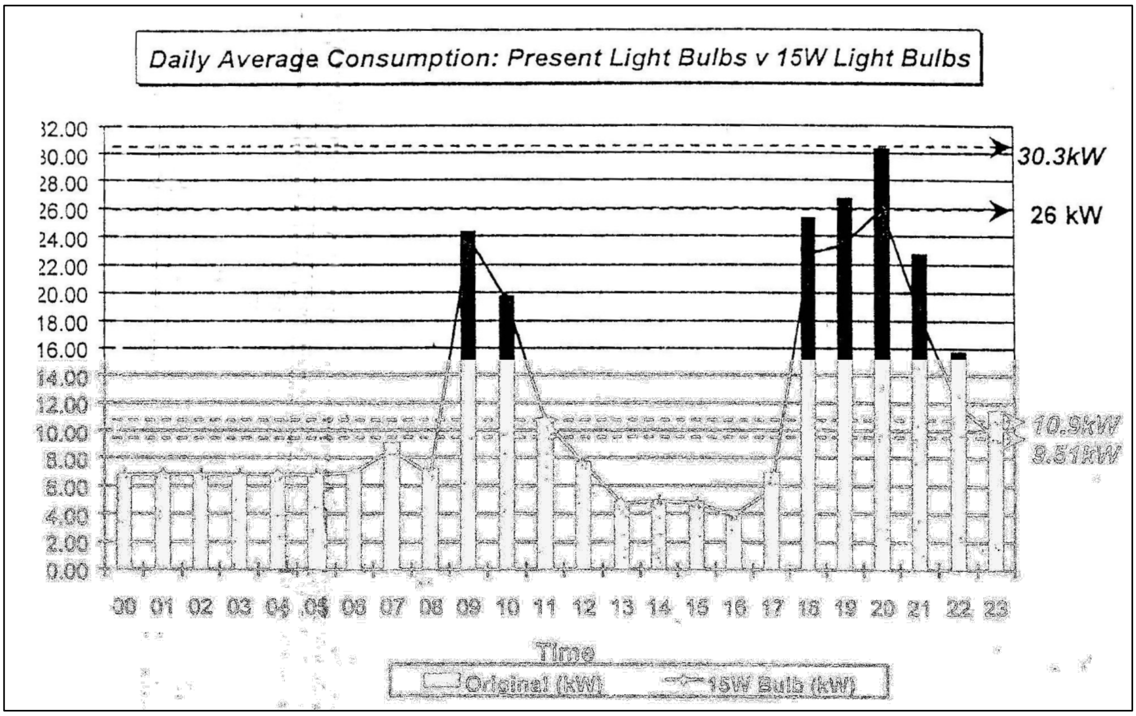

Figure 14 - Average predicted electrical demand (Ba-maung et al., 2000)

Due to the interactive demand management system, consumption will have adapted from Figure 14 since the scheme was put in place. The system is now more dynamic. Routines on the island relating to power use will predominantly follow priority periods, but also demand may increase during windy periods due to the consumer awareness of varying tariffs and source of energy.

More recent demand information for a typical winter and summer quarter from 2003 to 2004 was gathered in the form of meter readings. These readings enabled an average daily consumption (including heating loads) to be calculated. Calculating this for the winter and summer revealed that there was only a 4% variation in demand from winter to summer, likely due the increased demand for heating and electricity by locals in winter (and longer priority period) being cancelled out by increased demand for electricity in summer due to tourism.

This average daily demand could then be split into demand for the school and demand for the rest of the island, enabling an “average school demand per hour” and “average rest-of-system demand per hour” to be calculated, as shown in Table 7.

average daily demand	149.13	kWh
average priority hrs	11.5	h
school daily demand	46.9	kWh
school hours	8	h
school unit/hr	**5.9**	kW
without school daily demand	102.2	kWh
normal priority unit/hr	**9.3**	kW

Table 7 - Average demand calculations (2003-2004)

From talking to islanders, an understanding of the consumption pattern was gained and so this average figure could be adapted on an hourly or half hourly basis to build up a more detailed demand curve with the help of actual system data.

This demand curve was used as an input for supply-demand modelling exercises in the packages HOMER and MERIT discussed later in this report in section 7.2.2. The demand curve arrived at is shown in Figure 15 (MERIT) and Figure 16 (HOMER) on the following page. Some dips are observed in the MERIT chart that are not shown in the HOMER chart, as the figures for the MERIT chart are based on half hourly averages, whereas the HOMER figures are based on hourly averages. The charts give a good idea of how demand varies throughout the day according to the priority periods.

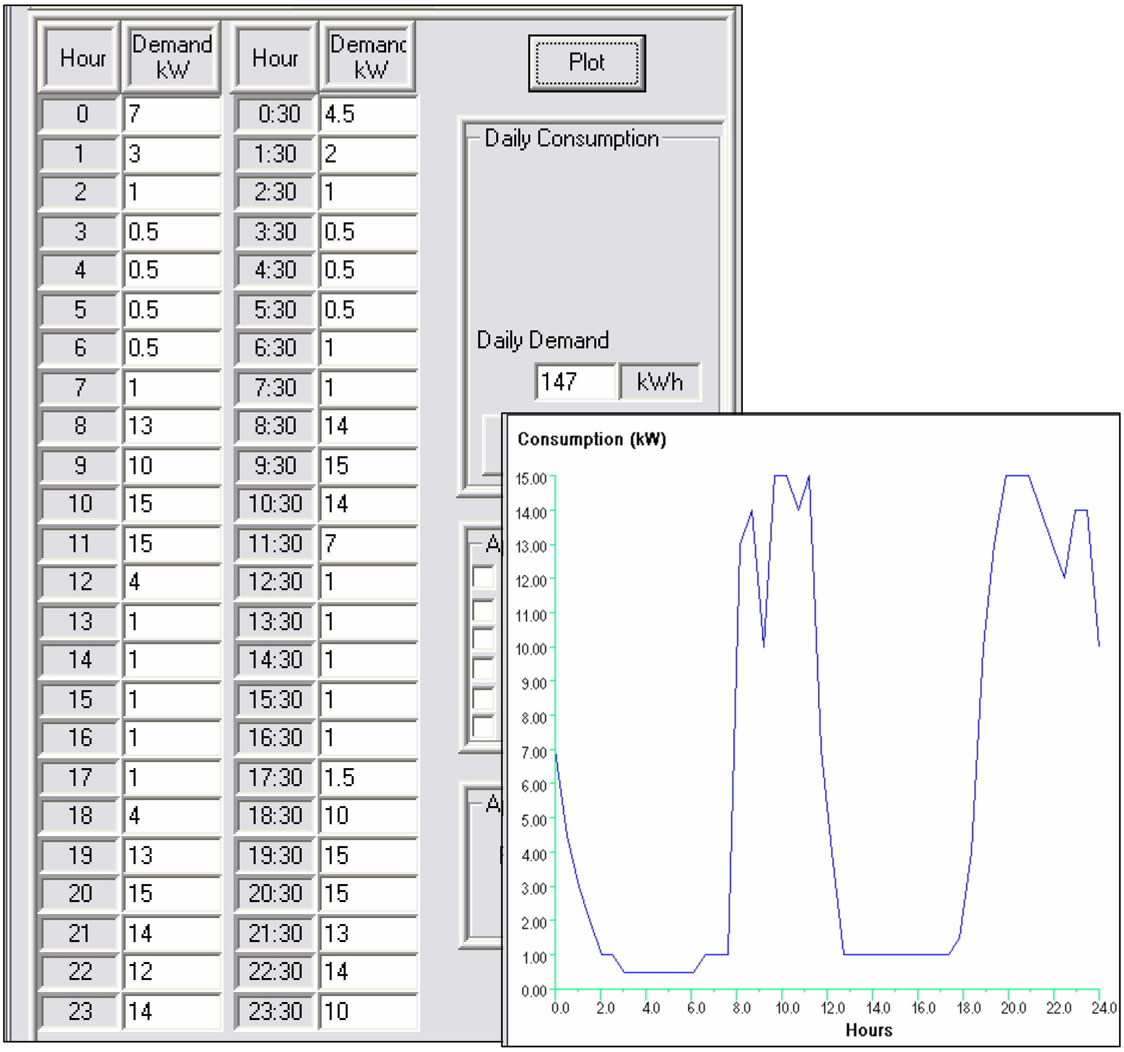

Figure 15 - Demand profile modelled in MERIT

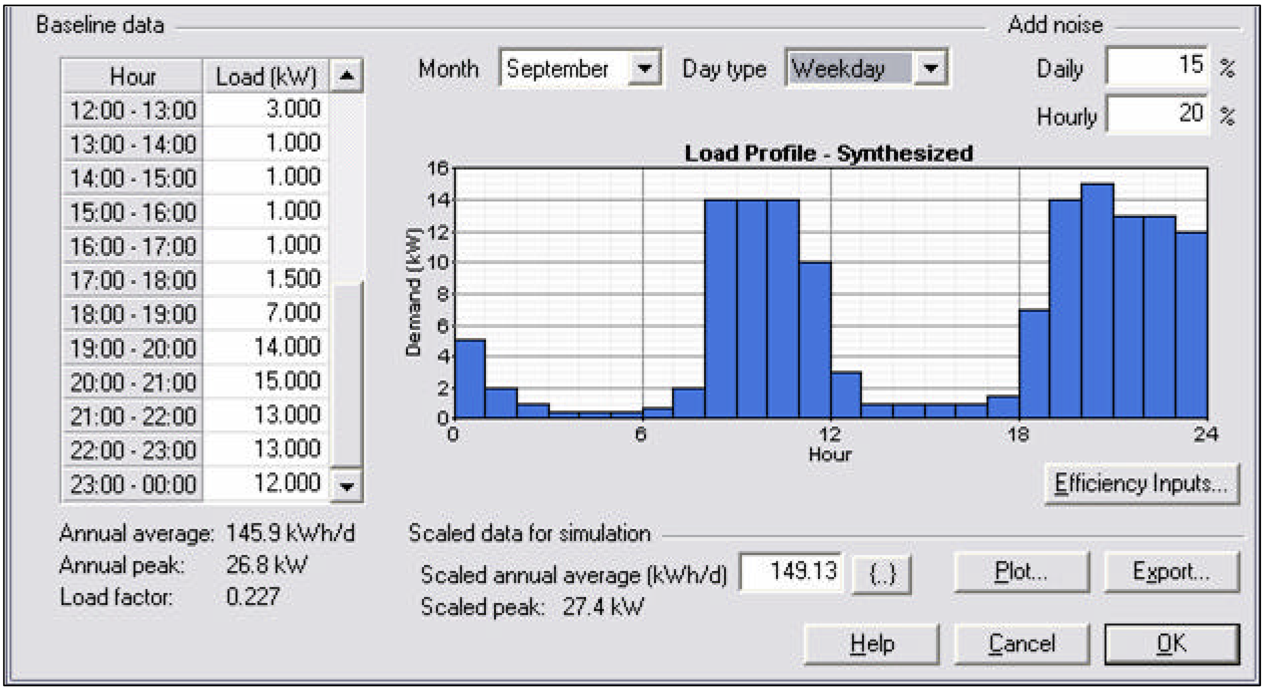

Figure 16 - Demand profile modelled in HOMER

A fluctuation throughout the day is observed. As the demand is varying by these amounts this implies that loading factors will usually be much less than 100%. In a real system, demand will fluctuate not only on a daily basis, but it will also fluctuate widely with respect to time and distribution, in a variety of weekly, seasonal and other cycles i.e. tourist seasons. These simulation programs have the ability to add noise to the profiles to account for variations, or it is sometimes possible to define different profiles for different days/seasons. However, an understanding of the average data is adequate for the purposes of this investigation.

6.5.4. Dump Loads

The SCADA "Dump Load Setup" screen (Figure 18) enables set-up of the automatic switching of resistive loads (immersion heaters and storage heaters) to regulate the grid. Each of the loads on the screen is listed by its name, charge-time, priority and status. The on-time is also given, which indicates the amount of time the load has been charged in this cycle. Additional screens give information on the ratings of the loads. The dump load setup can be edited to change priorities or charge time at the computer on Muck or via a remote connection to this computer.

In normal operation, with excess energy being generated by the turbines, the highest prioritized dump load will be charged first. When the on-time is equal to the charge-time, the load next in priority will be charged. If the surplus energy is no longer available, but the charging of a load has not finished (on-time not equal to charge time), the system will return to charge this load when excess is again available until the charging of this load is complete (on-time is equal to the charge time).

Although the residents of the island cannot personally change the operating level of these loads, they can switch them on or off at the appliance. If the control priorities on the SCADA system are not updated accordingly, which is difficult to administer, there may be an impact on the system performance, as the system could take some time to work through the prioritized list of loads before it can locate a load that is switched on and available to dump energy to.

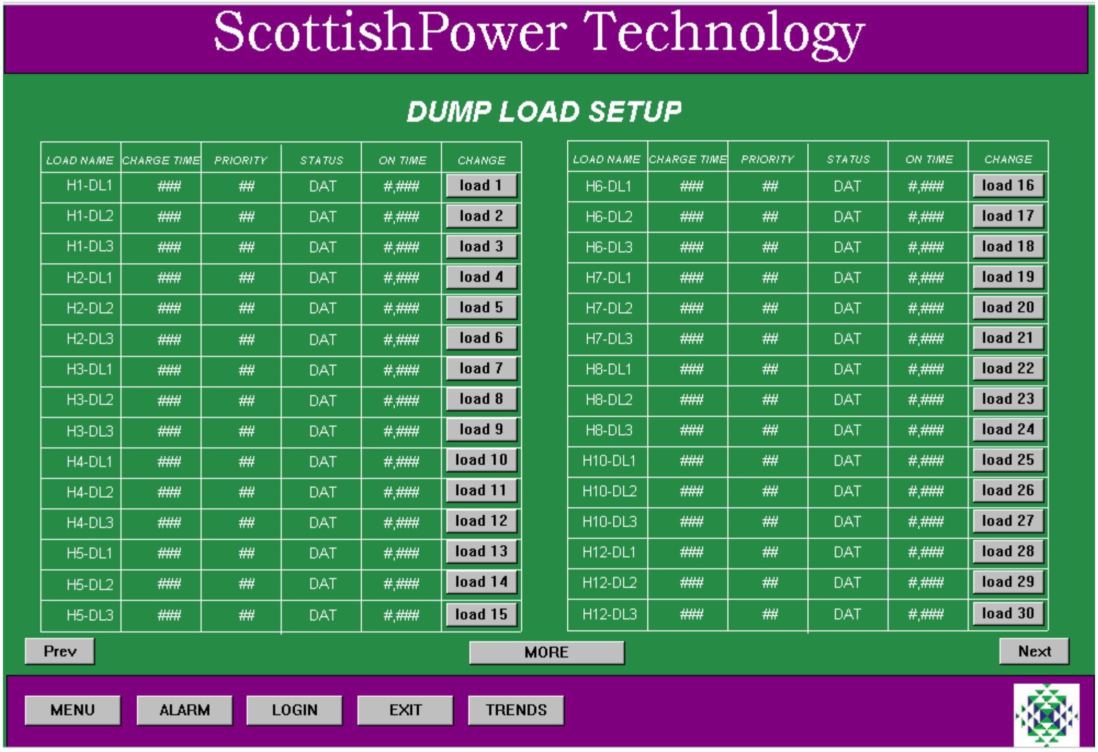

Figure 17 - Screenshot of console for changing the dump load setup

To determine how much of an issue this might be, a questionnaire was compiled and distributed to the residents of the island. The results (Table 8) show that overall usage of storage heaters is much lower than expected – the variation from the expected figure in winter is -27% and in summer is -59%.

Expected storage dump load available	109.7	kW
Expected Immersion heating dump load available	51	kW
Total expected dump load	160.7	kW
Total summer dump load available	14.2	kW
& immersion estimate	65.2	kW
variation from expected	59	%
Total winter dump load available	66.2	kW
& immersion estimate	117.2	kW
variation from expected	27	%
Winter to Summer variation	79	%
Total washing machines	13	
total fridges	16	
total freezers	14	
total TVs	12	
total workshops	2	

Table 8 - Resistive Load statistics (2004)

Additionally, these storage heaters have a non-linear consumption profile, and may consume more power when initially switched on. This could have the result of adding spikes to the demand/load curve, impacting the performance of the system as a whole e.g. resulting in sudden grid voltage drops or frequency changes.

This deviation from the intended operation of the system could cause problems with system stability due to poor load management. Fast-acting electronics interfaces would help in regulating the voltage and frequency and ensuring proper load-sharing among the various sources (Papathanassiou et al., 2004). A distributed method, as implemented on the Isle of Rum, close to Muck, (Taylor, 2001) may enable more control to be gained over the loads on the system. It would involve control of the individual loads making up demand (rather than just thermal loads), enabling non-essential loads to be shed momentarily to allow the system to ride through lulls and continue to generate from wind rather than initiating a diesel start-up. Fuzzy logic control units could be installed on various loads, to act as an electronic governor for the turbines, controlling frequency and making use of excess energy. A random element in the load control software would ensure that the available energy was shared fairly between the loads over time. An element of prioritisation could also be added in the sensitivity of the control. This distributed method has reliability advantages and permits a finer level of control. It could be implemented on Muck in addition to the thermal load management to reduce the number of blackouts during non-priority periods, to reduce voltage and frequency fluctuations and to improve the overall efficiency of the system.

6.6. Summary

This section has outlined the design of the current power system on the Isle of Muck. The wind regime and demand profiles have been investigated and historical system operation examined. Previously identified issues with the system operation have been discussed. Two main issues in particular for further consideration in the analysis sections have been raised:

? **Poor battery bank performance:** The lead acid battery bank was designed to deliver 54 kWh but the batteries have been found to produce only in the range of 12 to 20 kWh.

? **Potential problems due to slow reacting dump load control:** Research indicates that overall availability of dump loads is much lower than expected by the control system. A reduction of 27% in available loads in winter and 59% in available loads in summer will have a major impact on the ability of the dump load control mechanism to stabilise the network.

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7. *System Evaluation*

7.1. System Data

This project is based on data taken from the SCADA system on the Isle of Muck. The data is limited to 7 data streams and these cannot be easily altered. A set period in September 2000 has been chosen for analysis, as this period indicates the most reliable and most comprehensive readings for the system. The data being recorded in this period is shown in Table 9. The main SCADA system status display on which this data is displayed is shown in Figure 18 following.

Data	Units	Meter Type
1. "Grid Frequency"	Hz	Pulse
2. "Grid Voltage"	V	Pulse
3. "Battery Voltage"	V	Pulse
4. "Diesel" Power Generation	kW	Pulse
5. "Wind" *(after inverter = battery and wind total power out)* Power Generation	kW	Pulse
6. WTG1 *(wind turbine generator 1)* Power Generation	kW	analogue
7. WTG2 *(wind turbine generator 2)* Power Generation	kW	analogue

Table 9 - Data recorded from Muck site

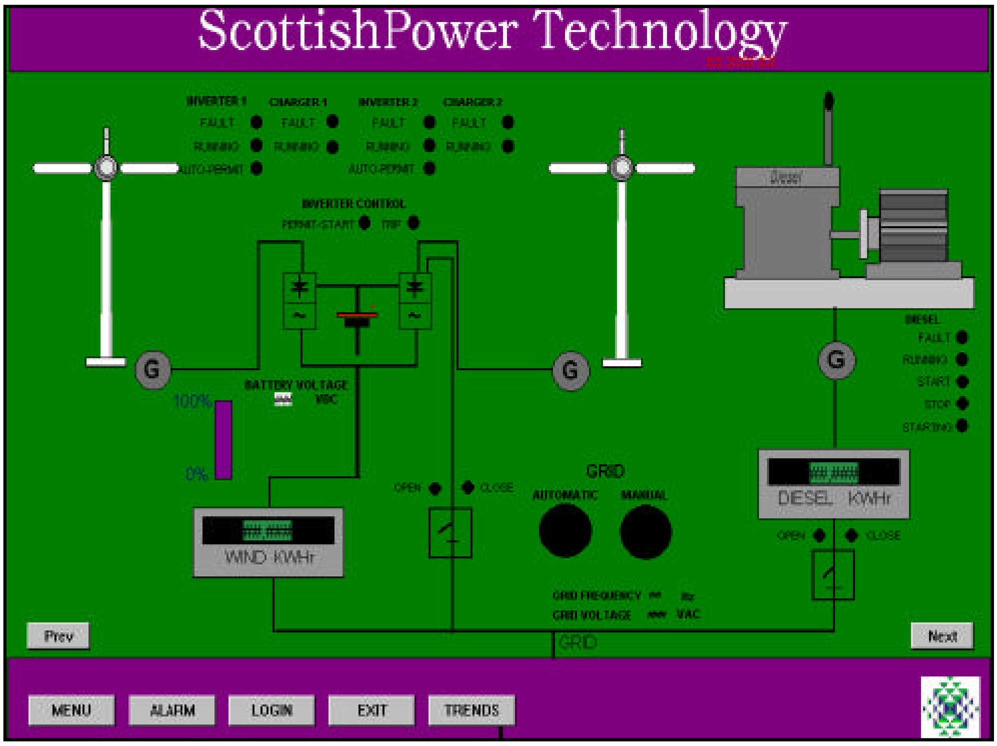

Figure 18 - Screenshot showing main SCADA system status display

7.1.1. Accuracy

This system is very complex, and only limited information is available on its performance. There are various inaccuracies and potential errors to be taken into account when utilising this data.

All of the data but for the wind turbine readings are measured on a pulse meter. Therefore, there is a built in inaccuracy. The pulse meter can only measure kWh. With some additional processing, the reading can be averaged to arrive at a kW reading. However, in a system operating at such low powers, the meter may often be inaccurate and slow to react. For example, if the demand being met is 1kW of power, the inverter pulse meter will take one hour to log this reading (1kWh). However, as the majority of the sensors are of this type, and this is the only data available, this data has been viewed as acceptable for these purposes, which are to get an understanding of how the system is operating rather than to carry out a very detailed numerical analysis.

In addition to the measurements above, there is a logger installed to measure wind speed and direction on an 18m tall redundant telegraph mast approximately 20m from the wind turbines. Accurate calibration of this logging equipment is important, as there are various settings that will alter the data format of the device. The output should be in m/s rather than miles per hour, and the times should match with the SCADA data. Careful installation of the logging chips ensures that the times are synchronised, and a quick calculation on the data ensures that the reading is in m/s. The wind data for the period in question has been compared with turbine activity to ensure that the timing is suitably calibrated.

It is worth noting that there is a difference both in distance from the turbines and in height (due to terrain) of the anemometer for wind readings. Although these readings provide a much higher accuracy than relying upon meteorological observations, any errors in wind speed measurements will have a direct impact on turbine power due to the speed-cubed relationship, see Equation 1. The wind readings from the logger are in 10 minute averages, and therefore gusts and short-term fluctuations that may impact operation of the turbine will not be apparent – however, the average is more representative of the time-step than an instantaneous reading, and is acceptable for the purposes of this analysis.

Notes on the various actual data streams, presented in graphical form in Section 7.3 are detailed below in Table 10.

Actual to grid from inverter (from battery and wind)	In the SCADA source, this is called "Wind", but is actually the measurement of total output from the battery bank and the wind turbines, measured after the inverters. This can be considered to be the demand on the island when diesel is not operating. When diesel is operating its data stream will represent demand.
Grid voltage **Battery voltage**	The grid and battery voltage are often scaled down by a factor to enable comparison with other system data. This scaling factor will be indicated in the key. When there is additional demand added to the system, grid voltage may decrease as the system attempts to compensate to meet this demand. When the battery is charging, an increase in the battery voltage should be observed, and when discharging, or connecting to the grid, a decrease in voltage is expected.
Diesel	Priority periods in 2000 ran from 08:00 to 11:00 and 18:00 to 00:00. Diesel is only used in these set periods. Operations below a set percentage load (40%) are avoided and a minimum run-time (3 hours) is applied.

Table 10 – Notes on data streams used in system modelling

7.2. System Modelling Background

7.2.1. Why Model?

There are two aims of the modelling carried out in this study. Firstly, the turbine model aids understanding the operation of the actual turbines at specific moments in time, referencing time-specific wind data. Secondly, modelling enables addition of new components such as fuel cells to the system and evaluation of their performance based on actual system data. The performance of the system and the size of the components are very much limited by the available renewable resource (Mills & Al-Hallaj, 2004), so modelling new components against actual system data enables crucial sizing decisions to be made.

7.2.2. Modelling Facilities

There are a number of custom-built programs available, for example; Hybrid2 and Hybrid 3 (Mills & Al-Hallaj, 2004) for hydrogen-hybrid systems, Simulink-Matlab for electrical modelling (Dutton et al., 2000; Mills & Al-Hallaj, 2004; Altener Programme, 2001), SIMELINT for electrolyser performance in simulated wind conditions (Dutton et al., 2000), TRNSYS language based programs (Martin & Muradov,2000), Merit (Smith et al., 2001; Smith, 2002) for demand matching and Homer (Canadian Government, 2004) for basic demand and economic evaluation. Both Homer and Merit have been used for simulation purposes in this project, discussed later in this report. In this study the main focus for modelling was advanced use of Microsoft Excel. Models were built to operate against actual system data that had been gathered in distinct time-steps. This allowed for a step by step analysis to take place, and easy evaluation of the impact of changes in certain parameters.

7.2.3. Previous Modelling Studies of Muck

A theoretical modelling study has in fact been previously implemented for the Isle of Muck (Smith, 2002). In this study, demand estimates were derived from climate statistics and good practice guides rather than actual information, and less accurate climate data was available. This study using MERIT assessed the potential of a range of renewable energy technologies on the Isle of Muck, assuming that there were no system currently installed except for diesel generation. The evaluation in this thesis differs from that of Smith (2002) as it assesses the island in its present state, with a hybrid wind-diesel system already installed with the objective of enabling the islanders to maximise the performance of this system through use of advanced storage. It is interesting to note however that having assessed a wide range of renewable possibilities for the island, the main finding of the Smith study is shown in Figure 19:

"As there is limited land available on this island, the simplest and best option would appear to be the use of substantial wind power provision, converting any excess electricity into hydrogen for use in vehicles, catalytic heaters and fuel cells."

Figure 19 - Outcome of the Smith (2002) Study

Another model which is relevant to the current study is that of Bonanno et al.(1998). Their model was slightly more detailed than other more general studies addressing a small island community, and based wherever possible on actual data. The model, written in AGSL, focused upon issues of power balance. The imbalance power was used to update the system design. Some of the findings from this model will be discussed in this chapter.

7.3. System Modelling Implementation[6]

7.3.1. Modelling a basic 25kW Wind Turbine

The power produced by wind turbines depends on two key factors - the strength of the wind, and the area swept by the rotor. The most important consideration is the annual mean wind speed at the site, as the power available increases with the cube of the wind speed (see Equation 1 below). The area swept by the rotor increases with the square of the rotor diameter. The power available (P) from a turbine can be calculated as follows:

$$P = C_p ½ ? A V^3$$

Equation 1 - Formula for wind turbine power (Sorensen, 2000)

Where *? = the density of air (1.223 Kg/m3),*
A = the swept area,
V is the wind velocity
C_p is the power co-efficient (the ratio of actual power to theoretical power, limited by the Betz efficiency).

Not all of the energy can be extracted from the wind, otherwise air would deflect from the turbine with zero speed. Betz' law states that a maximum of 59% of the kinetic energy of the wind can be converted to mechanical energy using a wind turbine (Sorensen, 2000).

In order to evaluate the performance of the wind turbines, a basic model of a turbine was created in Microsoft Excel. Initially, this was based around the manufacturer specified cut-in, cut-out and rated speeds and corresponding powers (as indicated in Figure 20), using the formula for a wind turbine in Equation 1.

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[6] It should be noted that many of the graphs in this and later sections could be represented as step functions rather than smooth curves. Smoothed plotting is preferred as it eases visual analysis of graphs.

However, this was not an accurate model, resulting in “peaking” behaviour (see Figure 20 and Figure 22) before the rated power was reached. This was due to the inaccuracies involved in following a set formula up to a manufacturer-specified rated speed-power point, rather than following a smoother manufacturer-specified power curve.

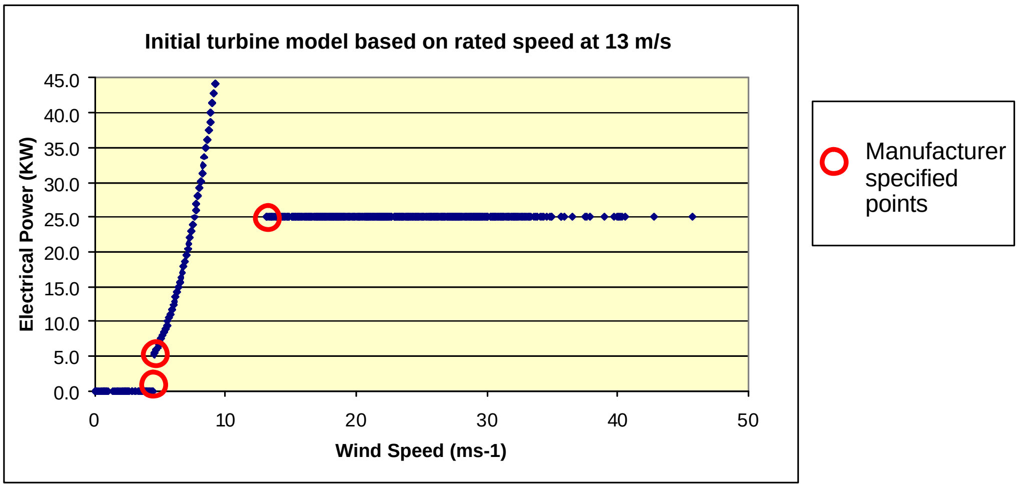


Figure 20 - Power curve for initial model

With the initial model, shown in Figure 20, power generation starts at the rated speed of 4.5. The formula for a wind turbine is followed up until the rated speed is reached at 13m/s, where the power output is expected to be relatively constant, modelled by a straight line. However, the rated power output is exceeded at speeds close to the rated speed (evident in the power curve in Figure 20). In reality a number of other factors impact the performance of the turbine, so that it takes longer to reach its rated speed. These have not been accounted for in the theoretical formula specified in Equation 1. Rated speed has not been taken into account in this formula at all. As a result of the speed cubed relationship in the Equation 1, large peaks are experienced as the model does not cut out when the manufacturer-quoted rated power is reached because it expects rated power to occur at a different speed. An improved model was devised, which derived formula for power output at different speed ranges from the manufacturer’s power curve (see Figure 21).

The formulae for different elements of the power curve were strung together using Excel based “if” statements for different speed ranges, in order to generate a smooth power curve. These formulae were then applied to actual wind data so that the calculated values could be compared with the actual system values.

When results for the two models were compared, based on actual wind speed data, it was clear that the second model was more accurate – eliminating the severe “peaking” behaviour observed with the first model, as shown in Figure 22:

	A	B	C	D	E
4		Wind Speed (m/s)	Power (kW)	Power (kW)	Power (kW)
5		1	0.00	0	0
6		2	0.00	0	0
7		3	0.00	0	0
8		4	0.00	0	0
9		5	1.00	0.925	0.925
10		6	2.50	2.575	2.575
11		7	5.00	4.975	4.975
12		8	8.33	8.3334	8.3334
13		9	11.67	11.6667	11.6667
14		10	15.00	15	15
15		11	18.33	18.3333	18.3333
16		12	21.67	21.6666	21.6666
17		13	25.00	24.9999	24.9999
18		14	26.50	26.5	26.5
19		15	27.00	27	27
20		16	27.00	27	27
21		17	27.00	27	27
22		18	27.00	27	27
23		19	27.00	27	27
24		20	27.00	27	27
25		21	27.00	27	27
26		22	26.90	27	27
27		23	26.80	26.9073	26.9073
28		24	26.70	26.7062	26.7062
29		25	26.50	26.4435	26.4435
30		26	26.40	26.1192	26.1192
31		27	25.80	25.7333	25.7333
32		28	25.30	25.2858	25.2858
33		29	24.70	24.7767	24.7767
34		30	24.00	24.206	24.206

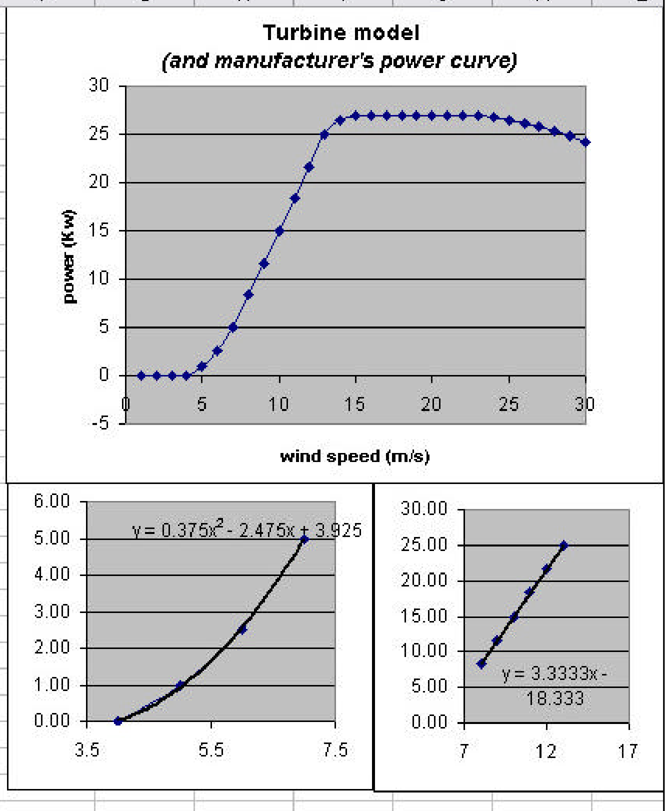


Figure 21 - Calculation of power-curve based model

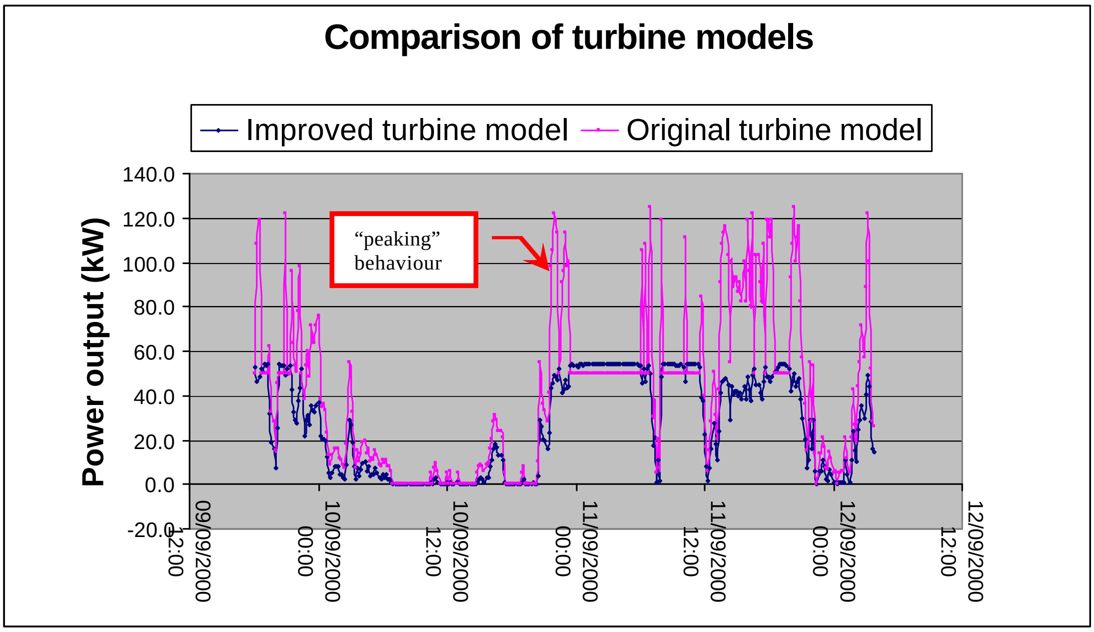


Figure 22 - Comparison of turbine models

The next stage of the investigation was comparison of this model with the actual turbine behaviour.

7.3.2. Analysing Actual Turbine Behaviour

First it was necessary to address how the actual wind turbines were performing with respect to the wind speed. Figure 23 illustrates the performance of one turbine. There appear to be moments of high wind speed where the turbine is operating at a relatively low level, and moments of low wind speed where the turbine is over-speeding.

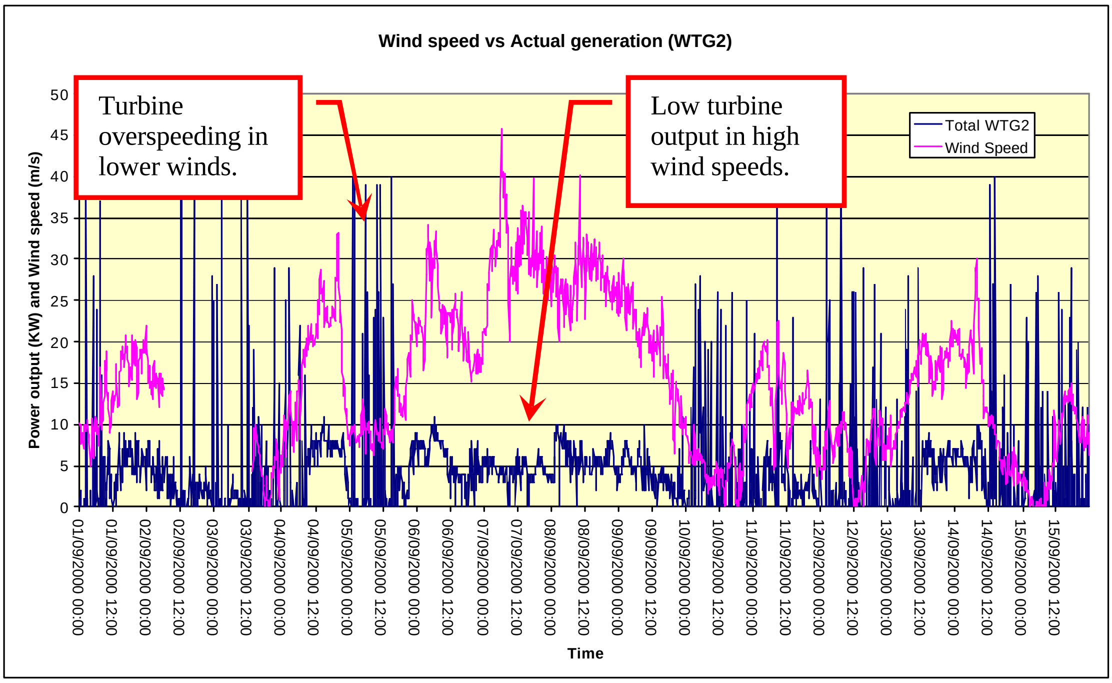


Figure 23 - Actual turbine behaviour

Adding the turbine model to this chart, and focusing in on a smaller time period, the behaviour shown in Figure 24 is observed. The actual turbine appears to be operating at levels of less than half the theoretical turbine performance indicated by the model. At some points the output drops to zero when the model predicts yields in the region of 5kW, and wavers at around 5kW when the wind speed would allow it to run at rated speed. In addition, the turbine output shows many spikes from zero power to a disproportionately high peak power, indicating many start and stop operations. Why is the turbine performing in this manner?

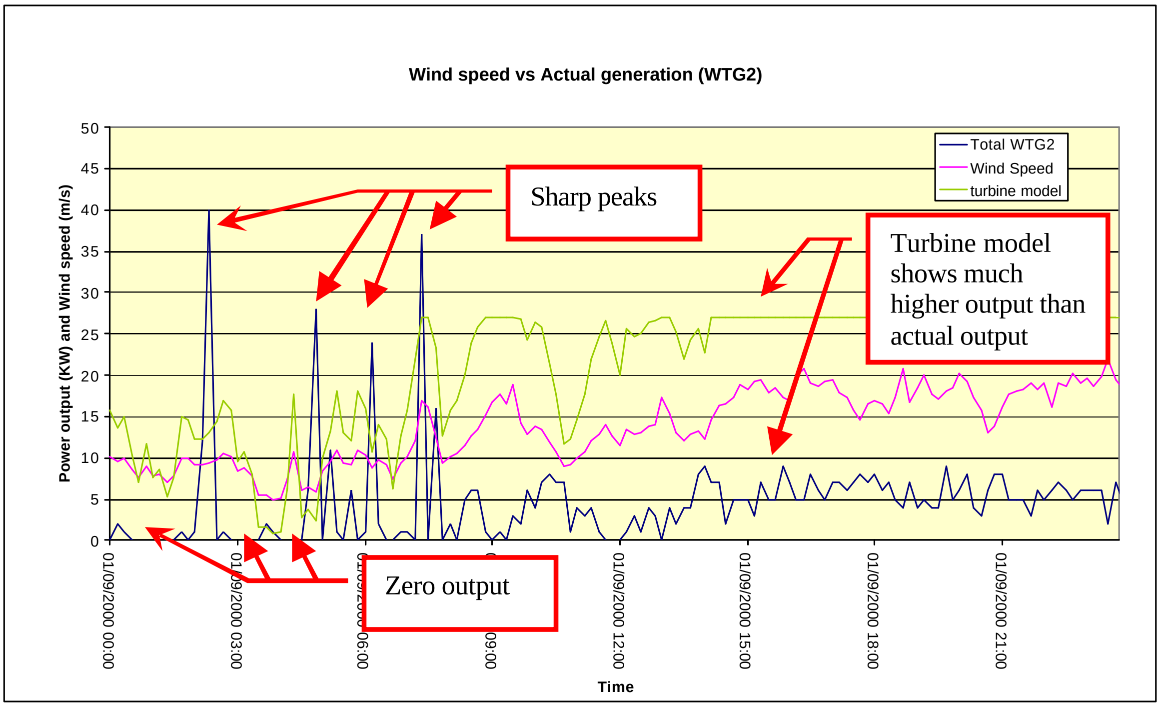


Figure 24 - Actual turbine generation compared with theoretical generation

Low performance of turbines in comparison to theoretical expectations was also experienced in a study by Costa (1998). He observed an energy yield of approximately half the predicted output (based on the average annual wind speed) occurring, with a high number of starting operations.

In order to analyse this mismatch of theoretical turbine behaviour and actual turbine behaviour, a turbine model as close to the actual turbine performance as possible will be developed. The investigation will address the following areas:

7.3.3 Power Curve Analysis

7.3.4 Differences in Performance of the Two Turbines

7.3.5 Impact of loading on Turbines

7.3.6 Overspeed

7.3.7 Electrical considerations

7.3.8 Final Turbine Model

7.3.3. Power Curve Analysis

7.3.3.1. Power Curve Comparison

The power curves for actual turbine versus that provided by the manufacturer are shown on the following page in Figure 25. Power curves are drawn from the higher values in the scatter, as it is likely that there are other factors causing the scatter below the lines, which will be investigated in Section 7.3.7.

From the charts, it can be observed that the wind turbines are not following the power curve as specified by the manufacturer. Expected output would be something similar to the model. The two turbines appear to be performing according to curves suited to 10kW rated turbines. When the total of the two are mapped together, a power curve similar to that of the model can be observed, but closer to 20kW rated turbine rather than the specified 25kW.

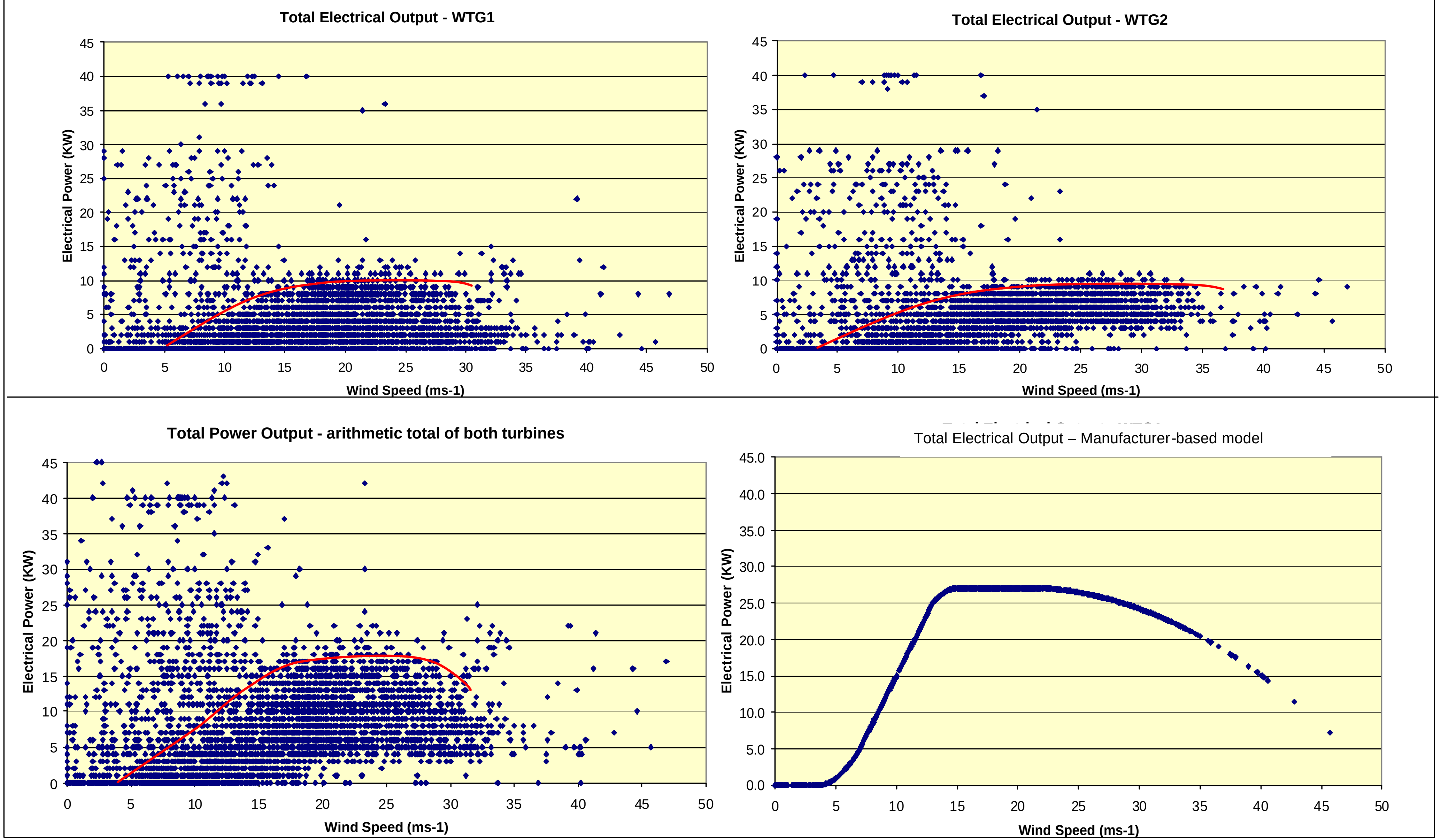
A number of sources have indicated that the Vergnet turbine used in this project was down-rated more recently, from 25kW rated power, to 20kW (suggesting perhaps some performance issues with the turbine itself). A turbine with identical specification, but lower rated power (and different model-name) was found on the Vergnet website.

The power curve for this down-rated turbine was modelled using a number of equations as explained previously. Replacing the 25kW model with a 20kW model brought the turbine model performance down considerably, shown in Figure 26.

7.3.3.2. Assumptions

As the power curves show that each of the turbines is performing in accordance with a 10kW power curve, with the arithmetic total of the two turbines corresponding to the manufacturer's 20kW power curve, a turbine model for a single 20kW machine (rather than two 20kW machines) will be assumed, for comparison against the arithmetic total of the two turbines.

Figure 25 - Power curve comparison



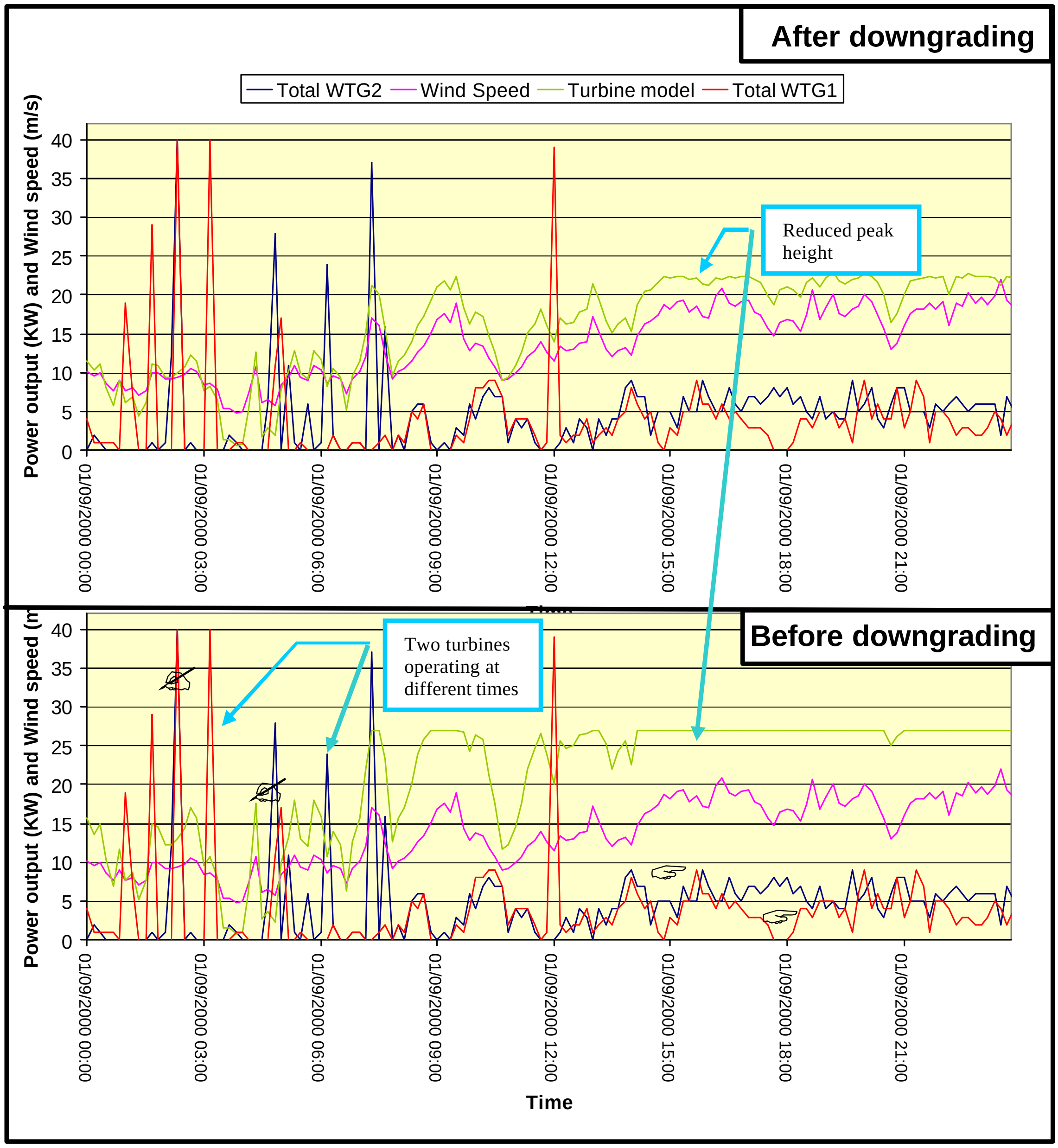


Figure 26 - Comparison of downgraded 20kW with 25kW model

7.3.4. Differences in Performance of the Two Turbines

7.3.4.1. Local Effects

As can be observed in Figure 26, the two turbines (WTG1 in red and WTG2 in blue) appear to be performing quite differently. The energy production of identical machines can be very different due to local effects (Bonanno et al., 1998). There may be interference due to terrain, trees etc affecting one turbine and not the other, depending upon position and wind direction. Another consideration is that of turbine wake. Depending upon the direction of the wind, one of the turbines may be operating in the wake of the other. However, considering the exposed location on Muck, it is likely that these considerations would only have a small impact on overall performance. For such extreme behaviour to be observed it is there must be other factors influencing the turbines.

7.3.4.2. Turbine Faults

Figure 27 indicates that sometimes only one turbine is generating power, with the other not operating for some period of time. When there is an excess of wind, such as at points 1 and 2 on the chart then both turbines begin to generate. The reason for this behaviour may be that during 2000 there was a fault where one of the turbines was only starting at the higher wind speeds as the passive pitch mechanism of the blades was not correcting to return to self-start position especially after overspeeding. Similar problems were identified in Costa, 1998. It is likely that this is why WTG2 seems less active than WTG1, observed also in the slight difference in the power curves shown in Figure 25, where WTG2 performs better in the higher wind speeds, but slightly poorer in the lower wind speeds.

7.3.4.3. Turbine Parameters

The erratic behaviour indicated in Figure 27 shows the turbines experiencing different numbers of starting operations. Costa (1998) found that at low wind speeds, near cut-in the turbines started and stopped frequently – 16 switchings in 40 minutes occurring at one point. This behaviour can be attributed to the specific wind conditions at each wind turbine as discussed previously, but also due to different operating behaviour of the wind turbines caused by turbine parameters being set differently and being poorly adapted for fluctuating wind conditions. Altering switching levels and averaging times could help the turbines to adapt to such conditions (Costa, 1998).

7.3.4.4. Inverter Efficiencies

For much of the time only one turbine is observed to be operating, even though it would be possible for both to operate. This may be due to a fault that occurred with the wind/battery inverter, the central component of the micro-grid system. The inverter is responsible for regulating voltage and frequency, and controlling active and reactive power (Papathanassiou et al., 2004). Problems with the two inverters running in parallel were encountered which meant that in low load situations the two inverters would only be run in parallel above a minimum load. It is unclear if this fault occurred during the period of study addressed here.

7.3.5. Impact of loading on Turbines

7.3.5.1. Variation between turbines due to load

It is important that there is enough evacuation capacity (load) on the system for the turbines to dump their power to. Outages may occur if this is not the case, and the output of the turbines may be altered depending upon the available load.

In Figure 27 for example, at point 3 the turbines are behaving quite similarly, with only a small variation, likely due to the effects of wake, interference etc mentioned previously. However, at point 4 there is a sudden dip in the power output of WTG1. Figure 27 also shows what is happening in the rest of the system at this point.

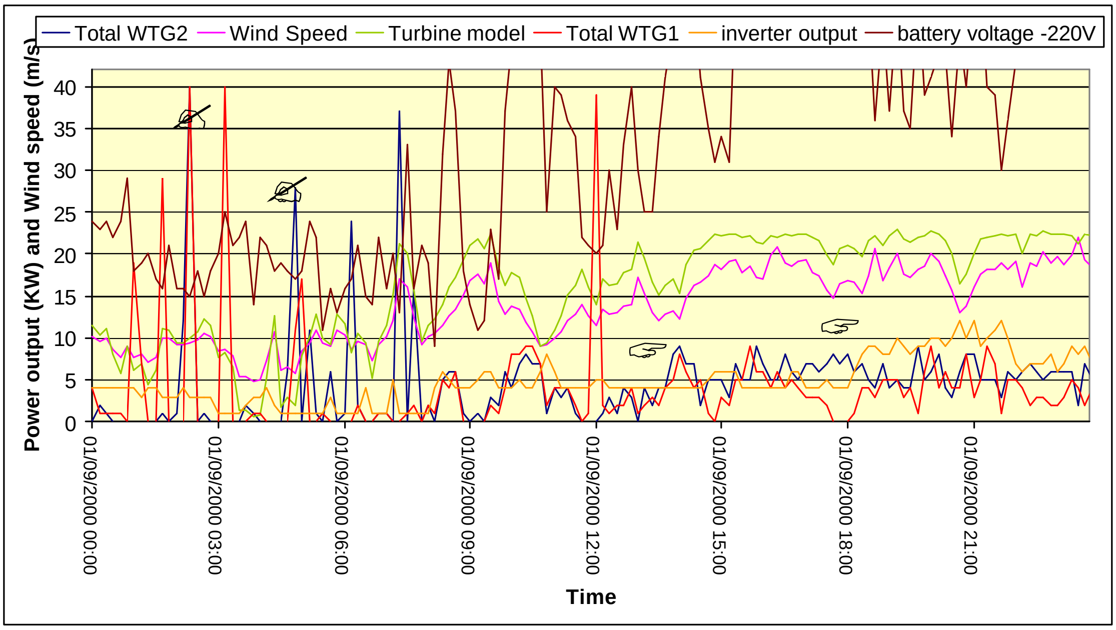


Figure 27 - Difference between operation of two turbines

The inverter output (orange) remains relatively steady. However, the battery voltage has been rising as the battery bank is charged by the excess the turbines are generating. At point four, it appears to reach full charge. There is nowhere for the excess power to be dumped at this immediate point and so turbine 1 cuts out. Later, the two turbines begin to generate similarly again – likely due to the system activating dump loads, and a slight increase in demand (shown in orange inverter plot). This analysis explains to some extent the variation in the operation of the two turbines.

7.3.5.2. Impact of Loading on Generator Efficiency

The operation of the wind turbines depends upon the load on the grid. If the load on the system is varying, then this will provide resistance to whatever the turbine is trying to put onto the grid – the load effectively behaving like a variable resistor. The maximum voltage out of the turbines is determined by the mechanical governor. If there is considerable load on the system, the turbine will operate efficiently. When there is not enough load on the system to absorb the energy in the turbine, the turbine will lose efficiency, there will be less reactive force and in a no-load situation the mechanical governor will effectively disconnect the turbine. This may lead to overspeeding, discussed in Section 7.3.6.

In order to model the response to loading, it was assumed that the reading for the inverter output was equivalent to demand – this is more or less true. Diesel will represent demand when it is operating, but this will not impact on the loading of the turbine. Therefore the potential load on the turbines can be calculated – this will be a combination of the inverter output (minus battery contributed component) and the battery charging activity. The percentage load can then be calculated, for comparison against the arithmetic total of both turbines. Once this is calculated, it can be applied using the chart in Figure 28, to determine how the efficiency of the generator is affected[7].

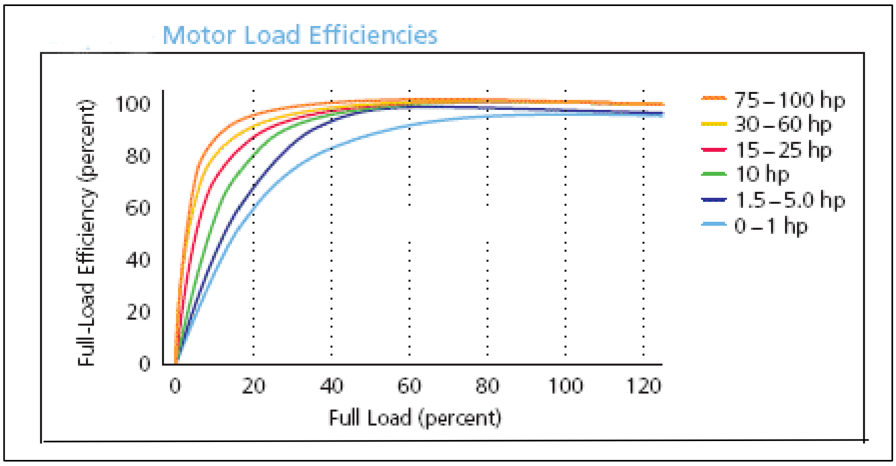


Figure 28 - Loading versus efficiency (Energy Innovator's Initiative, 2004)

A generator operating at a rated speed of between 20 and 25 kW translates to around 30 hp using a conversion factor of 1 Horse power = 0.7457kW. An approach similar to that for the manufacturer-based turbine model was taken, finding equations for components of the graph in order that an overall formula for the relevant curve could be derived. Figure 29 illustrates the result.

[7] This chart for motor loading/efficiency can be used as it is assumed that a generator is simply a motor reversed.

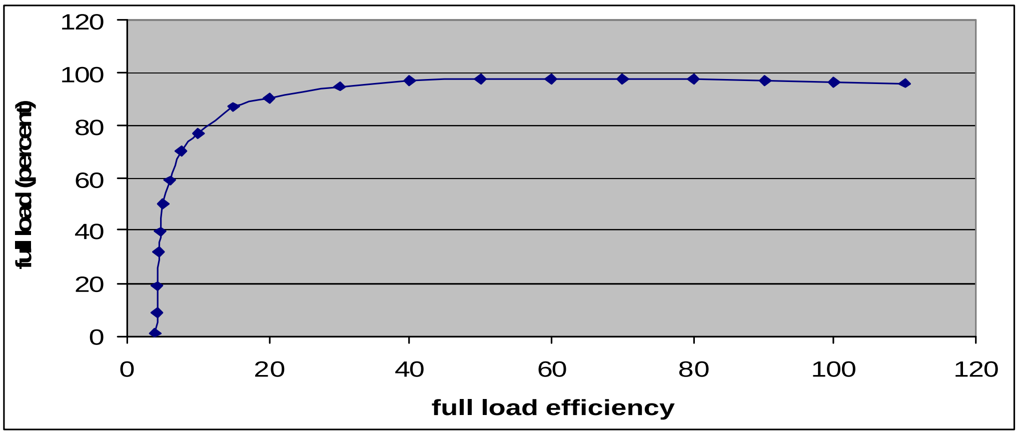


Figure 29 - Modelled load efficiency curve for 30hp generator

The formulae for the chart in Figure 29 were used to calculate the efficiency of the generator depending upon the load that was present in terms of demand and battery charging. This was combined with the turbine model, to produce two separate curves, one including the battery charging as a load, and the other not – so that observations could be made in terms of where the proportion of the wind turbine power was going. Figure 30 shows the model without battery charging (light blue line). All power generation indicated by this model would be expected to go to the grid.

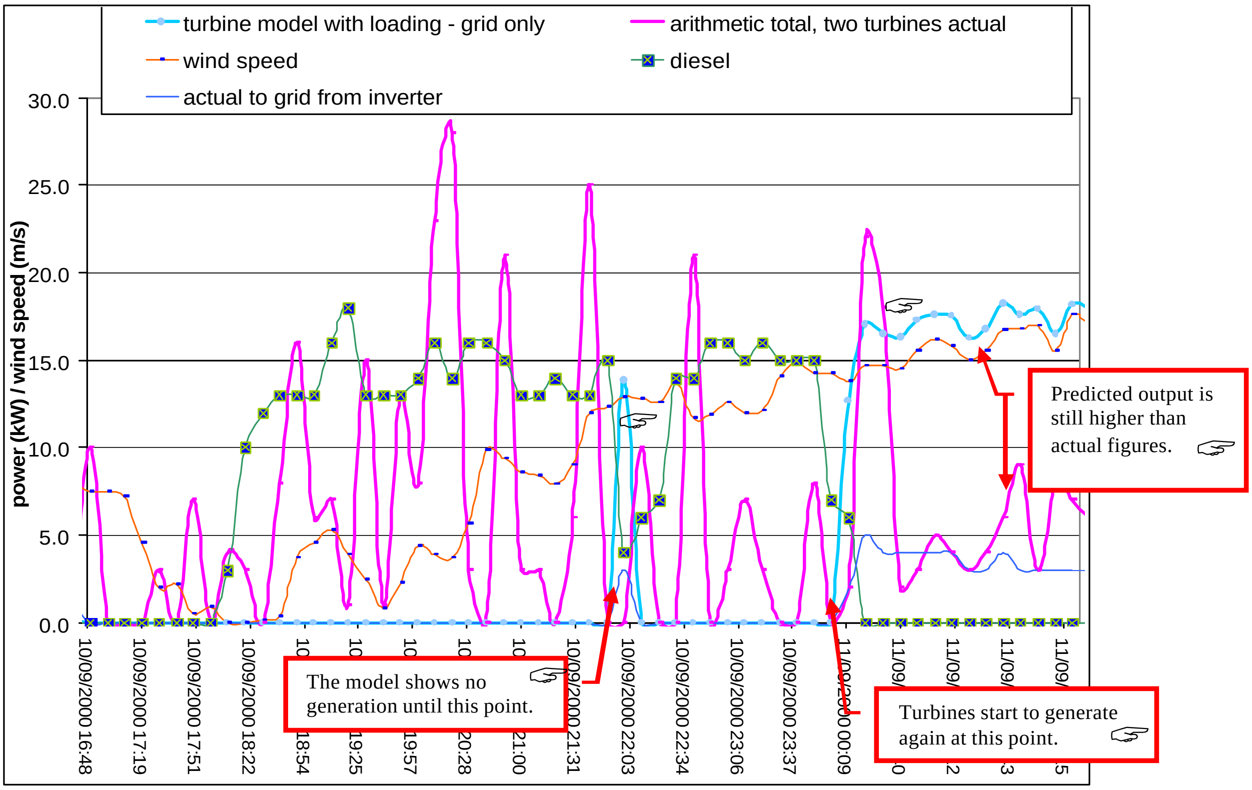


Figure 30 - Updated turbine model including grid loading

When the load efficiencies to the grid are taken into account in the gird-loaded model, it forecasts no operation of the turbine until point 1, where inverter activity can be observed (thin dark blue line). This occurs when the minimum diesel-on time has finished and the diesel generation reduces. However, the voltage of the battery must be too low, as the diesel starts again, and no generation occurs until point 2. Both the grid-model and the actual results indicate this, although the model shows predicted output of a much higher magnitude than the actual turbine performance. It is interesting to note the peaks at 4 and 5, which have a similar magnitude to the grid-model. It suggests that in some circumstances the model is reasonably close to the actual system in terms of translating wind speeds to power, but for some reason the power generated by the actual turbine drops away.

To analyse this problem further, the output including battery charging can be compared with this grid only model, shown in Figure 31.

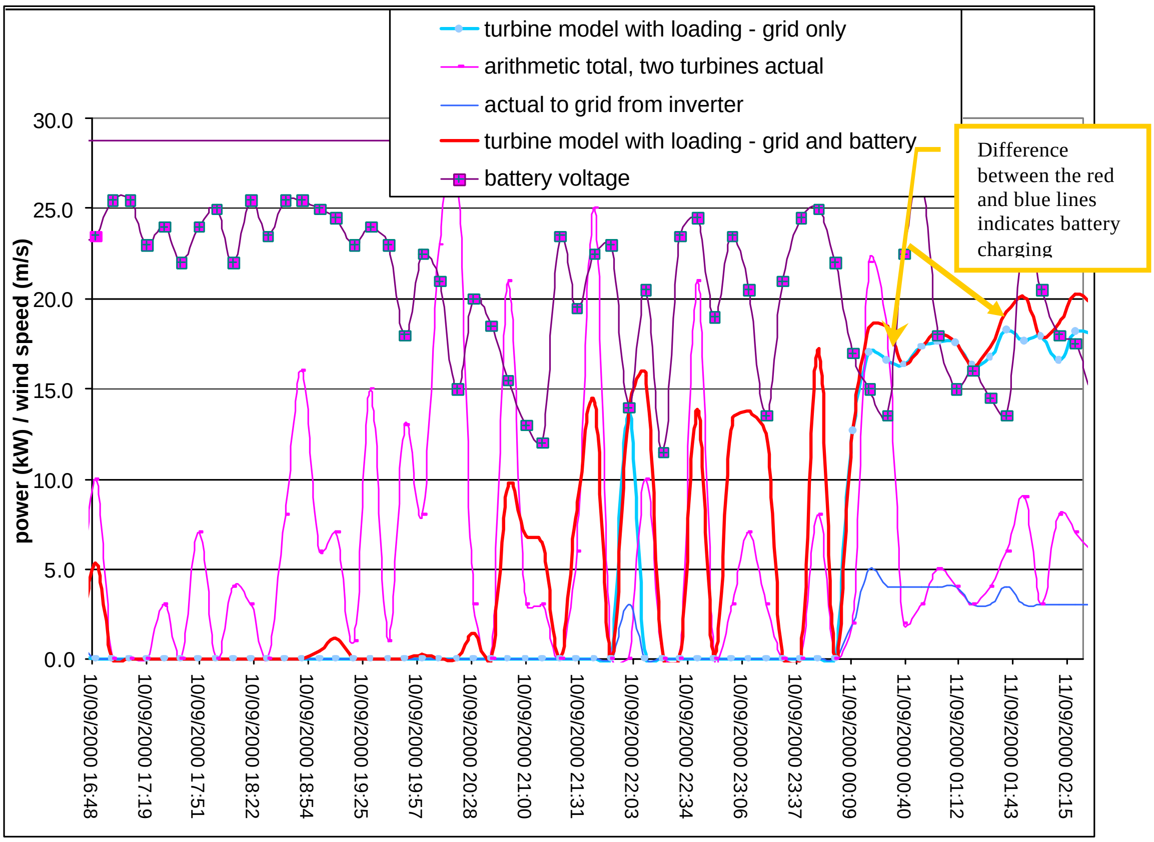


Figure 31 - Updated turbine model including grid loading and battery charging

The Battery-Grid model is shown in red. Using this model there is more of a correlation with the turbine peaks. This indicates that some of the peaks are due to control of the battery charging regime, perhaps based on particular set-points relating to battery voltage. Looking at the chart it can be observed that shortly after a decrease in battery voltage the turbine begins to charge the battery. The peaks of the Battery-

Grid model compared to the peaks of the actual turbines also vary in magnitude. Sometimes the predicted output is more than the actual output, and at other times it is less. This could be due to the assumption that one turbine is being modelled, whereas it is being compared with the arithmetic total of two.

The main observation that can be made from the performance of these models over different time periods is that when the model of the Grid and Grid-Battery converge, this means that no charging is taking place. At these points, the actual output of the system appears to drop to near zero. This is illustrated in more detail in Figure 33.

7.3.6. Overspeed Analysis

7.3.6.1. Turbine Faults

In the early operation of the turbines (information is not available regarding specific dates), a fault with the turbines occurred causing them to overspeed, stall and disconnect from the grid repeatedly. This was also identified as a problem in the study by Costa, 1998. Although it is unclear if this occurred during the chosen timeframe, the large peaks do suggest frequent overspeeding and cutting out.

7.3.6.2. Routine Overspeeding

When there is not enough load on the system to absorb the energy in the turbine, a mechanical governor will effectively disconnect the turbine. The turbine will hit its maximum voltage and run flat-out until the passive action of the blades stops it from exceeding its maximum speed. Similarly, if the batteries have been acting as dump load for the turbines and they reach full charge, when they disconnect from the turbine overspeeding may also occur so that the mechanical governor has to limit the speed.

7.3.6.3. Quality of Data

Overspeeding occurs when the turbines are disconnected from the network and therefore not generating. The presence of overspeeding-type behaviour in the power readings for the turbines, often when there is no demand being met by this apparent power, raises questions about the quality of this “turbine power” data. The power meters to measure the output of the wind turbines were provided for information only to the islanders. The measurements were taken before the inverters, which are in place to stabilise the output of the turbines. The power is calculated from a combination of the voltage, current and phase shift, based upon the relationship P=VI.

If the turbine is overspeeding, but not grid connected, then the electrical condition will be open circuit. In such a situation there will be no current flowing through the inverter or the charger. An open circuit voltage may be measured. A non-zero current may be read if an offset current value is used for measurement purposes and not corrected to zero in open circuit conditions. If the open circuit voltage is multiplied by an offset line current this could result in large powers being calculated when in fact no power is going to the grid. In spite of these overspeeds appearing as "phantom" power readings, they do provide a good indication of turbine activity.

7.3.6.4. Analysis of overspeeding behaviour

Comparing the models for Grid and Grid-Battery loading with the individual turbine traces, the result shown in Figure 32 is obtained.

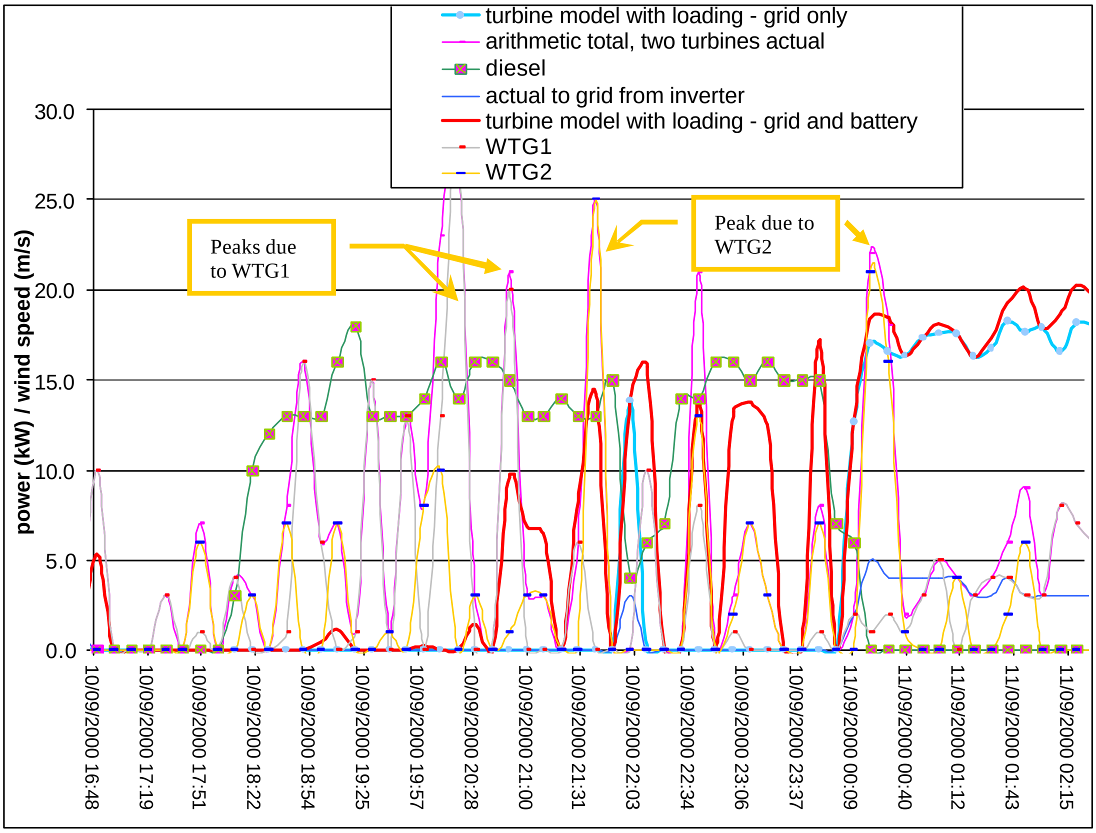


Figure 32 – Operation of two turbines against model

From this chart it can be observed that when large peaks occur, they are usually due to the operation of one turbine alone. This means that the turbines are overspeeding considerably compared to their power curves – the peak for a single turbine at some points (not shown) reaches as high as 40kW. This cannot relate to actual power generated by the turbine as it far exceeds the peaks of any power curves addressed.

To examine these peaks further, another period with no diesel operation, featuring with extreme peaks of power apparently being generated is addressed, as shown in Figure 33.

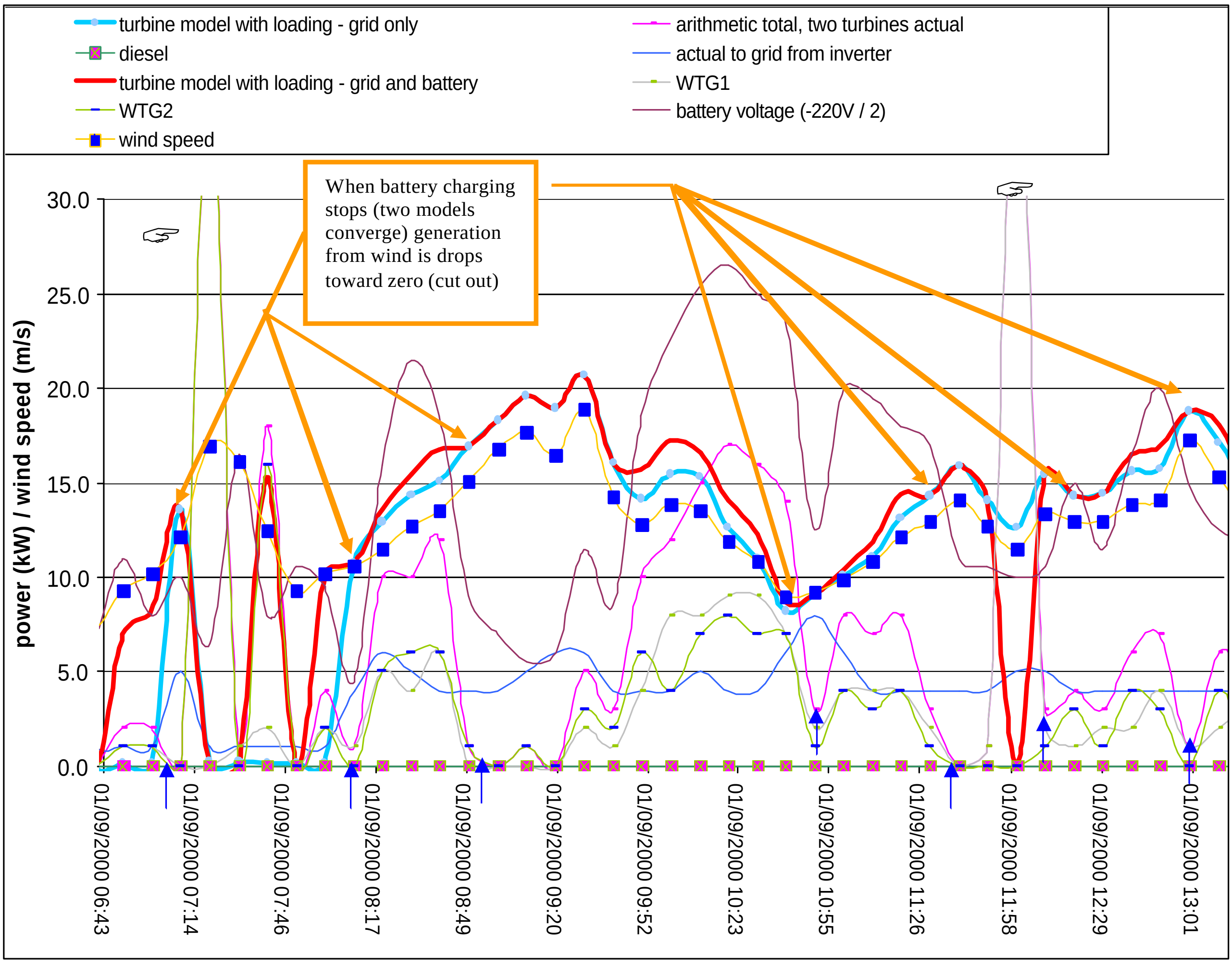


Figure 33 - Further analysis of peaking behaviour, windy day

If the arithmetic total of the two turbines is compared with the battery voltage in Figure 33, a very strong correlation can be observed. During this time the battery voltage is reasonably healthy – sitting at around 240V. Overspeeding still occurs at points 1 and 2. At point 1, demand (inverter output) decreases, as wind speed increases, resulting in a disconnection of the model from battery charging and grid supply (no activity between turbine and battery) and an overspeeding of the actual turbine – this seems logical behaviour. At point 2 the model shows no turbine activity to the battery, but an ability to still meet demand. The two peaks are very similar.

Lack of turbine-to-battery activity is the common feature of both overspeeds, and so may have been responsible for the overspeed in both situations. In order to confirm if this is the case, it was necessary to identify additional situations where overspeeding occurred and determine if these also indicated no turbine-to-battery activity. A thorough analysis of various different time periods resulted in the following observations:

? Battery voltage is the best reflection of the system. When diesel is running, the battery voltage mirrors the diesel behaviour. When wind is generating in good conditions, the battery voltage follows the wind generation or vice versa. When there is low wind and no diesel, the battery voltage follows demand, with some variations.

? In low wind conditions when the wind speed is very close to cut-in speed, the turbine often overspeeds, frequently switching from one turbine to the other.

? Overspeeding also occurs in higher wind conditions, when the battery takes over supply and the turbine is not connected to the grid or the charger.

7.3.7. Electrical considerations

7.3.7.1. Reactive power and capacitor compensation

Reactive power has a major influence on the power factor of the system. The power factor is related to the reactive power as shown in Figure 34:

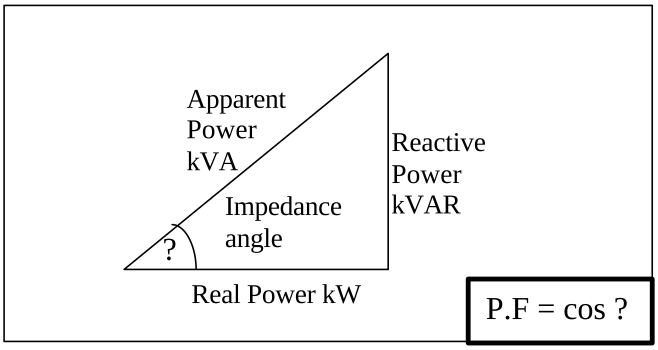


Figure 34 - Vectoral summation for power factor (Fetea & Petroianu, 2000)

In an ideal system there would be a reactive component which was very small and therefore an angle of impedance which was very small, so that the power factor would approach 1.0

The induction generators of the wind turbines on Muck would normally require reactive power from the grid for excitation (in order to create the magnetic field they require to initiate operation). Reactive power demand can cause losses in the transmission, and excessive reactive power consumption can be critical to the stability of the power system (Sorensen et al., 2000). In the islanded Muck system reactive power must come from a source other than the grid. In one study, a diesel generator was kept running continually in order to supply reactive power to the wind-turbine generators (Bonanno et al., 1998). In a system on the scale of the Isle of Muck scheme this is not viable, so capacitors are used to self-excite the generator and adjust the phase shift.

The addition of capacitors to a system improves the power factor, increasing the working power of the system, resulting in reduced distribution losses, and enabling the system to work more economically and efficiently. In the early days of the system there were problems with the capacitors blowing. Capacitors are sensitive to over-voltage, harmonics and high temperatures. Frequencies below 50Hz will reduce the power in the capacitor bank (Sorensen et al., 2000), and frequencies on Muck can go as low as -10% (- 5Hz). Voltage levels can also have a significant effect on the power of the capacitor bank. If capacitors are continuously exposed to high voltage levels their lifetime will be reduced. Grid voltages on Muck can increase by as much as +9.6% (252V). A high number of switchings will also affect the lifetime of the capacitor bank. Tolerances in the capacitors can cause the power factor to vary from 0.96 to 0.98 at rated power, with much larger differences when operating at 20% power production (Sorensen et al., 2000).

An example of the influence of capacitors on the voltage in a system is shown in Figure 35.

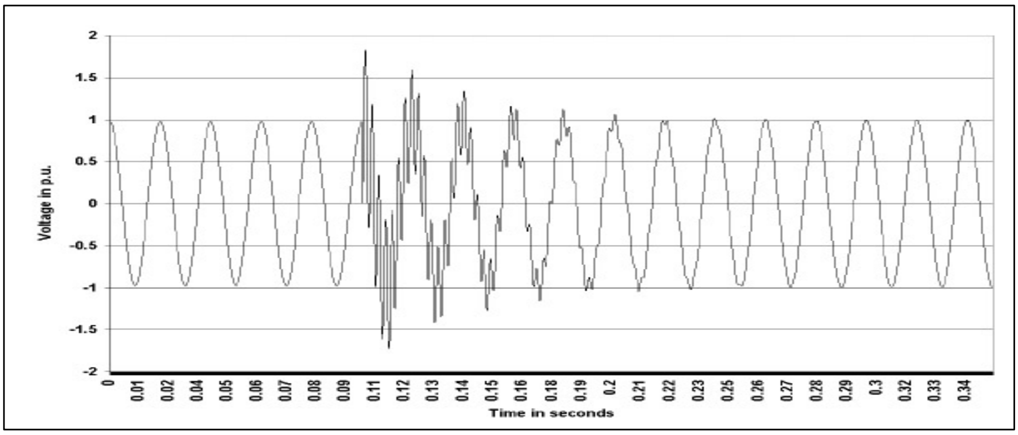


Figure 35 - Voltage when a capacitor sized for no-load compensation is connected (Sorensen et al., 2000)

The time for the capacitor operation is very small, and therefore the influence on the turbines will be minimal. However, the overall reactive power will impact the power factor of the system and may result in large voltage fluctuations, discussed in Section 7.3.7.3.

7.3.7.2. Frequency Range

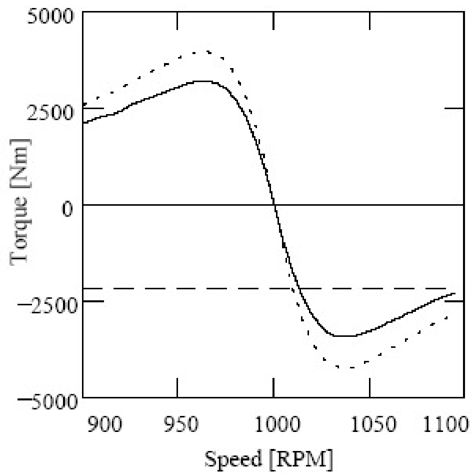
The frequency in the Muck power system varies from +2.1% (+1.1Hz) to -10% (-5Hz) in the period studied. The negative variation will result in rotor speed dropping, aerodynamic performance reducing and consumption of reactive power increasing slightly. However, the influence of frequency on power factor at rated power is minor compared to that of voltage (Sorensen et al., 2000).

7.3.7.3. Voltage Range

Delays in the ability of the system to identify dump loads to route excess turbine power to (as discussed in section 6.5.4) may make the grid more unstable. Load shedding / adding can cause significant voltage unbalance. This may be part of the reason for the widely fluctuating voltages experienced on Muck.

Voltage unbalance in the grid can have a significant impact on the generator performance. It can create a negative sequence voltage in the generator, affecting the sinusoidal flux and the current in the rotor. The magnitude of the distortion depends upon the degree of unbalance – large unbalances will increase generator losses. With power production unchanged, unbalanced voltage will also result in unbalanced current, increasing losses. However, a moderate voltage unbalance on the grid does not significantly reduce the three phase power factor (Sorensen et al., 2000). Data on voltage unbalance is not available for analysis in this study.

Voltage fluctuations can occur due to the nature of the generator. Depending upon the frequency and the amplitude of the fluctuations these may cause problems with flicker (e.g. flickering lights). This has been a problem in the past on Muck, where variations in grid voltage in the period of study range from +9.6% (252V) to -15% (200V). In extreme conditions, flicker may cause a voltage collapse due to voltage drop causing an increased reactive power consumption feeding back as an increased voltage drop (Sorensen et al., 2000). The graph in Figure 36 shows how the torque of the induction generator is affected if a voltage lower than that the generator was designed for occurs.



The generator torque versus the generator speed. Two cases are shown, U = 400 V (dotted line) and U = 360 V (solid line). The frequency is kept constant. The dotted line with a constant torque is the nominal torque on the main shaft of the wind turbine at a constant wind speed.

Figure 36 - Torque versus generator speed (Sorensen et al., 2000)

When voltage is reduced, the maximum torque reduces. As the voltage on the generator terminals decreases, the same amount of mechanical energy has to be converted into electrical energy by the generator (wind speed unchanged). The rotor speed of the generator will therefore increase until it reaches a new steady state point on the curve.

The power factor of the generator will begin to decrease significantly when the voltage is below 90% of the nominal voltage, a common occurrence in Muck. A voltage at 10% below rated voltage will cause the power factor to decrease from 0.96 to 0.94 (Sorensen et al., 2000). Variations in grid voltage will also affect the efficiency of the generator, as illustrated in Figure 37. With data for grid voltage available, the impact of voltage variation on the turbine model could be calculated using Figure 37 to derive an equation for efficiency variation (Figure 38).

Applying this efficiency to the model resulted in a small percentage performance variation in the turbine model. The results are shown in Figure 39 for a period exhibiting the maximum voltage variation. This only results in a change in model output of around 0.4kW maximum. In reality, the variations in voltage are not as detrimental as first thought. Motor efficiency impact appears to be relatively minimal.

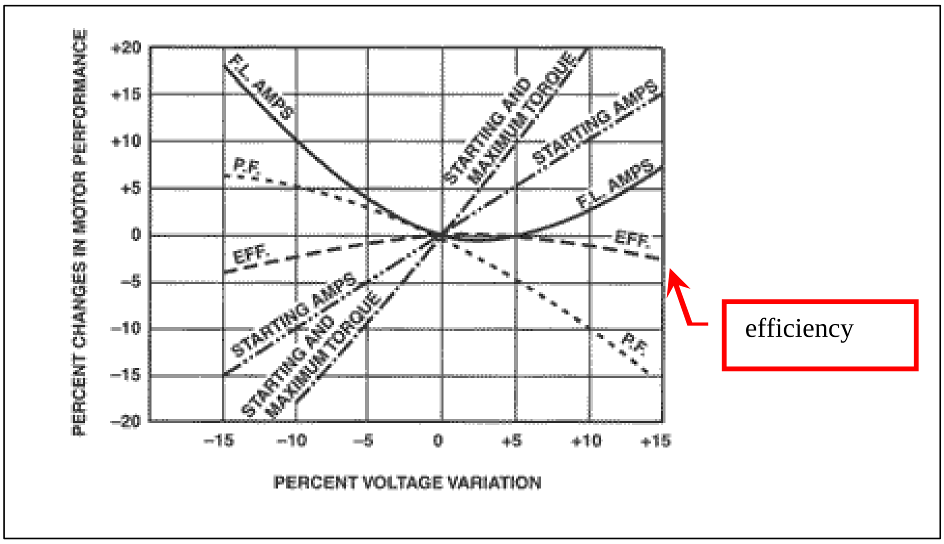


Figure 37 - Effect of voltage variation on motor efficiency (Cowern, 1995)

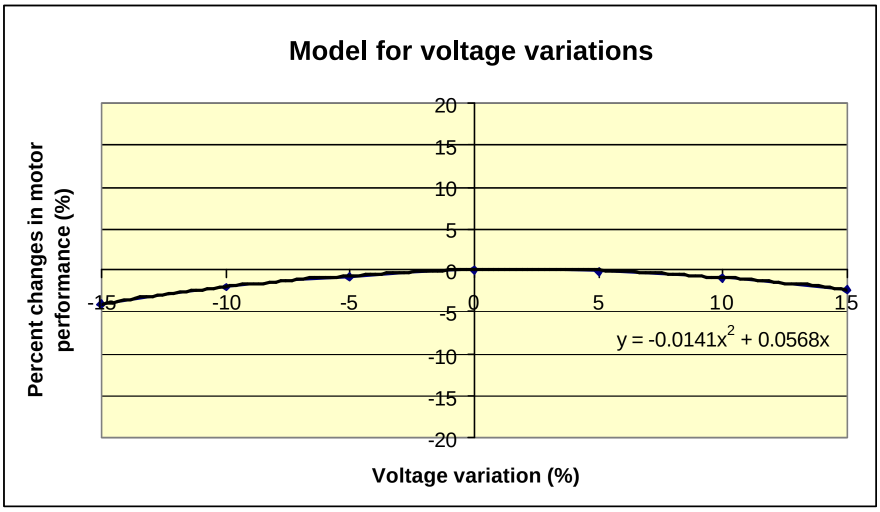


Figure 38 - Model for voltage variations

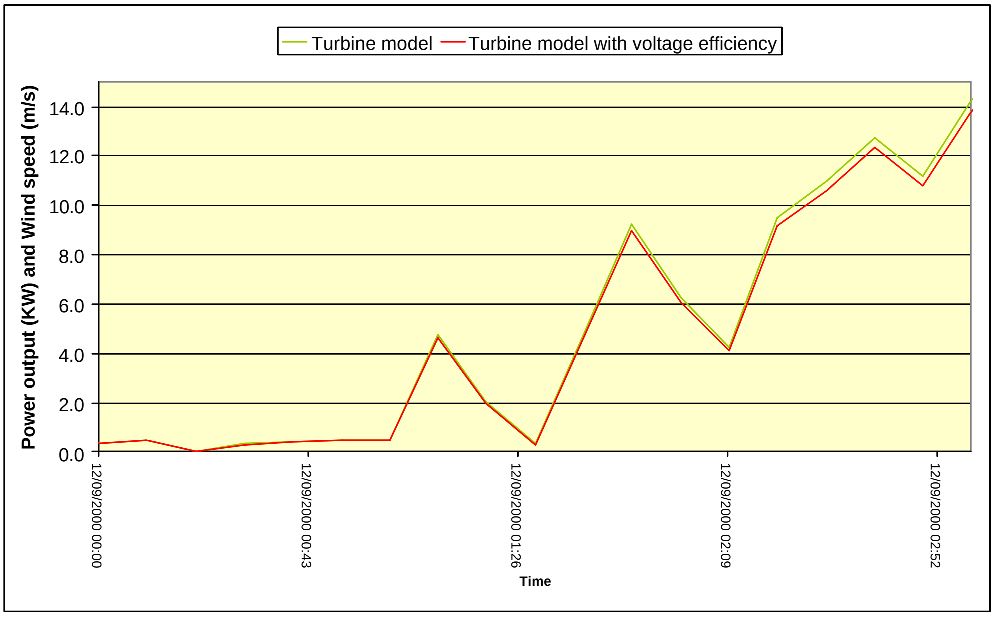


Figure 39 - Voltage efficiency application

7.3.7.4. Electrical Performance Summary

A no-load compensated turbine would be expected to have a power factor of around 0.91 when operating at rated levels, assuming worst case conditions of 10% undervoltage and 48Hz grid frequency (Sorensen et al., 2000). However, in Muck, the worst case conditions are 15% undervoltage and 45Hz grid frequency, so the power factor would be expected to be somewhat lower than this estimation. The actual impact of the voltage variation on the operation of the turbines appears to be minimal – more major impacts relating instead to the dynamics and switching of the system as a whole. Voltage variation has been accounted for in the turbine model although it has not been possible to account for power factor as a whole in the model. This area may merit further research.

7.3.8. Final Turbine Model

Taking into account the observations from previous sections, the basic rules for operation can be defined as shown in Figure 41. Using the observations from the loading-based models, the basic manufacturer-based model could be adapted to take account of particular system conditions and test if these theories were correct (see the flowcharts in Figure 44 and Figure 45 for full logic), with the results shown in Figure 40.

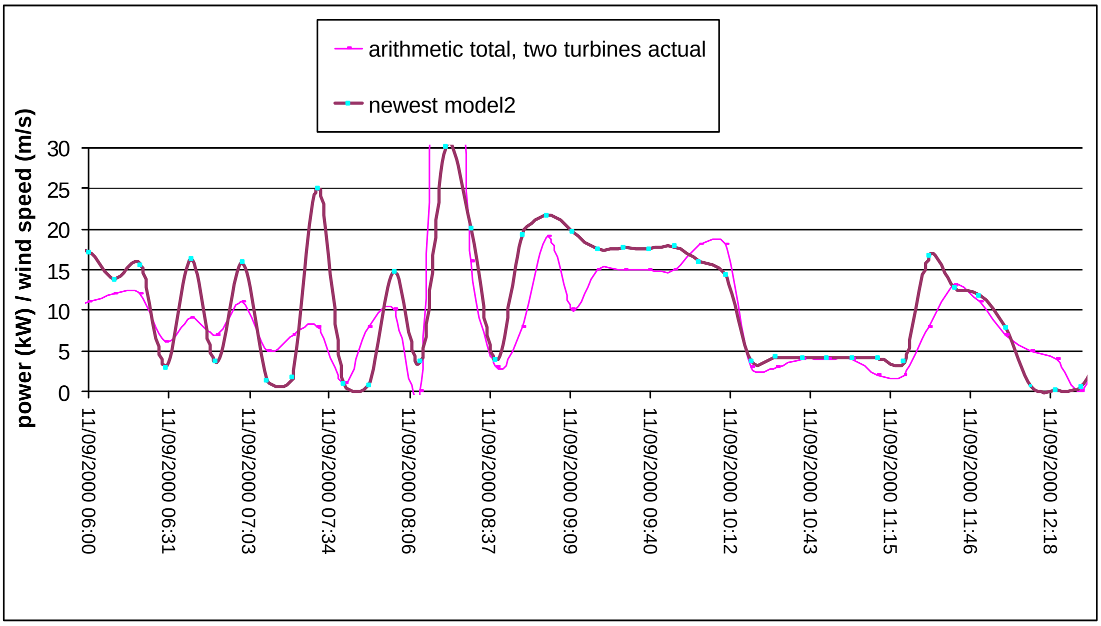


Figure 40 - Model adapted for rules, windy period

1. If there is no turbine activity to the batteries according to the models (red and blue lines meet), the wind turbines will not appear to generate much power, and may not generate at all.
2. If the battery takes over supply to the grid completely and there is no charging taking place there will be no power sent to the grid by the wind turbines, but they are likely to overspeed.
3. In low wind speed conditions, the turbine may overspeed.
4. The two turbines are generating jointly according to the equivalent power curve of one 20kW rated turbine.

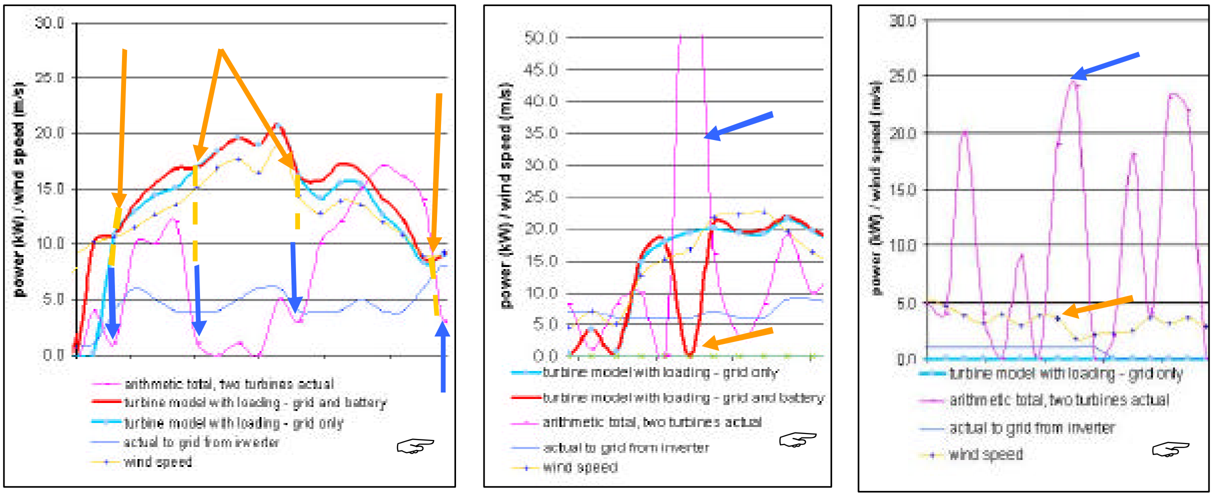


Figure 41 - Rules for turbine behaviour

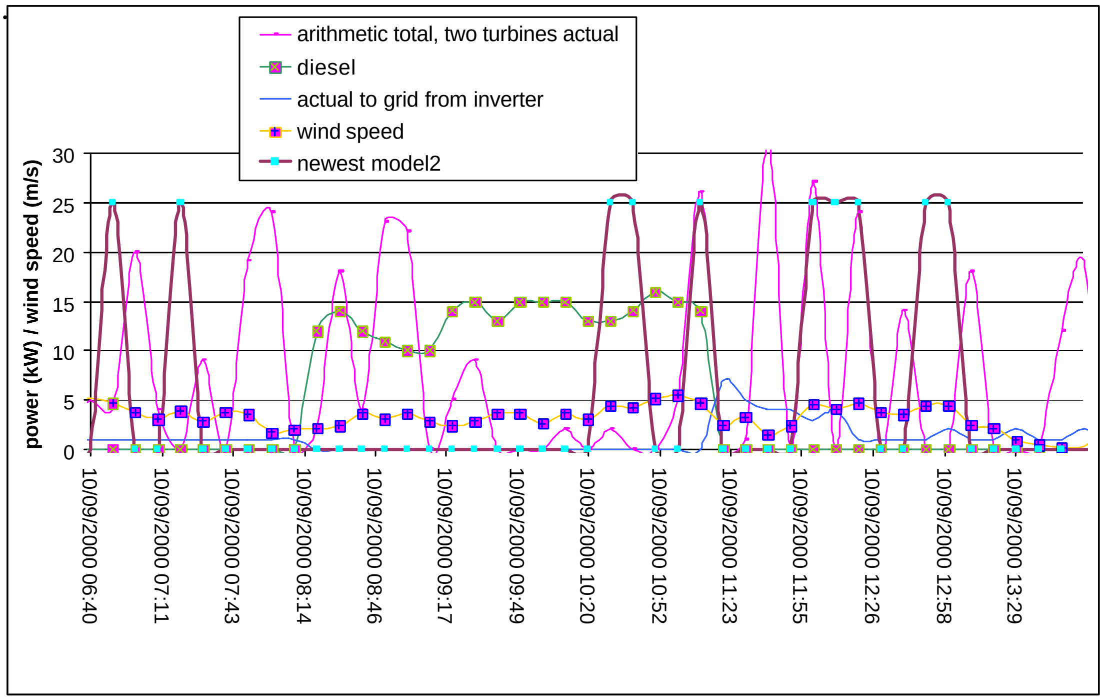


Figure 42 - Model adapted for rules, non-windy period

The turbine model (as shown in Figure 40), following these simple control conditions appears to achieve a much closer reflection of turbine behaviour, confirming that the conditions of operation defined are correct. However, testing the model for a non-windy period is shown in Figure 42.

This non-windy period is much harder to predict. Some overspeeds have been predicted correctly, but others have not been predicted, or in some cases overspeeds have been predicted when they didn't occur. Part of this could be down to the particular range of low speeds that are evaluated for overspeed activity in the model. However, it appears that there may be other factors influencing the overspeed behaviour. These are not clear from current data, but a more in-depth analysis of system performance with additional data may arrive at some conclusions regarding this. Further research into overspeeding is out with the scope of this project.

Overall, the model performs well. It identifies areas where overspeeds are likely to occur, if not predicting these exactly. It has the ability to predict general trends in turbine behaviour although sometimes magnitudes do not match the actual turbine output. The slightly more extreme peaks and troughs (Figure 43) were compensated for using a correction factor of 0.6 to bring the model closer to the actual turbine operation. This correction factor is due to friction losses, local effects, and additional system influences which it has not been possible to model. The final results in Figure 43 show an excellent correlation with actual turbine behaviour.

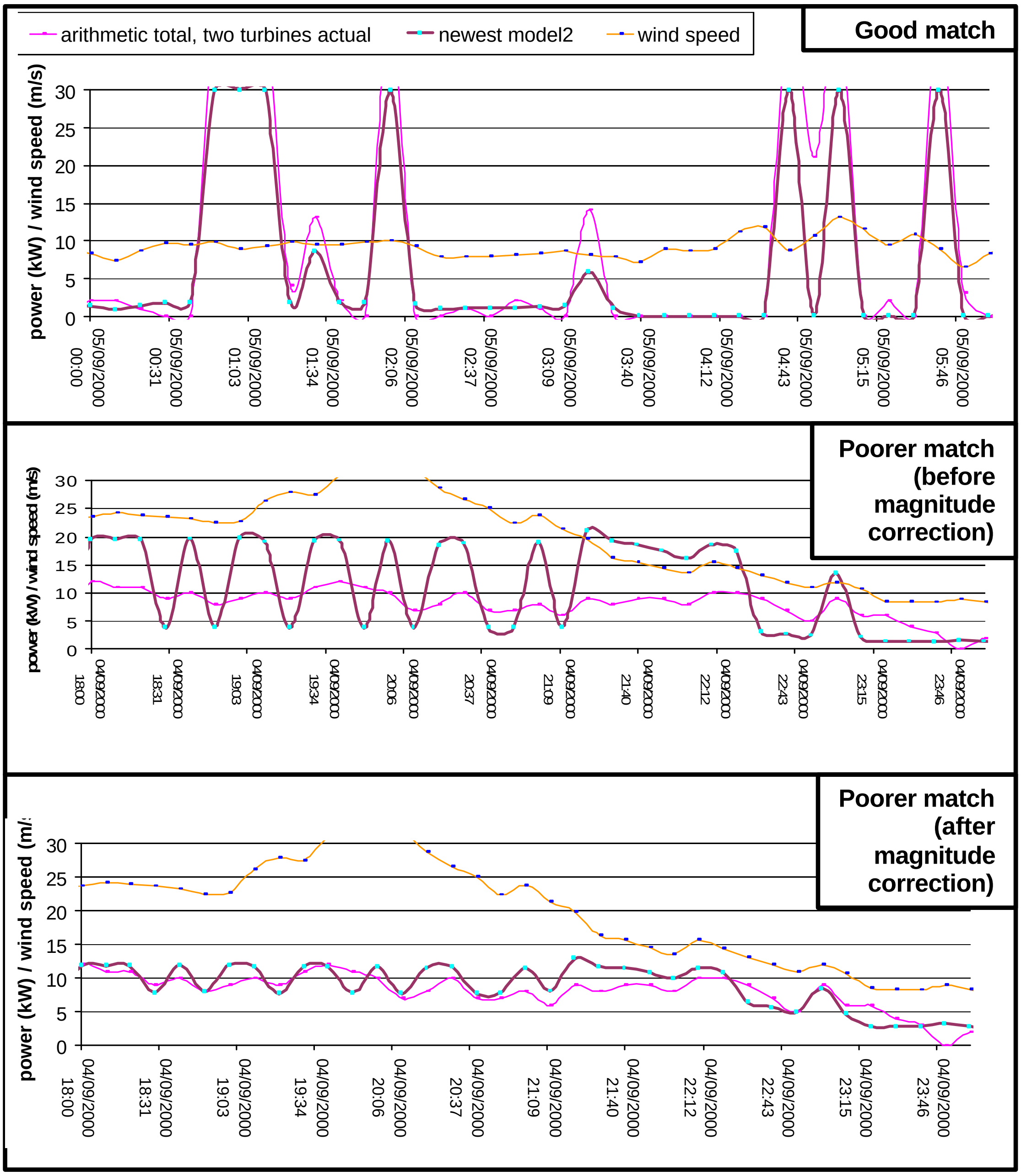


Figure 43 - Final turbine model examples

The following flow diagrams in Figure 44 and Figure 45 explain the design of this final turbine model in more detail.

Figure 44 - Finalised wind turbine model– STAGE ONE

Measure	Unit
Turbine power curve	kW/m/s
Wind speed	m/s
Cut in speed	m/s
Cut out speed	m/s
Rated speed	m/s
Actual Wind generation	kW/timestep
Inverter reading	kW/timestep
Turbine power curve	--
Loading efficiency curve	--

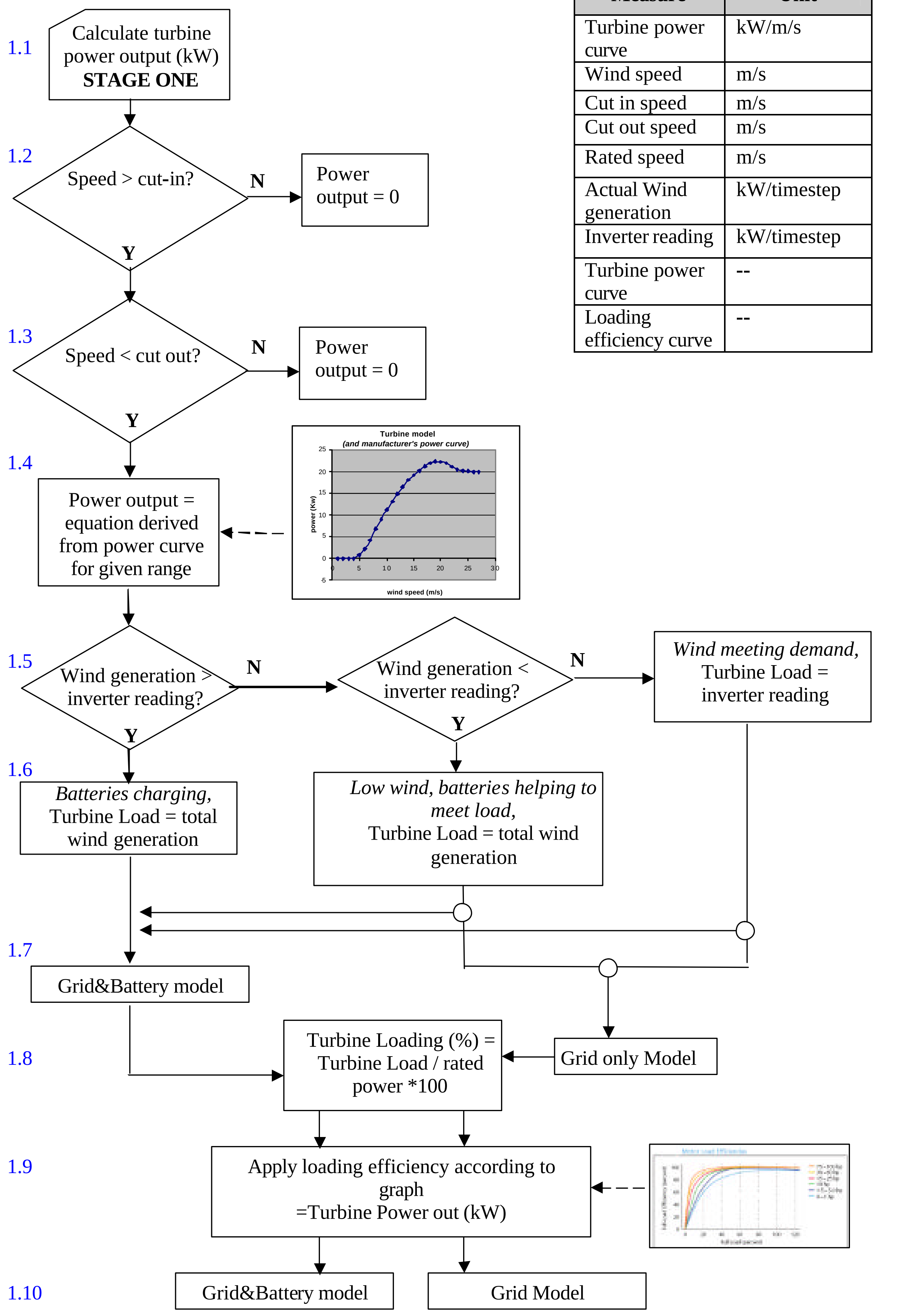


Figure 45 - Finalised wind turbine model – STAGE TWO

Measure	Unit
Grid&Battery model results	kW
Grid model results	kW
Voltage-efficiency variation curve	--

2.1 Calculate turbine power output (kW) **STAGE TWO**

Battery alone supplying Grid

2.2 Grid&Battery model – Grid model < 0 ?
- **Y** → CONDITION 2 Power output = 30kW (overspeed peak)
- **N** ↓

Low wind speed

2.3 (Cut-in – 1.2) < Speed < (cut-in + 0.3) ?
- **Y** → CONDITION 3 Power output = 25kW (overspeed peak)
- **N** ↓

No turbine to battery

2.4 Grid&Battery model – Grid model = 0?
- **Y** → CONDITION 1 Power output = 0.4 x Grid Model (kW) (trough)
- **N** ↓

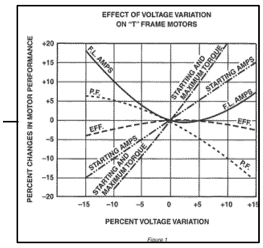
0.4 is assumed a realistic value from data for trough magnitude when no turbine-battery activity

2.5 Power output = Model (kW) x correction factor (0.6)

Correction factor for magnitude reduction due to additional effects

2.6 Calculate % voltage variation from datum

2.7 Apply voltage variation graph to calculate % change in efficiency



For clarity, this calculation has been shown here, but on the actual model this occurs near stage 1.9

2.8 Adjust turbine efficiency accordingly

2.9 Power output = (kW)

7.3.9. Worked Example of Turbine Model

In order to illustrate how the data in a time-step might be evaluated through the flowcharts, a worked example is shown below in Table 12. Each number in the left-hand column corresponds to a number on the flow chart. Table 11 shows the input/output data for the model during this time-step. Inputs from SCADA system data are shown against a light blue background, and important outputs for the flow chart highlighted in pink text. Comparison between Table 12 and the model output in Table 11 shows that the flow charts are following the same process as the model.

The definition of verification is "ensuring that the computer program of the computerised model and its implementation is correct" (Sargent, 1998). Carrying out similar analyses for specific time-steps meeting each of the flow chart criteria has enabled the wind turbine model to be thoroughly verified.

priority period	N		WT2	12
GRID FREQ	49.39		%load based on WIND RT (wind to grid)	20
GRID VOLTS	241		generator efficiency (grid only)	90.2
healthy grid V	Y		%load based on WIND RT (grid and battery)	60
healthy grid f	Y		generator efficiency (grid and battery)	97.72
INV BAT VOLTS	236		WT2 low?	N
% voltage varn for grid V	4.8		WT1	0
% change in eff	-0.1		WT1 low?	Y
v. low battery	N		Spd (m/s)	9.2
low battery	N		dir (degs)	71
healthy battery	N		new model WT2	9.47
Battery operation	8		V efficiency applied	9.46
DIESEL	0		arithmetic total for 2 WTGs	12
diesel running	N		new model, both efficiencies applied (grid and battery)	9.25
potential demand for FC (if wind to electrolyser)	4		new model with extra control mechanisms	25
wind to inverter and battery charging	12		new model, both efficiencies applied (grid only)	8.53
WIND (inverter)	4		new model combing grid batt minus negative of new	5.55
excess	Y			

Table 11 - Model data for worked example

1.1	**STAGE ONE**	
1.2	Speed > cut-in?	No, speed = 9.2 m/s Cut-in = 4.5 m/s
1.3	Speed < cut-out?	No, speed = 9.2m/s Cut-out = 60 m/s
1.4	Power output = equation derived from power curve *IF(windspeed<=6,(0.315*y^2-2.035*y+3.1),IF(windspeed<=13,(-0.0869*(y^2)+3.7845*y-17.993) where windspeed=y*	Power = 9.5kW
1.5	Wind generation > inverter reading?	Yes, Inverter = 4kW, Wind gen total = 12kW
1.6	Batteries charging, turbine load = total wind generation	Batteries charging Turbine load = 12kW
1.7	Grid and battery model	The full loading (12kW) is only considered in the Grid&Battery model Grid only model considers a load of 4kW at the inverter.
1.8	Turbine loading (%) = turbine load/rated power *100	=12 / 20 * 100 = 60% (Grid only = 20%)
1.9	Apply loading efficiency according to graph *IF(percent load <=40,(-0.0126*y^2+1.0992*y+73.249),IF(y<=110,(-0.0009*y^2+0.1161*y+93.993),0)) where y=percent load*	Generator efficiency **=** 97.7 (Grid only = 90.2%)
1.10	Grid&Battery model power out	9.28kW, *also calculate voltage efficiency (-0.1%) at this stage for simplicity = 9.19kW* (Grid only 8.53kW)
2.1	**STAGE TWO**	
2.2	Grid&Battery model – Grid model < 0 ?	No, batteries charging so Grid&Battery model > Grid model (condition 2 not valid)
2.3	Lower threshold(Cut in – 1.2) < windspeed< higher threshold (cut in +0.3)	No, speed is more than cut-in +0.3kW (9.2m/s) (condition 3 not valid)
2.4	Grid&Battery model – Grid model = 0	No, batteries charging so Grid&Battery model > Grid model (condition 1 not valid)
2.5	Power output = model output x correction factor (0.6)	= 0.6 * 9.19 = 5.55kW
2.6	Calculate voltage variation from datum	= 241 – 230 / 230 *100 = 4.8%
2.7	Apply voltage variation graph to calculate % change in efficiency *=-0.0145*y^2+0.0518*y* *where y=voltage variation %*	= -0.1%
2.8	Adjust turbine efficiency accordingly	Already implemented stages 2.6 to 2.7 in stage 1.10 due to convenience in Excel. (Kept separate in flow chart for readability).
2.9	Final power output	5.55kW

Table 12 - Worked example of turbine model

7.4. Detailed Analysis in Other Programs

Two typical days were chosen for a more detailed analysis, in periods where project data recording was at its most reliable. Day 1 was the 4th September 2000, Day 2 was the 10th September 2000. These days had quite different operating characteristics, shown in Table 13 and Figure 46:

		Day 1 (04/09/2000) Monday	Day 2 (10/09/2000) Sunday
Wind conditions	**average**	20.9	5.6
	maximum	33.1	14.9
	minimum	8.3	0
	direction	S to SE	Varying NE to NW
	comments	good wind conditions	light wind conditions
Wind/Battery to grid	**average**	5.6	0.9
	maximum	11	7
	minimum	0	0
	comments	Reasonable generation, but never near rated speed	Very little wind generation
Grid Voltage	**average**	239	237
	maximum	247	245
	minimum	223	200
	comments		More variation in voltage
Diesel to grid	**average**	0.09	4.90
	maximum	7	18
	minimum	0	0
	comments		More diesel used as poor wind conditions

Table 13 - Sample days summary data

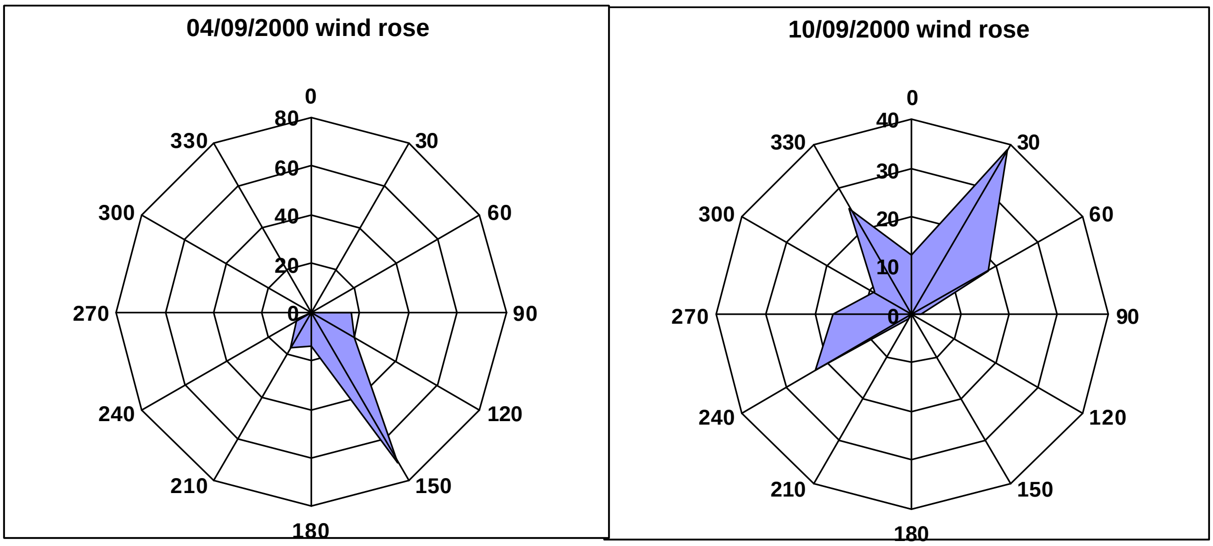


Figure 46 – Wind roses for sample days

The analysis in the appendix (Section 11) details the actual operation of the system on each of these days. To get an idea of the evaluation approach taken by other researchers, two packages for supply-demand evaluation were investigated using this data – MERIT and HOMER.

7.4.1. MERIT

Demand similar to that shown in Figure 15 was simulated in the package MERIT to evaluate the forecast output given the same environmental conditions.

A climate file with data for the chosen period of 4/09 to 10/09 was built from wind data so that the turbine performance, diesel generator and batteries could be modelled. Data for each component in the system was carefully input.

Due to the format of the available wind data, the climate information was input in periods of 6 time-steps per hour (10 minute periods). MERIT accepts multiple time-steps per hour for climate data. However, the fuel supply profiler, which is required in order to specify diesel supply for the diesel generator to function, only accepts two time-steps and hour. As a result, it was not possible to arrive at a model with a functioning diesel generator.

As it would be extremely time-consuming to reduce the climate data to two time-steps per hour, and this was not a major focus of the project, it was decided not to pursue MERIT modelling any further. Output from the MERIT model, shown in Figure 47, does allow some observations to be made about the model operation.

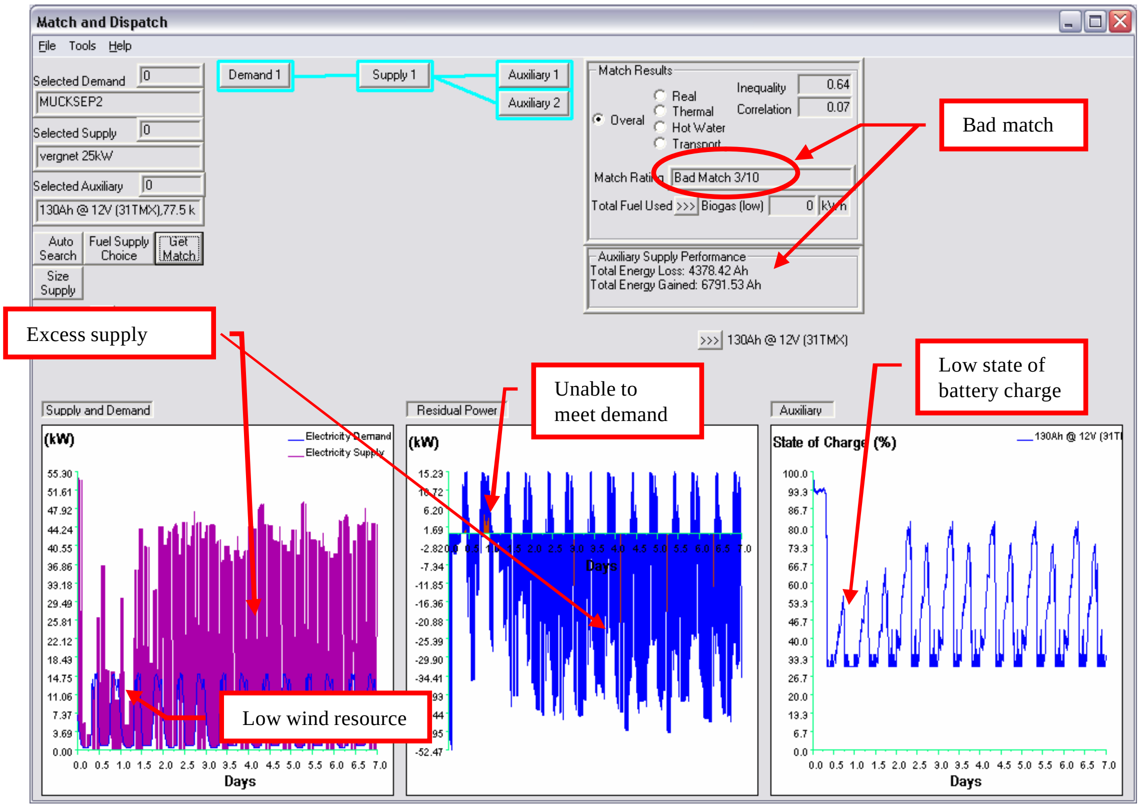


Figure 47 - MERIT output screen 1

The purple in the first graph shows supply in relation to demand which is shown in blue. It can be observed that the relationship of supply to demand in the MERIT model appears to be very favourable – suggesting a reasonably simplistic wind-turbine model that does not take into account loading efficiencies etc.
The residual power graph (second) and state of charge graph for the batteries (third) indicate some small areas where supply failed to meet demand as the wind resource during this time was not good and the batteries were not in a good state of charge.

MERIT classifies this supply-demand configuration as a "bad match" – most likely because the residual power shows that there is a large excess of power generated (due to the optimistic turbine model) which is not used to meet supply.

Toggling the auxiliary results to view the diesel generator in the right hand chart, it can be observed that this has been unable to operate due to the fuel supply issues mentioned previously (Figure 48).

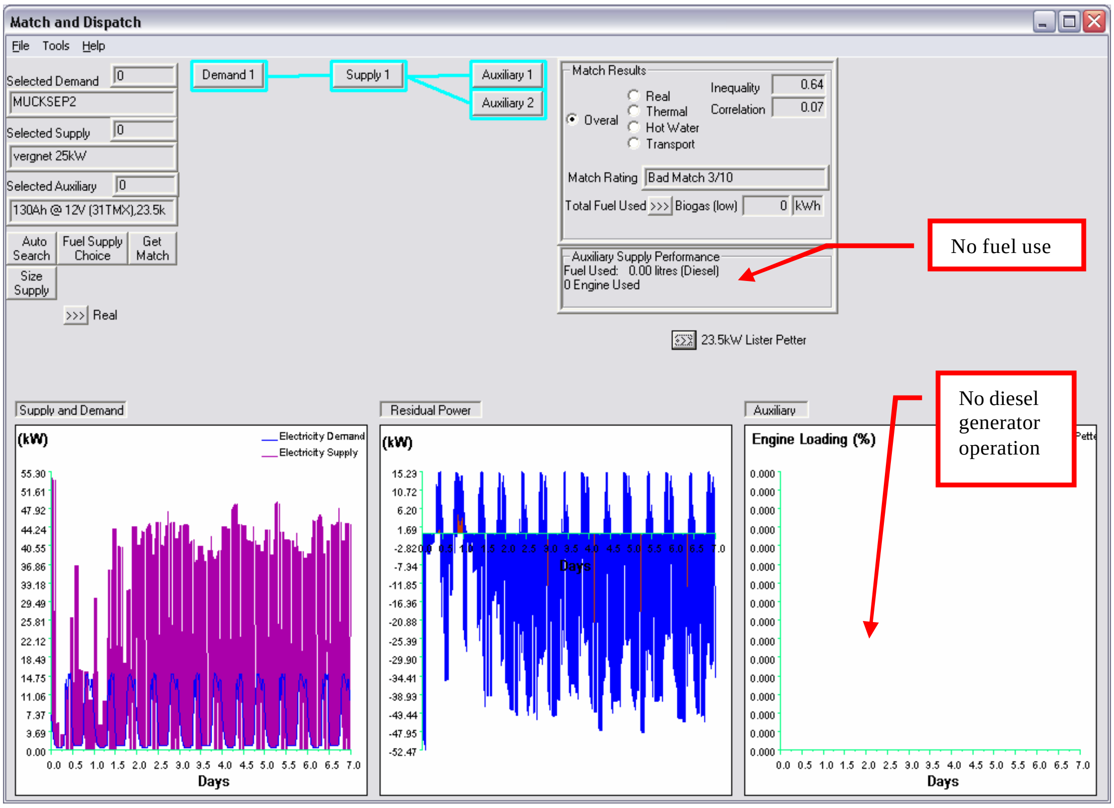


Figure 48 - MERIT output screen 2

It is anticipated that if the fuel supply stream could be specified, there would be short diesel runs to cover the periods where demand is not met. However, these results would still vary greatly from the actual results obtained from the SCADA data, as the wind-turbines and batteries perform very differently to the MERIT model – further justifying implementation of system-specific models rather than further use of this program for analysis purposes.

7.4.2. HOMER

The demand profile was again input to Homer (see Figure 16), with profiles for the wind turbines, diesel and batteries. Homer generates a wind profile based upon yearly averages month-by-month. The averages were calculated from actual wind data. For this reason it is not possible to obtain a direct comparison of the two days in question, as the model is not working from the same wind data. However, the simulation provided some interesting results, shown in Table 14.

7.4.2.1. General Observations:

The system is modelled without taking into account the fact that this is an islanded grid, and the impact that this will have on the system operation. It also does not take into account the limitations on operation of the turbines previously discussed. As such, the results produced in Homer relate to a very simplified model of the system.

However, results for the modelled period are still within the same region, as shown in Table 14. The Homer model reaches a maximum of 54kW between the 4th and the 10th, whilst the actual system reaches comparable maximums of between 57 and 41kW. The average output during this time is 14.4kW in the model, compared to between 8 and 9kW in the actual system – this will be due to wind speed differences and the considerations taken into account in this study such as turbine loading.

Based upon the Homer simulation, all load is met – although it is worth remembering that it is not possible to specify priority and non-priority periods in this program. Out-with the priority period in reality there may often be some unmet demand. Demand figures seem within a reasonable range. Table 14 shows that the actual system experiences an average load of around 5.6kV during this period. The Homer modelled system shows a load of around 6.3kV (a difference of around 12%) – potentially due to the fact that the demand profile input is based on averages of the actual data with some additional noise added. The maximum load, in the actual system met by diesel during a priority period is 18kW. The load predicted in the model is 19.4kW (a difference of around 8%).

		Day 1 (04/09/2000) Monday	Day 2 (10/09/2000) Sunday	Homer model Days 04 – 10/09/2000
Wind conditions	**average**	20.9	5.6	7.42
	maximum	33.1	14.9	-
	minimum	8.3	0	-
	direction	S to SE	Varying NE to NW	-
	comments	good wind conditions	light wind conditions	-
Turbines output	**average**	9.3	8.0	14.4
	maximum	57	41.0	54.0
	minimum	0.0	0.0	0.0
DEMAND = Wind/Battery or (Diesel) to grid	**average**	5.6 (0.09)	0.9 (4.90)	*overall load:*6.3 (1.70)
	maximum	11 (7)	7 (18)	*overall load:*23.1 (19.4)
	minimum	0 (0)	0 (0)	*overall load:*0.3 (0)
Excess Electricity		-	-	*Average:* 8.6 *Max:* 45.7 *Min:* 0.0
Unmet load		Some outside priority periods	Some outside priority periods	*Average:* 0.0 *Max:* 0.0 *Min*0.0
Battery charge		-	-	*Average:* 0.5 *Max:* 3.5 *Min:* -17.6
Battery storage %		-	-	*Average:* 75.1 *Max:* 99.9 *Min:* 21.0

Table 14 - Comparison of Homer results with actual data

The annual values Homer calculates are more revealing (Table 15). These show how optimistic the Homer model is. 92% of generation from wind is a very high level of penetration. The excess of 131 MWh is interesting in terms of potential for hydrogen production, but not a realistic figure considering the differences between the Homer model of the system and the way the system actually functions. However, this indicates the potential of the wind turbines given no system constraints, and does suggest that there is a potential for greater utilisation of the turbines if performance improvements and system re-design are possible.

Annual generation (kWh)		
Wind turbines	179,366	(92%)
Diesel generation	15,639	(8%)
Total production	195,005	
Total load served	55,161	
Excess electricity	131,012	
Unmet Load	2	

Table 15 - Annual HOMER calculations

Breaking down the Homer results for the day of the 4th September to get an understanding of the models they are using, the results shown in Figure 49 and Table 16 can be observed.

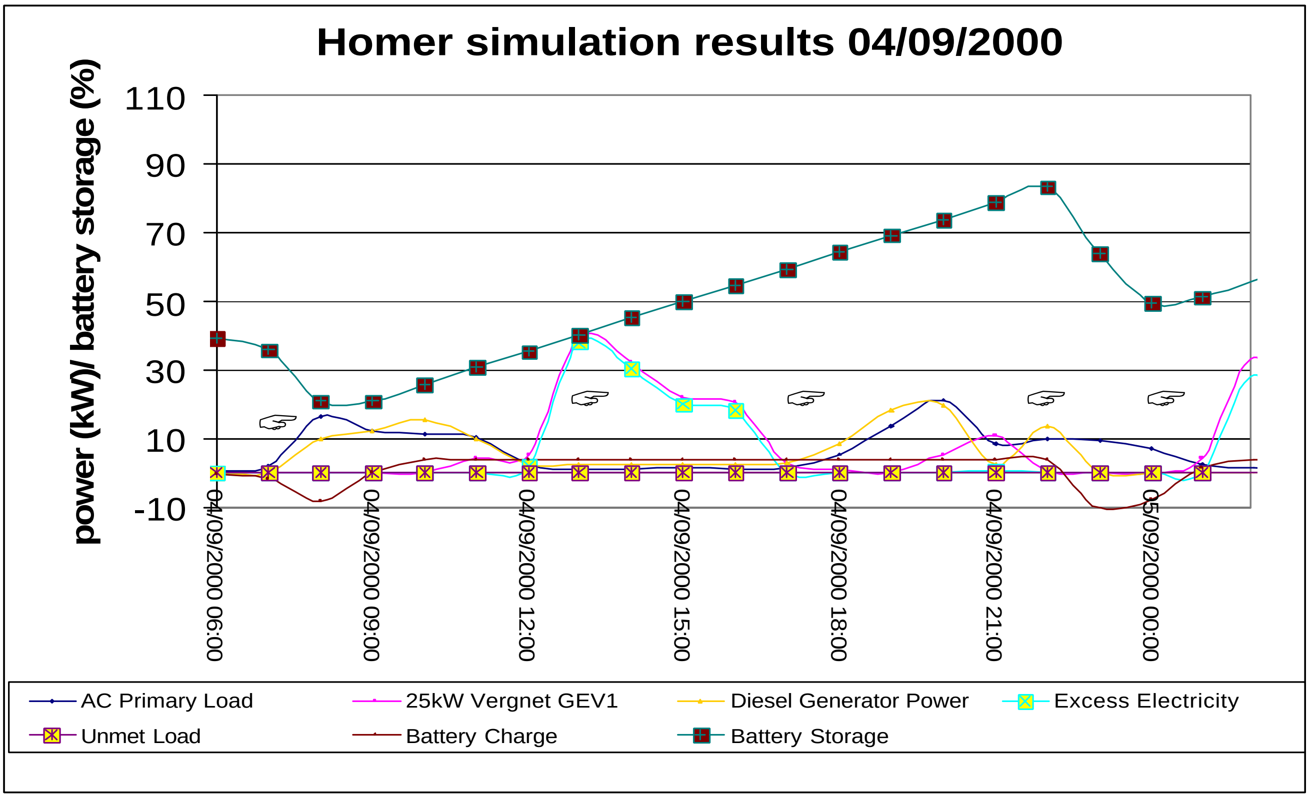


Figure 49 - Homer simulation results

The Homer results follow the same basic operation as the actual system, not accounting for priority periods. Where a wind excess is indicated in Homer, overspeeding might occur in the actual system. Although this is a very simplistic model, it is possible that it could be adapted to represent the system more closely and could be used for more detailed economic evaluations of system changes and predictions of yearly figures.

Point	**Description of events**
1	Turbine output low, diesel generator provides energy to meet load. Battery voltage decreases slightly when new load added, but then gradually charges from the diesel.
2	Wind energy increases, resulting in large excess energy as there is low demand during the day.
3	Wind energy reduces substantially. Diesel takes over grid supply to meet
4	No wind energy, diesel and battery take over
5	Diesel stops, battery takes over supply and discharges.

Table 16 - Analysis of Homer results

7.5. Summary

This section has involved a thorough analysis of the operation of the system, especially with reference to the wind turbine. A good understanding of the turbine operation has now been gained, and the sophistication of this understanding has been indicated by the more basic results of the other simulation packages.

A model based upon the manufacturer's power curve was used. Comparison of the basic model with data from one of the actual turbines indicated that the turbine was operating at levels of less than half the theoretical turbine performance, with many spikes from zero power to a disproportionately high peak power, indicating many start and stop operations. A power curve analysis indicated that the wind turbines were not following the power curve as specified by the manufacturer. For the purposes of developing a model to emulate the real-life turbine operation, the performance curve of a single turbine corresponding to a 20kW specification was assumed.

The two turbines were found to perform quite differently depending upon the wind conditions. Local effects such as interference, wake and turbulence could be responsible for part of this behaviour, but often one turbine was found to be generating whilst the other was not. This may have been due to a turbine fault with the passive pitch mechanism or due to problems with the inverter operation.

The frequent jagged peaks indicative of turbine over-speeding may be due to a turbine fault or simply be due to the way the mechanical governor is regulating the wind turbines. This overspeed behaviour was particularly evident at wind speeds close to the turbine cut-in speed, when the turbine was not connected to the battery, and in high wind conditions, when the battery took over supply. However, indications of overspeeding showing up in power readings when there was no inverter activity, raised questions about the quality of the actual wind turbine data. Power was being calculated where clearly no generation was occurring so that the reading appeared more reflective of the rotational speed of the turbine than of any power generation. Still, this reading provided a good indication of turbine activity, if not an exact power reading.

For the turbines to operate to their optimal level, there needed to be enough load for the turbines to dump their power to. When there was not enough load on the system to absorb turbine energy, the turbine would lose efficiency. This consideration was added to the turbine model and a better correlation with the actual turbine was found. In terms of magnitude the models were still very different.

Delays in finding a dump-load, as discussed in the Section 6.5.4, would cause a delay in the routing of excess power and may make the grid more unstable, resulting in frequency and voltage variations. The frequency in Muck varies from +2.1% (+1.1Hz) to -10% (- 5Hz), potentially influencing rotor speed, aerodynamic performance and reactive power consumption. Grid voltages on Muck vary from the design voltage of 230V by +9.6% (252V) to -15% (200V), affecting the efficiency of the generator. To add this to the model, the percent voltage variation was determined and an efficiency according to the voltage variation was applied to the turbine model. This resulted in only a small performance variation - a change in model output of around 0.4kW maximum.

The final turbine model takes into account loading and voltage variation. It expects overspeeds to occur in wind conditions near cut-in, and if the battery takes over supply to the grid. If the turbines are not connected to the battery, then the model will only show a minimal level of generation. This final model provides a good reflection of turbine behaviour, following the majority of peaks and troughs of the actual turbine. A correction factor for amplitude was assumed to take account of factors which had not been identified or which it has not been possible to model. This provided an excellent match in windy conditions, but in a non-windy period it was more difficult to predict exactly the turbine performance due to the nature of the overspeeding behaviour. Areas where overspeeds are likely to occur are identified, if not predicted exactly.

Introduction of a hydrogen system would enable more variable load to be added to the system, potentially improving the energy extraction from the wind turbines. The turbines can be modelled based on the manufacturer's power curve (without the loading efficiency reductions etc) in a way similar to that of the MERIT and HOMER packages to evaluate the maximum energy that could be gained from them if a hydrogen system were introduced. This will be discussed in the following sections.

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8. Choosing Types of Hydrogen Systems

8.1. Basic System Configuration

A hydrogen-based stand-alone power system requires some form of hydrogen production, storage and utilisation, often teamed with some short-term energy storage to act as a buffer to compensate for fluctuations in supply and demand and to enable smooth switching between devices, shown in Figure 50.

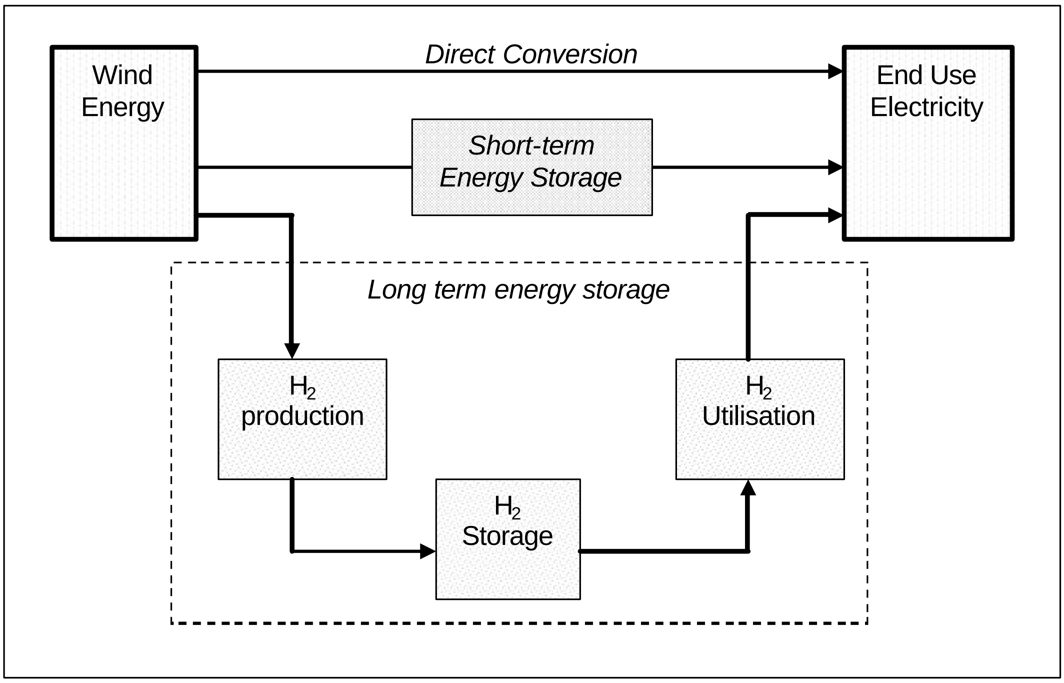

Figure 50 - Hydrogen-based stand-alone power system, adapted from Ulleberg (1998)

The hydrogen production device is usually an electrolyser, which uses an electrochemical reaction to generate hydrogen from water and air. Electrolyser options for the Muck scheme are discussed in Section 8.3. After generation, the hydrogen needs to be stored. There are a number of storage options, discussed in Section 8.5 but perhaps the most widely used currently is high pressure storage tanks. The next stage is using the hydrogen to generate energy. Hydrogen can be translated into end-use energy in two ways – via fuel cell reactions (Section 8.4) to generate electricity, or via combustion reactions, such as direct use for transport, cooking or heating.

8.2. The Case for a Hydrogen Economy on Muck

There are a number of reasons why introduction of hydrogen generation and storage to the power system on the Isle of Muck would be beneficial. These are detailed below in terms of energy, environmental and economic advantages.

8.2.1. Energy

? **Optimisation:** Currently due to loading limitations the wind turbines on the Isle of Muck are unable to operate at their full capacity – use of hydrogen storage would allow extraction of a much greater proportion of the available wind energy.

? **Security**: Use of hydrogen for storage would give residents greater security of supply by replacing unreliable and poorly performing batteries in non-priority periods, reducing black-outs.

? **Energy Potential:** Hydrogen has more energy per unit mass than any other fuel (Hagen, 2002).

? **Flammability:** Hydrogen is extremely flammable- it only takes a small amount of energy to ignite it and make it burn, and can be combusted very efficiently (Dutton, 2002)

? **Recharging:** Unlike a battery, a fuel cell does not run down or require lengthy recharging. It will produce electricity and heat as long as hydrogen and oxygen are supplied (Ulleberg, 2003)

8.2.2. Environmental

? **Emissions:** Hydrogen is a zero-emission alternative to diesel when the electricity used to create it is generated from a wind turbine. The only by product from fuel cell electricity generation is water. When combusted it does not produce any harmful pollutants like carbon monoxide (CO), carbon dioxide (CO_2), or particulate matter (Hagen, 2002).

? **Noise:** Fuel cells are near-silent and do not experience vibration compared to noisy diesel generator operation (Marschoff, 1998).

? **End of life disposal**: Hydrogen fuel cells have less environmental impact on disposal than lead acid batteries, which are composed of toxic materials (Fuel cell store, 2004).

- **Transport:** When used for transport hydrogen stores approximately 2.6 times the energy per unit mass as gasoline, although it does need about 4 times the volume for a given amount of energy. For example, a 15 gallon (0.057 m^3) automobile gasoline tank contains approximately 41 kg of gasoline. The corresponding hydrogen tank would need to hold 60 gallons (0.227 m^3), but the hydrogen would weigh only 15.5 kg (Hagen, 2002)

8.2.3. Economics

- **Import costs:** Using hydrogen as a replacement for diesel in terms of power generation, heating, cooking and transport will mean that there will be no fuel import costs, increasing the autonomy of the island (Isherwood et al., 2000).
- **Local Industry**: Implementation of hydrogen storage could have a very positive impact on the local industry of tourism. It is likely that the island would be a showcase for this new technology and attract many eco-tourists (Barton, 2003).
- **Financial Support**: There is potential for funding as government support is growing for this emerging technology as concerns over global warming escalate (Science & Technology Committee, 2003). Also, companies specialising in the technology are keen to showcase it and may reduce their prices for groundbreaking demonstration projects accordingly.
- **Relative costs:** Implementation of hydrogen in an island situation overcomes the previous economic constraints that have limited its development. It is viable for transport use on an island as refuelling would be possible very close to the generation point. The higher cost of hydrogen generation in relation to other fuels is less of an issue, as imported fuels to an island are much more costly than those on the mainland. In addition the long-term running costs are lower in comparison to diesel due to lower maintenance and fuel import requirements (Isherwood et al., 2000).

The environmental and energy benefits of implementing a hydrogen system on Muck make a compelling case. The costs of such a system may be high, but it is hoped that additional funding will be available to make the system affordable as a showcase project for how wind penetration can be maximised in an island situation. By 2010 or later, the technology will be more mature and prices will have reduced to a level which would make the project more affordable. Choosing a timescale for implementation will need to take into account the advantages in terms of funding of "getting in first" with the longer term reductions in cost and technology improvements. In the longer term, it is hoped that such a system will pay for itself due to the reduction in importation of fossil fuels and the increased autonomy of the island. This economics of a hydrogen storage system on Muck are discussed in more detail in Section 9.6.

8.3. Electrolysis

For the purposes of this project, hydrogen is produced by electrolysis using renewable energies via an acidic or an alkaline electrolyser. However, hydrogen can be produced by a number of other means, including reforming of intermediates, gasification, pyrolysis and photosynthesis. The timeline shown (Figure 51) gives an idea of the current capability of each technique, indicating that electrolysis using renewables is one of the more advanced technologies currently on the market.

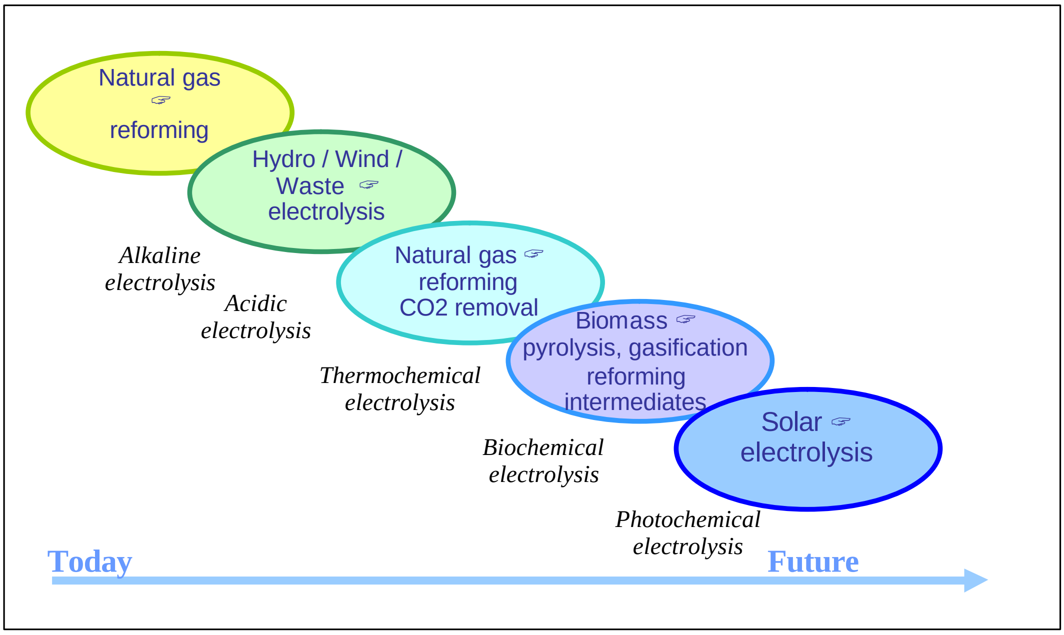

Figure 51 - Timeline for hydrogen production techniques (adapted from Hagen, 2002 and Ulleberg, 1998)

8.3.1. Alkaline Electrolysers

As shown in Figure 51 hydrogen can be produced from water in a number of ways. Within a renewable energy system, alkaline electrolysis is the most popular means of producing hydrogen. Commercial alkaline electrolysers have a typical efficiency of 75%, although efficiency can be improved by operating at higher temperatures.

Typical operating temperatures are 70 -100°C and typical operating pressures are in the range of 1-30 bar, so additional compression is normally required. (Dutton, 2002).

The decomposition of water into hydrogen and oxygen is achieved by passing a DC current between two electrodes separated by an aqueous electrolyte with good ionic conductivity. The electrolyte in an alkaline electrolyser is usually aqueous potassium hydroxide (Ulleberg, 1998). The electrochemical water-splitting process involves the reaction shown in Equation 2, below.

$$H_20 \rightarrow H_2 + \frac{1}{2} O_2$$

Equation 2 - Chemical reaction for electrolysis

For the above reaction to occur, a minimum electric voltage must be applied to the two electrodes. This minimum voltage or reversible voltage is determined by Gibbs energy for water splitting - for more details refer to Table 21.

An electrolyser stack consists of several cells linked together in series. In an alkaline electrolyser the cell can be of monopolar or of bipolar design, shown in Figure 52.

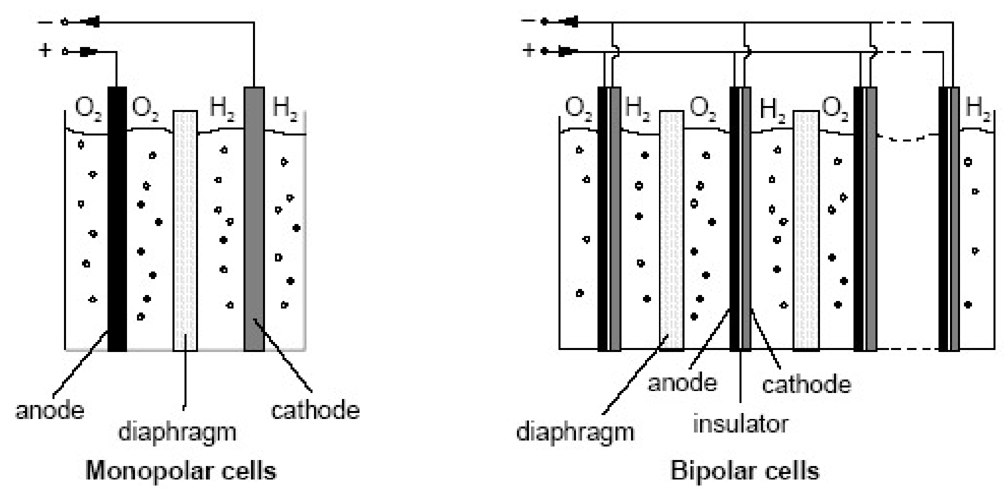

Figure 52 - Monopolar and bipolar cell designs (Ulleberg, 2003)

The monopolar design features electrodes which are either negative or positive with parallel electrical connection of the individual cells. In the bipolar design individual cells are linked in series. Monopolar designs are simple, sturdy and lower cost. However, most electrolysers are Bipolar. Bipolar designs are chosen for their compactness, resulting in lower internal losses and therefore increased efficiency. They can also operate at high pressures. The price of this efficiency increase however is that there can be some corrosion problems due to parasitic currents and their more complex design results in higher costs (Ulleberg, 2003).

8.3.2. Advanced Alkaline Electrolysers

"Advanced" alkaline electrolysers are now becoming more popular. The design of these focuses upon reduction of the practical cell voltages, resulting in a reduction in the unit cost of electrical power and therefore in operation costs. In addition, they aim to increase the current density (current per surface of electrode area) so reducing the investment costs. There are some conflicts in achieving these goals, but primarily design changes being made involve; new cell configurations to reduce resistance (zero gap cells where electrodes are pressed to either side of the diaphragm, see Figure 53), higher process temperatures to reduce resistance, and new electrocatalysts (Ulleberg, 1998).

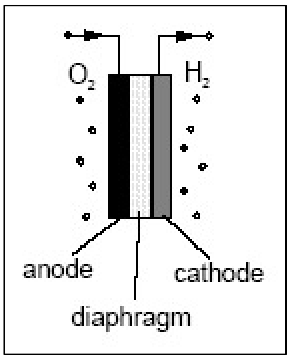

Figure 53 - Zero gap cell geometry (Ulleberg, 1998).

8.3.3. Acidic Electrolysers

The operation of a Solid Polymer Electrolyte (SPE) or Proton Exchange Membrane electrolyser is similar to that of a PEM fuel cell, but reactions are opposite, see section 8.4 (Crockett et al., 1995). PEM based electrolysers and fuel cells have the advantage that they operate at near-ambient temperatures, with rapid start-up and shut-down enabling a rapid response to intermittent and fluctuating loads. The rapid start-up and shut-down in comparison to conventional alkaline systems with liquid electrolyte is due to the fixed electrolyte requiring no re-circulation for removal of all reagents. The electrolyte is compact and stable, with no danger of leakage. High current densities are also possible. Additionally, their efficiencies are independent of the system size, and their costs increase linearly with size (Crockett et al, 1995).

Ideal electrolyser qualities for use with metal hydride storage (see section 8.5.2.1) include:

? Low operating temperature so that it can be reached quickly in intermittent operation.
? Operating pressure of at least 5 bar to charge a metal hydride store.
? High purity of hydrogen to avoid damage to metal hydride.
? High electrical efficiency and low auxiliary power consumption.

Acidic electrolysers have some advantages in meeting these design criteria over their alkaline counterparts. For example, they have been shown through experiments to have higher hydrogen purity for lower power consumption (Vanhannen et al., 1998). The technology has still to be proven in terms of electrical performance, and is in the early stages of development. A promising technology for the future, current costs are still high and advanced alkaline electrolysers have overtaken acidic electrolysers in terms of development (Ulleberg, 1998).

8.3.4. Electrolysers and Renewable Energy

The technical challenge in developing electrolysers is to make them function smoothly with intermittent supply from renewable resources (Ulleberg, 2003). Intermittent operation of alkaline electrolysers is usually characterised by power fluctuations with varying overload, partial load, shut-off and dynamic periods (Dutton et al., 2000).

In a previous electrolyser-based implementation, Jacobson et al., (2001) configured their electrolyser directly to their DC bus. They encountered problems as there was no way of controlling the current draw and the electrolyser draw was limited only by what voltage was on the bus. In this case the electrolyser was sized for peak power rather than an average generation level, and the drain of the electrolyser was quite considerable. This meant that it often could not be started if there were only a small amount of excess energy, as it would actually consume more energy than it was able to generate. It was concluded that an adjustable DC/DC converter would be a valuable addition to the system, enabling electrolyser current draw to be matched to the excess power available (Jacobson et al., 2001). Dutton et al., 2000 put this into practice in their wind-hydrogen hybrid system, which was less vulnerable to wind turbine fluctuations, indicating an experimental efficiency of 63% for electrolysis, including cooling (Dutton et al., 2000).

8.3.5. Water Requirements

For the hydrogen to be generated, water must be supplied to the electrolyser. In addition, electrolysers may need cooled to prevent overheating - often achieved using tap water (Ulleberg, 2003). On the island of Muck, an abundant water supply may not be available – in which case, collection and filtering of rain water may be required.

Another possibility is the production of hydrogen by electrolysis of desalinated sea water (Dutton, 2002). This area has not currently been researched in depth, but could be extremely important to islanded hydrogen systems. All commercial electrolysers currently available require fairly pure water, usually as pure as potable water, but in some cases even de-ionised water is required. If an electrolyser accepts standard potable water, it will normally have additional filtering systems built in, and the cleaner the water is on entry to the system, the less frequently filters will need to be changed. It is therefore likely that the salt-water would have to be desalinated before entering the electrolyser. This could be achieved using electricity generated from the renewable resource (Vujcic & Josipovic, 1996).

A few small projects have begun to investigate the potential of electrolysis of sea water. A project has been proposed in the Kimberly region of Australia, which would use tidal energy to produce hydrogen via electrolysis of sea water, for addition into the natural gas supply (Eng-Tips Forum, 2003). Use of salt water for electrolysis is also being seriously considered in the marine industry. There are plans in development for a hydrogen fuel cell powered boat, using fresh or saltwater to produce, store and consume hydrogen (HaveBlue, 2004). Hopefully electrolysis using seawater will become a real possibility in the future, as this would make implementation of hydrogen storage systems easier in remote island situations.

8.3.6. Processing Electrolysis Outputs

The output of the electrolyser is in the form of hydrogen and oxygen. Additional stages of compression, purification and filtration of the hydrogen may be carried out before the hydrogen is stored (Agbossou et al., 2004). If necessary, only the hydrogen output from the electrolyser need be stored, as oxygen for the fuel cell can be drawn directly from the atmosphere. This may however result in an efficiency reduction in the fuel cell of up to 10% (Crockett et al., 1995).

Using the oxygen by-product of the electrolysis process in the fuel cell has been found to increase system performance considerably – in terms of efficiency and power density (Agbossou et al.,2004). Potential increases in fuel cell efficiency can be in the region of 20%, resulting in increases in power density and a resultant reduction in the size of the fuel cell stack. The oxygen would be compressed, purified and dried, and then sent to the storage tank. The energy used by the oxygen compressor could be compensated for by the increased efficiency of the fuel cell. An alternative option is to use the oxygen to enrich rather than replace the air source – but this is not so beneficial or economical (Agbossou et al., 2004).

8.3.7. Electrolyser Manufacturers

Many projects have used electrolysers from Stuart Energy (Jacobson et al., 2001 ; Abbossou et al., 2001 ; Kolhe et al., 2003). Additionally Norsk Hydro Electrolysers (Norsk Hydro, 2004), Metkon-Alyser (Galli & Stefanoni, 1997) and Hoerner System electrolysers (Dutton et al., 2000) have been used in demonstration projects. For more details of these projects refer to Table 1. Another established electrolyser manufacturer to consider is Proton Energy (www.protonenergy.com).

8.3.8. Electrolyser Selection

Ideally, an electrolyser will have high electrical efficiency and low auxiliary power consumption. A high pressure electrolyser is preferred to a low pressure design as the need for compression into storage (and resultant losses due to leakage in compressor) can be eliminated (Ulleberg, 1998). A low operating temperature is favoured as it will better accommodate intermittent operation (less time to heat up). Generation of a high purity of hydrogen is preferred, especially if storage is to be metal hydride. Although a solid polymer electrolyser would provide this purity, and offer lower power consumption of auxiliaries (see Table 20), the cost of these electrolysers is currently prohibitively high (Ulleberg, 2003). Advanced alkaline electrolysers are therefore considered the most viable option for an implementation on the Isle of Muck.

8.4. Fuel Cell Generation

8.4.1. Principles of Operation

A hydrogen fuel cell is an electrochemical device that generates direct current electricity from the reaction of hydrogen and oxygen in the presence of an electrolyte. In most fuel cells oxygen (normally from air) and hydrogen (stored as hydrogen or derived from methane, methanol, ethanol or other hydrocarbons) are supplied to the fuel cell as gases (Canadian Government, 2004).

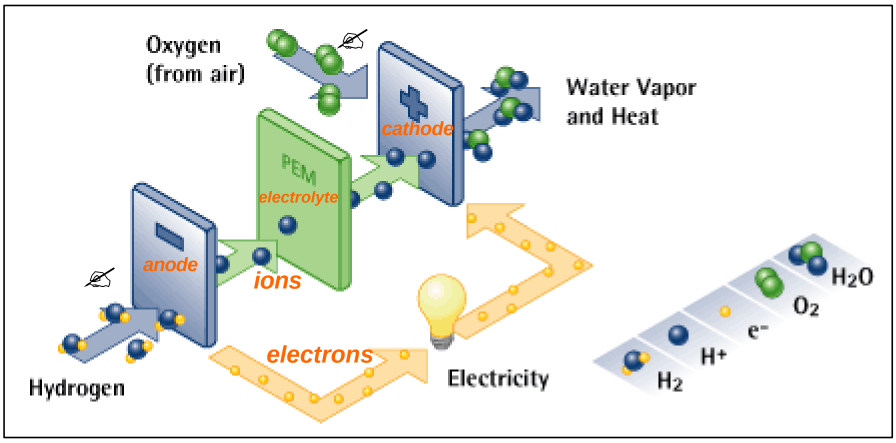

Figure 54 – PEM fuel cell operation (adapted from Aperion Energy, 2004)

Figure 54 above shows the electrolyte material (green) sandwiched in between two thin electrodes - a cathode (+) and an anode (-). The oxygen passes over the cathode (point 1) and the input fuel passes over the anode (point 2) where it catalytically splits into two hydrogen ions and two electrons. The ions move through the electrolyte toward the oppositely charged electrode, whilst the electrons travel through an external circuit to serve an electric load and then on to the cathode. At the cathode, the hydrogen, electrons and oxygen combine to form water.

In order to achieve the required voltage and current, a fuel cell stack is assembled from a number of individual cells as described above, stacked and wired together (U.S. Department of Defence, 2004).

8.4.2. Advantages and Disadvantages

Because fuel cells generate electric energy without combusting fuel, they have many advantages over conventional technology. These include low or no emissions, high energy conversion efficiencies when compared to internal combustion engines (Canadian Government, 2004; U.S. Department of Defence, 2004), low noise and vibration and production of high quality electricity. They are an attractive option especially for use with intermittent sources of generation because of their rapid load response, modularity and fuel flexibility characteristics (Shatter et al., 2001; U.S. Department of Defence, 2004).

As hydrogen energy is new, it is not known what the electrochemical effects of operation for extended periods will have on storage and generation devices (Dutton et al., 2000). However, component reliability is an important consideration in power systems in remote locations (Vanhannen et al., 1998), and fuel cells have the potential to improve system reliability as they have no moving parts, require almost no maintenance and have demonstrated long lives in trials (Isherwood et al., 2000).

One of the biggest disadvantages of fuel cells is cost. They are currently expensive, although large-scale production is expected to reduce these costs. Technological development is ongoing, but improvements in performance are expected as the technology matures (Canadian Government, 2004).

8.4.3. Fuel Cell Types

There are several different types of fuel cell, each with different performance characteristics. Their application often depends upon their operating conditions. The main types are listed in the following table, Table 17.

The temperature dependency of fuel cells is a very important consideration, especially in colder climates as discussed in Datta et al.(2002). Of the fuel cells detailed in the table, those used for SAPS will usually be alkaline, PAFC or PEM fuel cells due to their lower operating temperature.

As the fuel cell reaction is exothermic it generates an amount of heat, and so the cell must be cooled. In extreme cold temperatures, cooling water can freeze, and therefore air cooling has to be considered (Datta et al., 2002) though it is unlikely that this will be a major issue in Muck, as the powerhouse can be suitably insulated to keep out the worst of the Scottish winter.

Fuel cell type	Details	Electrolyte	Temp °C	Efficiency %
Akaline (**AFC**)	An older type of fuel cell that is not in common use, but can be attractive for SAPS	35 – 50 wt% Potassium hydroxide (KOH)	60 - 90	50 - 60
Phosphoric acid (**PAFC**).	Commercially available, can be used over a wide power range. Med-high temperatures makes them more suitable for co-generation e.g. CHP,although they have been used in smaller schemes (Isherwood et al., 2000)	Concentrated phosphoric acid (H_3PO_4)	160-220	55
Proton exchange membrane (**PEMFC**), also known as Polymer electrolyte (**PEFC**) and Solid polymer (**SPFC**)	Given most R&D attention due to high current densities and low weight (especially as this is attractive for transport). Attractive for SAPS. Considered ideal for a solar-hydrogen cycle as they are quick to operate, have high efficiency and can provide power quickly from a standby mode.	Polymer membrane	50 – 80	50 - 60
Solid oxide (**SOFC**).	High operating temperature, therefore most suitable for large power plants.	Yttrium-stabilised zirkondiooxide (Z_1O_2/Y_2O_3)	800 - 1000	55 - 65
Molten carbonate fuel cells (**MCFC**).	High operating temperature, therefore most suitable for large power plants	Molten carbonate melts (Li_2CO_3/Na_2CO_3)	620 - 660	60 - 65
Indirect fuel cells	Alternative fuels can be used but reforming is required. In low and medium temperature AFC, PEMFC and PAFC systems, external reforming is necessary for use with methane, methanol or ethanol, but high temperature SOFC and MCFC can also refine internally.	various	various	--
Direct methanol fuel cells (**DMFC**), also direct alcohol fuel cells (**DAFC**).	Convert methanol directly to electricity. Technology far from mature.	--	--	--
Regenerative fuel cells.	These function in a closed cycle of hydrogen production and electricity production. (see www.regenesys.com)	various	various	--

Table 17 - Types of fuel cells (data from Ulleberg, 1998; Canadian Government, 2004; Galli & Stefanoni, 1997)

8.4.4. Fuel Cell Manufacturers

Fuel cell manufacturers used on demonstration projects include Dais-Analytic (Jacobson et al., 2001), Ballard (Abbossou et al., 2001 & 2004; Galli & Stefanoni, 1997) and NTT labs(Mills & Al-Hallaj, 2004). Other fuel cell manufacturers include

Anuvu, Acumetrics, Plug Power, Teledyne, Aperion, BCS Fuel Cells, Electrochem and many more.

8.4.5. Fuel Cell Alternatives

As an alternative to using a fuel cell, electrolyser gases could be used to fuel a heat engine and drive a conventional generator – however, CHP would be required to maximise the overall system efficiency and reduced responsiveness would be a major issue in a renewable-based system (Crockett et al., 1995).

Another alternative to hydrogen fuel cells is the zinc-air fuel cell system. Zinc pellets are produced in the electrolytic process instead of hydrogen. They can be easily stored, and then consumed by a zinc-air fuel cell to generate electricity. Prototype zinc-air fuel cells have shown a turnaround energy storage efficiency of around 60% compared to 70% for lead acid batteries. A closed system can be achieved with very little maintenance required, making it particularly suitable for remote areas. Modelling of a zinc-air system in comparison with hydrogen based systems showed the zinc-air to have the best economic potential (Isherwood et al.,2000). However, it should be remembered that this model is based on manufacturer data which is likely to optimistic as at this point their product was not widely available, although some early commercial models are on the market. Leading manufacturers of zinc-air technology include Metallic Power, Zoxy energy and Reveo. These companies have predicted that total production costs will rival lead batteries on a per kW power basis– but this has yet to be confirmed, and will certainly not be the case for quite some time.

8.4.6. Fuel Cell Selection

Proton exchange membrane (PEMFC) or solid polymer (SPFC) fuel cells are the most commonly used in hydrogen-hybrid systems. They are the best researched due to their suitability for transport applications (high current densities and low weight). They are quick to operate, working at relatively low temperatures. They can provide power quickly from a standby mode and have high efficiency.

The development of alkaline fuel cells has been eclipsed by the development of PEMFCs. The higher operating temperature of phosphoric acid fuel cells (PAFC) makes them a less attractive proposition except in co-generation CHP applications. PEM fuel cells are considered the best option currently available for applications such as the potential Muck scheme, although zinc-air fuel cells also offer interesting possibilities for the future.

8.5. Storage

In an ideal system, supply will match demand. However, the fluctuating nature of renewables means that this is often not possible. Energy storage enables the supply to be shifted to meet the demand. Electricity can be drawn from the primary supply during periods of excess availability, stored and then returned during periods of excess demand. Correct sizing of the storage should allow the generation plant to operate closer to its optimal efficiency, therefore making better economic use of existing assets (Crockett et al., 1995)

8.5.1. Use of Batteries in Hydrogen Systems

Often, a small battery bank is still used in hydrogen systems for short-term "buffering", especially during changes in power consumption of devices such as the electrolyser or in periods of moderate wind speed (Mills & Al-Hallaj, 2004; Jacobson et al., 2001; Dutton et al., 2000; Kolhe et al., 2003). A battery array used as short-term storage can offer high round-trip efficiencies and convenience for fast charging and discharging (Agbossou et al., 2004). Batteries are not used for long-term storage due to the low energy density and high cost of large battery banks, whereas hydrogen has a high mass energy density, is convenient to store, and has relatively low tank costs (Agbossou et al., 2004). Additionally, costs incurred in extending hydrogen storage are much lower than those involved in extending a battery bank. A hydrogen system will simply require a larger tank, whilst purchase of additional batteries is much more costly. If additional storage is not used, it is important to have a good wind regime to allow for a reasonable electrolyser operating time (Dutton et al., 2000).

8.5.2. Hydrogen Storage Options

The ability of hydrogen-based storage systems to stock-pile fuel for back-up provision in the event of power cuts provides a more secure system to the user without imposing constraints on their current behaviour (Crockett et al., 1995). The means of storing the hydrogen fuel varies from project to project, although some types of storage are more popular than others.

Hydrogen can be stored mechanically or chemically. Each storage type has its advantages and disadvantages. Some of the methods listed in the following section (adapted from Ulleberg, 1998 and Fuel cell store, 2004) are currently available, others are in development. The diagram below in Figure 55 gives an overview of the different storage types available. Each of these types will be discussed in more detail in the following sections.

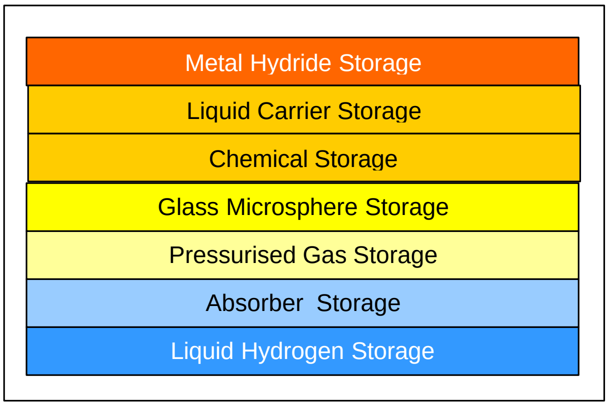

Figure 55 - Different types of hydrogen storage

8.5.2.1. Metal Hydride Storage

Metal hydrides have a high specific energy - 12 to 15 times that of a conventional lead-acid battery. They are specific combinations of metallic alloys that store hydrogen in a similar way to a sponge soaking up water. Metal hydrides simply absorb the hydrogen and release it later - either at room temperature or through heating of the tank. The total hydrogen absorbed is generally 1% - 2% of the total weight of the tank, but some hydrides are capable of storing 5% - 7% of their own weight. These higher ranges of absorption are only possible however when the hydrides are heated to temperatures of 250^0 C or higher. In terms of mass, metal hydrides do not appear to be very promising in relation to other technologies, but it is their volumetric measure that provides the advantage. Metal hydrides require one of the lowest volumes to store 1kg of hydrogen, holding more hydrogen per unit volume than pure liquid hydrogen (Larminie et al., 2003), see Table 18.

The metal hydride must have the appropriate material characteristics and thermal (heat transfer) properties to avoid overheating and pressure build up during charging and excessive cooling and pressure drop during discharge (Vanhannen et al., 1998). The life of a metal hydride storage tank is directly related to the purity of the hydrogen it is storing. As the alloys act as a sponge to absorb the hydrogen, they also absorb any impurities introduced into the tank by the hydrogen. The hydrogen released from the tank is very pure, but the tank's storage capacity reduces as impurities gradually fill the spaces in the metal that the hydrogen once occupied. With reasonable purity levels, usually several hundred charge/discharge cycles can be completed. The ability of the hydride storage to purify the hydrogen means that the more costly fuel cell is protected from damage due to impurities (Galli & Stefanoni 1997). If the system is filled at high pressure, the charging reaction may proceed too fast and the metal material will get too hot and will be damaged (Larminie et al., 2003).

The metal hydride charging reaction is mildly exothermic, therefore some cooling is required during the hydrogen absorption process (often this can be provided using normal air cooling) and heating during the hydrogen desorption process. The cooling and heating requirements depend on the ambient temperature, but waste heat from the fuel cell may be used to assist this process (Vanhanen et al., 1996).

Metal hydrides have the advantage that they can safely deliver hydrogen at a constant pressure. Low pressure simplifies the design of the fuel supply system. One of their main advantages is safety. The hydrogen is only stored at a modest pressure, typically up to 2 bar, so cannot dangerously discharge. If the valve is damaged or there is a leak on the system, the temperature of the container will fall, actually inhibiting release of the gas.

The price of metal hydride storage is however still high, limiting large scale usage. In addition, the ideal qualities required of hydride storage have yet to be met in full by a current design, including; release of hydrogen at relatively low temperatures, high volumetric density, low mass density, rapid charge and discharge rates, high resistance to decrepitation and low fabrication and material costs (Tran et al, 2003).

8.5.2.2. Liquid Carrier Storage

This is when hydrogen is stored in fossil fuels, for example gasoline, natural gas or methanol. The fossil fuel requires reforming to remove the hydrogen and the reformed hydrogen is then cleaned of excess carbon monoxide, which can poison certain types of fuel cells. Reformers are currently being tested and many companies have operating prototypes (Fuel cell store, 2004).

8.5.2.3. Chemical Storage

Hydrogen is found in numerous chemical compounds. Many of these compounds can be used as to store hydrogen. The hydrogen is combined in a chemical reaction that creates a stable compound. A second reaction is exploited to release the hydrogen. The exact reaction varies from compound to compound. Chemical storage techniques include ammonia cracking, partial oxidation and methanol cracking (Fuel cell store, 2004). Hydrogen can be stored in a solid form in a chemical called sodium borohydride, created from borax. As sodium borohydride releases its hydrogen, it turns back into borax so it can be recycled. Daimler Chrysler are currently working on development of this storage method for portable applications.

8.5.2.4. Glass Microsphere Storage

Tiny hollow glass spheres can be used to safely store hydrogen. The glass spheres are warmed to increase the permeability of their walls, and then immersed in high-pressure hydrogen gas to fill them with hydrogen. Cooling of the spheres locks the hydrogen inside, and a subsequent increase in temperature will release the hydrogen again. Microspheres have the potential to be very safe, resist contamination, and contain hydrogen at a low pressure increasing the margin of safety (Fuel cell store, 2004).

8.5.2.5. Pressurised Hydrogen Gas Storage

The most straight forward method of hydrogen storage is high-pressure storage in vessels, in tanks, or even underground (Larminie et al., 2003). Hydrogen is a bulky gas, and compressing it for storage purposes requires substantial energy, making this type of storage somewhat expensive. A study in Larminie et al (2003) found that use of pressurised storage in a hydrogen energy storage system was “absurdly expensive” when compared with mains electricity, but still considerably cheaper than electricity from primary batteries.

The space that the compressed gas occupies is usually still quite large resulting in a lower energy density when compared to a traditional gasoline tank. A hydrogen gas tank that contained a store of energy equivalent to a gasoline tank would be more than

3,000 times bigger than the gasoline tank (Hagen, 2002) For this reason, pressurised hydrogen gas is used mainly in small quantities. Data on this type of storage is contained in Table 18.

The following formula, according to the ideal gas law, can be used to find the pressure of a pressurised storage tank:

$$\boxed{P = nRT / V}$$

Equation 3 - Ideal gas law (Ulleberg, 1998)

Where P = *Pressure (Pa)*

$R = 8.314$ *(J K^{-1} mol^{-1}) universal gas constant*

T = *temperature (K)*

N = *number of moles, (mol)*

V = *volume of storage tank (m^3)*

The work of a compressor for the storage tank can be calculated from the formula below:

$$\boxed{W_{comp} = n_{gas} (w_I + w_{II}) / ?_{comp}}$$

Equation 4 - Compression work (Ulleberg, 1998)

Where W_{comp} = *total compressor work, W*

n_{gas} = *gas flow (mol/s)*

$w_{I,}\ w_{II}$ = *polytropic work, J/mol*

$?_{comp}$ = *compressor efficiency*

In order to minimise the requirements on the compressor, the hydrogen produced by the electrolyser could be temporarily stored in a water sealed tank within the electrolyser (depending upon electrolyser design). When this tank became full, the compressor would then start automatically, sending the hydrogen at high pressure through the purification and drying processes to the main storage tank (Agbossou et al., 2004).

In high-pressure tanks, each additional cubic foot compressed into the same space will require around one additional atmosphere of pressure of 14.7 psi. In such high pressure storage situations, safety is an important consideration. Great care is necessary when transporting the pressurised gas. Additionally, material for the storage containers has to be chosen very carefully as hydrogen can diffuse into materials, affecting their mechanical performance even to the point of causing cracks or blisters in steel. A leak from a cylinder would generate very large forces as the gas is propelled out, threatening torpedo-like behaviour which could result in considerable damage. Vessel fracture could result in auto ignition of the released hydrogen and air mixture. Safety problems can be avoided with careful design, and this type of storage is often used because of its simplicity, indefinite storage time, and lack of purity limits on the hydrogen. It is most widely used where hydrogen demand is lower and variable, for example in buses or for storing electrolyser output in a small power-system.

8.5.2.6. Absorber Storage (super-activated carbon or carbon nanostructures)

Carbon nanostructures are microscopic tubes/structures of carbon (see Figure 56), of around two nanometers across. Molecules can be absorbed into the active carbon in microscopic pores on the tubes and within the tube structures. Their mechanism for storing and releasing hydrogen is similar to that of metal hydrides.

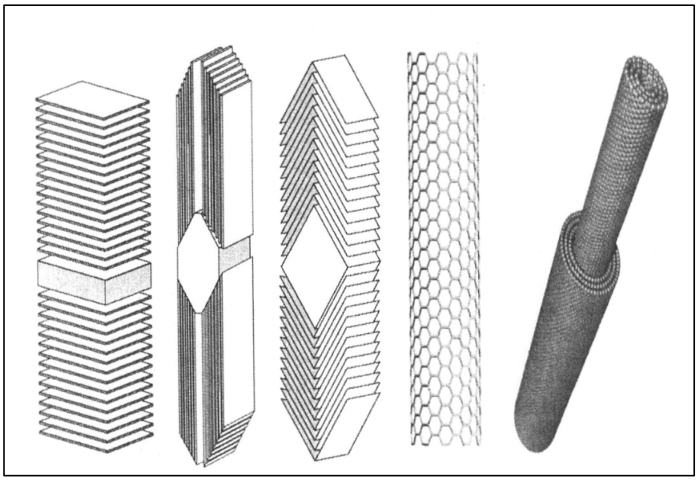

Figure 56- Schematic representation of different types of carbon nanostructures (Larminie et al., 2003)

The advantage of carbon nanostructures is the amount of hydrogen they are able to store. They have a high weight percentage at ambient temperatures, with an ability to store anywhere from 4.2% - to 65% of their own weight in hydrogen (Fuel cell store, 2004). To achieve this, cooling to low temperatures is necessary, and therefore expensive heat insulation required. Carbon nanostructures for hydrogen storage are still in the very early research and development stage. The viability of this storage option is still disputed by some scientists in the field (Larminie et al., 2003).

8.5.2.7. Liquid Hydrogen Storage

Liquid storage of hydrogen is the only widely used method of storing large quantities of hydrogen (Larminie et al., 2003). Hydrogen exists in a liquid state only at extremely cold temperatures. Liquid hydrogen typically has to be stored at 20^{o} Kelvin or -253^{o} C. When a gas is cooled to be stored as a liquid in this way it is known as a cryogenic liquid. Energy is necessary to mechanically compress (75%) and cool (25%) the hydrogen. The cooling and compressing process is energy intensive, resulting in a net loss of at least 30% of the energy that the liquid hydrogen is storing. This makes it a highly inefficient means of storing energy (Larminie et al., 2003). Storage tanks require to be insulated to preserve the temperature and to be reinforced to store the liquid hydrogen under pressure. The combination of the cost of the energy required for liquid storage and the cost of the storage tanks to sustain the storage pressure and temperature make liquid hydrogen storage very expensive compared to other methods (Fuel cell store, 2004).

In terms of safety, there are concerns regarding frostbite if human skin comes into contact with cryogenic surfaces, but in general the hazards associated with liquid storage are less than those with pressurised storage (Larminie et al., 2003)

The high expansion rate of this type of storage gives it an explosive potential for mobile applications. Research in this area centres on the development of composite tank materials for lighter, stronger tanks, and improved liquefying methods (Fuel cell store, 2004).

8.5.3. Storage Findings from Previous Projects

The most popular storage mechanisms assessed in projects are high pressure storage and metal hydride storage. In a similar high pressure compressor configuration to that mentioned in section 8.5.2.5, Mills & Al-Hallaj (2004) used a low pressure tank to high pressure tank via an intermediate reservoir system. This meant that the compressor was only run when excess energy was available, so that energy from the fuel cell or batteries was not used for compression. Such a design reduces the operation requirements of the system components, and therefore their necessary size.

In Abbossou et al., (2001), options of a pressurised 10 bar fuel tank, nanotubes and metal hydride storage were considered. The high pressure tank was preferred for practical experimentation due to its easy availability. Vanhannen et al. (1998) experimented with three storage alternatives; metal hydride containers, lightweight aluminium ball containers and conventional industrial steel bottles. It was concluded that for small scale self-sufficient applications, metal hydrides were best for use with solid polymer (SPE/PEM) electrolysers and fuel cells. Galli & Stefanoni (1997) used a metal hydride storage unit originally designed for automotive applications by HWT of Germany, consisting of several slim cylinders and a 20 bar pressurised gas cylinder. The alloy equilibrium pressure was above atmospheric pressure, which meant that very little heating was required to obtain the pressure necessary to feed the fuel cell (approximately $18Nm^3$).

Many projects have found metal hydride to be a more efficient means of storage than pressurised storage (Vanhannen et al.,1998; Datta et al., 2002; Tran et al, 2003; Mills & Al-Hallaj, 2004). The metal hydride option has the advantage that it takes a modest pressure to charge (5 to 10 bar), and can discharge to the fuel cell at ambient pressure. It is also safer than high pressure storage from a handling perspective (Datta et al., 2002).

Recent research has addressed magnesium-misch metal alloys as alternatives to metal hydrides. Misch metals are a mixture of naturally abundant unrefined rare earth elements. They are low cost with the ability to reduce creep and increase durability. Magnesium has a high theoretical hydrogen storage capacity, but is limited by high de-hyrdriding temperatures and poor oxidation resistance. Alloying resolves these issues - enabling a high capacity for reversible hydrogen absorption and discharge, and a low specific gravity. This technology is however still very much in the early stages of development (Tran et al, 2003).

As mentioned previously in section 8.4.5, an alternative to storing hydrogen is to adopt a system based on zinc-air. Zinc pellets are produced in the electrolytic process instead of hydrogen, easily stored, and then consumed by a zinc-air fuel cell to generate electricity.

8.5.4. Storage Selection

To ensure a reliable system operation, a small battery bank will be necessary to buffer the system in fluctuating and low wind situations and when low loading of the hydrogen devices does not permit them to operate. Although high pressure storage has been the most popular on trial projects to date, metal hydrides appear to be catching up, and have many advantages in remote renewable systems. Their volumetric potential in some cases has been found to be similar to that of cryogenic liquid storage (see Table 18), but with the advantage of much greater safety.

Storage type	**Volumetric mass kg H_2 m^{-3}**	**Mass ratio Kg H_2 kg^{-1}**	**Specific Energy kJ kg^{-1}**	**Gravimetric storage efficiency, % mass H_2**
Pressurised gas (PH_2)	15	0.012	1,440	0.7 – 3.0
Reversible metal hydride (MH)	50 – 53	0.012 – 0.015	1,440 – 1,800	0.65
Cryogenic liquid (LH_2)	65	0.150 – 0.500	18,000 – 60,000	14.2
Nanostructure storage	--	--	--	0.1 - 67.55

Table 18- Comparison of storage techniques,
adapted from Larminie et al. (2003) and Ulleberg (1998)

Metal hydride storage has been proven as a viable alternative to low storage density options such as high pressure gas storage (Tran et al, 2003). In general, lower pressures are necessary for metal hydride storage, enabling the storage to be directly coupled to a low pressure electrolyser. This eliminates the need for a compressor (Ulleberg, 1998). Handling of hydride bottles is much easier, enabling flexibility in terms of the end use of the fuel. Easy transportation for use in other areas as combustible fuel for heating or cooking is possible. Further development of hydride storage should improve the storage capacity, bring the price of components down, and improve performance characteristics. Metal hydride appears to be the best option going forwards for a remote renewable system requiring storage flexibility such as the system on the Isle of Muck. For transport purposes, pressurised gas storage is better suited (siGEN, 2004), so the storage system could potentially be a combination of high pressure storage for vehicle refuelling and pipelines to houses to enable converted boilers to run on hydrogen, and metal hydride storage for electricity use, and smaller scale use in heating or cooking.

8.6. Previous Standalone Hydrogen System Studies

A study by Jacobson et al. (2001) combining wind and PV showed that a standalone hydrogen hybrid system could be used to meet a controlled load. Although the system met the demand, it should be noted that the environment they were operating in had a good balance of both wind and solar energy. However, the components were not optimised for the renewable resource available. The efficiencies of the hydrogen storage and generation system overall were considered to be around 20 to 30% depending upon the conditions.

In one of the few studies which focused on a wind-hydrogen system without a PV component, Dutton et al. (2000) investigated the performance of an electrolyser under variable wind-turbine output conditions. In this paper they concluded that power fluctuations over a short period did not lead to overall system instability. They did result in a small reduction in efficiency compared to steady load operation and longer term power fluctuations over minutes (not seconds) could result in reductions in the purity of the hydrogen. However, reductions in efficiency compared to steady operation were only by a few percent, and reduced purity could be compensated for by using sophisticated pressure and level control systems. It is important to note that the location chosen for the study had a poor wind regime, and is therefore not a realistic comparison with Muck, or in fact any viable wind-hydrogen scheme (Dutton et al., 2000).

In a study carried out by Vanhannen et al (1998) alkaline electrolysers, pressure vessel hydrogen storage and phosphoric acid fuel cells (PAFC) were used. Problems were encountered due to preheating requirements resulting in poor fuel cell efficiencies and the open-end stack construction causing significant hydrogen loss. A preferred option of a solid polymer (SP/PEM) electrolyser and fuel cell, and metal hydride fuel store was implemented, finding a round trip efficiency of 30%, with target future efficiency of 40%.

8.7. Sizing of Overall System

The recommended system configuration is summarised in Figure 57. The next consideration is how the components of the system should be sized, and how they will perform as a result.

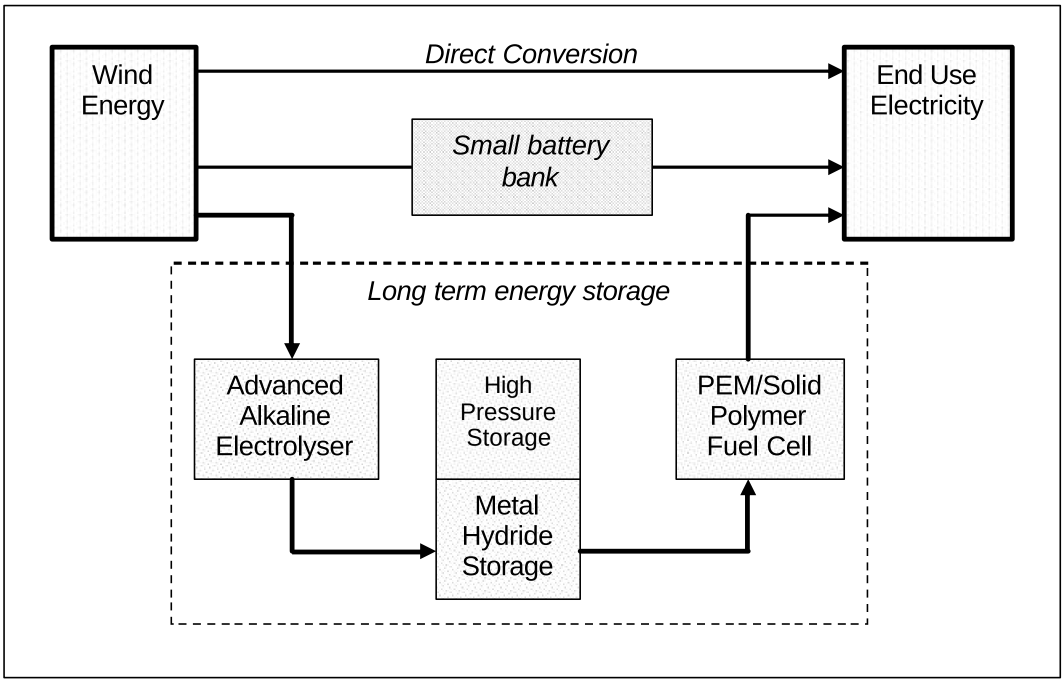

Figure 57 – Recommended system components

Table 1, earlier in this report, gives some idea of the sizes of components used in previous projects. The relative rating of components can vary greatly from project to project, depending upon the goal of the actual project. On a few projects, fuel cells and electrolysers have been rated at around half of the rated generation capacity of the renewable resource in a few projects, although on others a trend for relative ratings cannot be discerned, or information regarding ratings is simply not available.

Theoretically, matching the ratings of the turbine and electrolyser should result in utilization of all the generated power without the use of additional storage, but in reality this is not the case. Dutton et al.(2000) showed that for a wind regime similar to Muck (average speed 8m/s), with a 10kW turbine and 10kW electrolyser, the electrolyser could be operated for 78.6% of the time. The loss of operation of the electrolyser for the remainder of the time was due to low wind speeds causing electrolyser shut down due to impurity levels in the product gases.

Down-rating of the electrolyser with the respect to the wind turbine can often have economic and operational benefits. An over-sized wind turbine increases the mean power generated, and so increases electrolyser use (Dutton et al., 2000). However, when the available generated power exceeds the electrolyser rating, the power has to be directed to a dump load (if no additional storage is used). These dump loads could be space heating or water heating, as on Muck. Decreasing the electrolyser to 80% of turbine rating resulted in a slight decrease in hydrogen volume produced and higher auxiliary energy costs for cooling, which could be offset against the reduced electrolyser capital cost. Table 19 summarises the difference between the two strategies:

	Wind turbine 100%, Electrolyser 100%	**Wind turbine 100% Electrolyser 80%**
Rationale	Theoretically all energy will be used without additional storage requirements.	Increases electrolyser use as it is operating at a relatively higher mean power.
Operation	Some loss of operation of the electrolyser due to impurity levels in the product gases at low wind speeds causing shut down.	Increased electrolyser use but when available generated power exceeds the electrolyser rating, power has to be dumped (if no additional storage is used).
Disadvantages	Costly for higher rated turbine.	Higher auxiliary energy costs for cooling, less hydrogen produced.
Advantages	Higher volume of hydrogen generated	Can often have economic and operational benefits - reduced electrolyser capital cost.

Table 19 - Electrolyser sizing strategies (based on Dutton et al, 2000)

With additional energy storage added to such a systems, the electrolyser can be operated continually at part load – resulting in improved efficiency and increase in volume of hydrogen produced, although there are down sides to this type of operation (see section 9.4.1 on electrolyser control).

Optimal sizing will depend on site meteorology, capital cost of components, gas quality, and availability for alternative markets for hydrogen, oxygen and excess wind electricity (Dutton et al., 2000). Many models do not take into account all these criteria - optimal size of electrolyser was found by Mills & Al-Hallaj (2004) by simply finding the rated power of the electrolyser that led to the highest overall ratio of energy converted to hydrogen. In this study, modelling of the electrolyser, storage capacity and fuel cell will be implemented to determine the optimal size for the Isle of Muck power system (Section 9).

8.8. Summary

This section has given an introduction to hydrogen systems, justified why these should be used on the Isle of Muck, and has made a number of recommendations regarding the types of technology that would be best to implement on a scheme. Table 20 summarises the justification for the choices made.

	Electrolysers		Fuel cells		
Criteria	AEL	SPEL	AFC	PAFC	SPFC
Operation pressure above 5 bar possible	✍	✍			
High Hydrogen purity	✍	✍			
Operation near to ambient pressure			✍	✍	✍
Air breathing			✍	✍	✍
Low operation temperature	✍	✍	✍	✍	✍
High electrical efficiency	✍	✍	✍	✍	✍
Low power consumption of auxiliaries	✍	✍	✍	✍	✍

Table 20 - Comparison of electrolysers and fuel cells for use with metal hydride (adapted from Vanhannen et al., 1998)

The recommended system configuration is summarised in Figure 57. An alkaline electrolyser (AEL) was chosen as it is the best established and most researched electrolyser. The solid polymer (PEM/SPEL) electrolyser, although more ideal, is prohibitively expensive in comparison to the alkaline design. Different fuel cell alternatives were considered, but it was decided that the PEMFC/SPFC design offered the best characteristics for a standalone power system, especially as these have achieved most attention in terms of research and development.

In terms of storage, it was decided that a small battery bank would be beneficial to enable reliable system operation and best utilisation of appliances. Metal hydrides were preferred as the main hydrogen storage system due to their storage flexibility, enabling easy collection for use in combustion applications, and also as they operate at low temperatures and pressures. Some high pressure storage may also be required for transportation applications.

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9. Hydrogen Component Modelling

9.1. Previous Hydrogen Component Modelling

Complex electrolyser models include Ulleberg's (2003) model to predict the cell voltage, hydrogen production and purity, efficiencies and operating temperature of an advanced alkaline electrolyser. The model, intended for the purposes of system design and control strategy optimisation, was written in FORTRAN, compatible with TRNSYS and MATLAB-SIMULINK. Although it was based on an alkaline electrolyser, the model and theory could also be applied to a PEM electrolyser.

Another of the most detailed models of electrolysers can be found in the SIMELINT program developed as part of the HYSOLAR project (Ulleberg, 2003). Additionally, the model by Agbossou et al.(2004) is discussed in more detail later in this section.

However, for the purposes of this project a high-level model is preferred, with the ability to take manufacturer's data and turbine/system performance data and approximately predict hydrogen output from the electrolyser and power output from the fuel cell. Very little work has been done relating to high level models of fuel cells which can take in manufacturer's specifications to model output against system data (Cruden, 2004; Smith, 2002). Two such cases have been identified.

The first is the MERIT study (Smith, 2002). This allowed for any type of fuel cell to be treated as an internal combustion engine assuming that the performance of the fuel cell was not significantly affected by ambient temperature. The fuel cell model calculated part-load efficiencies, assuming no external heating requirement. Output from the electrolysis process was based upon manufacturer's figures for power consumption per unit hydrogen and loading considerations.

Secondly, the HYBRID2/3 package enabled input of manufacturer-specified parameters (Mills & Al-Hallaj, 2004). The fuel cell was treated as similar to a diesel generator in that it had a linear relationship for fuel consumption and a non-zero consumption rate at zero output power. A linear relationship between output power and hydrogen gas consumption rate was assumed e.g. for a 1 kW system, a fixed gradient of 840 litres per KWh, and a zero power consumption rate of 180 L/kWh was used. Because of the similarities with diesel, Mills & Al-Hallaj (2004) believed it may be possible to model a fuel cell using the module for a standard generator in many packages (given that the required information was available from fuel cell manufacturers).

The electrolyser model assumed a relatively constant efficiency at approximately 70% for a range of power inputs, translating to a linear relationship between input power and hydrogen production rate. However, when the input power dropped below a critical level, experimental data showed that the output became highly variable and difficult to predict. The model uses a critical minimum power level that the power must be above to avoid this variable output area, and a rated power that is the highest level of power the electrolyser can accept.

9.2. Modelling Electrolysers

9.2.1. Detailed level modelling

The performance of an electrolyser and a fuel cell depends mainly on voltage, current and operating temperature (Agbossou et al., 2004). The impact of each of these factors is indicated in the charts in Figure 58 below.

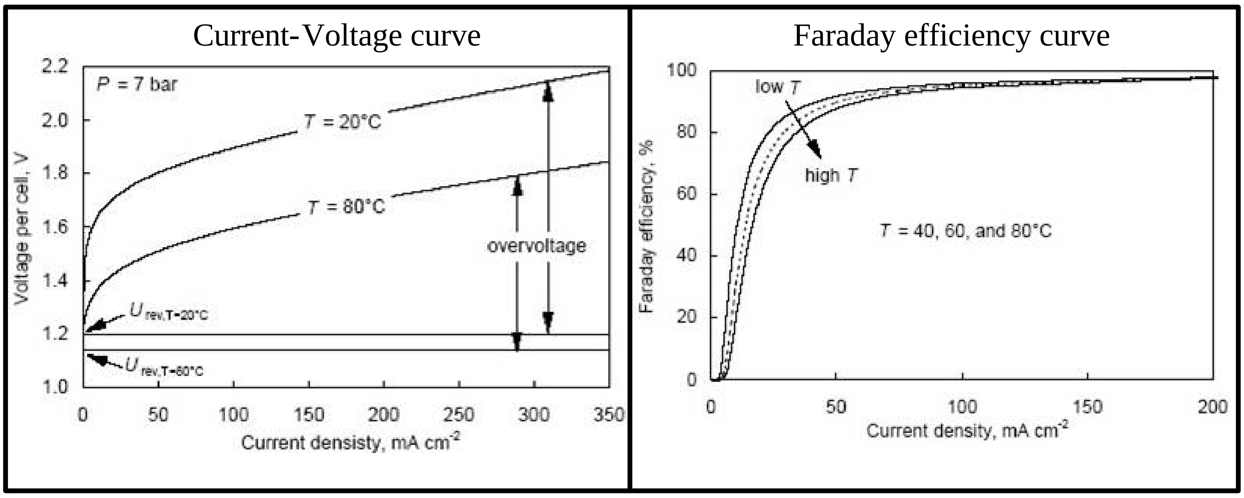


Figure 58 - Typical curves for an electrolyser cell (Ulleberg, 1998)

The Faraday efficiency is defined as the ratio between the actual and theoretical maximum amount of hydrogen produced in the electrolyser, sometimes called the current efficiency. As current density increases so does voltage per cell and the Faraday efficiency. The higher the temperature, the lower the efficiency, and the lower the voltage per-cell. Further thermal modelling in terms of heat generation and losses is out with the scope of this project, but more detail can be found in (Ulleberg, 1998).

An alkaline electrolyser will consist of several cells connected in series. Most models are based on the characteristics of individual cells – the calculations for required voltage, mass flow production rates of gases and internal heat generation are done on a per-cell basis, and then multiplied by the number of cells in series to find the values for the whole electrolyser. The Table 21 shows some of the basic equations used in such models. However, these equations are complex to apply and to be able to use these formula in a simulation it is necessary to have a detailed knowledge of the system on a molar level and in terms of voltages. The parameters of voltage, current and operating temperature will not be addressed in detail in the simplified model used in this project which will be based mainly on loading and consumption.

For a reversible reaction, the electrical work needed to split water is equal to the change in Gibbs energy ?G.	$W_{el} = ?G$ **Equation 5**	
The EMF is related to the electrical work by the electrical work transferred in a circuit external to the cell, q.	$W_{el} = qE$ **Equation 6**	
Using Faraday's law to relate the electrical work to the chemical conversion in molar quantities,	$W_{el} = ?G = qE = nFE$ **Equation 7**	*where:* *n = 2 (number of moles of electrons transferred per mole of water)* *E = EMF across electrodes of single cell = U_{rev} the reversible voltage* *F = 96,485 C mol^{-1} (Faraday constant)*
Rearranging.	$U_{rev} = ?G / nF$ **Equation 8**	=1.229V at standard conditions, but changing with temperature and pressure.
And the total energy demand is related to the thermoneutral voltage:	$U_{tn} = ?H / nF$ **Equation 9**	=1.482V at standard conditions, but changing with temperature and pressure
The energy efficiency in a cell is:	$?_e = U_{tn} / U$ **Equation 10**	*Where U is the actual cell voltage.*

Table 21 - Cell-based electrolyser calculations (Ulleberg, 1998)

9.2.2. Power Available to the Electrolyser

Considering the electrolyser at a higher level, the first step of modelling is to calculate the excess power available to the electrolyser, see Equation 11.

$$\boxed{\text{Power available to electrolyser} = \text{wind turbine model} - \text{demand}}$$

Equation 11 - Power available to electrolyser

This is the difference between the wind turbine model power and the power that is necessary to meet demand (the inverter reading, combining output from battery and wind). The version of the turbine model used is the basic theoretical model based upon the manufacturer's power curve for one 20kW rated turbine. Loading and other inefficiencies have not been taken into account. This strategy has been chosen because the electrolyser will be acting as additional load on the system, and so will change the system dynamics and potentially improve the performance of the turbine by providing extra variable load for the turbine to dump its excess power to. Results for electrolyser output may be slightly over-optimistic as a result. However, it should also be noted that only one ideal turbine is modelled, when in fact there are two turbines installed, which could mean that the system output has actually been considerably under-estimated (see Recommendations in Section 10).

It is then necessary to take into account the rated power of the electrolyser in order to evaluate if there is any excess of energy that cannot be used, so that a figure for actual power going to the electrolyser can be arrived at, shown in Equation 12.

if power available= > electrolyser rating
Actual power to electrolyser = electrolyser rating
And power wasted = power available – electrolyser rating

Equation 12 – Actual power to electrolyser, rated

The power will either be equal to the rated power (possibly with some excess that cannot be used due to the electrolyser rating) or less than the rated power, but cannot be below a certain minimum loading level. Due to unpredictable behaviour at lower loading levels, most alkaline electrolysers, even newer models designed for fluctuating currents can only operate down to around 20 to 25% of their rated power (Ulleberg, 2003, Mills & Al-Hallaj, 2004), as evaluated in Equation 13.

if power available < 0.25 electrolyser rating*
Actual power to electrolyser = 0
And power wasted = power available

Equation 13 – Actual power to electrolyser, minimum load

9.2.3. Electrolyser Consumption

The next stage is to consider how this energy is consumed within the electrolyser. Equation 14 shows the basic components of the electrolyser that consume the input power. Primarily the power is consumed by the hydrogen production process, but there are secondary operations of the electrolyser that also consume power, including the production of heat, the process control mechanisms and the working of the compressor. Manufacturers often specify the power consumption of hydrogen production and of the auxiliaries in kWh/Nm3 (Stuart Energy, 2004; Smith, 2002). In the absence of additional technical information, it is assumed that these consumption values include any compression and heat production that takes place within the electrolyser.

Electrolyser Power Input ⇒ Hydrogen Production + [Heat production + Process control + Compressor]

Equation 14 - Applications of the input electrolyser power, adapted from Agbossou et al (2004)

It would be possible to take into account the outlet pressure from the electrolyser, and compare this with the desired storage pressure to calculate the energy demands of the storage stage of the cycle. The hydrogen could be made available in the next time-step, but as the electrolyser and fuel cell are prohibited from working simultaneously, it would be expected to go into storage even for a short time.

The power required for compression can be calculated using the pressure difference, as shown in Equation 15:

$$\textit{Compression energy } (kJ/Nm^3) = \frac{PoVo}{(k-1)*?}\left[1 - \left(\frac{\text{Pressure out}}{\text{Pressure in}}\right)^{\frac{(k-1)}{k}}\right]$$

$$= \frac{101.3(kJ)}{0.4x0.63}\left[1 - \left(\frac{\text{Pressure out}}{\text{Pressure in}}\right)^{\frac{0.4}{1.4}}\right]$$

Equation 15- Energy required for storage, adapted from Agbossou et al (2004)

Where *k = adiabatic constant = 1.4*

? = compressor efficiency =assume approximately 63%

PoVo = 101.3kJ for a standard gas

However, to use this equation correctly, a more detailed analysis of the hydrogen storage would need to be undertaken. More detailed information on storage can be found in Howes (2002). This level of modelling is considered out of scope for this analysis, especially as metal hydrides are the preferred means of storage, and very little high-level information is available on their operation. It is therefore assumed that the electrolyser chosen will produce hydrogen at the same pressure as the fuel cell requires it. Previous modelling studies have made similar assumptions, adopting a 100% storage efficiency (Vanhannen et al., 1998; Crockett et al., 1995).

Realistically, storage will require some energy consumption, but this could be provided directly from the renewable resource or from batteries. The output of the turbine model has been adapted by a factor of 0.95 to allow for 5% of the energy being used to meet storage demands.

Analysing the units of total consumption as specified by the manufacturer, Equation 16 can be arrived at:

$$\text{Energy used (kWh)} = \text{Consumption (kWh/Nm}^3) \times \text{Hydrogen output (Nm}^3)$$

$$\textit{therefore } \text{Hydrogen output} = \frac{\text{Energy used}}{\text{Consumption (H}_2\text{, auxiliaries and compression)}}$$

Equation 16 – Hydrogen output

It is necessary to calculate the energy used. The time-steps are in 10 minute periods, equal to 1/6 hours, so using the formula in Equation 17, the equation in Equation 18 can be derived.

$$\text{Energy} = \text{Power} \times \text{Time}$$

Equation 17 - Energy law

$$\text{Electrolyser energy consumed (kWh)} = \text{Electrolyser power (kW)} \times \text{time-step (h)} = \text{Electrolyser power} \times 1/6$$

Equation 18 – Electrolyser energy consumed

The results of this equation can be input to Equation 16. Once the hydrogen output has been determined, the amount of water used can be estimated (Equation 19) as this is equal to roughly 1 litre per Nm^3 (Smith, 2002).

$$\text{Water used (litres)} = 1 \times \text{Hydrogen output (Nm}^3)$$

Equation 19 - Water used for electrolysis

9.2.4. Electrolyser Efficiency

Efficiency is influenced by the hydrogen consumption figures. If a hydrogen production rate can be calculated, the energy efficiency of the electrolyser can then be determined using the formula below for each time-step, as shown in Equation 20. This formula requires a hydrogen production rate. A value for hydrogen output for the time-step of 10 minutes is known, therefore the hourly production rate can be calculated as shown.

$$
\begin{aligned}
\text{Electrolyser efficiency} &= \frac{\text{Power out}}{\text{Power in}} \\
&= \frac{\text{Calorific value of H2 x production rate}}{\text{Power in}} \\
&= \frac{\left(\text{3kWh/Nm3 x hydrogen output this time-step x time-steps/hour}\right)}{\text{Power in}} \\
&= \frac{\text{18 x hydrogen output this time-step}}{\text{Power in}}
\end{aligned}
$$

Equation 20 - Energy efficiency of an electrolyser

This gives an output of a constant value for efficiency. Mills & Al-Hallaj (2004) assumed that efficiency would be relatively constant during loading conditions over 25%, as illustrated in Figure 59.

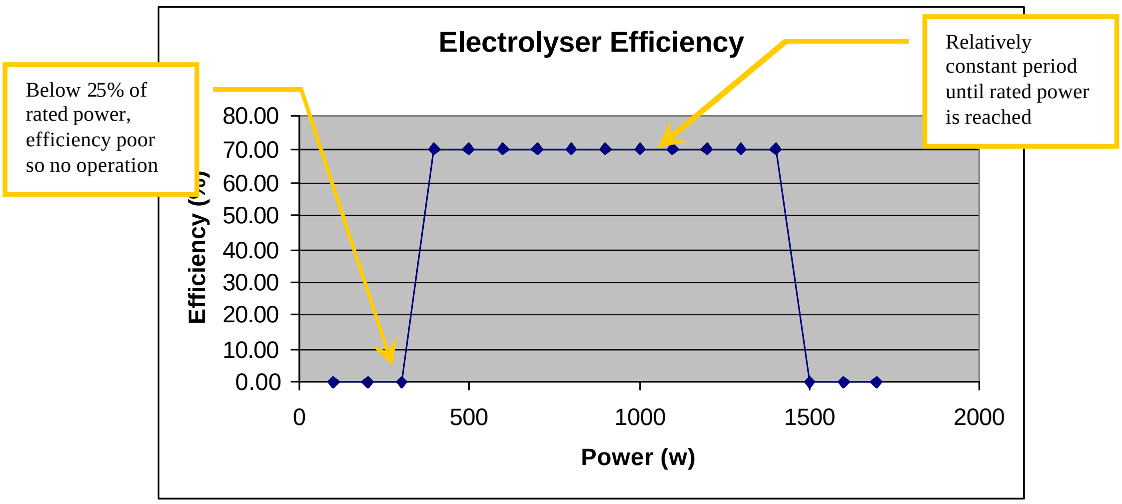


Figure 59 - Electrolyser efficiencies (adapted from Mills & Al -Hallaj, 2004)

However, when using an electrolyser with renewables, there may be some loss of efficiency due to the fluctuating nature of the supply. Electrolyser efficiency varies with current. Vanhannen et al. (1998) found a near-linear variation of 10% in hydrogen production efficiency with current variations for a SPEL electrolyser, as shown in Figure 60 below.

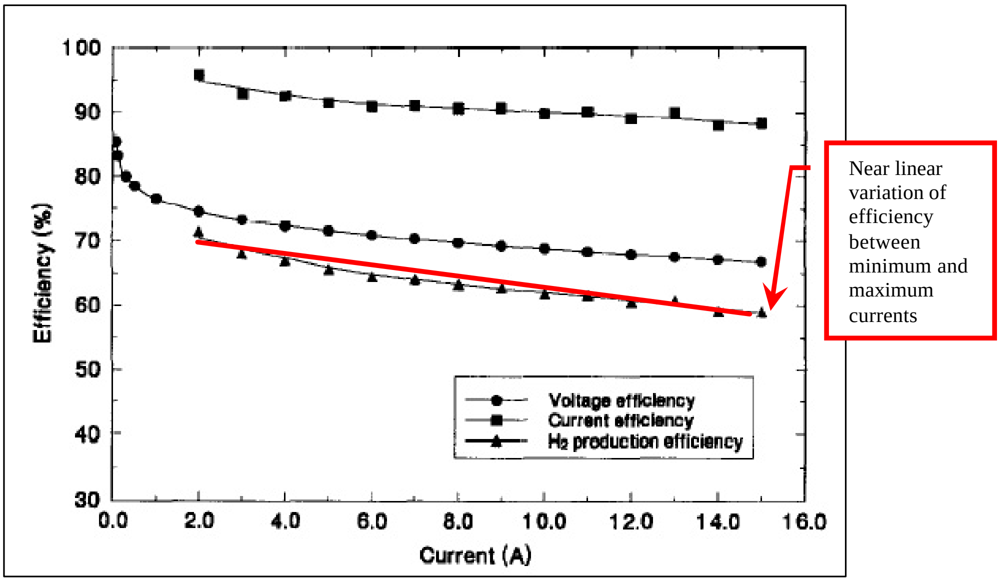


Figure 60 - SPEL efficiency at 50°C (Vanhannen et al, 1998)

This 10% linear variation of efficiency over the range of electrolyser current values is assumed to be standard for SPEL electrolysers (in the absence of additional high-level operational studies). Data for potential electrolyser current is not available, but the load on the electrolyser (kW) and the operating grid voltage (V) is available. Using this data and equation Equation 21 below, a variation in P/V (Load/Grid Voltage) over time can be approximated.

$$\boxed{\begin{array}{c} P \text{ a } VI \\ I \text{ a } P/V \end{array}}$$

Equation 21 – Power law

This will not provide the exact current at the electrolyser (especially as the electrolyser will be operating on DC rather than AC), but is simply used to gain an idea of where on the linear graph (Figure 60) the efficiency will sit. P/V is calculated for each time-step, the maximum and minimum values found (representing the range of currency operation), and then a 10% variation applied to the consumption rate for the scale in-between, shown in Equation 22.

$$\text{Electrolyser efficiency} = \text{Calculated constant efficiency} - \text{efficiency variation}$$
$$\text{Electrolyser efficiency} = \text{Calculated constant efficiency} - (10\%*\text{fraction})$$

Equation 22 - Variation in electrolyser efficiency (1)

Where fraction of 10% = where the P/V value lies between the minimum and maximum value.

Equation 23 shows how this fraction is calculated.

$$\text{Fraction} = \left(\frac{\text{P/V} - \text{min P/V}) \quad \text{x } 100}{\text{Max range in P/V}} \right)$$

Equation 23 - Variation in electrolyser efficiency (2)

The static value for efficiency, Equation 20, is assumed to be for the best loading conditions (low current or P/V ratio), corresponding to the manufacturer's quoted value for consumption. To adapt the operation of the electrolyser model to take account of the new variable efficiency, the electrolyser consumption can be altered accordingly. Consumption will increase With higher P/V values (current as shown in Figure 60), efficiency will decrease and so consumption will increase. The efficiency variation is used to increase the figure for consumption by this percentage, as shown in Equation 24 below:

$$\text{Hydrogen output (Nm3)} = \frac{\text{Energy used}}{\text{Consumption } (H_2\text{, auxiliaries and compression})}$$
$$= \frac{\text{Energy used}}{\text{Consumption x } (1 + \text{efficiency variation}/100)}$$

Equation 24 - Correction of hydrogen output for efficiency

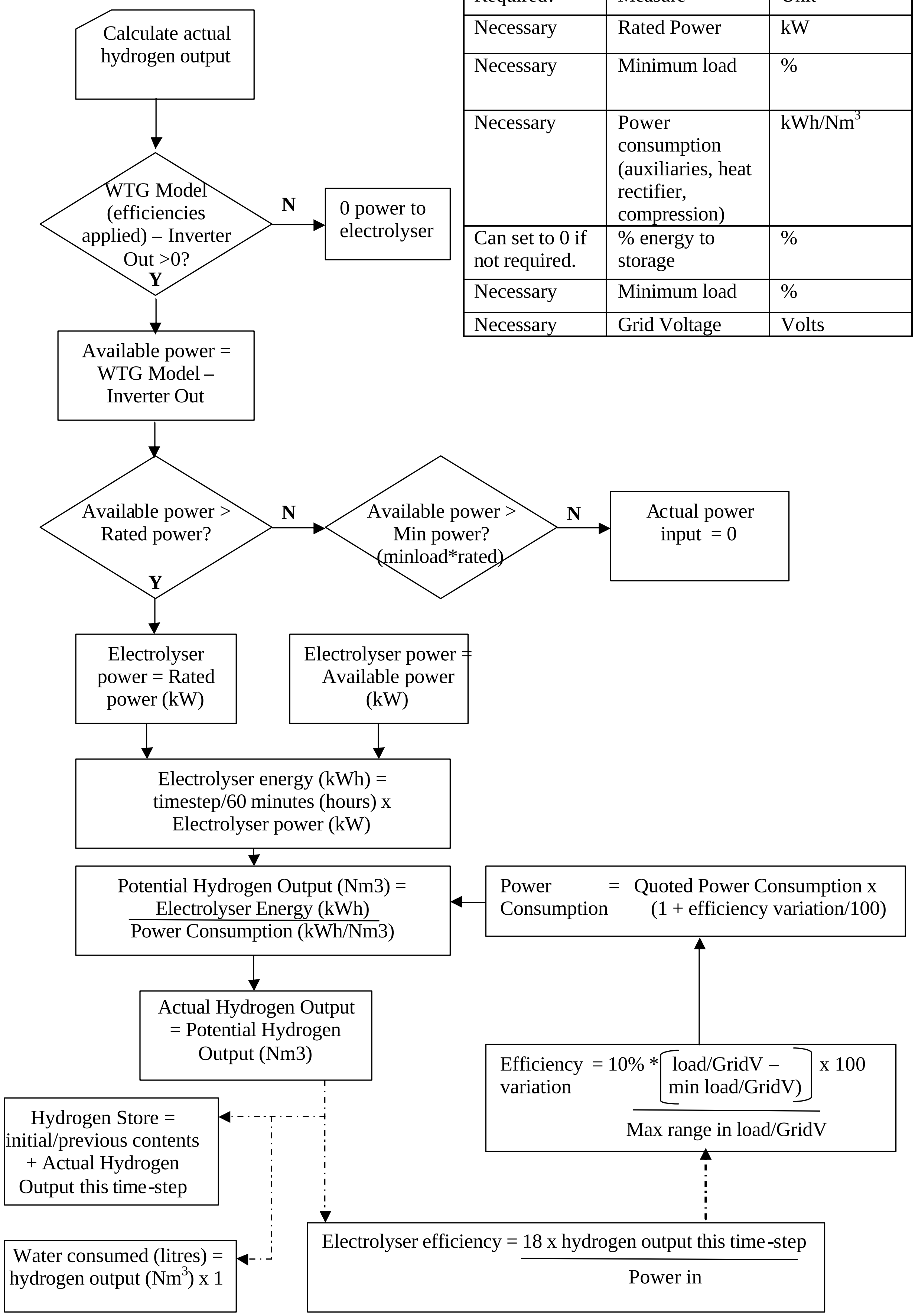
9.2.5. Accumulating hydrogen

Calculating the cumulative amount of hydrogen in storage gives in indication of the required storage sizing, and will indicate if there is a mismatch between the electrolyser and the fuel cell (storage calculation will go negative). As a set time period is being addressed, the model needs to know how much hydrogen was in the tank at the start of the period. The tank will accumulate output hydrogen from the electrolyser each time-step the electrolyser operates, and the quantity of hydrogen in the tank will decrease based on fuel cell usage (following section). This process has been included in the flow chart for the fuel cell operation (Figure 72).

The following flow chart in Figure 61 gives an overview of the processing for the electrolyser model. Time-step analysis as in section 7.3.9 was carried out to verify the operation of the model.

Figure 61 - Flow chart for hydrogen electrolyser model

Required?	Measure	Unit
Necessary	Rated Power	kW
Necessary	Minimum load	%
Necessary	Power consumption (auxiliaries, heat rectifier, compression)	kWh/Nm^3
Can set to 0 if not required.	% energy to storage	%
Necessary	Minimum load	%
Necessary	Grid Voltage	Volts



9.3. Fuel Cell Modelling

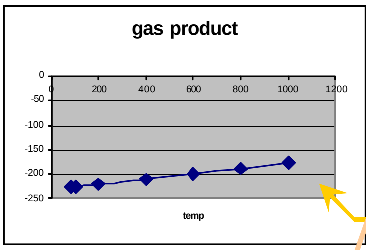
9.3.1. Initial Model

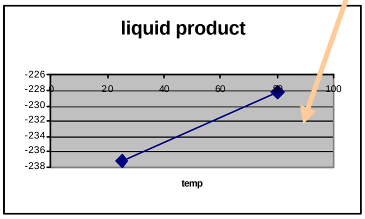
Many complex models exist for particular types of fuel cells (Ulleberg, 2003; Datta et al,2002; Ferguson et al, 2001; Larminie 2003 etc), but a model is required for this study that can be applied to all fuel cell systems.

Initially, a more complex model of the fuel cell was embarked upon, based upon the principles of fuel cell irreversibilities, activation losses (the Tafel equation), transportation and ohmic losses, see Figure 66 and Figure 67.

The first stage evaluated the change in Gibbs free energy for the fuel cell. Equations were derived for liquid product and gas product values, see Figure 62, and logic was built into the spreadsheet so that only valid temperature values for the chosen state (liquid or solid) would be accepted, as shown in Figure 63:

Form of product	Temp deg C	? ¯gf (energy released) kJ mol-1
liquid	25	-237.2
liquid	80	-228.2
gas	80	-226.1
gas	100	-225.2
gas	200	-220.4
gas	400	-210.3
gas	600	-199.6
gas	800	-188.6
gas	1000	-177.4





Graphs derived for variation of change in Gibbs free energy with operating temperature

*please choose from values in above table

for a gas:

Temp:	700		y=mx+c	
			c	-230
? ¯gf	-196.4		m	0.048

for a liquid

Temp:	700		y=mx+c	
? ¯gf	invalid temp		c	-241.3
			m	0.164

Figure 62 - Calculation of Gibbs free energy change

Fuel Cell Specification:

Operating Temp*		700	deg C	
Form of Product (liquid enter 1, gas enter 2)*		2	(1 or 2)	
Actual Cell Voltage Vc		1	Volts	
mass of fuel reacted		1	kg	
mass of fuel input		1.1	kg	
? ¯gf		-196.40	kJ mol-1	

Fuel Cell Specification:

Operating Temp*		700	deg C	
Form of Product (liquid enter 1, gas enter 2)*		1	(1 or 2)	
Actual Cell Voltage Vc		1	Volts	
mass of fuel reacted		1	kg	
mass of fuel input		1.1	kg	
? ¯gf		invalid temp	kJ mol-1	

Gas state is valid for 700ºC, but cannot have liquid state at 700ºC.

Fuel Cell Specification:

Operating Temp*		79	deg C	
Form of Product (liquid enter 1, gas enter 2)*		1	(1 or 2)	
Actual Cell Voltage Vc		1	Volts	
mass of fuel reacted		1	kg	
mass of fuel input		1.1	kg	
? ¯gf		-228.36	kJ mol-1	

Fuel Cell Specification:

Operating Temp*		79	deg C	
Form of Product (liquid enter 1, gas enter 2)*		2	(1 or 2)	
Actual Cell Voltage Vc		1	Volts	
mass of fuel reacted		1	kg	
mass of fuel input		1.1	kg	
? ¯gf		invalid temp	kJ mol-1	

Liquid state is valid for 79ºC, but cannot have gas state at 79ºC.

Figure 63 - Evaluation of valid states for given temperatures

The maximum EMF for a fuel cell was then calculated using Equation 25.

$$E = ?\,\bar{g}f / 2F$$

Equation 25 - Maximum EMF of a fuel cell (Larminie et al., 2003)

Where *F = the Faraday constant, equal to 96,485 Coulombs.*

The next stage was to use the change in enthalpy of formation (? $\bar{h}$f) to calculate the maximum efficiency possible (or thermodynamic efficiency), using Equation 26.

$$\text{Max efficiency} = (?\bar{g}f \,/\, ?\bar{h}f) \times 100\%$$

Equation 26 - Maximum cell eficiency (Larminie et al., 2003)

For hydrogen there are two values for ? h*f*, the value for the lower heating value (LHV) = -241.83kJ mol^{-1} and the value for the higher heating value (HHV) = -285.84kJ mol^{-1}. Te LHV is mode commonly used, as it results in a higher efficiency value.

The actual cell efficiency is calculated using Equation 27 for EMF if all the energy from the fuel were transferred to electrical energy:

$$E = \frac{-\,?\,hf}{2F} = 1.48V \textit{ for HHV}$$

Equation 27 - EMF for fuel cell (Larminie et al., 2003)

The result is used in Equation 28.

$$\text{Cell efficiency} = \frac{\text{Actual voltage (Vc)}}{1.48} \times 100\%$$

Equation 28 – Cell efficiency (Larminie et al., 2003)

In practice not all of the fuel fed into the fuel cell can be used, so a fuel utilisation co-efficient can be built in, shown in Equation 29.

$$\mu f = \frac{\text{mass of fuel reacted in cell}}{\text{mass of fuel input to cell}}$$

Equation 29 - Fuel utilisation co-efficient (Larminie et al., 2003)

Therefore the actual cell efficiency is:

$$\text{Cell efficiency} = \mu f \times \frac{Vc}{1.48} \times 100\%$$

Equation 30 – Cell efficiency with fuel utilisation (Larminie et al., 2003)

The model in Excel allows for these factors to be taken into account, shown in Figure 64, inputs are highlighted in yellow and the rest is calculated:

Fuel Cell Specification:

Operating Temp*		79	deg C	
Form of Product (liquid enter 1, gas enter 2)*		1	(1 or 2)	
Actual Cell Voltage Vc		1	Volts	
mass of fuel reacted		1	kg	
mass of fuel input		1.1	kg	
? ¯gf		-228.36	kJ mol-1	
Max EMF, Eoc		1.18	Volts	(-? ¯gf/2F)
? ¯hf	burning (LHV)	-241.83	kJ mol-1	
	liquid (HHV)	-285.84	kJ mol-1	
	diff	44.01	kJ mol-1	
Efficiency Limit	HHV based	79.89	%	¯gf/¯hf x100%
	LHV based	94.43	%	¯gf/¯hf x100%
Operating voltage@100%	EMF (LHV)	1.25	Volts	(-? ¯hf/2F)
	EMF (HHV)	1.48	Volts	(-? ¯hf/2F)
Actual Cell efficiency (1)	HHV based	67.51		Vc/OpVoltage at100%x100%
Fuel utilisation co-efficient	µf	0.91		mass fuel reacted /mass fuel input
Actual Efficiency (2) incl fuel	?	61.37		µf(Vc/opVolt)*100

Equation 25 - Maximum EMF of a fuel cell

Equation 26 - Maximum cell eficiency

Equation 27 - EMF for fuel cell

Equation 29 - Fuel utilisation co-efficient

Equation 30 – Cell efficiency with fuel utilisation

Figure 64 - Model for equation calculation

The next stage is to account for losses in the fuel cell. To do this, Equation 31 is used to account for the ohmic losses (? V_{ohm}), activation losses (? V_{act}) and transport losses (? V_{trans}).

$$V = E - ?\, V_{ohm} - ?\, V_{act} - ?\, V_{trans}$$

$$V = E - ir - A \ln (i) + m \exp (ni)$$

Equation 31 - Accounting for irreversibilities (Larminie et al., 2003)

Where *E is the reversible OCV given by Equation 25*

i is the current density (input)

A (in Volts) is the slope of the Tafel line, calculated from Equation 32.

Equation 32 is used to calculate the slope of the Tafel line.

$$A = \frac{RT}{2\,a\,F}$$

Equation 32 - Slope of the Tafel line

Where *a = charge transfer co-efficient (between 0 to 1.0) (input)*

R = Universal gas constant = 8.314 J K^{-1} mol^{-1},

T = operating temperature in Kelvin

m and n are the constants in the mass-transfer over voltage equation (3 x 10^{-5} V and 8 x 10^{-3} $cm^3 mA^{-1}$ respectively)

r is the area specific resistance. kOcm^2 (input)

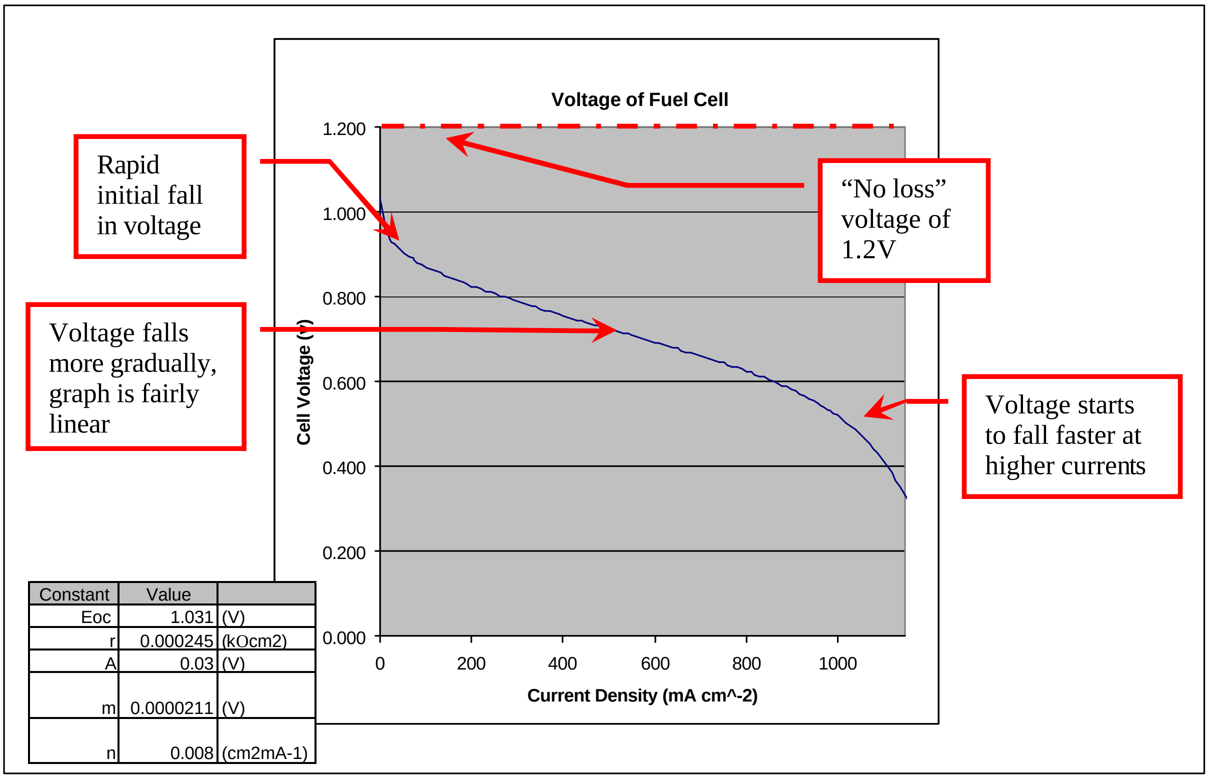
Ohmic losses are linear (proportional to the current density) and are due to the resistance to the flow of electrons/ions through the material of the electrodes, the interconnections and the electrolyte. Activation losses are non-linear, they relate to the proportion of the input voltage that is required to drive the chemical reaction to transfer the electrons to or from the electrode. Mass transport losses result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. The reduction in the concentration is a result of the failure to transport sufficient reactant to the electrode surface.(Larminie et al., 2003)

The Excel components are shown Figure 65. Inputs are shown in yellow, and constants in grey.

current density	i	1.00	mA cm ^-2	
area specific resistance	r	0.0002000	kO cm^2	
	RT	2926.53		
charge transfer co-eff	?	0.50		0 to 1.0, usually 0.5
Slope of the Tafel line	A	0.03033		RT/(2 x ? x F)
constant of mass transfer over voltage eqn	m	0.000100	Volts	
constant of mass transfer over voltage eqn	n	0.008000	cm^2 mA^-1	
Voltage at i=1		1.18	Volts	Eoc-ir-Aln(i)-mexp(r

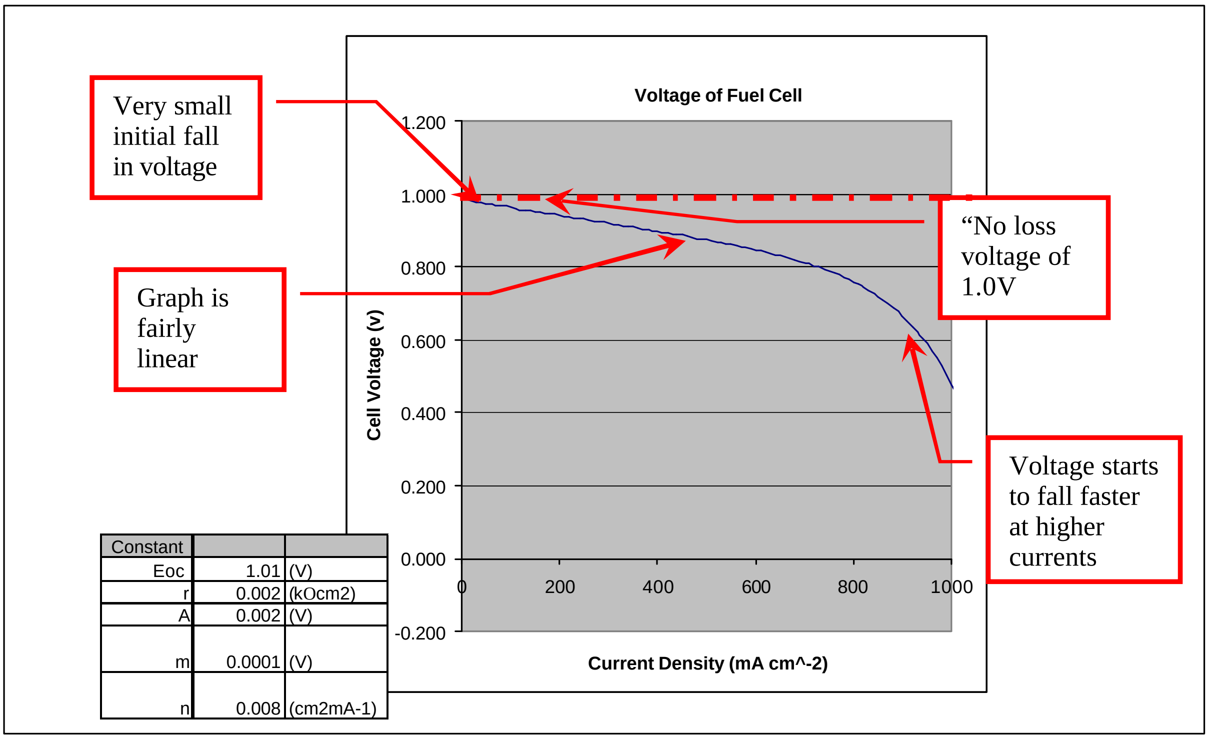
Figure 65 - Accounting for irreversibilities

Using the formula for voltage, Equation 31, the current density can be varied in order to generate a graph of the fuel cell behaviour. The graph shown Figure 66 is for a Ballard Mark V PEMFC at 70C. The difference between a low temperature and high temperature fuel cell can be observed Figure 67, generated for a high temperature SOFC specification:



Constant	Value	
Eoc	1.031	(V)
r	0.000245	(kOcm2)
A	0.03	(V)
m	0.0000211	(V)
n	0.008	(cm2mA-1)

Figure 66 - Graph showing voltage for a low temperature fuel cell



Constant		
Eoc	1.01	(V)
r	0.002	(kOcm2)
A	0.002	(V)
m	0.0001	(V)
n	0.008	(cm2mA-1)

Figure 67 - Graph showing voltage for a high temperature fuel cell

This model was useful in gaining an understanding of how the performance of the fuel cell was impacted by the variation of different variables in the voltage equation, but was difficult to apply to the given system data for Muck. A more simplistic approach similar to that taken by Smith (2002) and Mills & Al-Hallaj, (2004) was adopted.

9.3.2. Improved Fuel Cell Model Rationale

Smith (2002) used a generic model which could be applied to different fuel cell types, to be simulated under varying load conditions in the same way. The performance of the fuel cell was assumed not to be significantly affected by ambient temperature or altitude. It was modelled in the same way as an internal combustion engine using percentage part-load efficiency values as the performance measure. The operating temperature of the fuel cell would be initially reached using an external heat source and then maintained at a constant level by waste heat from the fuel cell operation. Assuming the fuel cell system was running fairly continuously with some degree of loading, it was considered that several days of standby could be achieved without the need for external heating. For the purposes of this model, heating requirements have not been taken into account, especially as there is potential for excess heat from the electrolyser to be used to heat the fuel cell (see Recommendations in Section 10). The MERIT based model was kept at a very high level, with percentage load being the major focus. There were considered to be no other factors significantly affecting the fuel cell that needed to be taken into account at this level of modelling. The model in this thesis differs from the MERIT model, as it takes into account the efficiency of the fuel cell under different loading conditions and allows for a zero-level fuel consumption to be entered if required.

9.3.3. Demand for the Fuel Cell

The fuel cell stack power output is affected by the following 3 factors:

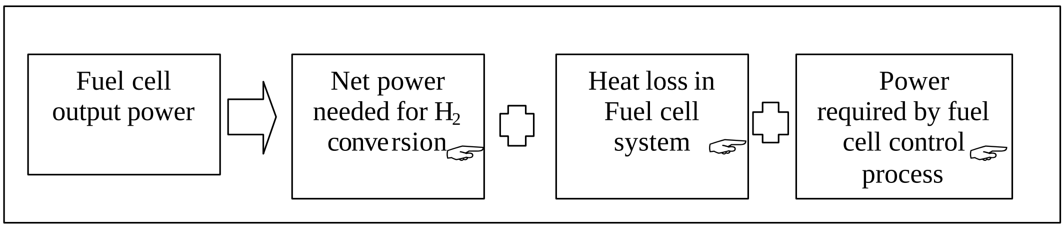


Figure 68 – Fuel cell output power, adapted from Agbossou et al (2004)

Manufacturer's figures are not available for the breakdown of each of these three components, so it was necessary to base the fuel cell model on more basic principles.

The first stage was to identify how much energy required to be generated by the fuel cell. The fuel cell would effectively be replacing the diesel and the batteries (although some operation of the batteries may still be required when required power is below acceptable fuel cell load, or for backup purposes). Therefore, the required fuel cell demand, based upon actual system data will be:

Fuel cell demand (kW)= diesel output(kW) *or* inverter output (kW)

Equation 33 - Fuel cell demand

Then it is necessary to evaluate if the power required is of a suitable level for the fuel cell to operate:

if power required= > fuel cell rating Actual generation = fuel cell rating And demand not met = fuel cell demand – fuel cell rating
if power required < minimum load Actual generation = 0 And demand not met = fuel cell demand

Equation 34 - Actual generation and demand not met

9.3.4. Fuel Cell Efficiency

The efficiency of the fuel cell varies with the type of electrolyte being used and its required working temperature, although scaling up or down has little impact (Fuel cell store, 2004). The efficiency of the fuel cell stack will increase with lower loads, though this may vary with overall plant design. The variation of efficiency needs to be defined for a meaningful model to be produced. Efficiency information may be quoted in the form of a graph showing fuel consumption against percentage load (Mills & Al-Hallaj, 2004). It also may be given as a measure of efficiency at given percentage loadings (25%, 50%, 75% and 100%) (Smith, 2002). The typical efficiency of a fuel cell stack under partial loading is given in Smith (2003), shown in Figure 69.

The characteristic of the fuel cell efficiency being higher at partial load as indicated in Figure 69 can be taken into account when considering load sharing between multiple fuel cells. It would be more efficient to run two fuel cells at lower load than one cell at full load, though there are economic considerations which will impact which scenario is chosen.

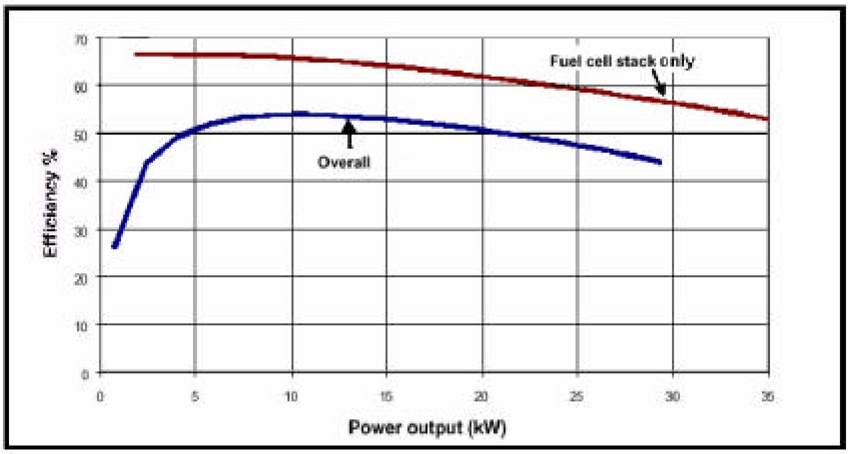


Figure 69 - Typical fuel cell efficiency under partial loading (Smith, 2002)

The graph of efficiency in Figure 69 was assumed to be standard for all electrolysers, and so was used to create a load-efficiency profile based on fraction load, through deriving equations for the components of the line, shown below:

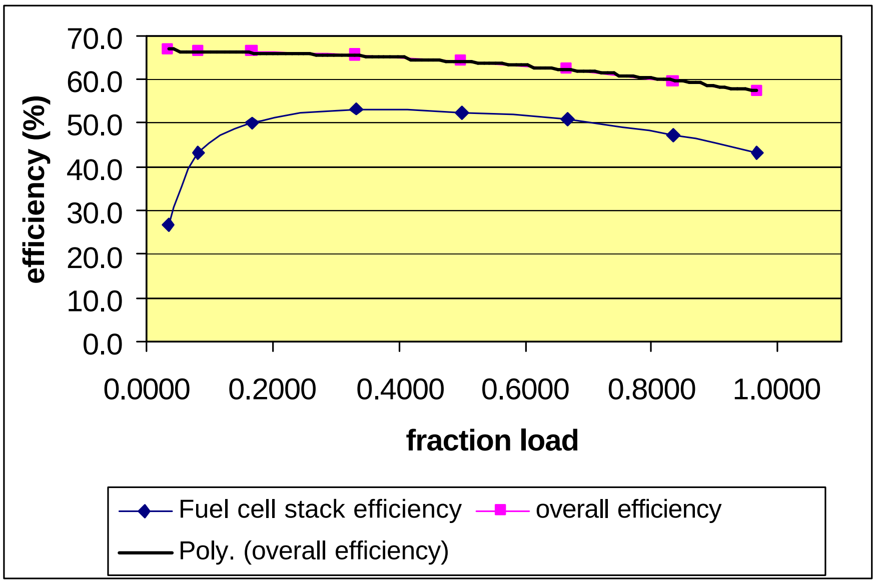


Figure 70 - Graph of fuel cell efficiency versus loading

To find the efficiency, the percentage load must first be calculated (Equation 35), and then the formula for the graph in Figure 70 can be applied to derive the efficiency value.

$$\text{Percentage load} = \frac{(100 \text{ x actual generation})}{\text{rated power}}$$

Equation 35 – Fuel cell percentage load

The calorific value of hydrogen is equal shown in Figure 71.

$$1Nm^3 = 3kW \text{ or } 1kWh = 1/3Nm^3$$

Figure 71 - Calorific value of hydrogen (Smith, 2002)

In the absence of good high level manufacturer's information, the optimum fuel consumption at 100% efficiency conditions is assumed based on the calorific value of hydrogen (Figure 71). Operation at lower efficiencies can be adapted accordingly using loading figures, as fuel consumption will increase with a reduction in efficiency. The fuel consumption can be calculated using Equation 36.

$$\text{Fuel consumption} = \text{actual generation} \times 1/3Nm^3 \times (100 - (\text{max efficiency} - \text{actual efficiency}))*0.01$$

Equation 36 - Fuel consumption variation with efficiency

Zero load fuel consumption has also been taken into account in this model, but can be set to 0 if not required.

if actual generation = 0
Fuel consumption = zero level fuel consumption

Equation 37 - Zero level fuel consumption

The following flow diagram shows the flow chart for the hydrogen fuel cell model.

9.3.5. Consuming hydrogen

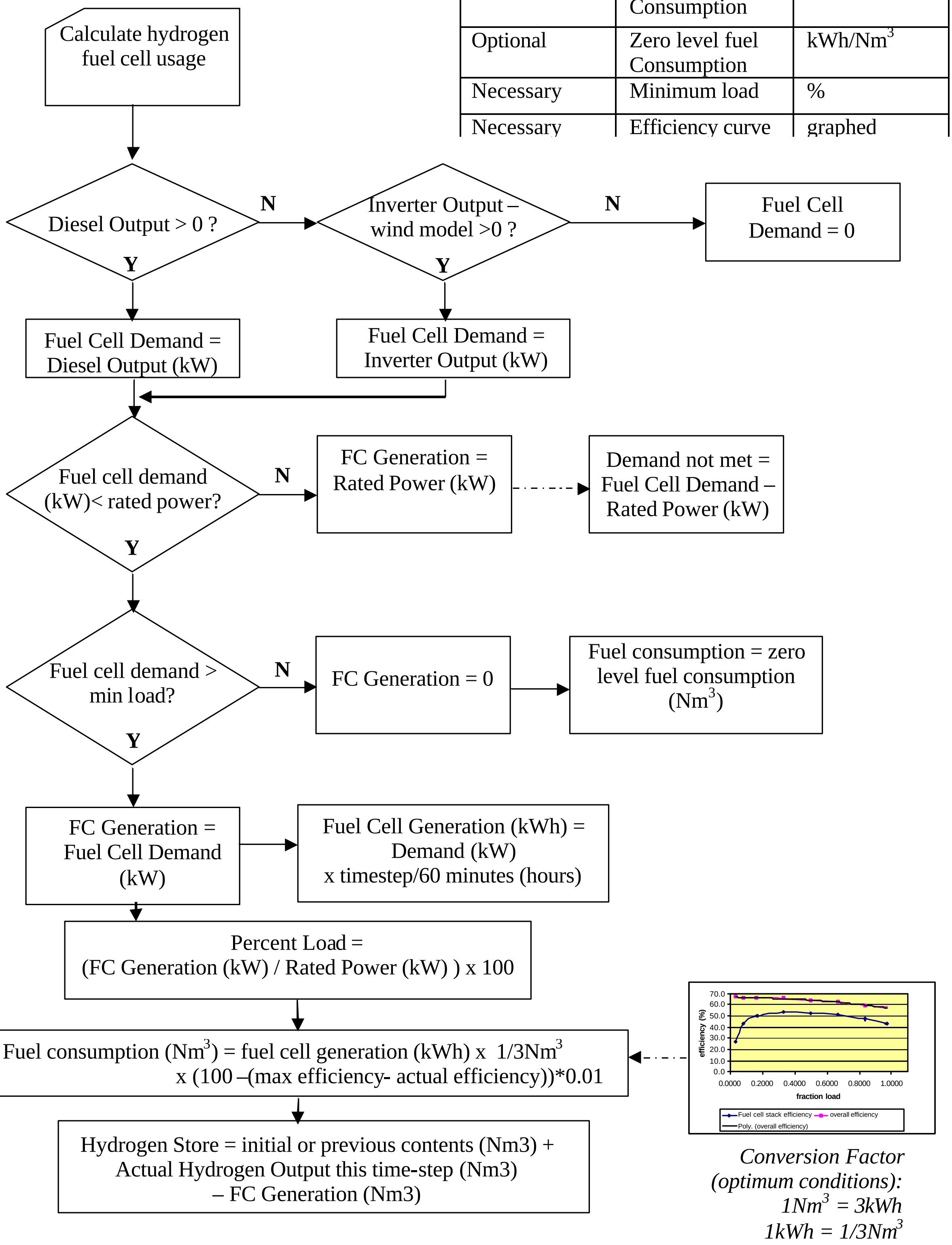
The cumulative hydrogen store must be updated as hydrogen is used for power generation. This is achieved by the following formula:

Hydrogen Store = initial or previous contents (Nm3)
+ Actual Hydrogen Output this time-step from electrolyser (Nm3)
– FC Generation (Nm3)

The electrolyser and fuel cell will not operate simultaneously, but the operation is written in this way to ensure the cumulative total is correct, and to take account of the zero level fuel consumption, if one has been input. The following flow chart (Figure 74) provides an overview of the operation of the fuel cell model. Time-step analysis as in section 7.3.9 was carried out to verify the operation of the model.

Figure 72 - Flow chart for hydrogen fuel cell model

Required?	Measure	Unit
Necessary	Rated Power	kW
Necessary	Optimum Fuel Consumption	kWh/Nm^3
Optional	Zero level fuel Consumption	kWh/Nm^3
Necessary	Minimum load	%
Necessary	Efficiency curve	graphed



9.4. Control

Within the models of the hydrogen system components, the main controls are focused upon:

1. Evaluating when excess energy is available for electrolyser operation,
2. Evaluating when there is demand (not met by wind resource) needing met for fuel cell operation,
3. Ensuring loading on the appliances is above a minimum amount,
4. Ensuring that the electrolyser-fuel cell based system can be by-passed when electricity is available directly from the resource to meet demand,
5. Ensuring that the fuel cell and the electrolyser do not operate simultaneously (Agbossou et al., 2004; Dutton et al., 2000).

Although in-depth modelling of the control mechanisms for the electrolyser and fuel cell has been out-with the scope of this project, some interesting findings from previous projects are worth noting.

9.4.1. Electrolyser Configuration

Wind energy by definition is difficult to develop control for as the duration and strength of the wind resource is critical, but unknown (Jacobson et al., 2001). Powering the electrolyser directly by wind only is complex – some start-up time is required before production can begin but the wind may blow in brief gusts (Jacobson et al., 2001).

There are two possibilities for configuring the wind resource with an electrolyser and battery combination. Firstly, the energy from wind generation can be used to power the electrolyser directly. This is sometimes termed variable-current mode, as only the excess available current is sent to the electrolyser. Battery state of charge should be more or less constant, whilst the activity of the electrolyser will fluctuate (Ulleberg, 2003). Additional controls relating to minimum time periods for wind power generation can also be added to ensure that on-off switchings of the electrolyser are minimised (Dutton et al., 2000)

Secondly, the wind energy can be used to keep the batteries charged, and the batteries can be used to feed the electrolyser (Jacobson et al., 2001). Fixed current mode involves the battery being charged during periods of excess current and being discharged in periods where the current is in deficit. The electrolyser will only see a steady current, and so can be configured to operate more efficiently (Ulleberg, 2003).

Although fixed mode reduces fluctuations in electrolyser operation, running the electrolyser in variable mode is more economical. It is likely that if this type of set-up were to be used on Muck, the variable option would be the most favourable. If fixed mode is absolutely necessary, it is best that the electrolyser is run at moderate power, reducing battery wear (Ulleberg, 2003).

9.4.2. Control Parameters

Important system control parameters in a real system are:

1. Quantity of excess energy available,
2. Battery state of charge,
3. Hydrogen availability
4. Load demand (Kolhe et al., 2003).

Battery levels in particular have been used to determine whether the electrolyser should be used or not (Agbossou et al., 2004). The battery state of charge (SOC) depends on two variables – the user load and the wind turbine output (or the diesel output, if charging from diesel is permitted as on Muck). The electrolyser will be disconnected if the state of charge on the battery is insufficient for a significant time (Dutton et al., 2000). As it has not been possible to model the full system for Muck, this consideration has not been taken into account in the current electrolyser model, but could be important to more detailed future studies.

9.4.3. Thermal Loads

In Muck the thermal dump loads may still be required – though alternatively if hydrogen generation levels are good, hydrogen could be adopted for heating purposes. If heating loads are still a consideration for the system, two different strategies can be considered:

Heading first: Surplus electricity is used to meet heating demands first, and then subsequently all left over electricity is used for generating hydrogen for storage.

Storage first: Surplus energy is immediately stored as hydrogen and once the storage system is full it is then used to meet heating demands (Isherwood et al., 2000)

It seems likely that on Muck a strategy combining these two might be best, whereby a threshold of hydrogen production is specified, over which the heating loads will receive the excess energy, or alternatively, power could be sent to the heating loads until a threshold is met, after which all power is routed to hydrogen production. Switching between the two over a longer time period could be developed to ensure the most efficient dump load strategy for the power system. In the current model, the actual data used for demand already includes these heating loads, and shows that an excess of energy can still be used to generate hydrogen on top of these loads.

9.4.4. Use of Batteries

Batteries are often used in renewable systems to correct for renewable energy source intermittency, electrolyser ripples and load peaks. In a real system, there will be periods when a deficit of input power would not result in hydrogen consumption, and when an excess would not cause hydrogen production due to the loading requirements of the hydrogen devices and the buffering action of the batteries (Agbossou et al., 2004).

To ensure devices do not switch off and on too quickly, the trigger level that a device is turned on at is different to the control level at which it is turned off (Agbossou et al., 2004). When batteries are used in a hydrogen-based system, triggering levels can be chosen to ensure that they are kept at near-full charge for most effective and efficient operation (Agbossou et al., 2004). It is likely that a small battery bank will still be required in the scheme on the Isle of Muck. This will be considered in the model analysis section, Section 9.5.

9.5. Model Analysis

9.5.1. Data Input

The data input requirements are shown in Figure 73 below. Yellow indicates user input is required, whilst white values are calculated. The total period assessed is 11days.

fuel cell specification	value	units
rated power	5	kW
min % load	25	%
zero load fuel consumption	0.01	Nm3

electrolyser specification	value	units
P_{Emin} (critical level/idling current)	2.5	kW
P_{Erated} (max power in)	10	kW
power consumption (total incl storage)	4.9	kWh/Nm3
minimum load	25	%

storage specification	value	units
initial hydrogen in store	10	Nm3
original energy to storage %	5	%

Figure 73 - Hydrogen model user inputs

Standard system data as detailed in Table 9 earlier is held for each time-step, and the operation of the hydrogen system is calculated for each time-step against this data. It has not been possible to split the operation of the battery bank from the rest of the actual system data to enable analysis of the system without this storage capacity. As this storage only appears to be operating with a capacity of 12kWh, and a small battery bank would be required in the hydrogen system anyway, it is considered acceptable to keep the current battery operation in. The hydrogen fuel cell will have to work harder if a smaller battery bank is used. Replacement of the battery bank with a much smaller battery bank will result in a reduction in the excess hydrogen in the storage. A larger electrolyser than that indicated from these results may therefore be necessary.

9.5.2. Performance Analysis

The performance of the system is evaluated using the metrics shown in Figure 74:

Performance:

electrolyser	**10 kW**	**fuel cell**	**5 kW**
hydrogen produced (Nm3)	365.1	hydrogen used (Nm3)	78.7
electrolyser use (% timesteps)	73	FC use (% timesteps)	18
Energy not utilised (kW)	3007.5	demand not met (kW)	1264.4
store initial vol:	**10 Nm3**	energy generated (kWh)	215.8
minimum (Nm3)	10.2		
maximum (Nm3)	271.3		
period end (Nm3)	271.3		

Figure 74 - Hydrogen model performance evaluation

The electrolyser and fuel cell "use" metrics relate to the number of time-steps that the devices are operating for. For a configuration of a 10kW electrolyser, 5kW fuel cell and initial hydrogen store of 10Nm^3, the following can be observed:

? The electrolyser produces a volume of hydrogen in excess of that required by the fuel cell to meet demand.

? The electrolyser is in use 73% of the time, with the fuel cell in use 18% of the time, indicating a period of 9% of the time that neither are operating (likely due to no wind, no demand, or moderate wind meeting demand).

? The initial volume in storage is not necessary. It appears that the storage could function quite easily in this period without any initial volume in the store. A build up of hydrogen occurs as it is not all used by the fuel cell. This allows for additional to be available for it to be available for cooking/heating/transport purposes.

9.5.3. Electrolyser Down-Rating

Down rating the electrolyser, has the effect shown in Figure 75.

electrolyser	10 kW
hydrogen produced (Nm3)	365.1
electrolyser use (% timesteps)	73
Energy not utilised (kW)	3007.5
store initial vol:	10 Nm3
minimum (Nm3)	10.2
maximum (Nm3)	271.3
period end (Nm3)	271.3

electrolyser	5 kW	
hydrogen produced (Nm3)	201.5	↓
electrolyser use (% timesteps)	75	↑
Energy not utilised (kW)	7814.9	↑
store initial vol:	10 Nm3	
minimum (Nm3)	-1.0	↓
maximum (Nm3)	118.5	↓
period end (Nm3)	118.1	↓

Figure 75 – Down-rated electrolyser performance

A halving in the rated power of the electrolyser results in a near-linear reduction in hydrogen production (Chart 3, Figure 76). Due to lower hydrogen production, the hydrogen store requires a slight addition to the initial volume, as it depletes to -1Nm^3 at one point (Figure 75).

As the rated power is decreased, the amount of unused energy increases in a near-linear manner (Chart 1, Figure 76). This is because the lower rating of the electrolyser limits its peak production (point 1, Figure 77). Electrolyser frequency of use also increases for the lower rated electrolysers, although this variation is not linear due to the specific data for each time-step (Figure 76).

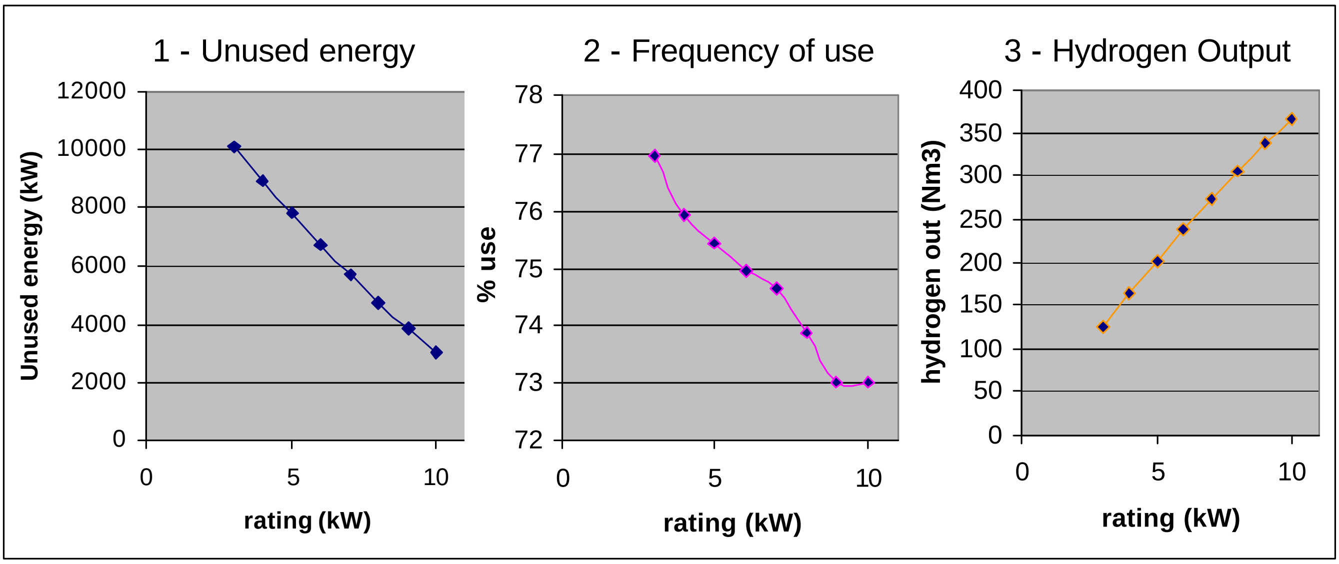


Figure 76 - Variation of electrolyser rating

The additional frequency of use of the electrolyser after down-rating is explained by Figure 77. The electrolyser is able to operate more of the time as the relative-minimum load of the electrolyser is lower, enabling additional smaller amounts of energy to be utilised (point 3).

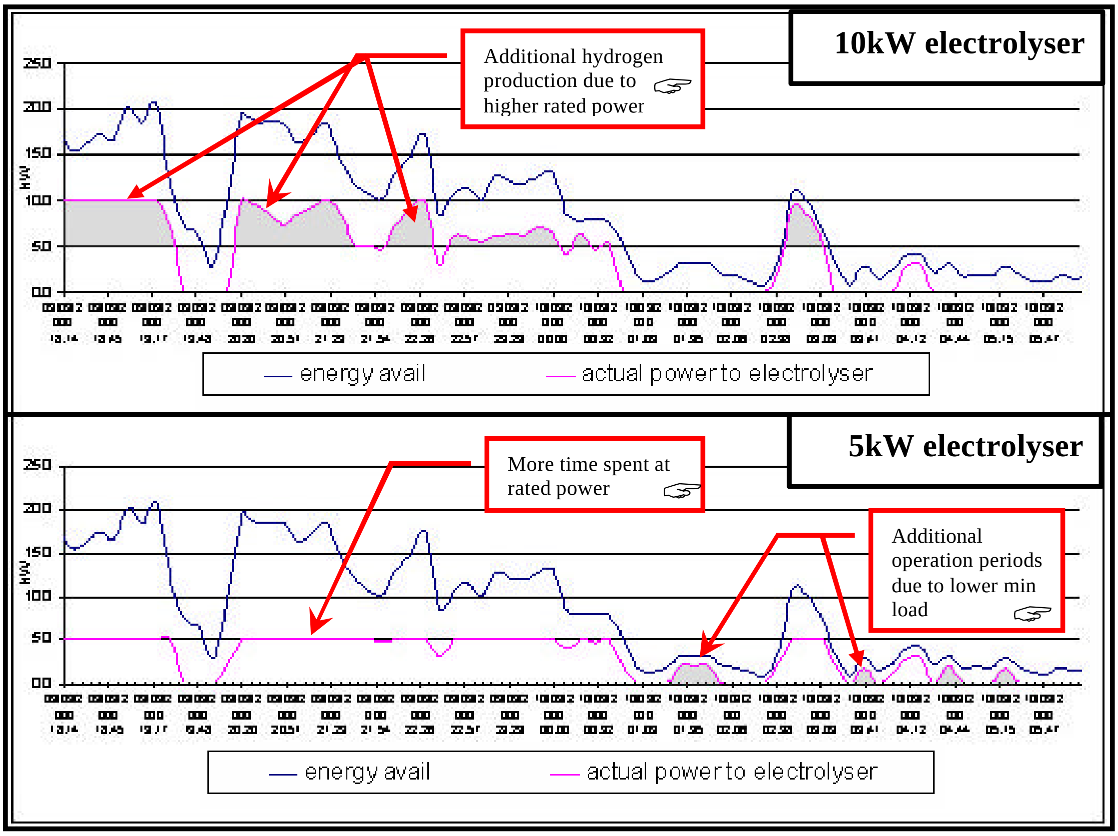


Figure 77 - Impact of down rating electrolyser

Increased operation at lower levels results in increased on-off switching of the electrolyser. This may reduce the performance of the electrolyser, as in reality a start-up time is required before production can begin (Jacobson et al., 2001). It has not been possible to model the start-up time in this implementation.

After down-rating the electrolyser, it operates more frequently at rated power (Point 2, Figure 77) as the rated power is much smaller in relation to the peaks and troughs of the energy supplied. Increased time at full load may result in an additional decline in electrolyser efficiency (Jacobson et al., 2001) as electrolysers operate better in lower load conditions.

9.5.4. Fuel Cell Down-Rating

Down rating the fuel cell to a 2kW model has the impact shown in Figure 78.

fuel cell	5 kW
hydrogen used (Nm3)	78.7
FC use (% timesteps)	18
demand not met (kW)	1264.4
energy generated (kWh)	215.8

fuel cell	2 kW
hydrogen used (Nm3)	44.5
FC use (% timesteps)	22
demand not met (kW)	1925.4
energy generated (kWh)	105.7

Figure 78 – Down-rated fuel cell

Down-rating the fuel cell results in a reduction in hydrogen used (Figure 78 and Chart 3, Figure 80). The fuel cell operates more frequently, due to lower minimum loading requirements (Points 1 and 3, Figure 79), although this variation is not linear due to the individual qualities of each time-step (Chart 2, Figure 80). The kWh generated reduces to less than half as the fuel cell rated-power limits the peak power that can be generated (points 2 and 4, Figure 79). The 'demand not met' increases as a result.

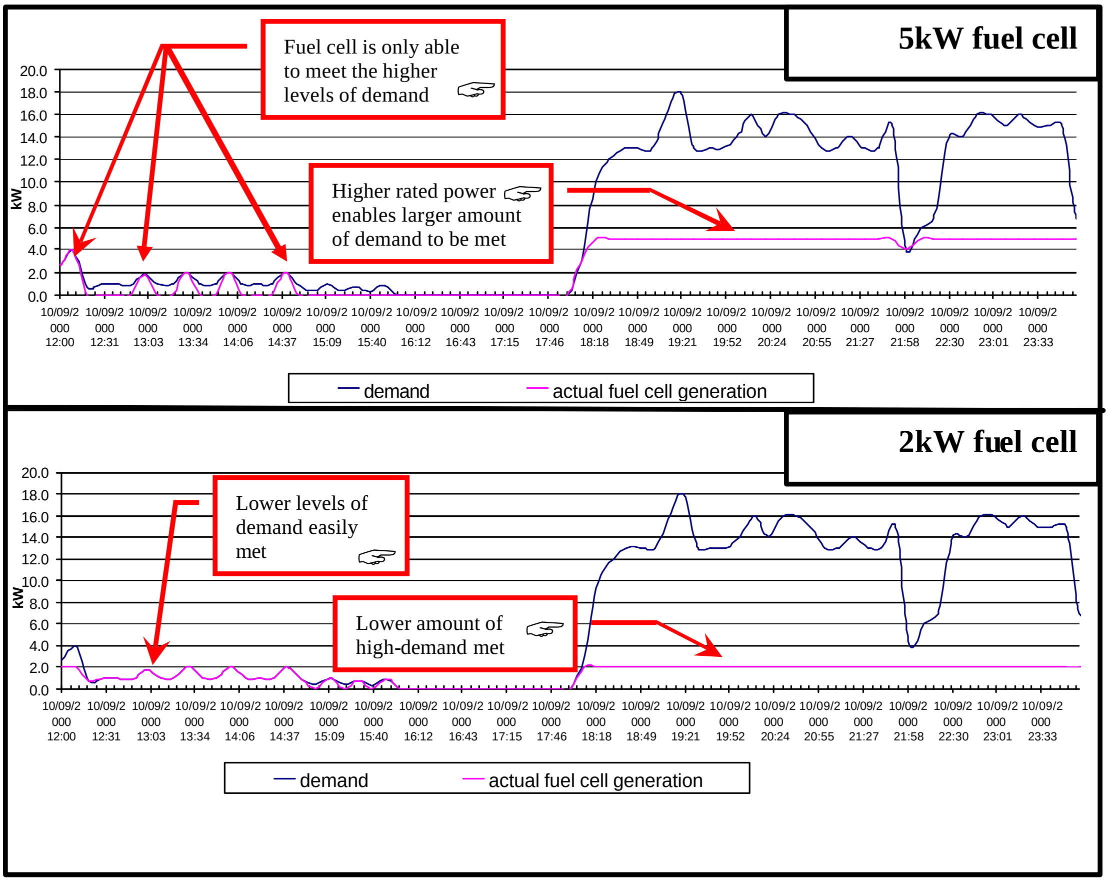


Figure 79 - Impact of down-rating fuel cell

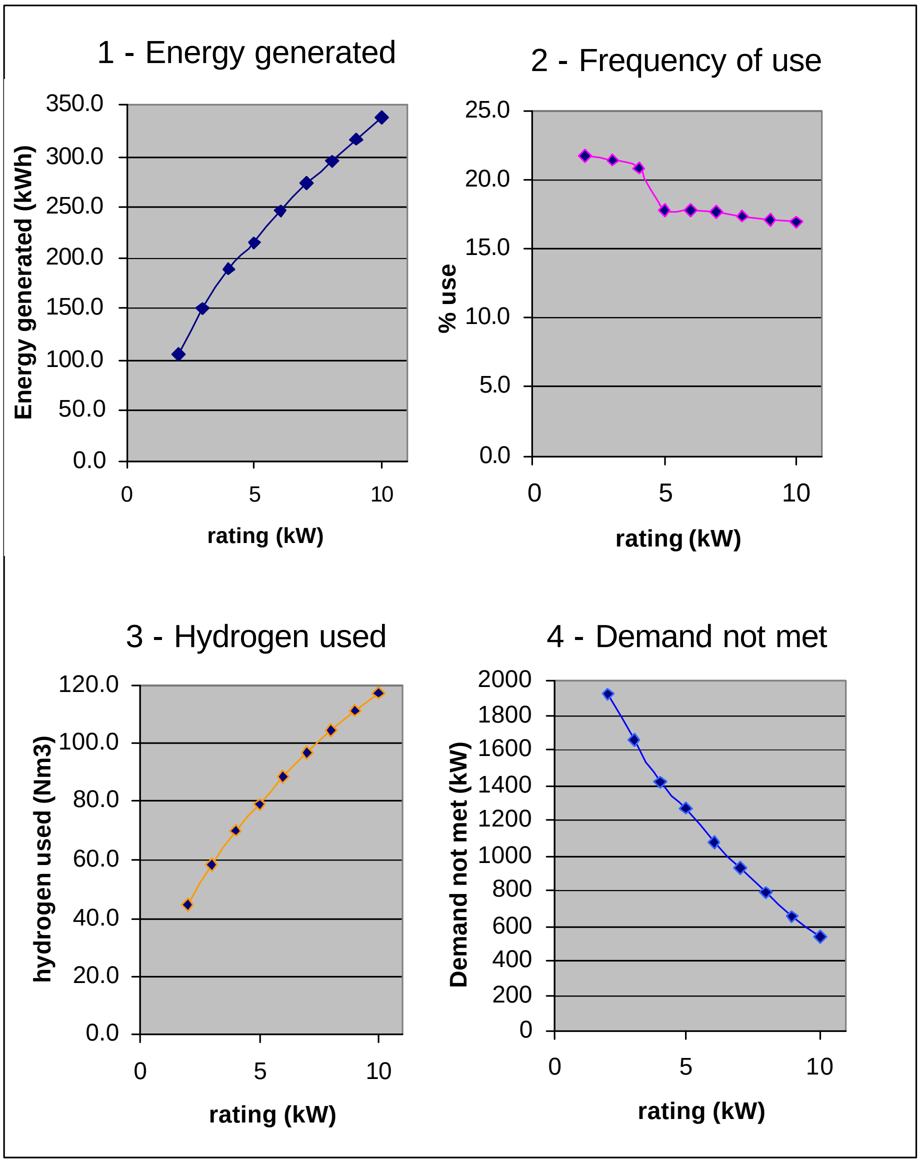


Figure 80 - Variation of fuel cell rating

A higher rated fuel cell would appear to be a better option, as the lower levels of demand and the short-term demand fluctuations could be met by a battery bank. It is the higher levels of demand that are important to meet, as these extended periods of peak demand would cause a massive drain on a battery bank.

9.5.5. Additional Considerations

9.5.5.1. Electrolyser

Two other input parameters of the electrolyser that can be altered are the consumption and the minimum load. First to be addressed is consumption. The impact of reducing the level of consumption in a 5kW electrolyser from 4.9 kWh/Nm^3 to 4 kWh/Nm^3 is shown in Figure 81 below. Hydrogen production increases for lower consumption rates and the efficiency improves considerably. The reverse is true for increased hydrogen consumption.

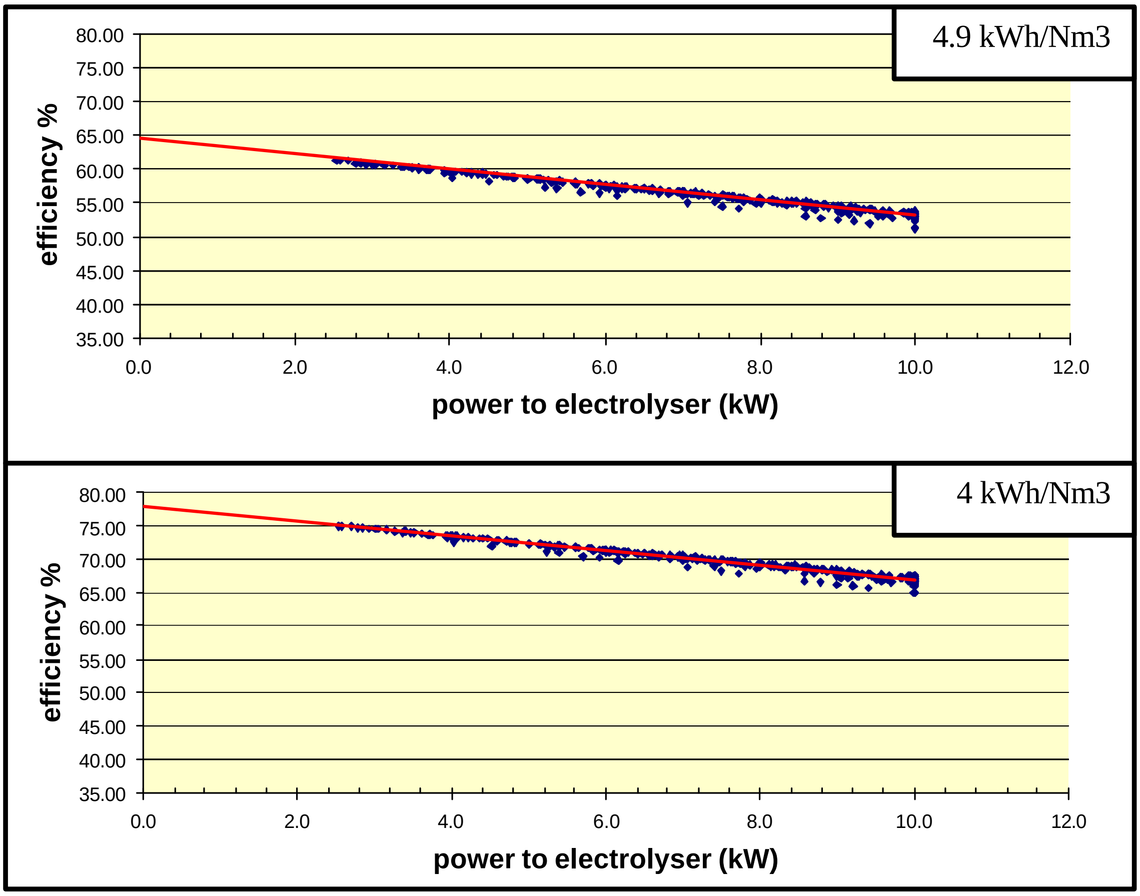


Figure 81 - Altering consumption of electrolyser (5kW rated)

The scatter is likely to be due to the impact of voltage variations, but overall the efficiency performs as expected in section 9.2.

Figure 82 shows how electrolyser production varies with consumption levels. As consumption increases, the hydrogen production decreases considerably. In reality, an electrolyser with too high a consumption rate would not make economic sense.

Quotes from manufacturers suggest a consumption rate at around 4.8 kWh/Nm3, including auxiliaries (Stuart Energy, 2004).

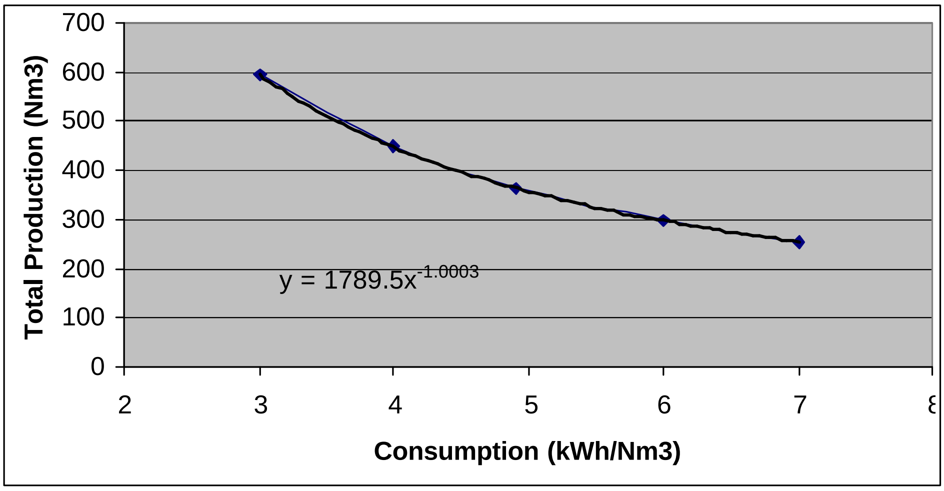


Figure 82 - Impact of consumption variation on total hydrogen production (5kW rated)

Next to be addressed is the minimum loading of the electrolyser. This is more apparent on the higher rated electrolysers, so a 10kW electrolyser has been chosen for this investigation (Figure 83). Changing the minimum loading from the standard 25% level to lower level results in an increase in hydrogen production (Chart 1, Figure 85) and electrolyser use (Chart 2, Figure 85), with more of the renewable energy being converted through electrolysis (Chart 3, Figure 85),

25% min load		5% min load	
electrolyser	**10 kW**	**electrolyser**	**10 kW**
hydrogen produced (Nm3)	365.1	hydrogen produced (Nm3)	368.2
electrolyser use (% timesteps)	73	electrolyser use (% timesteps)	78
Energy not utilised (kW)	3007.5	Energy not utilised (kW)	2915.7

Figure 83 - Impact of changing minimum loading on total hydrogen output

The reason for this increase can be observed in Figure 84. A lower minimum loading enables more generation at lower energy levels, whilst still allowing generation at the same rated peak. Ideally the minimum load will be low, but this is limited by efficiencies and the idling current of the electrolyser. The 25% minimum loading value was chosen as current electrolyser designs encounter unpredictable behaviour and highly variable efficiencies at operation below this critical level (Mills & Al-Hallaj, 2004). It also matches with manufacturer specified minimum loading levels (Stuart Energy, 2004).

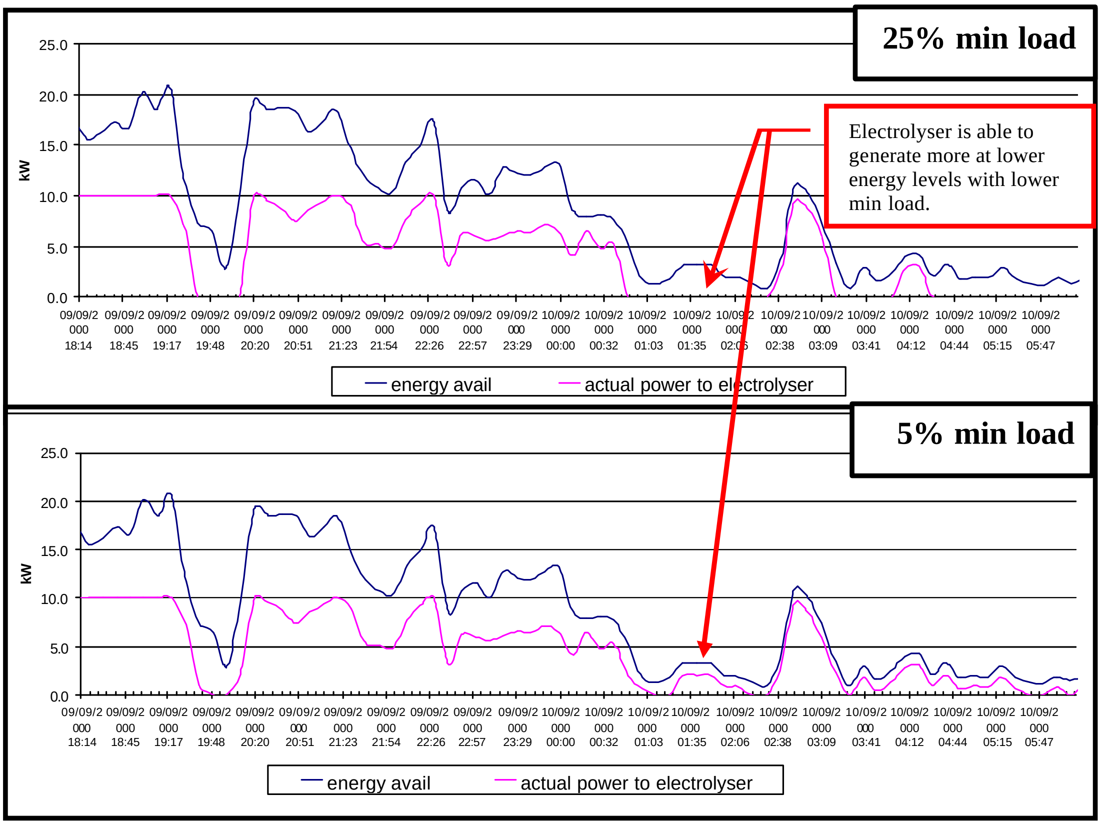


Figure 84 - Impact of changing minimum loading on electrolyser power

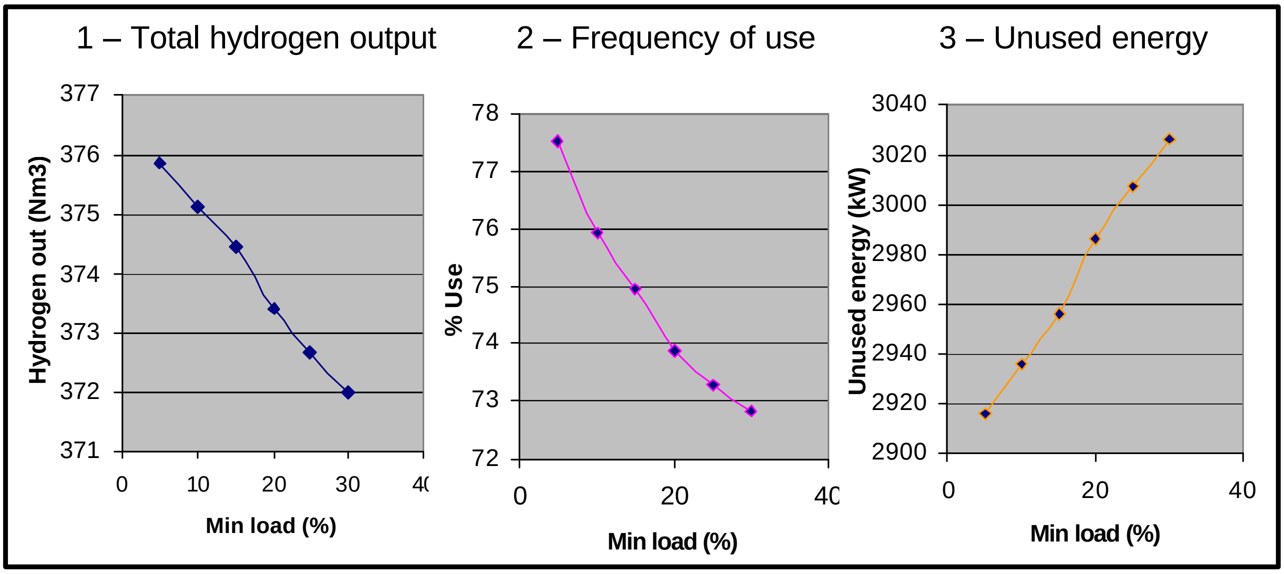


Figure 85 - Variation of Minimum load (10kW rated electrolyser)

9.5.5.2. Fuel Cell

Two additional input parameters of the fuel cell can be altered – the zero load fuel consumption and the minimum load. First to be addressed is the minimum load. Decreasing the minimum load of the fuel cell has a similar impact as in the electrolyser scenario. Performance at lower loads is improved, enabling the fuel cell to meet a larger percentage of the lower levels of demand, as shown in Figure 86, resulting in a decrease in the demand that is not met (Figure 88).

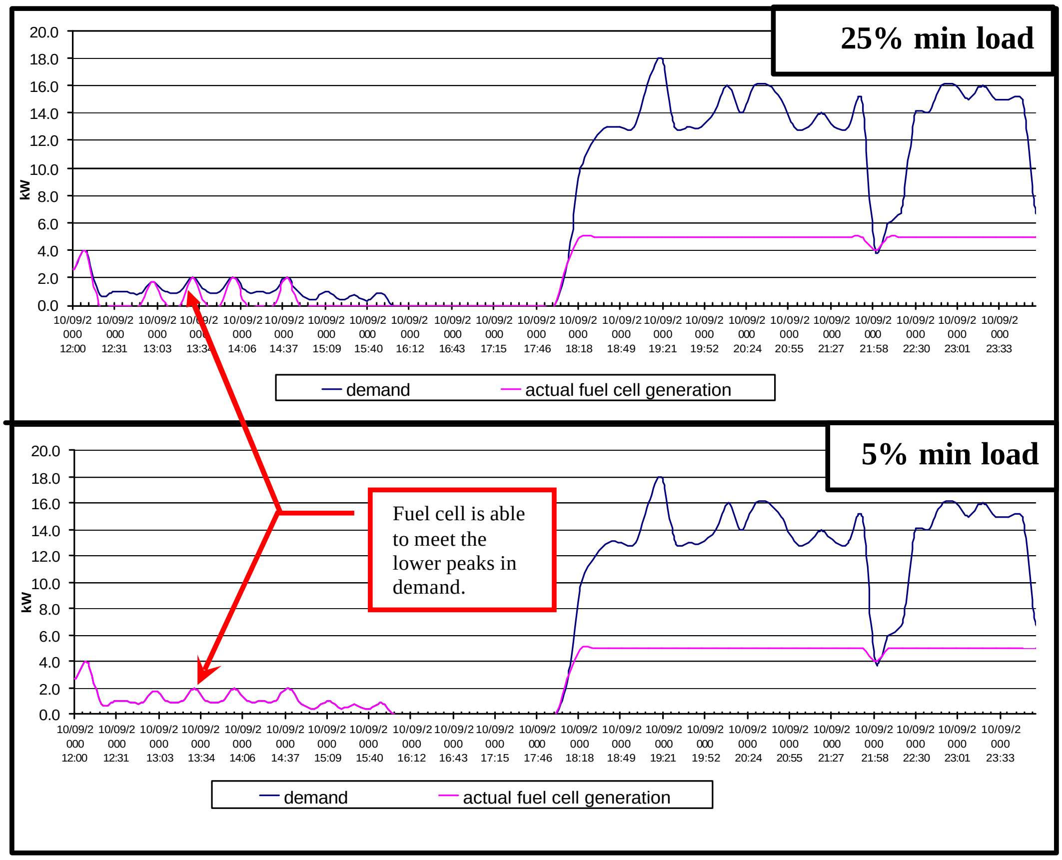


Figure 86 - Reducing minimum load of fuel cell (5kW)

The total energy generated increases, as does the quantity of hydrogen used and the frequency of use. However, these increases are not linear, as shown in Figure 88. A large jump is experienced at around 25% minimum load. Of particular interest is the behaviour of the hydrogen consumption chart (Figure 87) which indicates a rise in the hydrogen used for minimum loads just after 25%. This is due to the variation of efficiency with load, as indicated in Figure 87.

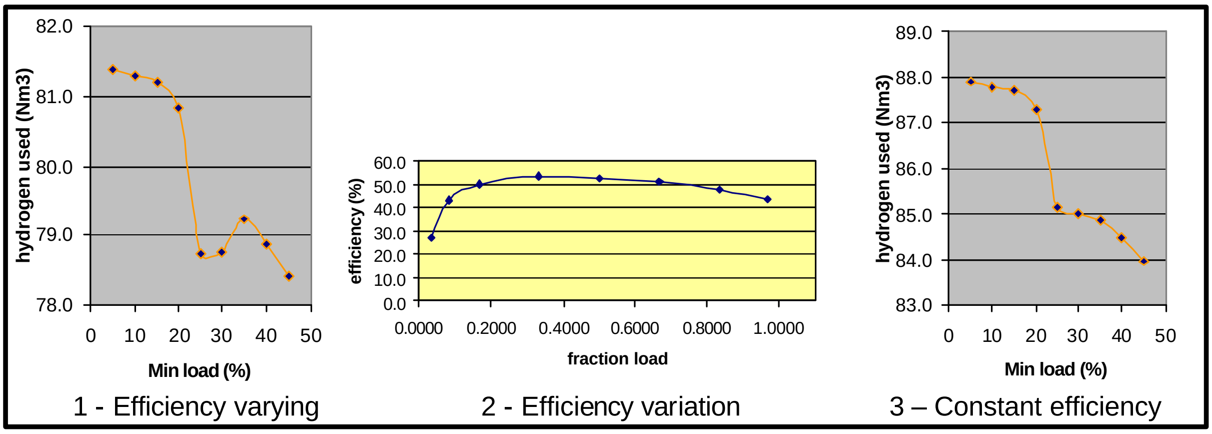


Figure 87 – Influence of efficiency on hydrogen use

Changing the efficiency to a constant value, this graph smoothes out, as shown in Figure 87.

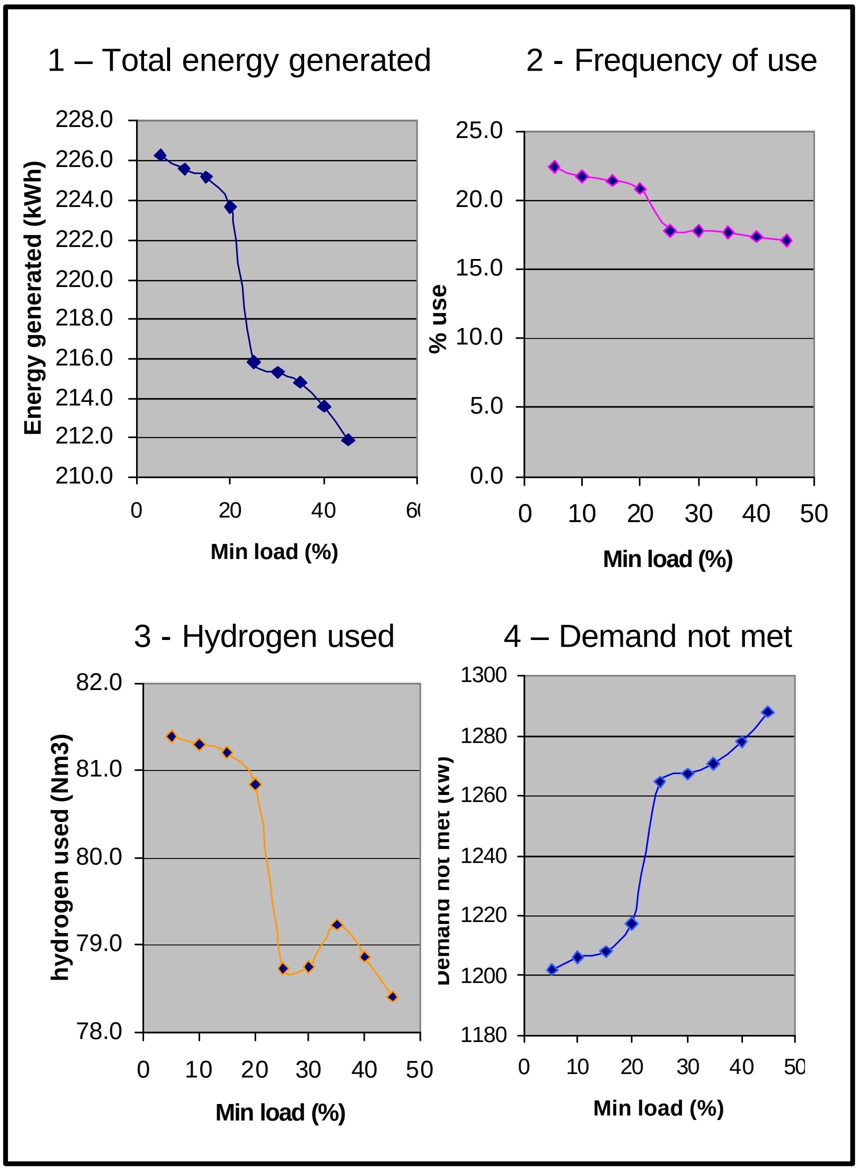


Figure 88 - Variation of minimum load (5kW fuel cell)

The jump at around 25% load can be explained by analysing the ability of the fuel cell to meet demand at the different minimum loads, illustrated in Figure 89. These charts show the difference between the fuel cell generation and the demand for a limited timescale. At 5% minimum load, the fuel cell all of the demand. At 20% minimum load, the fuel cell is still able to meet a considerable amount of the lower level demand, but some grey areas can be observed, indicating load not met. At 25% load, the fuel cell is suddenly unable to meet a much of the demand. This sudden change due to the size of the demand profile in relation to the minimum load explains the sudden jump in the graphs of Figure 88.

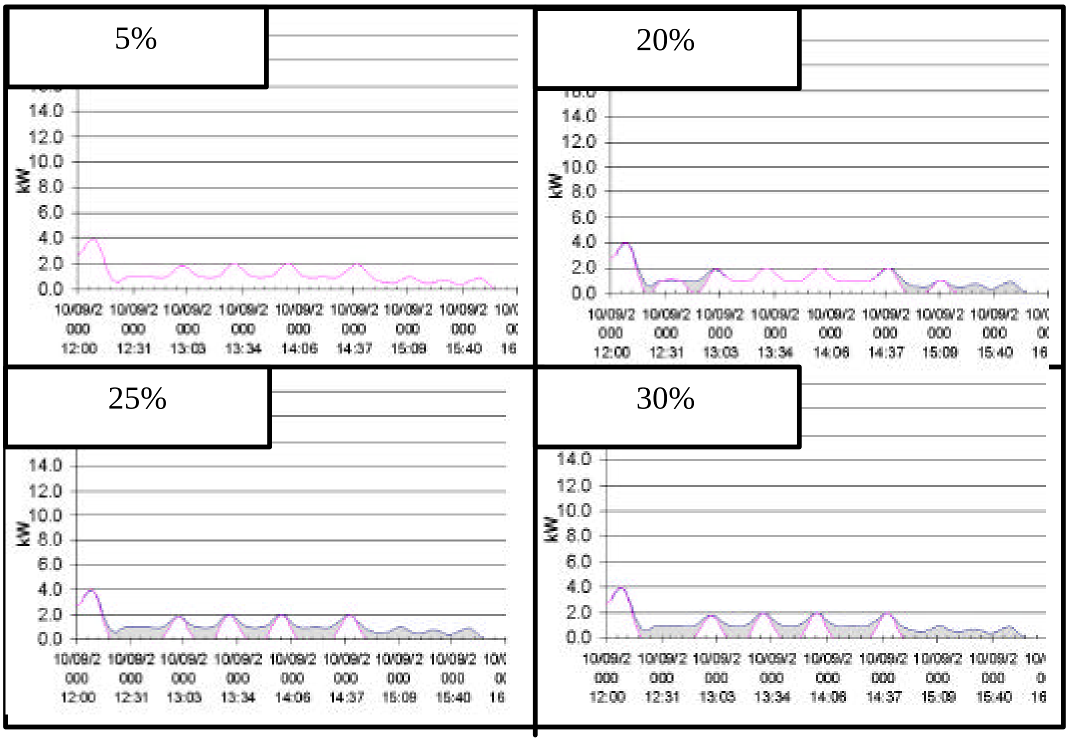


Figure 89 - Variation of demand met by fuel cell with changes in minimum load

Very reduced minimum loading, although ideal may be difficult to achieve, as discussed in section 9.5.5.1 on electrolyser considerations. Additionally, reduced minimum loading may not result in the most efficient operation of the fuel cell as it may require more on-off switching interfering with the fuel cell start-up processes.

To address how the zero load fuel consumption impacts the operation of the fuel cell, zero load fuel consumption levels were plotted against hydrogen use (Figure 90).

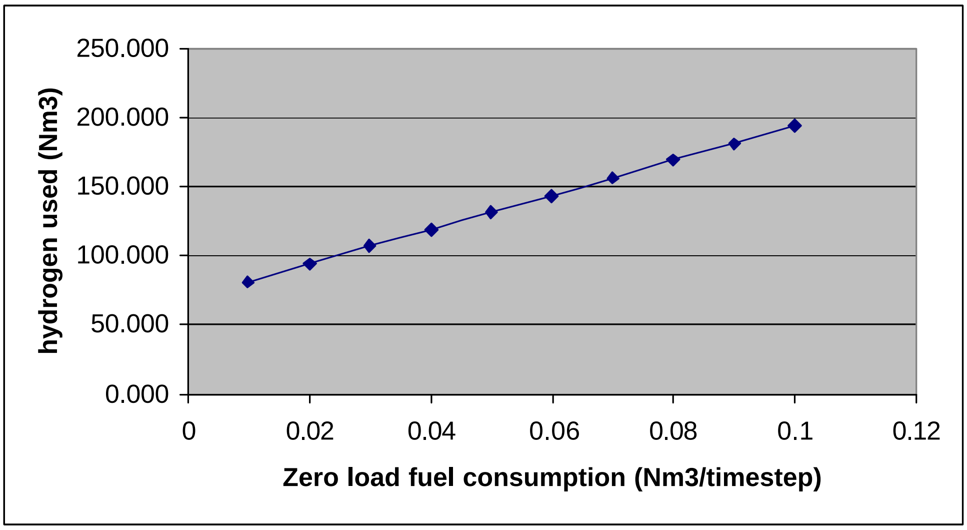


Figure 90 - Zero load fuel consumption variation

Increasing the zero load fuel consumption results in a linear increase in the quantity of hydrogen used by the fuel cell. For an efficient system, the zero load fuel consumption will need to be minimised, as over the lifetime of the fuel cell high zero load consumption will result in substantial additional hydrogen usage.

9.5.5.3. Wind Turbines

The current turbine model that electrolyser operation is based on is a single 20kW machine. To assess what the outcome would be with two 20kW machines operating, the formula for the wind turbine output was doubled, giving the potential energy to the electrolyser as shown in Figure 91.

It can be observed that a greater excess of energy is available to the electrolyser with two 20kW turbines. The behaviour observed is similar to that when the minimum load of the electrolyser is reduced, in that the electrolyser is able to operate at more points than previously (point 2 in Figure 91). However, the electrolyser is now also able to operate for longer periods at a time as the presence of two turbines has a smoothing effect (see point 1 in Figure 91).

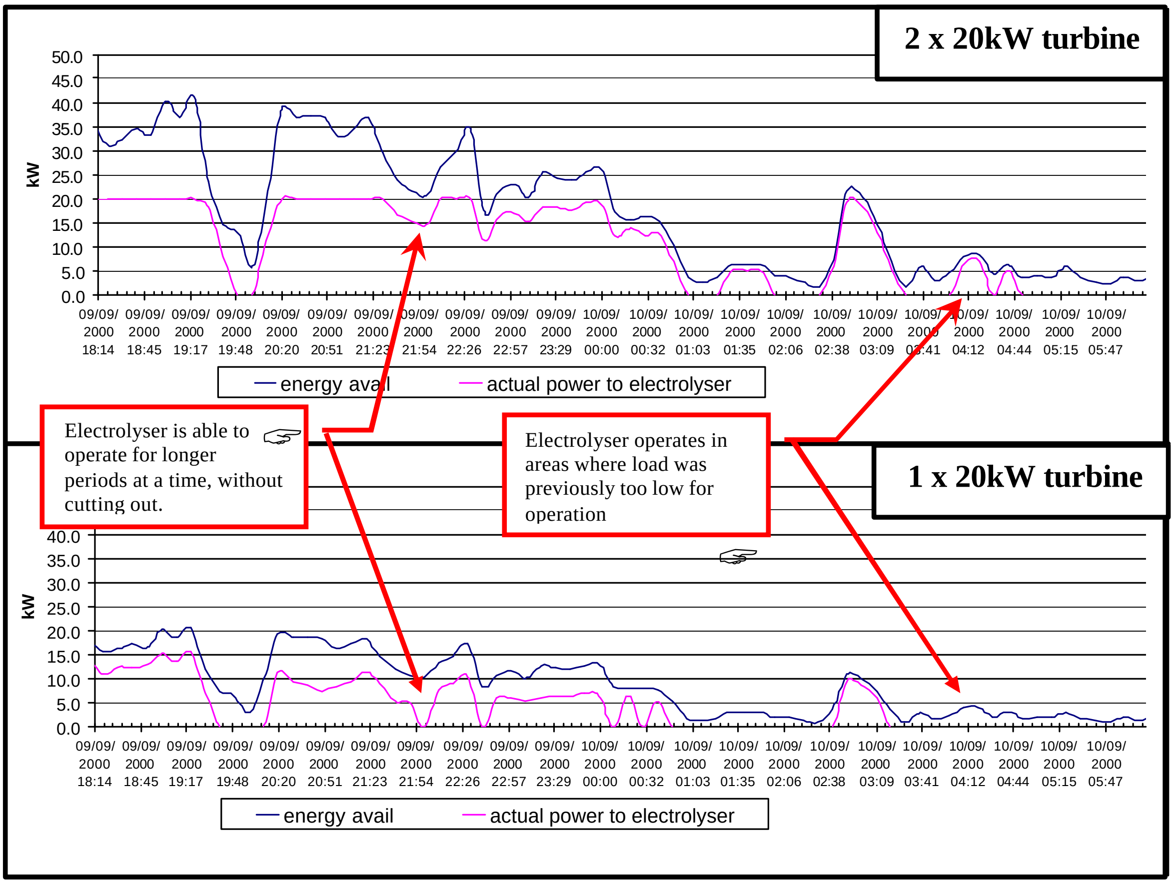


Figure 91 - Comparison of two turbine operation against one (20kW electrolyser)

Although the graphs show a positive result, with an additional 20kW rated machine resulting in hydrogen production increasing by 72%, a considerable amount of energy is now wasted. The advantage of two turbines is only considerable if the electrolyser is sufficiently rated. For example, the difference between the two scenarios for a 5kW machine is very small (shown in Figure 92) – resulting in a small increase of $12Nm^3$ in hydrogen production and an increase of 4% in electrolyser usage time.

The more wind generation available to the electrolyser the better, but the benefits will be most obvious in the larger rated machines. For lower rated electrolysers, the sensitivity to variations in the wind turbine model is reduced.

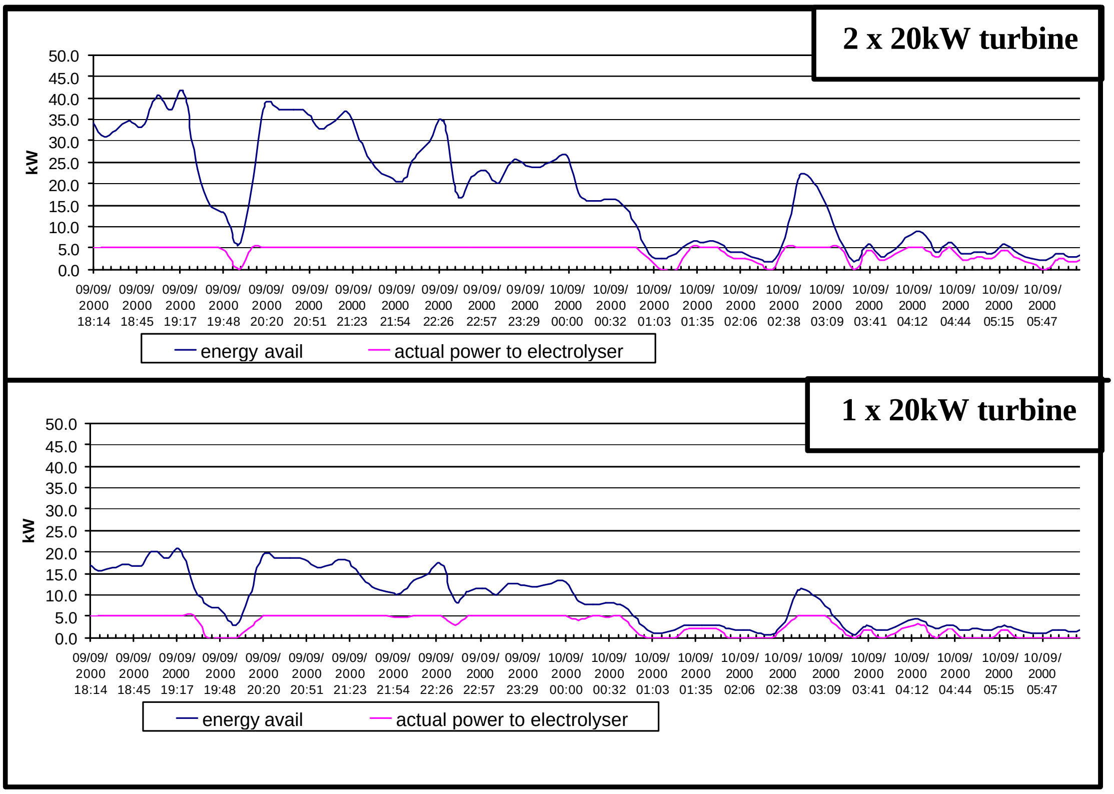


Figure 92 - Comparison of two turbine operation against one (5kW electrolyser)

9.5.6. Efficiencies

Efficiency of the electrolyser is proportional to the electrolyser consumption, as shown in Figure 93.

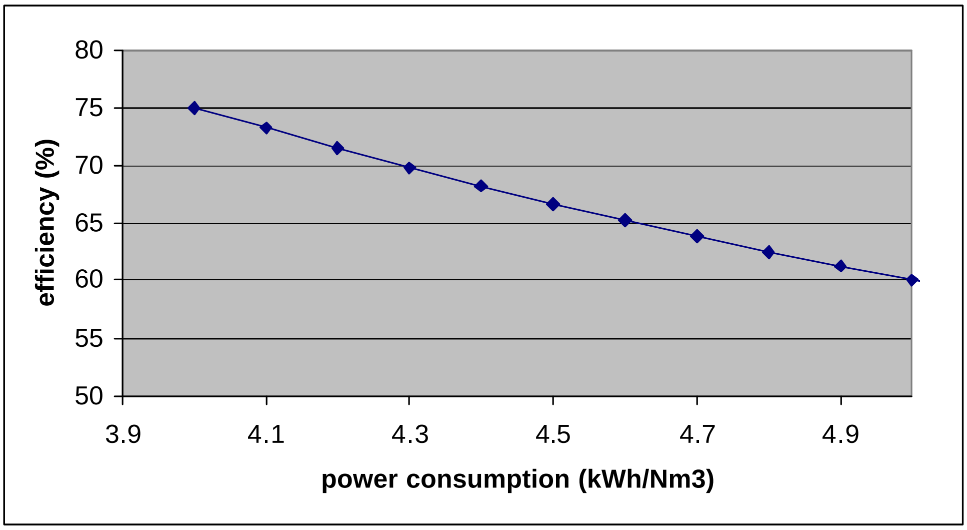


Figure 93 - Electrolyser efficiency against power consumption

The fuel cell efficiency is shown in Figure 94, based upon a fuel cell with 5% minimum load so that the full range of efficiencies can be observed. This follows the efficiency curve expected, as discussed in Section 9.3.4.

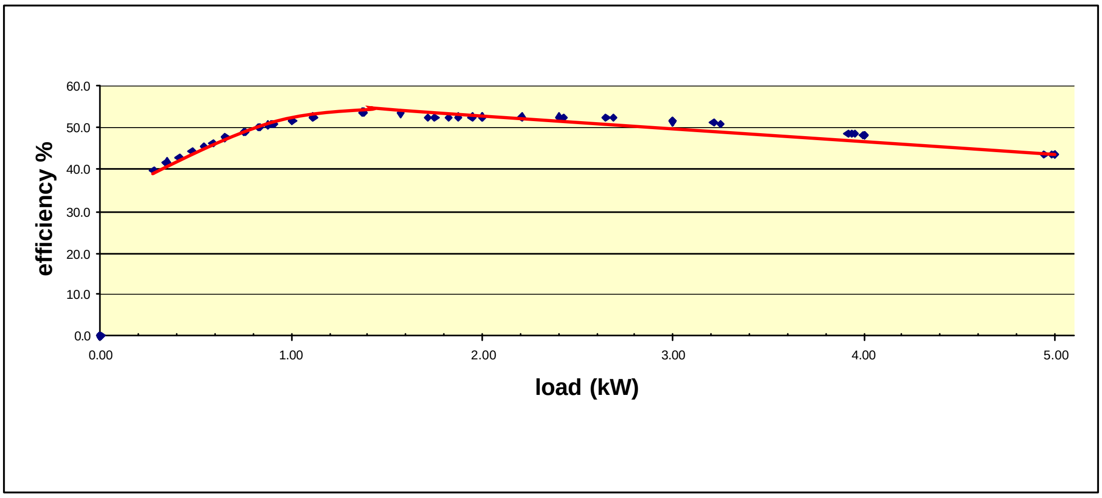


Figure 94 - Fuel cell efficiency vs load (5% min load to show the variable area)

Based upon a manufacturer's specified fuel consumption of 4.8Nm^3/kWh, a 10kW electrolyser has a maximum efficiency of 62.5%. For a 10 kW fuel cell the maximum efficiency is 54%. Taking the maximum efficiencies for the system, the following maximum overall output efficiency can be calculated (Figure 95).

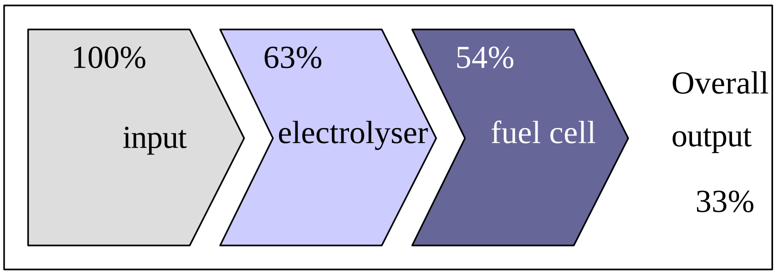


Figure 95 - Overall system efficiency

The greatest inefficiency is encountered at the fuel cell. Use of hydrogen fuel directly for thermal end uses such as heating would reduce the conversion losses associated with fuel cells. The efficiencies generated from the model compare realistically with other studies. Crockett et al,(1995) considered the efficiencies on a more detailed scale, broken down as shown in Figure 96.

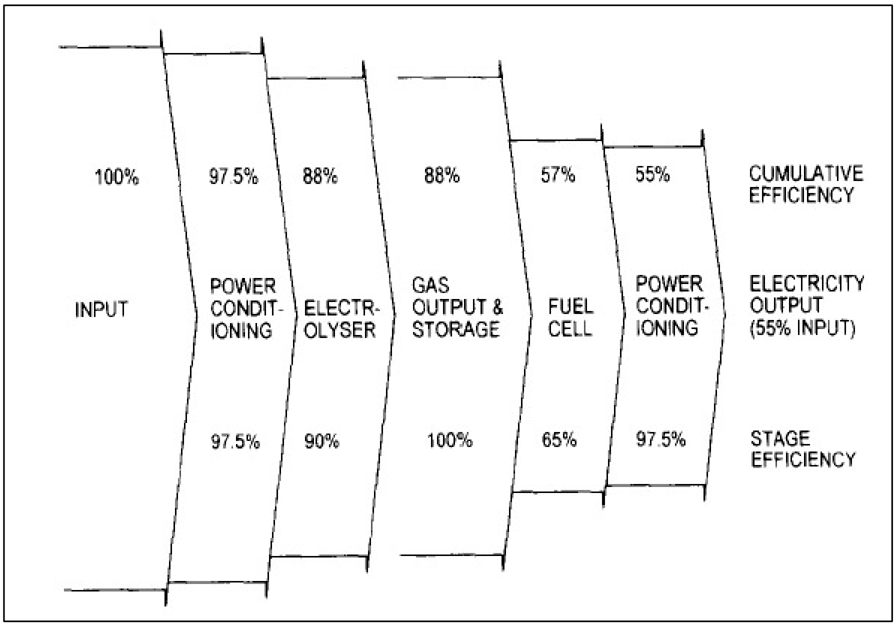


Figure 96 - Energy throughput of a PEM-based electrolyser system (Crockett et al., 1995)

Many studies do not go down to this level of detail of system components. Table 22 shows the results of a number of projects compared against those of the model.

Source		Electrolyser		Fuel cell	Overall
Model	AEL	53– 63%	PEMFC	43 – 54%	23 - 33%
Agbossou et al. (2004)	AEL	current efficiency 85% energy efficiency 60% (with compressor), 65% (without)	PEMFC	current efficiency 90%, energy efficiency 45%.	--
Crockett et al. (1995)	SPEL	90% (gases stored at operational pressure of electrolyser)	PEMFC	57% (fuel cell takes gases at pressure provided from storage)	~60%
Vanhannen et al. (1998)	SPEL	60 – 70%	SPFC	40 – 45%	24 – 35% believed that 40% can be achieved with improvements to the technology.

Table 22 - Efficiencies found on various studies

The figures of Vanhannen et al,(1998) are reasonably close to those calculated by the model. The electrolyser efficiency is slightly worse than that identified in Vanahannen (1998), whilst the fuel cell performs slightly better. This is likely due to the use of different manufacturer specifications or different loading configurations. The overall efficiency is almost the same as Vanahannen (1998) found, suggesting that the results of the model are not unrealistic.

9.5.7. Optimising for Muck

Electrolyser and fuel cell relative sizing is an important consideration. Relative rating of fuel cells and electrolysers to renewable generation varies from project to project (see Table 1), although often devices are rated at around half of the rated generation capacity of the renewable resource. The electrolyser should be matched to the fuel cell to ensure the minimum amount of hydrogen generated is adequate for the fuel cell demand, although it can over-sized if hydrogen is to be used for other purposes. If the electrolyser is generating vast amounts of hydrogen, demand will still fail to be met if the rated power of the fuel cell is too low.

There are various strategies for deciding upon the best size of the electrolyser.

? Size electrolyser to take advantage of the maximum amount of wind generation (if all hydrogen generated can be used)

? Size electrolyser to provide just enough hydrogen for the fuel cell (no extra hydrogen for other applications)

? Size electrolyser according to maximum economic capability to exploit wind generation (depends upon requirements for hydrogen for cooking, heating and transport)

9.5.7.1. Sizing the electrolyser to match the turbine:

Matching the electrolyser rating to the turbine rating (20kW) will result in production of a large excess of hydrogen. The majority of the energy available will be utilised, with only a small fraction not being used. This is an expensive option as such a high rated electrolyser is required. It would only be advised if high performance of the turbines was guaranteed and if there was a potential use for all the additional hydrogen.

9.5.7.2. Sizing the electrolyser to provide just enough hydrogen for fuel cell

A 3.25kW electrolyser will provide just enough hydrogen for the fuel cell (provided there is some initial hydrogen in storage. A considerable amount of the available energy would not be utilised. There would be no additional hydrogen to account for a smaller battery bank and for use in other applications, but this would be the least costly option.

9.5.7.3. Sizing the electrolyser according to potential for H_2 utilisation

Ideally, the electrolyser would be sized according to the capability to exploit the hydrogen generated. This will depend upon requirements for hydrogen for cooking, heating and transport. Information is not available regarding these potential demands and would need to be gathered for future study. However, allowing for some extra hydrogen generation to account for a smaller battery bank and some use in additional applications, a 10kW electrolyser can be used.

9.5.7.4. Fuel cell sizing

A fuel cell rating of 15kW, close to the prolonged peak demand level, enables the majority of demand to be met by hydrogen generation (if no wind is available directly to the grid). Further increases in demand can be dealt with in the short-term by the battery storage, as can the areas of low demand that the fuel cell is unable to operate in due to its minimum loading requirements. Potential for battery operation is shown in Figure 98.

9.5.7.5. Recommended System Configuration

A near-optimum configuration for the system on Muck is shown in Figure 97 and Figure 99. This is an approximation of the desired attributes of a system for the Isle of Muck power scheme, generating a fair excess amount of hydrogen from the available wind with a 10kW electrolyser and meeting all of the demand through a 15kW fuel cell and battery storage (Figure 98). Ideally, devices chosen will have the best minimum load and zero load consumption characteristics. It is expected that some of the excess hydrogen will be required to replace battery operation as the battery bank is down-sized, therefore the storage requirement will be less than that listed.

9.5.7.6. Additional Energy Availability

If such a scheme were to be implemented, a substantial increase in energy from fuel sources would be available to the islanders. Hydrogen storage would effectively be replacing diesel fuel that was imported to the island for use in the diesel generator, in transport and to meet any other fossil fuel demands. It would also be taking over some of the operation of the batteries.

Diesel usage on the island is equivalent to 23,400 litres per year. Using a conversion factor of (10.8kWh/litre) this amounts to a potential 252,720 kWh of energy from this fuel required per year.

electrolyser	10 kW	fuel cell	15 kW
hydrogen produced (Nm3)	372.7	hydrogen used (Nm3)	136.1
electrolyser use (% timesteps)	73	FC use (% timesteps)	15
Energy not utilised (kW)	3007.5	demand not met (kW)	215.9
store initial vol:	**10 Nm3**	energy generated (kWh)	390.6
minimum (Nm3)	1.8		
maximum (Nm3)	222.1		
period end (Nm3)	221.0		

Figure 97 - Recommended system results

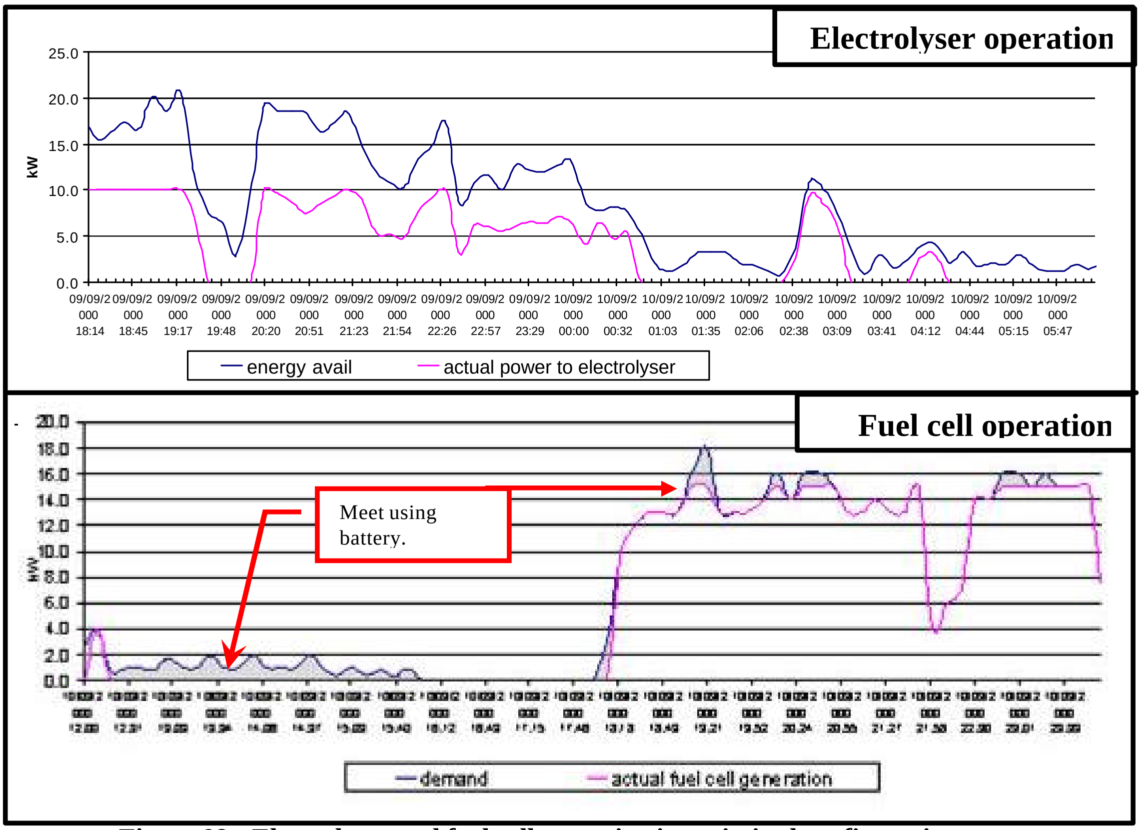


Figure 98 - Electrolyser and fuel cell operation in optimised configuration

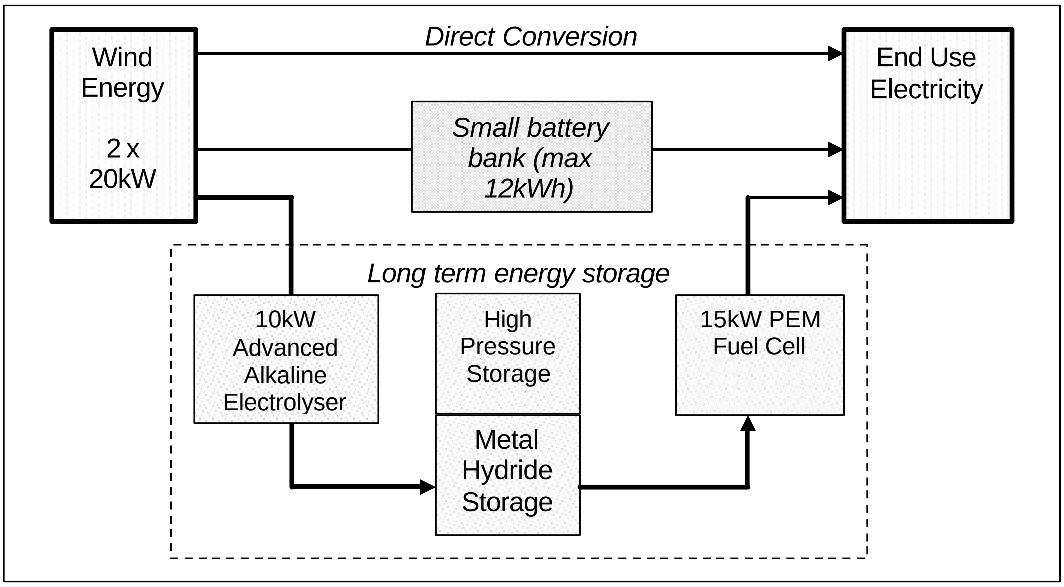


Figure 99 – Recommended system component sizes

The total Nm^3 generated figure for the 11 days studied can be multiplied by the number of these periods in the year, and then corrected for wind conditions. The average speed in this period was 15m/s. The average for the site has been found to be 8.4m/s (Section 6.5.2). The deviation from the average is 6.6m/s. To bring this back to the average, the total must be multiplied by 56%. A factor of 0.56 was used as the correction factor for the average wind speed, see Figure 100 .

DIESEL		H2	
10.8	KWH/LITRE	373	NM3/PERIOD
23400	LITRES	33	PERIODS/YR
252720	KWH	12374	NM3/YEAR
		6929	CORRECTION
		24836	DIESEL LITRES
		268229	KWH
		6	% INCREASE

Figure 100 - Annual diesel requirements and potential hydrogen production

One cubic metre of hydrogen gas is equivalent to 0.279 litres of diesel (Hionsolar, 2004). The annual figure for hydrogen gas can then be converted to diesel litres, indicating 24,836 litres of diesel equivalent to 268,229 kWh of energy. This indicates an ability to meet all the diesel requirements and have an additional 6% of energy available in the form of fuel. This is based on only one turbine is included in the model, rather than the two that actually exist. Potentially, all the power of one turbine could be used to power a hydrogen storage system. A considerable hydrogen yield could therefore be gained. If an additional turbine model is considered in normal operation of the system, an increase of 72% (Section 9.5.5.3) in hydrogen production can be expected, resulting in and overall 86% increase in energy available from fuel.

This additional energy would provide security of supply, enabling all-day-round power to be guaranteed rather than just during the priority periods. There would be no further requirement for diesel imports if the possibilities of hydrogen combustion were exploited fully in transport, heating and cooking applications. For transport purposes, pressurised gas storage is better suited (siGEN, 2004). The storage system could potentially be a combination of high pressure storage for vehicle refuelling and pipelines to houses to enable converted boilers to run on hydrogen, and metal hydride storage for electricity use, and smaller scale use in heating or cooking.

9.5.8. Hydrogen Storage System Observations

This model has provided valuable insights into the general relationship of various electrolyser and fuel cell parameters to performance. The major findings are shown below in Figure 101.

	Fuel cell			Electrolyser		
	Down rating electrolyser	Increasing Electrolyser consumption	Reducing electrolyser minimum load	Down rating fuel cell	Increasing zero load fuel consumption	Reducing fuel cell minimum load
H2 production/ consumption						
Usage time		*				
On-off switching	*		*	*		*
Use of available energy						
Demand met						
Time at full load						
Efficiency	*		*	*	*	*
Ability to exploit lower levels (energy/ demand)		*				

Key

No change	Further research required	Increase	Decrease
	*		

Figure 101 - Modelling results summary

9.5.9. Model Limitations

9.5.9.1. Turbine Model

The turbine model used in this evaluation is ideal, based on manufacturer's data. This model has been proven to differ from actual turbine behaviour, but much of the reduction in performance between the actual and modelled turbine is thought to be due to turbine loading and the overall stability of the system. The model used does not take account of loading or other aspects of previous system behaviour that would reduce turbine performance as it is expected that behaviour will improve when the additional load of an electrolyser is added to the system. For this reason, the model of the turbine and therefore the electrolyser output may be slightly over-optimistic.

As in Costa (1998), it may be worth implementing a more detailed study of the actual performance of the turbines to examine power quality, relate distortions in the grid to turbine behaviour, identify the exact reasons for the poor turbine performance, and evaluate the potential performance improvement of the turbines with addition of the electrolyser load.

On the other hand, the model used represents only one turbine, due to the poor performance of the turbines in the evaluation section of this report (section 7.3.2). As there are two turbines, the potential for electrolyser hydrogen generation may be even greater. In fact, one turbine could be solely connected to the electrolyser and fuel cell, whilst the other could be used by the system to meet demand and charge batteries and to meet dump loads. Further investigation would be necessary to assess whether this was a viable option.

The sensitivity of the electrolyser output to the turbine model is greater at higher rated turbine values (Section 9.5.9.1). 10kW is reasonably low in relation to the wind resource available, so the impact of inaccuracies in the turbine model on the results can be considered to be reasonably low.

9.5.9.2. Battery Bank

Due to the system data available, it has not been possible to split the current battery bank operation from the data used for the fuel cell evaluation. This means that the current system design incorporates a sizable battery bank. However, the battery bank in the data given is working quite inefficiently (12kWh capacity) and behaving in a way similar to a much smaller battery bank. A small battery bank will be required for buffering purposes. Reduction in the size of battery bank will place more demands on the fuel cell, but as the fuel cell is not running at full capacity for much of the time in the optimised solution and the electrolyser is generating extra hydrogen, it is anticipated that the system would not change considerably - a slightly larger electrolyser than indicated may possibly be required, but further detailed study is necessary to determine if this is a requirement.

9.5.9.3. Water Requirements

One consideration for the implementation of a hydrogen storage system on the Isle of Muck is the provision of water for cooling processes and for the electrolysis process itself. This could be collected rainwater, although it is unclear if this would provide adequate volumes of water. Alternatively desalination of seawater using a proportion of the renewable energy would be a possibility, but the water would be required to be filtered through a number of stages to achieve sufficient purity for the electrolyser (Dutton, 2002). Use of seawater directly for electrolysis may be a future possibility, but is far from being a realistic option for a near-future implementation. The model has not accounted for any energy for desalination, and has not analysed the water requirements, although a previous study assumed 1 litre per Nm^3 of hydrogen (Smith, 2002), which would represent an annual water requirement of 9,280 litres.

9.5.9.4. Modelling Facilities

This model has been implemented in Microsoft Excel. This has the advantage that the impact of changes in one parameter can be easily evaluated in the model. It enables blocks of logic to be built upon in a modular manner without requiring the use of programming code, and can enable focusing in on specific areas of interest in the data and flexible graphical analysis. The model is at a relatively simplistic level. Other modelling packages are available which could provide more detailed insights into how a hydrogen system would perform on Muck, although these were not available for use at the time of writing this project. The system described by Bonanno et al. (1998) would be useful as it takes account of the power dynamics of the system, although in 1998 did not have a facility to model hydrogen components. More powerful optimisation of the system could be carried out using similar programs to those of Isherwood et al.(2000). In terms of modelling storage, which has not been addressed in this study, the work of Vanhanen et al.(1996) contains a good source of formula for future work on metal hydride storage.

In order to take the modelling further, the methodology for predicting performance of renewables described in Celik et al.(2000) could be used to project performance of the energy system into the future. Costing of the systems could be carried out in more detail using a methodology similar to that of Weisser (2004).

9.6. Economics

9.6.1. Hydrogen System Savings

Long-term cost reductions can be achieved when replacing diesel generators with fuel cells. Although the initial capital cost is high, in the longer term (8 years plus), fuel cells are lower maintenance, and do not consume costly fuel (Isherwood et al., 2000). The cost of diesel fuel is expected to increase in future, and the simulations of Isherwood et al.(2000) showed that the outcome of economic analyses were very sensitive to fuel cost, which is already very expensive on Muck. Additional benefits of decreasing diesel use include reduced noise, cleaner air, lower risks of fuel spillage, attraction of eco tourism, reduction of greenhouse gas emissions (Barton, 2003) and transportation savings (Isherwood et al., 2000).will potentially make hydrogen storage technologies more competitive in the future.

A detailed economic costing of a hydrogen storage scheme is not possible within the scope of this project. However, it is possible to attain a general understanding of costs and assess the economic benefit of such a system in terms of money saved on diesel imports and battery bank upgrades.

Annual diesel import costs to Muck are detailed below in Table 23. The cost per year for diesel imports to the island is at least £5,800. If hydrogen could be used in place of diesel, these imports would be no longer required, increasing the autonomy of the island.

import frequency (times/year)	quantity imported each time (litres)	shipping cost per 200 litres	ship cost per litre	standard cost per litre	combined cost per litre
4.5	5200	£6	£0.03	£0.22	£0.25
total imported in year (litres)		total cost of shipping per year		standard diesel cost per year	total overall cost for year
23400		£702.00		£5,148.00	£5,850.00

Table 23 - Diesel import costs for Muck (Isle of Muck Power Company, 2004)

In addition, the battery bank is due for upgrading in 2007/2008, or possibly even sooner due to very poor performance. The disappointing performance of the current battery bank raises questions about how much more reliable another battery bank would be with the current system in place. Without assurances that it will operate any better than the previous battery bank, any new investment is a risk. The cost of the battery bank in the current scheme as implemented in 1998 is shown below in Table 24.

	COST BREAKDOWN				
BATTERY STORAGE COSTS	specification and design	capital outlay	shipment, installation and commissioning	total	cost incurred in upgrading?
10kW INVERTER	80	8000	80	8160	N
LEAD ACID BATTERIES [6 HOUR SUPPLY]	102	10150	102	10353	Y
BATTERY STANDS	13	1250	13	1275	N
BATTERY CHARGER	30	3000	30	3060	N

Table 24 - Battery bank costing

In comparison to lead-acid battery use, hydrogen storage has the economic advantage for long-term storage. Increased energy storage can be added by increasing only the size of the hydrogen storage component (i.e. storage tank), therefore the cost of extending storage is relatively low per kilowatt hour (Isherwood et al., 2000). Instead of incurring this capital cost in a potentially poorly performing battery bank, the capital could be put towards a hydrogen storage scheme.

Combining the saving in diesel imports with the saving in capital investment in a new battery bank, the cost saving over 10 years is shown in Table 25.

10 year saving	
capital	£10,353.00
annual	£5,850.00
total	£68,853.00

Table 25 - Cost saving of hydrogen storage scheme

This £69k saving can be taken into account when considering the cost of any hydrogen storage scheme. An optimistic study by Marschoff (1998) concluded that potential cost savings from the use of fuel cells largely justified their installation, although other studies have raised concerns about the influence of fuel prices, wind regimes, and the system size (Dutton et al, 2002).

9.6.2. Hydrogen Storage System Capital Costs

In terms of capital cost of the hydrogen components for this project, only vague figures are available. The potential costs of the recommended system include primary components of:

? 10kW electrolyser or electrolyser combinations

? 15kW fuel cell or fuel cell combination (3 x 5kW)

? 100 Nm3 storage (split between metal hydride and high pressure storage)

The electrolyser is expected to cost around half of the total cost of the power system (Jacobson et al., 2001). The use of the electrolyser can be made more economic if a commercial use can be found for the oxygen by-product (Agbossou et al., 2004). This may be a worthwhile area of future research. The economies of scale in terms of size of electrolyser are evident in the chart below (Dutton et al., 2000)

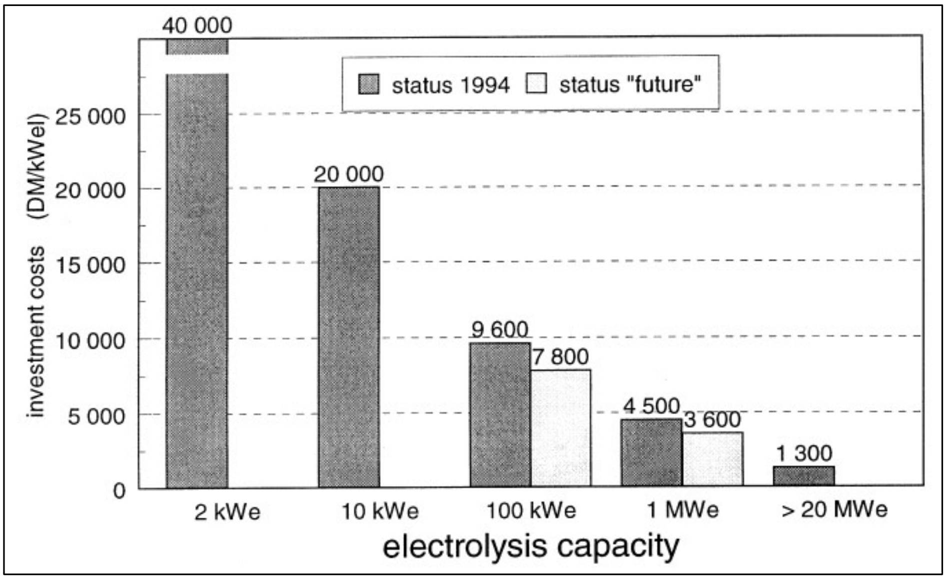


Figure 102 - Electrolysis economics (Dutton et al., 2000)

It should be noted that these costs are from four years ago, and were based on tender exercises from different manufacturers and literature surveys. Costs will have decreased since the time of publication of this paper due to advances in manufacturing, increases in production volumes etc. The investment costs (in Deutche Marks) range from an estimated 40,000 DM/kWel (£13,960/kWel) for a one-off 2KW plant down to an estimated 1300 DM/kWel (£453.7/kWel) for a 20MW plant. The cost of auxiliary components such as control systems, compressors and safety systems remains more or less the same for small and large systems, so clearly the economics are more favourable for larger system implementations.

Current installed component cost estimates have been obtained for the components shown in Table 26 (siGEN, 2004). From this year to last year, a drop of 20% in technology prices was experienced. It is expected that this trend will continue, although it may even accelerate if there are technology breakthroughs or if larger players become involved (siGEN, 2004). Table 26 assumes a 20% reduction rate over the first three years, with a 15% then 10% discount in the fourth and fifth years respectively.

	Costs (Current)	Projected (3yrs)	Projected (5yrs)
electrolyser 15kW	£100,000 to £200,000	£51,200 to £102,400	£39,168 to £78,336
fuel cell 15kW	£50,000 to £60,000	£25,600 to £30,720	£19,584 to £23,501
storage 50m3	£50,000	£25,600	£19,584
total	£200,000 to £310,000	£102,400 to £158,720	£78,336 to £121,421

Table 26 - Hydrogen system component costs

It should be noted that the electrolyser considered in this pricing exercise has been sized to match the fuel cell. In the recommended configuration of the hydrogen storage for Muck, the frequency of fuel cell operation is reasonably low, but the 15kW rating is still required to meet peak daytime demands. Due to the low demand at other times of the day and good wind regime, a lower rated electrolyser will still allow for considerable quantities of hydrogen to be generated, as indicated in section 9.5. This allows for a smaller electrolyser. As the electrolyser is the most expensive component, reducing its size has considerable economic benefits (though the economies of scale as indicated in Figure 102 should still be taken into account). Therefore, the lower end of the electrolyser cost estimate should be used.

It is clear that over time hydrogen-based storage systems will become more competitive. However, pioneering schemes can receive substantial funding, so it may be more prudent to implement the scheme sooner rather than later. To implement the scheme currently, costs in the region of £205,000 may be incurred (offset against a potential 10 year saving of approximately £70,000 in diesel and battery costs). Potential funding for this kind of scheme can be considerable if the project is on the cutting edge. On Unst, grants of 300,000 were sourced for a smaller scale hydrogen scheme (siGEN, 2004) in a semi-grid connected situation (see section 4.5.1 for more details). The uniqueness of the Muck scheme, being entirely islanded and community owned, means that it could potentially demand just as great sums, if not more.

9.7. Summary

This section uses models of generic electrolysers and fuel cells to provided valuable insights into the potential of a hydrogen system on the Isle of Muck, and into the general relationship of various electrolyser and fuel cell parameters to performance. An evaluation of sizing strategies for electrolyser–fuel cell combinations against actual system data was carried out using these models which would not have otherwise been possible. The validity of the model is reinforced by the fact that efficiency calculations for the electrolyser and fuel cell are a good match with previous studies.

Results for implementation of a scheme with a 10kW electrolyser and 15kW fuel cell indicates a considerable potential increase in energy available to the islanders in the form of fuel (from 6 to 86%), with diesel being completely replaced by hydrogen. This additional energy provision from the existing wind turbine system will enable the islanders to get much more out of their previous investment, freeing them from the restrictions of “priority periods”.

A number of strategies for the electrolyser sizing have been illustrated. These should be considered in the context of the wind resource and turbine operation, the hydrogen requirements of the fuel cell, and the hydrogen combustion requirements.

Implementation of such schemes is still very costly as the technology is still in the early stages of commercialisation. However, improvements in the technology may reduce the cost of implementing scheme to potentially 40% of current cost in 5 years time. In addition, if the scheme is to be implemented sooner rather than later considerable funding may be available.

Participation in such a scheme would not only improve the environment on Muck, making it a truly “green island”, it could also offer considerable tourism opportunities.

9.8. References

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10. Conclusions and Recommendations

10.1. Conclusions

Two main issues in particular were identified in the early analysis of the current power system on the Isle of Muck. These were poor battery bank performance and potential problems due to slow reacting dump load control. The overall availability of dump loads was much lower than expected by the control system - a reduction of 27% in available loads in winter and 59% in available loads in summer impacting on the ability of the dump load control mechanism to stabilise the network.

A thorough analysis of the operation of the system was implemented, especially with reference to the wind turbine. Data from the actual turbines indicated that they were operating at levels of less than half the theoretical turbine performance, with many spikes from zero power to a disproportionately high peak. A model based upon the manufacturer's power curve for a single 20kW turbine was used to represent the total power output of the two turbines (rationale discussed in Section 7.3.3).

The two turbines were found to perform quite differently depending upon the wind conditions. Often one turbine was found to be generating whilst the other was not. Local effects such as interference, wake and turbulence could be responsible for part of this behaviour, but it may also have been due to turbine or inverter faults. The frequent spikes in the power readings were indicative of turbine over-speeding. The fact that these showed up in power readings when there was no inverter activity (so the turbine was effectively disconnected), raised questions about the quality of the actual wind turbine data. Power was being calculated where clearly no generation was occurring so that the reading appeared more reflective of the turbine activity than of actual power generation.

The final turbine model took into account loading and voltage variation. Inadequate load on the system to absorb turbine energy, resulted in considerable loss of turbine efficiency. Delays in dump-load allocation resulting in voltage fluctuation (+9.6% to -15%) also impacted on the turbine efficiency, though only resulting in a maximum change in model output of around 0.4kW. The model expected over-speeds to occur at wind conditions near cut-in, and if the battery took over supply to the grid. If the turbines were not connected to the battery, then the model would only show a minimal level of generation.

This final turbine model identified loading as being one of the biggest influences on the turbine behaviour. A model accounting for the impact of loading on the turbine provided a good reflection of turbine behaviour, following the majority of peaks and troughs of the actual turbine. A correction factor for amplitude was assumed to take account of factors which had not been identified or which it has not been possible to model. This provided an excellent match in windy conditions, but in a non-windy period it was more difficult to predict exactly the turbine performance due to the nature of the overspeeding behaviour.

As loading has such an influence on the turbine behaviour, introduction of a hydrogen storage system would potentially improve the system stability and energy extraction from the wind turbines by enabling more variable load to be added to the system. Modelling of generic electrolysers and fuel cells based upon manufacturer-specified parameters provided valuable insights into the potential of a hydrogen system on the Isle of Muck, and into the general relationship of various electrolyser and fuel cell parameters to performance. An evaluation of sizing strategies for electrolyser–fuel cell combinations against actual system data was carried out using these models which would not have otherwise been possible.

Modelling results for implementation of a recommended scheme including a 10kW electrolyser and 15kW fuel cell indicated a considerable potential increase in energy available to the islanders in the form of fuel (from 6 to 86%), with diesel imports being completely replaced by independently generated hydrogen. The additional hydrogen could be used in combustive applications with an even greater efficiency for transport, heating or cooking. The addition of long-term energy storage to the existing wind turbine system could also free the islanders from the current restrictions of “priority periods,” with power being guaranteed 24 hours a day. Participation in such a scheme would not only improve the environment on Muck, making it a truly autonomous “green island”, it could also enhance the attractiveness of the Isle of Muck to tourists, having a substantial positive impact on the main local industry.

Implementation of such schemes is very costly as the technology is still in the early stages of commercialisation. However, improvements in the technology may reduce the cost of implementing scheme to potentially 40% of current cost in 5 years time. In addition, considerable funding is currently available for unique groundbreaking projects such as this provided the interest in the community exists to take on such a venture. The findings of this project indicate that a full and detailed engineering feasibility study to consider in more detail how such a study may be implemented and financed would be of considerable merit.

10.2. Recommendations

If further investigation into the potential of a hydrogen storage system on the Isle of Muck is to be carried out, a number of recommendations for further analysis, which it has not been possible to address within this thesis, should be taken into account.

? **Detailed System Modelling:** Modelling of the operation of the system as a whole in terms of the impact the hydrogen devices will have on the power quality and turbine operation, without the current battery bank impacting on the model, and with separation of thermal loads from demand figures would provide valuable insights. Additional modelling programs are available for these purposes, discussed in various sections in this report. Improved measuring devices (not pulse meters) in the actual system would give better data to work from.

? **Turbine Performance:** A more detailed study of current turbine performance would enable better prediction of turbine performance with electrolyser installed on system (performance of turbine, and thus electrolyser may have been over or under estimated in this study).

? **Device Specifications:** Gather more data on electrolyser and fuel cell specifications to analyse performance of different models.

? **Electrolyser Control Strategies:** Take into account strategies for electrolyser interaction with batteries (variable/fixed current mode).

? **Electrolyser and Fuel Cell Warm Up:** Minimum on and off times have not been taken into account in the current model, but these could have a major impact on the overall system dynamics. Also on-off trigger levels should be considered.

? **Electrolyser Efficiency Calculation:** Variation in efficiency has been based upon the ratio of electrolyser load to grid voltage, but it is likely the introduction of the electrolyser will have an impact on grid voltage. The electrolyser will be working at a DC voltage. Provision of more detailed electrolyser parameters would enable a more accurate calculation of efficiency.

? **Water Supplies:** Provision of water for such a scheme on Muck is an important consideration. Ability to meet water requirements is essential for the success of the implementation, and should be considered in the initial stages of any feasibility studies.

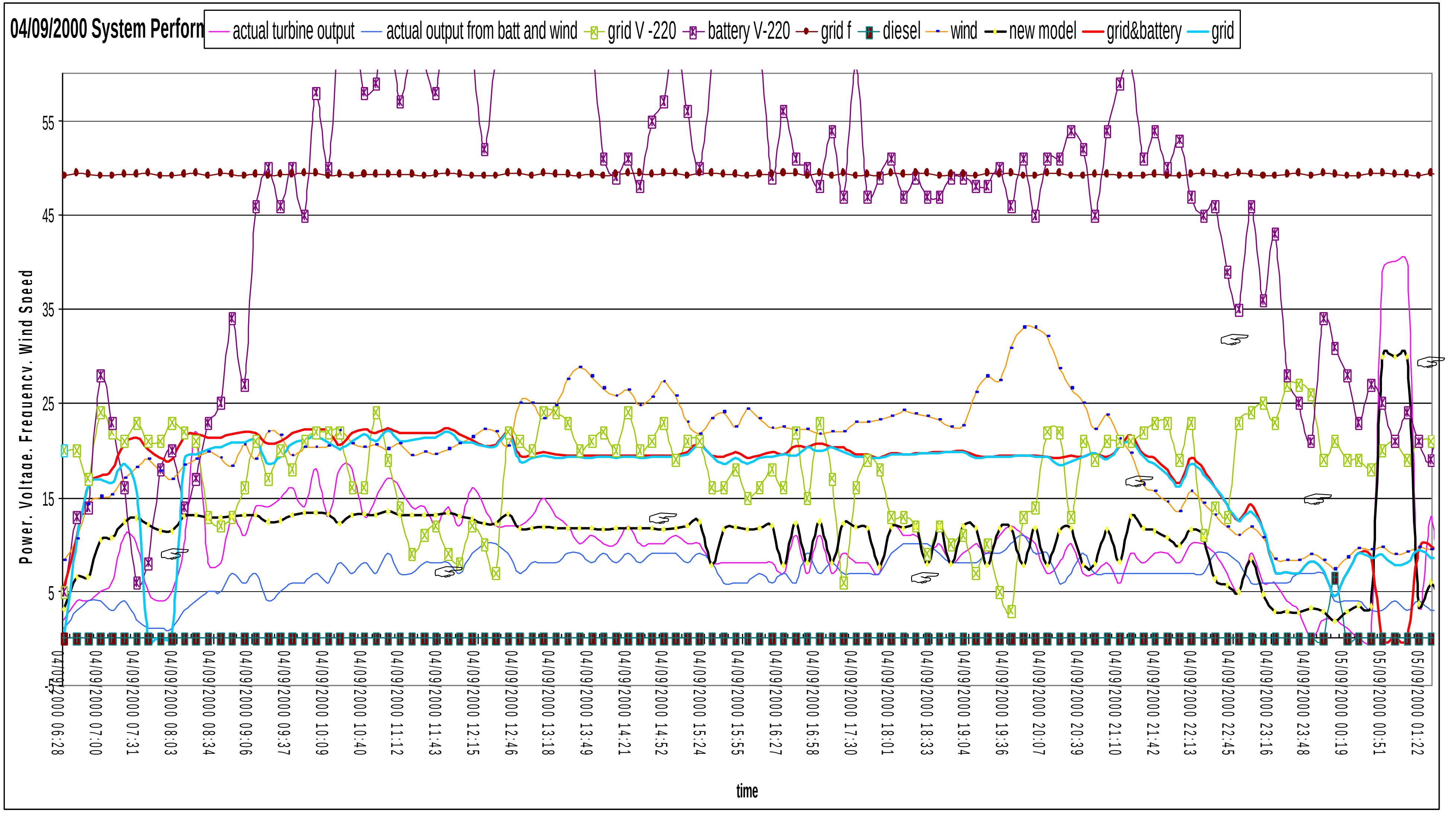
? **Temperature:** Consideration of the impact of local temperature variations and operating temperatures on the performance of fuel cells and electrolysers e.g. requirements for heating to reach operation temperature.

? **Storage modelling:** More detailed modelling of storage is required, as it has not formed part of the modelling in this study.

? **Costing:** A detailed cost analysis working with hydrogen system suppliers would provide a much better idea of potential system costs. Homer could be used for this purpose.

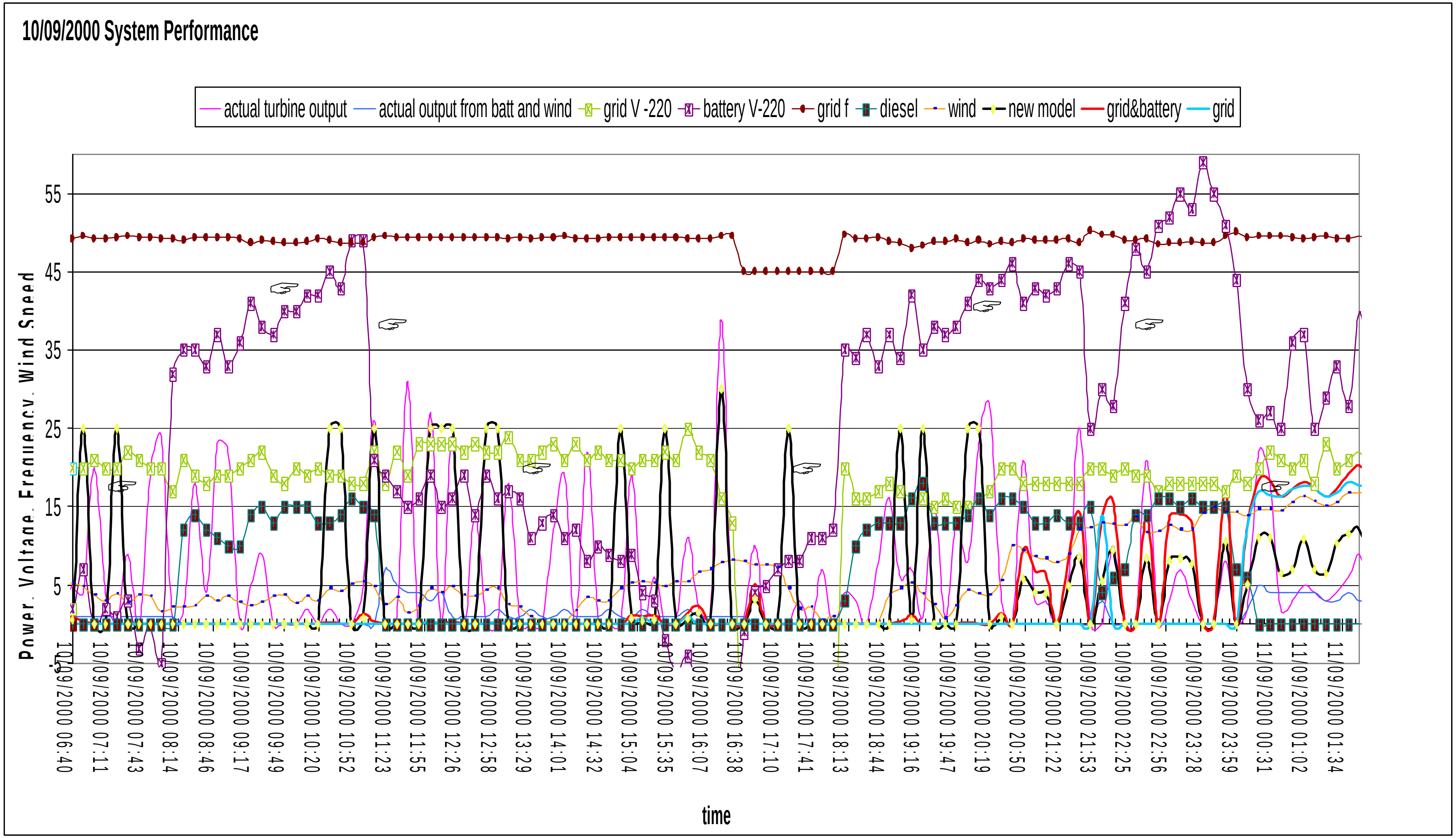
11. Appendices

1.1. Actual System Activity – 04/09/2000



Point	Description of events
1	Before the priority period (08:00), wind conditions are slightly lower, so the battery has been drained a little to meet this demand. However, as the priority period begins and demand increases, so does the wind speed and therefore the turbine output. The turbines meet demand and are able to charge the battery.
2	At 11:00 hours, the end of the priority period, there is a drop in grid voltage (green) as demand increases and some battery discharge is required. However, this extra demand is not on the system for long, and by 12:30 hours the grid voltage improves again. The system is supplied with around 9kW throughout the day – on a day like this, demand will be more level as washing machines etc. will be switched on outside of priority periods when the excess wind indicator is alerting residents.
3	From points 1 to 3 the model does not appear to be predicting the same peaks and troughs as the turbine is experiencing, suggesting that there are still other factors that need to be taken into account in the model design. However, after this time there is a good correlation between the model and the actual turbine.
4	At point 4, the actual data for the turbines shows them struggling at times to meet demand (indicated by drops in grid voltage and the closeness of the thin blue and pink lines), and so the batteries assist in smoothing the output of the turbines to the grid.
5	The wind speed begins to decrease at this point, but demand decreases slightly so the grid voltage stabilises.
6	At this point, the battery discharges reasonably quickly, as the wind conditions worsen and the turbine output drops considerably. Demand is also slowly decreasing as it gets closer to the end of the priority period – however, there is one short rise in demand at around 22:45, which could be down to a washing machine or similar being switched on. This causes a dip in grid voltage and requires additional power from the batteries (crossover of pink and blue lines)
7	Point 7 is in the very last stretch of the priority period. There is still a demand of around 8kW, but output from the wind turbines drops considerably, and battery voltage is reasonably low, so the diesel generator experiences a false start as it tries to start just before the priority period end, and promptly cuts out.
8	The turbines overspeed at this point, with the model also predicting this occurrence. The batteries are acting as the main source of power.

1.2. Actual System Activity – 10/09/2000



Point	Description of events
1	The jagged line of the battery voltage (burgundy) shows that the battery is discharging due to the low speed of available wind (the turbine is not generating), to provide limited power to the grid. Demand at this point is likely to be devices such as fridges etc, as it remains relatively static (see flat dark blue line) at around 1.5kW. A steep increase in battery voltage indicates the start of the priority period (08:00 hours). At this point, the power from the battery and turbine are not enough to meet the actual demand, so the diesel is initiated (turquoise line), and supplies not only the demand but also charges the battery.
2	The battery is charging from the diesel generator. There is no output from either the turbines or the battery to the grid – the turbines are effectively disconnected – not surprising, as the wind speed wavers around the cut-in speed of 4.5 m/s. However, the turbines are overspeeding at this point.
3	End of priority period. Sudden sharp decrease in battery voltage. This occurs because the diesel has disconnected, but there is still load on the system. The turbines are still supplying no energy to the grid, but occasionally charge the battery when the wind speed exceeds the rated speed. The pink line, actual data for the turbines, indicates that they are disconnected and running freely– this power is not going to the grid
4	The battery is discharging, (we can tell as the thin dark blue line indicates power low from the turbine/battery inverter to the grid, but we know that the turbines are not generating). Demand is gradually decreasing (blue line) as we move further away from the priority period. The battery becomes very discharged, and voltage drops rapidly. As the wind speed increases, the turbine is able to generate a small amount of power for the grid and to charge the batteries (indicated by the thick light blue and red lines).
5	The turbines slowly begin to charge the battery from a low state of charge (red line), but is not sending any power to the grid. Without enough energy to meet demand (which would start to increase at 17:00 hours, though not a priority period), the grid voltage plummets, as does the grid frequency. At this point the grid has shut down. However, at 18:00 hours the priority period begins, giving the opportunity to charge the batteries from the diesel, and meet demand of around 12kV. The grid voltage recovers.
6	The battery is charging at this point, from the turbine and possibly the diesel generation. There is no power flow from the battery or the wind turbines to the grid.
7	A sudden drop in battery voltage is observed. This is because the battery and wind turbines momentarily take over as the wind conditions improve, and the diesel is past it's minimum on-time. The turbines charge the battery and send some power to the grid, but this does not appear to be sufficient to meet demand, which is still high, and so the diesel re-starts, whilst the turbines charge the battery due to increased wind speeds.
8	At 00:00 hours, the priority period is finished, so the diesel cuts out. The battery voltage decreases suddenly, and the turbine continues to meet some of the grid demand whilst also charging the battery (thick red and blue lines).