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Modelling and Analysis of Hydrogen-based Wind Energy Transmission and Storage Systems:

HyLink System at Totara Valley

A thesis presented in partial fulfilment of the requirements for the degree of

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Abstract

Distributed generation has the potential to reduce the supply-demand gap emerging in New Zealand's electricity market. Thereby it can improve the overall network efficiency, harness renewable energy resources and reduce the need for upgrading of existing distribution lines.

A typical New Zealand rural community consisting of three adjacent farms at Totara Valley near Woodville represents a demonstration site on distributed generation for Massey University and Industrial Research Limited. Local renewable energy resources are being used for the purpose of sustainable development. Alternative micro-scale technologies are being combined to achieve a valuable network support.

This paper is an in-depth report on the implementation process of the HyLink system; a system which utilises hydrogen as an energy carrier to balance and transport the fluctuating wind power. The report documents its development from the laboratory stage to commissioning at Totara Valley, which was carried out under direction of Industrial Research Limited.

The PEM electrolyser's performance at different stack temperatures was investigated. It was found that hydrogen production increases at the same voltage with a higher stack temperature. This is due to the improved kinetics of the electrochemical reactions and decreased thermodynamic energy requirement for water electrolysis. The electrolyser efficiency measurement at the half of its maximal power input (247 W) resulted in 65.3 %. Thereby the stack temperature attained less than half of the allowed limit of 80°C. The capture of the excess heat by insulation can improve the electrolyser's efficiency.

Pressure tests were performed on the 2 km long pipeline at Totara Valley using hydrogen and natural gas in order to test their permeability. The results were compared with previous studies at Massey University and with data obtained from the industry. The hydrogen permeability was measured to be 5.5×10^{-16} mol m m⁻² s⁻¹ Pa⁻¹ for a 2 km MDPE pipe. This is about half the result obtained from previous studies on

hydrogen permeability through MDPE at Massey University which was undertaken at room temperature. The reason for this discrepancy is likely to be the lower ambient temperature during the measurement at Totara Valley, which can be supported with the Arrhenius equation. It was furthermore measured that the power loss due to hydrogen diffusion through the pipeline walls during the fuel cell operation is about 1.5 W at the current system operation mode.

A techno-economic analysis of the system was undertaken applying the micro-power optimisation software HOMER as a simulation tool. Two operation modes of the system were investigated, the load following and the peak demand compensating. The simulation results reveal that the durability and the cost of the electrochemical energy conversion devices; electrolyser and fuel cell, are the main hurdles which need to be overcome on the path in introducing hydrogen based energy systems like HyLink.

Finally, economic optimisation modelling of the small-scale system by best component alignment was performed. It was found that the electrolyser capacity down-rating of 80% in relation to the wind turbine capacity, leads to a minimal system levelised cost. In addition to this, the impact of various wind turbine/electrolyser subsystems and pipeline storage capacities on the fuel cell capacity factor and on the system levelised cost in the load following operation mode was analysed. The outcomes can be useful for further HyLink related energy system planning.

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1. Introduction

New Zealand, like other countries, moves progressively towards a more sustainable energy future. The Energy Efficiency and Conservation Authority's (EECA) efforts on the further development of the National Energy Efficiency and Conservation Strategy, as well as the upcoming Biofuels Sales Obligation administered by the Ministry of Economic Development (MED), underpin the government's long-term view. The country's hydro power dominated electricity generation allows the maintenance of its nuclear free status. However, the emerging constraints on natural gas supply and increasing public resistance to new large hydro developments require adequate supplements to meet the ever growing energy demand.

The electricity infrastructure in New Zealand, a sparsely populated country, is characterised by few major load centres and a widespread rural network. Large central power stations cover the general electricity demand including the high number of lightly loaded remote communities. This means that the distances between the power plants and the customers become often significantly long. As a result, about 15% of the electricity generated in NZ is lost as heat in the power lines during transmission and distribution (PCE, 2005).

This traditional system of large power plants will likely be complemented by smaller plants located closer to their loads. Not only do such distributed generation (DG) systems reduce power line losses and maintenance costs, but also have the potential to capture and utilise waste heat on site and hence increase their overall efficiency. Many integrated smaller units that are spread over a wide territory reduce the threat of massive outages. The major aim of DG investment in New Zealand from an economic point of view is to extend the network capacity, lower the need for upgrading the existing power lines, and additionally provide consumers with an opportunity to hedge against the increasing electricity prices.

The distributed energy systems may differ in size, configuration and energy source depending on their respective application. While some of them may serve as stand-by

power systems or cogeneration plants at industrial and commercial sites, others can appear as wind farms supplying directly into local distribution networks.¹ The subject of this study relates to grid-connected remote area power supplies (RAPS).

A typical New Zealand rural community consisting of three adjacent farms in Totara Valley near Woodville represents a demonstration site on DG for Massey University (MU) and Industrial Research Limited (IRL). The general objective of the project is to create a renewable hybrid micro-power system at the end of a 10 km long 11 kV distribution line with the task to supplement the energy provided by mains, and at the same time, to establish a platform for research on new energy concepts with a direct application aspect.

After the monitoring of local renewable energy resources and the community's energy load profiles for over one year, several small-scale technologies have been installed in Totara Valley such as photovoltaics, solar water heating, bio-diesel generator, hot water heat pumps and micro-hydro. This study focuses on the implementation of the hydrogen link system dubbed the HyLink.



Figure 1.1 Totara Valley community

¹ Wind farms supplying directly into transmission lines can't be considered as distributed generation systems.

As the community is located in a valley, one of the surrounding hills was chosen as the appropriate wind site at a distance of two kilometres (Figure 1.1). The hilly terrain and the unfavourable distance would make the power line installation expensive and the use of high voltage equipment unavoidable, not to mention the issues associated with the storage of the intermittent wind power. A potential niche for hydrogen technology was identified.

An electrolyser can be powered by the wind turbine to produce hydrogen, which will be piped down the hill to feed a fuel cell or a hydrogen burner. In this configuration the pipeline undertakes the task of storing and transporting energy. Middle Density Polyethylene (MDPE) was identified as the most suitable pipe material in a previous study at Massey University, and a Zebedee furl system controlled wind turbine manufactured by Proven was installed on the hilltop. A test model of the HyLink system including control and monitoring electronics was designed at IRL's laboratory.

1.1 Objectives

This paper is an in-depth report on the implementation process of the HyLink system in Totara Valley. Its primary objective is to document the development of the system from the laboratory stage to the commissioning at Totara Valley.

The practical work will include collaboration in the process design of the HyLink as well as electrolyser and pipeline testing.

The study's focus is the system analysis from the economic and the technical point of view. The purpose is to provide an effective analytical method which can be applied to identify the economically most optimal system component configuration for any related project.

For this reason a model will be developed, which enables the simulation of energy and cash flows realised by the HyLink system. The micro-power optimisation software (HOMER) will be applied as a simulation tool, in particular the latest versions with improved hydrogen load modules.

It is expected that the simulation outcomes will be useful for further HyLink related energy system planning.

2. Background

2.1 Motivation for Hydrogen as an Energy Carrier

The increasing use of fossil fuels accelerates its depletion and, at the same time, causes serious environmental problems. Worldwide efforts are being made to introduce hydrogen as a viable energy carrier with the potential to counter these issues.

Hydrogen has many unique properties compared with other fuels. It is the lightest and most abundant element. At standard temperature and atmospheric pressure, hydrogen has high energy content by weight and low energy density by volume. Table 2.1 compares hydrogen's physical and chemical properties with methane and propane.

| Properties | Gas | | |
|--|----------------------------|----------------------------|--|
| | Hydrogen (H ₂) | Methane (CH ₄) | Propane (C ₃ H ₈) |
| Density (kg/Nm ³) ^a | 0.0838 | 0.6512 | 1.870 |
| Lower heating value: | | | |
| kWh/kg | 33.31 | 13.90 | 12.88 |
| kWh/Nm ³ | 2.80 | 9.05 | 24.08 |
| Upper heating value: | | | |
| kWh/Nm ³ | 3.30 | 10.04 | 26.19 |
| Diffusivity in air at NTP (cm ³ /s) | 0.61 | 0.16 | 0.12 |
| Ignition energy (mJ) | 0.02 | 0.29 | 0.26 |
| Explosion limits in air (vol %) | 4-75 | 5.3-15.0 | 2.1-9.5 |
| Explosion energy [(kg TNT)/m ³] | 2.02 | 7.03 | 20.5 |
| Autoignition temperature (°C) ^b | 585 | 540 | 487 |

"Density for a normal cubic metre at 293.15 K, 0.101 MPa.

| Table 2.1 The physical and chemical properties of hydrogen as compared w | with |
|---|------|
| methane and propane (Ackermann, 2005) | |

Hydrogen can be converted directly into electricity in fuel cells without involving any moving parts. The process is noiseless and carbon neutral. Unlike combustion engines, fuel cells are not subject to Carnot Cycle limitations. This implies that they can have high efficiencies in converting chemical energy to electrical energy.

Thanks to their highly scalable design, fuel cells have already been developed for different applications. For example, Proton exchange membrane (PEM) fuel cells were used on NASA's Gemini space missions and were replaced by the alkaline fuel cells (AFC) in the Apollo programme and the Space Shuttle.

The largest potential commercial market for fuel cells is the stationary power generation for utility applications, including:

- Residential applications in the size range of around 1 to 5 kW using PEM fuel cells. Besides electricity generation, waste heat can be used for hot water or space heating.
- Onsite cogeneration power plants in the size range of about 200 kW to 1 MW capacity. Phosphoric acid fuel cells (PAFC) dominate this fuel cell market with a combined heat and power efficiency of about 80%. The 200 kW PAFC was introduced into the market in 1991 by International Fuel Cells/ONSI, now called UTC Fuel Cells. PAFC units have been installed in various applications commercial, small industrial, landfill, and military and some are used for cooling, heating, and power. By 2004 there have been 250 units sold, at roughly US\$4,500/kW. The U.S. Department of Defence (DOD) subsidised three-quarters of those produced (Committee on Alternatives and Strategies for Future Hydrogen Production and Use, 2004).
- Dispersed electric power generation in the size range of around 2 MW to 20 MW. At present, electricity is typically generated in a central thermal power plant and then distributed through the grid. In the future, it could be possible to have a fuel cell system, based on molten carbonate (MCFC) or solid oxide fuel cells (SOFC), generating electricity and heat. These fuel cells would be able to provide a neighbourhood of several blocks of streets with natural gas as the primary fuel for fuel cell operation.
- Base-load electric power plants, MCFC or SOFC, in the size range of about 100 MW to 300 MW operate on coal or natural gas. In the United States alone one can find 750 GW of installed capacity (Li, 2006).

Unlike alkaline, phosphoric acid and PEM fuel cells, the molten carbonate and solid oxide fuel cells don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which they operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming. In regards to direct methanol fuel cells (DMFC), which are a further development of PEM fuel cells, methanol, is not reformed but fed directly to the fuel cell. Table 2.2 outlines the applications of different fuel cell types.

| Fuel cell type | Mobile ion | Operating temperature | Applications and notes |
|--|-------------------|--------------------------|--|
| Alkaline (AFC) | OH- | 50-200°C | Used in space vehicles, e.g. Apollo, Shuttle. |
| Proton exchange membrane (PEMFC) | H+ | 30-100°C | Vehicles and mobile applications, and for lower power CHP systems |
| Direct methanol (DMFC) | н+ | 20-90°C | Suitable for portable electronic systems of low power, running for long times |
| Phosphoric acid (PAFC) | H+ | ~220°C | Large numbers of 200-kW CHP systems in use. |
| Molten carbonate (MCFC) | CO3 ²⁻ | $\sim 650^{\circ}C$ | Suitable for medium- to large-scale CHP systems, up to MW capacity |
| Solid oxide (SOFC) | O ²⁻ | 500-1000°C | Suitable for all sizes of CHP systems, 2 kW to multi-MW. |

 Table 2.2 Summary of fuel cell types (Larminie & Dicks, 2003)

The rapid improvements in PEM technology during the past decade have made hydrogen fuel cells the automotive power plant of choice for the car manufacturers. In the portable power market, micro fuel cell systems compete with batteries. Unlike batteries, fuel cells draw fuel and the oxidant from outside the cell, and are therefore not dependent on the limited storage capacity of the cell.

Hydrogen does not exist in its molecular form on earth. For this reason it is currently being produced from various fossil fuels such as oil, natural gas, and coal. This is mainly for the different applications in the chemical industry. The technologies to produce hydrogen include the steam reforming of natural gas, partial oxidation of hydrocarbons, and coal gasification. These technologies will however, not help to decrease the dependence on fossil fuels. Electrolysis of water is a mature technology which is efficient, but requires large amount of electricity. Currently about 4% of hydrogen gas produced worldwide is created by electrolysis. The environmental benefits of using electrolysis depend on which method is used to produce electricity required for water splitting. When electricity is generated from nuclear or renewable sources, it produces hydrogen in a carbon neutral process.

2.2 Hydrogen as a Means of Balancing Wind Power

2.2.1 Large-Scale Considerations

Today's electricity power generation is based on a complex system of frequency and voltage control and electricity exchange between subgrids. Power production is ruled by a time schedule taking the forecast of load and basic meteorological parameters into account. The introduction of an intermittent energy source like wind electricity provides an additional stochastic factor to power system scheduling. This may lead to power mismatch with conventional backup power production. Consequently, additional control power is required from conventional, fast-responding electricity generation; otherwise, renewable energy production is lost (Ackermann et al., 2005).

Lipman et al. (2005) differentiate the issues involved in integrating fluctuating wind power into electrical grids as primarily technical or economic/administrative, and the timescale² involved. In general, the issues include the balancing of generation and load, technical interface of individual generators or arrays with the broader utility grid, assurance of adequate reserve capacity on an aggregated control area basis, and market structures for bidding, forecasting, assessing, and compensating the output of different types of generators.

Steinberger-Wilckens (1993) states that the amount of surplus energy caused by fluctuating sources in electricity networks depends on the amount of renewable power capacity installed, the characteristics of the renewable sources utilised and the

² Timescales for power system planning: (a) regulation timescale (several seconds to 10 minutes), (b) load-following timescale (10 minutes to several hours), (c) unit commitment time scale (several hours to several days), (d) timescale of years. The integration of increased amounts of renewable resources can involve impacts across all of these timescales.

characteristics of load and conventional power generation. Ackermann et al. (2005) infer that in rigid grids with a large contribution from base load and/or with slow or limited response in the power generation to fast load gradients, a surplus situation will occur more often that it will in flexible grids.

Steinberger-Wilckens (1993) provides a model calculation for surplus energy that cannot be absorbed by the electricity grid as a function of wind penetration in the grid (see Table 2.3). Wind power penetration is defined as the ratio of wind energy production to total load requirement. The electricity grid assumed corresponds with the German system in 1990, with a contribution of about 30% nuclear energy and 4% hydro energy, with the majority of contribution from coal-fired generation.

According to this, the surplus energy production starts to occur at a wind power penetration level of about 25% and reaches a value of 7% at a penetration of about 50%.

| Wind power penetration (% of load) | Surplus energy (% of load) | Surplus wind energy (% of wind energy) | Surplus wind energy (TWh/year) | |
|---------------------------------------|-------------------------------|---|-----------------------------------|--|
| 25 | 0.0 | 0.00 | 0.0 | |
| 30 | 0.5 | 0.15 | 0.8 | |
| 35 | 1.2 | 0.42 | 2.3 | |
| 40 | 2.8 | 1.12 | 6.2 | |
| 45 | 4.7 | 2.12 | 11.7 | |
| 50 | 6.8 | 3.40 | 18.8 | |
| 55 | 9.2 | 5.06 | 28.0 | |
| 60 | 12.0 | 7.20 | 39.8 | |

Table 2.3 Model calculation for surplus wind energy that cannot be absorbed by the electricity grid as a function of wind penetration in the grid

 (a)
 (b)

 (c)
 (c)

 (c)

(Steinberger-Wilckens, 1993)

Similarly, Boyle et al. (2007) indicate that the point at which surplus wind power required to be rejected or diverted to other markets will depend upon the capacity factor of the wind and the electricity demand pattern. This situation is occasionally being observed, in western Denmark now that the penetration level has reached 23%. The surplus wind energy increases from 0.5% with 30% wind, to 3.5% with 50% wind, 17.5% with 80% wind, and 30% with 100% wind. Because of the surplus wind

energy, the nominal 100% wind case actually delivers only an average of 70% wind to consumers.

Ackermann et al. (2005) furthermore state that the integration of high wind power penetration levels will be easier in interconnected grids like the Union for the Coordination of Transmission of Electricity (UCTE) in Europe, than in isolated power systems as in New Zealand. UCTE allows the export of surplus electric power to interconnected networks. This option is certainly possible in the case of western Denmark, although it may not be possible to export all the power at very high penetration levels if the magnitude of the surplus power exceeds the capacity of the links.

Boyle et al. (2007) conclude that although energy storage technology has been widely discussed in the context of electricity supply systems, aside from large-scale pumped hydro-systems, such as Dinorwig, that have the disadvantage of being geographically very specific, no cost-effective solutions currently exist.

The introduction of an energy storage medium into the generation system can enable a flexible usage of the produced power and avoid the discarding of surplus energy. Ackermann et al. (2005) highlight the following characteristics of hydrogen, which are advantageous in this context:

- It can be reconverted to electricity with a reasonably high efficiency in fuel cells.
- It enables peak power production and load following, either from central installations or from virtual power stations (i.e. it offers decentralised generation capacity).
- It can constitute an alternative means of energy transport (e.g. using pipelines where electricity cables are undesirable) while offering high energy density and low transport losses.
- It can be sold as industrial gas outside the electricity market; on the one hand, it reduces market pressure and, on the other, develops alternative markets for renewable energies (e.g. transport fuels).

Ackermann et al. (2005) indicate further on that apart from controlling onshore wind resources, the more immediate role of hydrogen in wind exploitation appears to be the transportation and compensation of energy from offshore wind farms to the shore. The installation of a hydrogen pipeline is no more difficult than that of a sea cable. A hydrogen pipeline is likely to take up less space, which may be an important aspect, given the massive wind capacity that may have to be transferred to the shore. Transport losses are lower for hydrogen, and the required investment costs for the production of hydrogen and its reconversion to electricity are similar to those of high-voltage transmission (Ackermann et al., 2005).

2.2.2 Renewable Hydrogen Pilot Projects

Although at the current stage no demonstrations for large-scale grid-intertied application exist, hydrogen-based storage systems are beginning to be used in conjunction with isolated renewable power systems. A well-known example is the demonstration of a combined wind power and hydrogen storage scheme at Norway's Utsira Island. A community of ten households has been living off-grid since 2004 with its peak load requirement of 55 kW covered by a remote hybrid power system based on two 600 kW wind turbines. A 48 kW electrolyser and a 5.5 kW compressor with 2,400 Nm³ (214 kg) hydrogen storage tank, together with a 10 kW fuel cell and a 55 kW hydrogen combustion generator which can convert the surplus wind power into enough energy reserve for 2-3 windless days. The project budget is about £3.3 million and is supported by the Norwegian government (Hydro, 2004).

Meanwhile, a number of renewable hydrogen power systems of varying sizes and configurations have been implemented all over the world (CEG, 2006). Their aim is to provide remote communities, where the traditional power supply often is based on costly and polluting diesel, with balanced local renewable power. The HyLink system being prepared by Massey University and IRL represents a novel hydrogen-based remote area power system evolved from prevailing conditions at Totara Valley. A polymer pipeline is about to be used to store and transport the intermittent small-scale wind power over a distance of 2 kilometres to a rural community. Thereby the pipeline represents the only link between the wind site and the load; no power line is planned for this project.

A very scarce amount of information relating to the above scheme can be found in the literature. The existing hydrogen pipeline infrastructure worldwide is mostly used in the chemical industry. Predominately carbon steel materials like, X42, X52, X60, A106 Grade B, A357 Grade 5 are being used (Adams, 2005). The transmission pressure is limited to 800 psi and the pipe sizes up to 12''. The issues of hydrogen transportation in high strength metal pipelines are corrosion and embrittlement. Very little is known about hydrogen effects on polymers.

2.3 Previous Studies at Massey University

The three following paragraphs summarise the outcomes of the previous Totara Valley related studies at Massey University, which are most relevant for the present research paper.

2.3.1 Totara Valley Community Electricity Load Profiles

The community's electricity demand was monitored at eight individual sites at Totara Valley from September 1999 to July 2001 (Murray, 2005). The recorded data was separated into domestic, water heating and farm load (shearing and freezer sheds) for further analysis. The contoured plots below, depicting mean hourly profiles on a monthly basis, deliver insight into the electricity demand of the whole Totara Valley community.



Figure 2.1 The 1-year modelled domestic and farm load profile for the community (Murray, 2005)



Figure 2.2 The 1-year modelled water heating electricity load profile for the community (Murray, 2005)

The electricity load profiles of the Totara Valley community indicate seasonal and daily trends of electricity use. While the yearly path denotes a consumption increase during winter time (May – August), the daily pattern reveals a lower peak demand in the morning and a higher peak demand in the evening. The delay of the water heating peak load until later in the evening from November to February (Figure 2.2) arose from the 'ripple' control of the load undertaken by the utility. The shearing in January and July, accounts for a daily mean power consumption increase of approx. 1 kW (Figure 2.1) with an hourly peak demand of approx. 2 kW. An extensive analysis of the community load profiles can be found in Murray's *Designing Sustainable Distributed Generation Systems for Rural Communities*.

2.3.2 Wind Energy Resource – Totara Valley Region

Within the scope of previous studies at Massey University (Irving, 2000; Murray, 2005) the wind resource was monitored at five different locations in the Totara Valley surrounding area (Figure 2.3). There was a good readily usable wind energy resource at Wind Sites 1, 2, 3, and 5 with mean wind speeds of 5.61 m/s, 6.04 m/s, 6.27 m/s, and 5.95 m/s respectively (Murray, 2005). It is also worth noting that the monitoring duration at Wind Site 1 was taken over two years while at the other sites it was over a period of less than one year. The slightly lower value for the mean wind speed at Wind Site 1 can be explained by the fact that this site is less exposed to the west than the other monitored sites (P. Murray, personal communication).

The studies at Massey University also included the comparison of the monitored wind energy resource with the NIWA (National Institute of Water and Atmospheric Research) database. According to NIWA, the Totara Valley region is located within the zone of a median annual wind speed in the range of 5.1-6.0 m/s (refers to the time period between 1971 and 2000) which corresponds approximately with the Massey University's results³.



Figure 2.3 Wind sites monitored in the previous study

A useful outcome from the previous studies at Massey University is the estimation of the four following statistical parameters: the Weibull shape factor k, the autocorrelation factor, the diurnal pattern strength (DPS), and the hour of the peak wind speed. These parameters used in HOMER modelling for a more accurate description of the respective wind resource input differ from site to site, and can be estimated only by monitoring of a particular site. The parameters for the wind sites monitored at Totara Valley are summarised in the table below. A detailed analysis of the wind energy resource around Totara Valley can be found in Murray's "Designing Sustainable Distributed Generation Systems for Rural Communities."

³ All wind speeds refer to the anemometer height of ten metres.

| Site | Hours of data | Mean wind-speed (m/s) | Standard deviation (m/s) | Confidence interval (95%)(m/s) | Weibull 'k' shape factor | Auto- correlation factor | Diurnal pattern strength | Daily hour of peak wind-speed |
|------|---------------|-----------------------------|--------------------------------|--------------------------------------|--------------------------------|--------------------------------|--------------------------------|-------------------------------------|
| 1 | 16,319 | 5.61 | 3.07 | 0.047 | 1.77 | 0.91 | 0.13 | 1500 |
| 2 | 1,994 | 6.04 | 4.02 | 0.026 | 1.52 | 0.93 | 0.18 | 1600 |
| 3 | 1,340 | 6.27 | 3.78 | 0.202 | 1.65 | 0.94 | 0.20 | 1800 |
| 4 | 5,144 | 4.29 | 2.76 | 0.075 | 1.50 | 0.91 | 0.23 | 1400 |
| 5 | 7,002 | 5.95 | 3.51 | 0.071 | 1.66 | 0.93 | 0.12 | 1400 |

Table 2.4 The descriptive statistics useful for wind modelling in HOMER at the end ofthe monitoring duration (Murray, 2005)

HOMER provides only ranges for typical parameter values, so that average values are taken usually as a compromise when no parameters are available.

2.3.3 Pipe Material Selection

In the preliminary stages of the HyLink system development at Massey University, eight various pipes made of three different materials namely:

- Iplex Novathene LDPE
- Iplex Poliplex POLIgas MDPE
- Aquatherm Fusiotherm PP-R 80

were investigated on hydrogen gas diffusion through their walls. The specifications of the pipes tested, including their wall thickness and length, are shown in Table 2.5.

The pipes were filled with hydrogen up to the pressure of 4 barg and then the pressure drop in the pipes was measured over a time period of 1-3 weeks. The pressure loss in the pipes made of MDPE material was lower compared to the LDPE and PP pipes and equalled approximately 25 kPa/week, the wall thickness *z* of 4.15 mm and an outside diameter d_o of 42 mm.

| Pipe number | Material | Length [m] | Inside diameter [mm] | Outside diameter [mm] | Wall thickness [mm] |
|-------------|----------|------------|----------------------|-----------------------|---------------------|
| 1 | LDPE | 1.96 | 31.5 | 38.0 | 3.25 |
| 2 | LDPE | 0.49 | 31.5 | 38.0 | 3.25 |
| 3 | MDPE | 1.99 | 33.7 | 42.0 | 4.15 |
| 4 | MDPE | 0.49 | 33.7 | 42.0 | 4.15 |
| 5 | PP | 2.00 | 29.0 | 40.4 | 5.70 |
| 6 | PP | 0.50 | 29.0 | 40.4 | 5.70 |
| 7 | MDPE | 1.99 | 33.7 | 42.0 | 4.15 |
| 8 | MDPE | 20.00 | 33.7 | 42.0 | 4.15 |

Table 2.5 Specifications of the pipes tested at Massey University (Sims, Hargreaves,McQueen & Guldin, 2005)

Furthermore, the permeability for each tested pipe was calculated in order to find out material specific values. The following equation was used.

$$P = \frac{Q * z}{A_{mean} * t * \Delta p}$$
(2.1)

- *P* permeability
- *Q* quantity of hydrogen which passes the wall [mol]
- z pipe wall thickness [m]
- Δp pressure difference of H₂ between inside and outside of the pipe [Pa]; as the partial H₂ pressure outside of the pipe is zero, Δp represents the H₂ pressure inside of the pipe
- t time [s]
- A_{mean} mean surface area of the pipe [m²] calculated using the logarithmic mean of the inner and the outer pipe radius

$$A_{mean} = 2\pi * \frac{r_o - r_i}{\ln r_o - \ln r_i} * L$$
(2.2)

- L length of the pipe
- r_o outer pipe radius
- r_i inner pipe radius

Table 2.6 summarises the permeability values calculated for each tested pipe.

| | * |
|-------------------------|--|
| | Permeability P |
| Pipe 1: LDPE, 1.96m | $3.29459E-15 \frac{mol \cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 2: LDPE, 0.49m | $2.39452E-15 \frac{mol \cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 3: MDPE, 1.99m | $1.48899E-15 \frac{mol \cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 4: MDPE, 0.49m | $1.24901E-15 \frac{mol \cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 5: PP, 2.00m | 5.83215E-15 $\frac{mol \cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 6: PP, 0.50m | $2.99254E-15 \frac{mol\cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 7: MDPE, 1.99m | $1.38243E-15 \frac{mol\cdot m}{m^2 \cdot s \cdot Pa}$ |
| Pipe 8: MDPE, 20.00m | $1.01445E-15 \frac{mol\cdot m}{m^2 \cdot s \cdot Pa}$ |

Table 2.6 Permeability values calculated for each pipe tested (Sims, Hargreaves,McQueen & Guldin, 2005)

Consequently, MDPE proved to be the most suitable material for the hydrogen pipeline with the lowest permeability of approximately $1.3*10^{-15}$ mol m m⁻² s⁻¹ Pa⁻¹.

3. HyLink System in the Laboratory Stage

3.1 Overall System Description

A test station was constructed in IRL's laboratory by the engineers there to trial the HyLink system before installing it at Totara Valley. A 24-volt Chinese turbine MK2 modified by EcoInnovation⁴ in New Zealand was set up on the roof. The wind turbine had a power output of about 400 W and was connected parallel to a string of two 12 V lead-acid car batteries and then to a dc/dc converter designed by IRL. The task of the converter was to convert the battery voltage to 10.5 V, the most suitable voltage to drive the Lynntech PEM electrolyser which consisted of five electrochemical cells. The pipeline storage system was as follows:

- 150 m MDPE POLIPlex pipe, $d_0 = 32$ mm, SDR 11, $d_i = 26$ mm
- copper connection pipe, outer diameter 10 mm, inner diameter 6.5 mm
- the total volume of the pipeline storage system about 80 L

The pipes were pressurised with hydrogen by the electrolyser without mechanical compression up to 4 bar gauge pressure. The MDPE pipe was located outside the laboratory in a container filled with sand. The gas was consumed on demand by the 1.2 kW DCI 1200 alkaline fuel cell. The electricity produced was used to charge batteries or was inverted to the grid. A schematic diagram of the lab system can be found in Appendix E.

3.2 Electrolysis System Description

The electrolysis system consisted of two main subsystems, hydrogen production and hydrogen dehydration. The LabVIEW computer programme was used to enable unsupervised operation, in particular, to prevent electrolyser overheating, to keep the pressure limit settings and to stop operation in case of water shortage. Pressure sensors, thermocouples and water level sensors were attached at appropriate locations and set at adequate limit values.

⁴ http://www.ecoinnovation.co.nz/p-194-chinese-turbine-mk2-24-volts.aspx

The PEM electrolyser stack operates as follows. Distilled water is provided to the anode side of the cells by the recirculation pump. The catalyst coated on the anode side of the membrane promotes water dissociation. The positive electrical potential strips two electrons from each water molecule. The produced diatomic oxygen gas is released together with the circulating anode water into the circulating water reservoir. The two hydrogen cations produced from one water molecule are transferred through the proton permeable membrane under the influence of the negative electrical potential. Two to three water molecules enclose each hydronium ion which drags them through the membrane. The cathode catalyst promotes the recombination of hydrogen cations and electrons to form hydrogen molecules.



Figure 3.1 Electrolysis system setup (left) and MDPE pipe container (right)

The hydrogen gas flows through the dehydration equipment starting with a pressure relief valve preventing system over-pressurising. This valve opens at 65 psi and releases excess hydrogen and water. The relief valve is followed by two vapour separators and a catalytic recombiner which aims to eliminate any oxygen molecules by recombining them with H_2 to form water. The overall collected water is returned to the circulating water reservoir. On the way to the pipeline storage system



Figure 3.2 Water tank (left), H₂ production unit with circulating water reservoir underneath (middle), H₂ dehydration unit (right)

hydrogen passes through a flash arrestor and a configuration of valves - including a 5 psi check valve keeping the downstream at 5 psi lower than the upstream - for additional pressure control. A larger water tank is situated above the circulating water reservoir to provide it with water, when the water level sensor in the reservoir indicates. A deionisation column is integrated into the water cycle with the task to prevent membrane contamination. The recirculation water pump works currently at 24 V dc consuming approximately 12 W.

The main advantage of the electrolysis set-up is that the distilled water does not have to be pumped into the pressurised hydrogen compartment, the cathode, which would result in higher electricity consumption by the water pump.

3.3 Integrated Electrolyser Stack

The present water electrolyser stack is a PEM (proton exchange membrane) stack designed for hydrogen at high pressure. It can consume up to 500 W and $7.5*10^{-4}$ m³ hr⁻¹ of water (including osmotic drag) while producing $1.05*10^{-1}$ Nm³ hr⁻¹ of hydrogen and $5.25*10^{-2}$ Nm³ hr⁻¹ of oxygen (Lynntech, 2002). These specifications apply to the work temperature of 60°C. The stack can produce hydrogen at pressures

up to 27.5 bar gauge (cathode) and oxygen at ambient pressures up to 2 bar absolute. Figures 3.3 and 3.4 show the electrolyser stack connection from two slightly different perspectives.



Figure 3.3 Electrolyser stack connection

The stack consists of five electrochemical cells with an active area of 33 cm² each. Each cell requires a driving voltage of approximately 2 V. Gas and water streams connect to the stack through $\frac{1}{4}$ inch tubes located on the titanium endplate. The power supply is connected to the current collector protruding from the corner of the stack (+) and the centre of the titanium endplate (-).



Figure 3.4 Electrolyser stack connection from another perspective to show better the hydrogen outlet with the hydrogen pressure gauge

Water circulated through the anode side of the cells serves also as a temperature conditioner for the stack. Operating temperatures below 0°C or above 80°C can damage the electrolyser. Figure 3.5 illustrates the PEM electrolyser stack being used.

According to manufacturer's specifications⁵, the circulating water will reach a steady state temperature of 50°C by continuous electrolyser operation at rated output, which



Figure 3.5 Expanded view of the Lynntech electrolyser stack without titanium endplate (source: Lynntech Industries)

can be considered as the stack's work temperature. At this point the heat transfer with the surroundings acts as a natural coolant keeping the stack temperature down at 50° C.

The stack is constructed from titanium separator plates, plastic cell frames, metal flow fields, a steel endplate and a titanium endplate. The catalysed membranes are situated in between the metal flow fields. Figure 3.5 illustrates the same electrolyser as it was used for a previous application. The steel endplate with the electronics is replaced by the titanium endplate in order to adapt it to the HyLink system.

⁵ No specifications are made about the duration of the heating up process at specific ambient temperature and electrical input as well as flowrate of the circulating water and circulating water content by the manufacturer.

3.4 Integrated Alkaline Fuel Cell

In the monitored system a 1.2 kW Hercules DCI 1200 alkaline fuel cell was used. The plant was designed and built by IRL using Mk2-4 alkaline stack from Intensys (formerly Zetek), a subsidiary of E-Vision. The stack was rated to 1.5 kW within an ambient temperature range of -10°C to 75°C. The difference between the stack and the system rating is due to the power consumption of the system's auxiliaries. It has been designed for stationary applications in residential or light commercial power supply.

The nominal operating voltage of the DCI 1200 is 56 V dc, default by the manufacturer to charge a 48 V battery bank, which is suitable for use within RAPS. The unit is approximately 45% efficient electrically; with somewhat less than half this again potentially available as low grade heat (McQueen & Gardiner, 2004).

The fuel cell fuelled with hydrogen, uses alkaline solution, 12 mol L^{-1} potassium hydroxide (KOH), as an electrolyte which is pumped through twenty-four electrochemical cells within the stack. The temperature of the electrolyte is controlled by a heater and water cooler (including heat exchanger) in order to observe default temperature limits.

The DCI 1200 system is a low pressure fuel cell with an operating pressure of approximately 60 mbar gauge, which is monitored by an integrated pressure regulator.



Figure 3.6 Alkaline fuel cell DCI 1200 setup


Figure 3.7 DCI 1200 system overview (RISE, 2006)

The unit receives its oxygen from ambient air obtained using a centrifugal fan which is situated behind the inlet air filter. The air is then distributed through the cathode side of the cells and finally exhausted. The system is protected by an open enclosure except for the electronics, which are covered and provide a user interface. However for the present testing, the LabVIEW user interface has been in use.



Figure 3.8 LabVIEW user interface for the DCI-1200 fuel cell (IRL)

3.5 Estimating the Overall System Efficiency

In order to estimate the overall system efficiency, the efficiencies of the electrolyser and the fuel cell were calculated. At the time of the testing the wind turbine was not operating, so an ac/dc generator connected to mains power was used.

3.5.1 Lynntech Electrolyser Efficiency

The efficiency of electrolysers can be described in different ways, such as the stack efficiency, voltage efficiency, overall efficiency, energy efficiency and water to hydrogen conversion efficiency (Roy, Watson & Infield, 2005). The efficiency η_e of the Lynntech electrolyser was estimated as follows.

The Lynntech electrolyser ran for 2 hours consuming 23.5 A dc at 10.5 V dc, hence, 1.77 MJ at average rate of 246.75 W. It was assumed that the electricity used represented the total electrolyser power input.

$$P_{E,in} = V_E * I_E = 246.75W \tag{3.1}$$

In order to estimate the total electrolyser power output, the energy content of the hydrogen produced (Q_{H2}) was calculated using its lower heating value (LHV) of 120,000 kJ kg⁻¹ which corresponds with 10 MJ m⁻³ (at atmospheric pressure and 15°C). The pressure increase in the 80 L pipeline storage system was therefore measured. During the electrolyser operation of 2 hours a pressure increase of 21 psi was recorded, which resulted in an average hydrogen production rate of 10.5 psi hr⁻¹. This value corresponds with 57.93 L hr⁻¹ due to Boyle's Law ($p_1*V_1 = p_2*V_2$) and hence with 115.86 L of hydrogen produced in 2 hours.

$$Q_{H_2} = LHV_{H_2} * V_{H_2} = 1.16MJ \tag{3.2}$$

$$P_{E,out} = \frac{Q_{H_2}}{t} = 161.1W \tag{3.3}$$

$$\eta_{e} = \frac{P_{E,out}}{P_{E,in}} = 65.3\%$$
(3.4)

The calculated efficiency does not consider the electrochemical hydrogen compression by the electrolyser because the average operating pressure during the test was low. Furthermore, the heat transfer between the stack and the circulating water as well as the power consumption of the water pump are not included in the above electrolyser efficiency calculations.

3.5.2 DCI 1200 Fuel Cell Efficiency

In order to calculate the alkaline fuel cell's efficiency, the pressure drop in the pipeline storage system was measured during its operation. The DCI 1200 -

generating 650W net electrical power - needed 12.2 minutes (35 seconds per 1 psi pressure drop) to consume the hydrogen amount produced by the electrolyser in 2 hours⁶. That means the fuel cell consumed 115.86 L (at atmospheric pressure and 15° C) in 12.2 minutes, hence, 0.000158 m³ in 1 second. Applying hydrogen's lower heating value of 10 MJ m⁻³, the fuel chemical power input equals 1583 W.

$$\eta_{AlkFC} = \frac{650W}{1583W} = 41.1\%$$

The above calculated efficiency represents only the fuel/electricity conversion efficiency. It doesn't consider the thermal power output of the DCI 1200. It does, however, consider the power consumption of the fuel cell's auxiliaries (electronics, inlet air fan, electrolyte pump etc.) as they run using the electricity coming from the consumed hydrogen.

As the alkaline fuel cell's thermal power output represents approximately 20% of the contributed power input, its combined heat and power efficiency should be anticipated to be over 60%.

3.6 Recording VI Curves at Various Electrolyser Stack Temperatures

The HyLink system design doesn't plan to use a battery bank as an energy buffer between the wind turbine and the electrolyser. One reason is avoiding the additional system efficiency loss – charging and discharging action of a usual flooded lead-acid battery with a liquid electrolyte has an efficiency of approximately 75%. This means that the electrolyser will be powered by the fluctuating wind power, hence, will not operate continuously. This means furthermore that the electrolyser stack temperature will fluctuate too. In order to predict electrolyser's performance at various stack temperatures, VI curves were recorded.

 $^{^{6}}$ As unacceptable inaccuracies during the pressure drop measurements occurred, the hydrogen consumption (0.048 kg H₂ per hour at 650 W output) of an identical DCI 1200 measured at RISE, was used to accomplish the system efficiency calculations.



Figure 3.9 Recorded electrolyser stack VI curves at various temperatures with a reference VI curve recorded by Lynntech at 60°C

VI curves can be considered a tool in which to present the voltage/current ratio of an appliance, and thus, allow for a comparison with other cognate appliances. VI curves of PEM electrolysers show additionally a dependency on their work temperature. While the stack temperature increases, the current flow increases at the same voltage. This is due to thermodynamical correlations of water electrolysis and, in particular, improved reaction kinetics.

The same ac/dc generator as for the efficiency estimation was used in order to create VI curves. The voltage was increased in 0.5 V stages (from 7.5 V to 10.5 V) and electrical current was measured in each case. The same procedure was repeated at different stack temperatures controlled by cooling and heating respectively the circulating water. More VI curves were recorded, however, in order to avoid confusion just the above shown were chosen for a comparison. The complete VI curves measurements including temperature can be found in Appendix A.

The recorded VI curves refer to the temperature range between 8.2°C and 36.4°C. With the aid of the VI curves, the anticipated current flow and hence the anticipated hydrogen production at a chosen stack voltage and stack temperature can be calculated. This can be done by using the Faraday's Law of Electrolysis. There is no VI curve at the stack's work temperature of 50°C available, but using the above chart current flows in the range of 35-40 A dc at 10.5 V dc can be estimated, which corresponds with the rated current flow of 36 A (Lynntech, 2002) for the present electrolyser.

This results in the membrane current density of 1.1 A cm^{-2} and the below calculated hydrogen (at atmospheric pressure and 15° C) production rate per cell.

$$\dot{V} = \frac{I \cdot V_M}{n \cdot F} = \frac{36A \cdot 24L/mol}{2 \cdot 96487C/mol} \cdot 3600s/hr = 16.12L/hr$$
(3.5)

In summary, the Lynntech electrolyser produces 80.6 stdL hr⁻¹ of hydrogen when running continuously at its rated cell temperature. However, it can be assumed, that due to the non-continuous wind power availability and the cooling effect of the ambient air at Totara Valley, the electrolyser will hardly attain its rated cell temperature and will therefore work at a lower power output. An insulation of the electrolyser and the circulating anode water system could help to capture the heat lost from the cell.

4. HyLink System Transition to Totara Valley

4.1 Pipeline Installation

The complete system transition was carried out under the direction of IRL. Fourteen coils of 150 m MDPE gas pipe were purchased at the cost of NZ\$2,500 including electrofusion accessories and pressure gauges. It was a gas pipe manufactured by Waters & Farr and supplied by Humes.



Figure 4.1 HyLink system overview

The pipe was manufactured from PE 80B material with the outer diameter (d_o) of 21 mm, internal diameter (d_i) of 16 mm and wall thickness (z) of 2.5 mm. The Standard Dimension Ratio (SDR = $d_{o,mean}/z_{min}$) was specified at 9 by the manufacturer which implies the maximal allowable operating pressure for gas of 8 bar. PE 80B has a design life of 50 years at surrounding temperatures and is fully serviceable for the same time period at elevated fluid temperature of 45°C with a reduced long term hydrostatic strength $\sigma_{LCL} = 6$ MPa (Iplex).



Figure 4.2 Mole ploughing of the pipe (left), an electrofusion coupling between two pipeline sectors (right)

PE 80B contains anti-oxidants, chemical ultra violet absorbers and yellow pigments which are added to the PE polymer base resin during the compounding process by the raw material manufacturers. According to Borouge NZ Ltd and Polymers International Ltd the PE 80B material does not contain cross-linkers. The minimum required strength (MRS) value for PE 80B is 8 MPa (Iplex).



Figure 4.3 Electrofusion welder

The pipe was buried 60 cm underground along a farm track in order to reduce PE expansion or contraction due to changing temperature, to avoid PE degradation by UV radiation as well as for other safety reasons. Mole ploughing was chosen as the most

cost-effective method with an accrued expense of NZ\$7,800 including pipe sectors connection and delay due to unfavourable weather conditions⁷.



Figure 4.4 Hose clamps (left), crimping method (right)

The electrofusion method was applied to join the fourteen pipe sectors to a continuous line. Polyethylene electrofusion couplings with an electrical heater coil embedded along its curved surface were merged with the pipe sector ends using a 2.8 kW electrofusion welder. A portable 5 kW diesel generator was used to power the welder. The pipes outer surface was treated with acetone to enable a successful welding. The connection sites were indicated with thirteen wooden marker stakes sprayed with yellow paint. A crimping method rather than hose clamps was preferred to connect the both pipeline ends with the metal tubing which proved more stable and leak proof. Approximately 2 km of MDPE gas pipe was necessary to connect the top pressure gauge at the electrolysis container with the bottom pressure gauge at the woolshed.

4.2 Electrolysis Setup

The complete electrolysis setup as described in Chapter 3 was transported from IRL's laboratory to Totara Valley and located in the container near the wind site. A

⁷ Mole ploughing would cost NZ\$5,960 at right weather conditions.



Figure 4.5 Electrolysis setup in the container

larger 240 L distilled water tank located outside of the container replaced the smaller water tank automatically refilling the circulating water reservoir as necessary. Using water from a farm rain water tank for electrolysis is an obvious option for a continuously operating HyLink system which would require a filter system and a more frequent deioniser inspection. However, at the current stage of the progress purchased distilled water represents an adequate solution.

4.3 PEM Fuel Cell Integration

A 1 kW PEM fuel cell manufactured by ReliOn was preferred at the current stage rather than the alkaline DCI 1200. It was designed to charge a 48 V battery bank with 36-40% efficiency (based on hydrogen's LHV) at the full load. The PEMFC consumes 15 std L min⁻¹ (SLM) of hydrogen at 1 kW output and 7.5 SLM at 500 W output. It requires hydrogen in the pressure range of 4-6 psi gauge. The only by-products of the fuel cell's electrochemical reaction are water vapour and low grade heat.

The present PEMFC does not utilise a conventional stack of cells architecture, but instead placement of individual MEA's within the cartridge housing. This construction method aims to increase system reliability and to reduce maintenance costs. The Independence 1000 system employs six individual cartridges with ten cells respectively. Cartridges can be "hot swapped", meaning that the system can continue to operate and produce power, even with up to three cartridges removed simultaneously (HARC, 2004). This reduces the risk of failure of the entire unit due to problems with a single cell. The unit is air-cooled and can be fed with industrial grade hydrogen.



Figure 4.6 PEM fuel cell integration

The PEMFC was located in the woolshed and was connected to the MDPE pipe via a ¹/₄ inch PE tube. An integrated pressure regulator kept the hydrogen pressure in the required range at the fuel cell inlet. During the system operation a 4 bar gauge pressure sensor situated between the MDPE pipe and the fuel cell sent pressure readings to the controller which turned the fuel cell on when the high pressure threshold of currently 2 bar was reached and turned the fuel cell off when the pressure dropped below the low pressure threshold of 1 bar. When the fuel cell ran it supplied the grid-connected inverter and the controller as well as recharged the 48 V bank of 4 gel-cell car batteries. The high efficient gel batteries (97%) were utilised to power the control and data logging equipment as well as provide a necessary buffer for the fuel

cell and the inverter The batteries supplied the energy required for the start up from the ReliOn's "cold state". The inverter discharged excess energy to the grid when battery voltage was above 54 V (E. McPherson, personal communication).

4.4 Installing the Wind Turbines

Two different wind turbines were installed on the hilltop: a mechanically controlled Proven and an electronically controlled Air-X.

4.4.1 Proven

Prior to the pipeline installation, a 2.2 kW wind turbine manufactured by Proven was put into operation on the hilltop at two kilometres distance from the community. Like the most small wind turbine systems it was a direct-driven, variable-speed system with permanent magnet generator producing three-phase ac which was rectified to charge a 24 V battery bank. The mast height was 6.5 m.



Figure 4.7 Proven wind turbine on the hilltop (left), Zebedee furl system drawing by Proven (right)

The robust wind turbine with its unique furl system is predestined to work at the turbulent wind conditions of the hilly Totara Valley region. The patented Proven Flexible Blade System enables the turbine to generate power in light or strong winds. During stormy winds the three polypropylene blades connected to the rotor via Zebedee hinge system twist and flex to reduce their aerodynamic efficiency and hence to keep a high power output (Proven Energy, 2005).

The Proven wind turbine was connected as shown in the simplified drawing (Figure 4.8) below to the 24 V deep cycle lead acid battery bank with a fluid electrolyte having a capacity of approximately 400 Ah, hence 9.6 kWh, at C100 rate (= 4 A). As the batteries were not used as electricity buffer for electrolysis (also, the water recirculation pump was planned to run just in times of electrolyser operation), their charging/discharging efficiency of approximately 75% did not influence the overall system efficiency. The batteries were used solely to power the data logging and the data transmission as well as the system monitoring and system controlling equipment.

A Campbell CR500 data logger working at 12 V collected wind speed data, battery voltage data (or rectified wind generator voltage during its operation) and rectified wind generator current data. The wind speed was measured by a NRG anemometer at 10 m height. The data was transmitted by a custom-made GPRS modem to Massey University's FTP server. The data was then available on Massey University's website. The server's IP address was retyped at the GPRS after each disconnection from the voltage source. The logger was able to record data for several months before starting overwriting it. The Campbell logger can also be programmed to collect wind gust data and wind speed standard deviation to observe the wind turbulence intensity.

The dump load controller consisting of MOSFETs can be cut into the system at arbitrary boost voltage which can be set in 1 V intervals via display. In the current configuration the boost voltage should be around 29-30 V. The controller will dump from this voltage level for the first stage of charging, then drop down to the float voltage – set at 27-28 V – after it has been at the boost voltage for the boost charge time interval, which can be also set via display (M. Carter, personal communication).



Figure 4.8 Proven wind turbine installation

A maximum power output of 460 W was achieved during the ongoing installation process of the Proven wind turbine prototype (see Appendix B). The twisted wires in the tower and the eventual blockage of the rotor indicate mechanical issues within the rotating system. The wind turbine is currently under repair.

4.4.2 Air-X

Prior to the Air-X installation, two Chinese MK2 turbines were put into a test operation without measuring their output. Both of them had issues with their furl

systems in the strong and gusty winds. After an operation period of maximal 2 weeks, both wind turbines lost their blades due to too high rotational speed. One of the turbines was shorted, i.e. in the stall mode, when the damage took place.

A 400 W Air-X on a 12 m mast with a new controller, dump load and batteries was installed under direction of IRL. A Xantrex C40 charge controller was connected in parallel to control the turbine voltage at the 24 V (nominal) lead-acid car battery bank. The C40 cut in at 27-28 V in order to prevent the batteries from overcharging. This means that the controller sent power to the resistive dump load only when the voltage rose above the default threshold. The dump load in this configuration needed to be between 0.7-0.875 Ohms. Less than 0.7 Ohms would draw more than 40 A at 28 V and would therefore exceed the rating of the controller, whilst more than 0.875 Ohms would cause the voltage to rise above 28 V at 32 A – the peak intended current to give a 20% margin (E. McPherson, personal communication).



Figure 4.9 Air-X (manufactured by Southwest Windpower) during operation on the hilltop

The Air X's electronic furl system responds immediately to occurring high wind gusts by activating the stall mode. The wind turbine is well protected and lasts long, however, the frequent switch into the stall mode leads to a low overall energy generation. The Air-X's measured power output can be found in the Appendix C.

4.5 Wind Power to Water Electrolysis Connection

IRL's dc/dc converter was the device which coupled the wind power and the water electrolysis systems by adjusting the turbine's voltage to the electrolyser's characteristics. It was designed to start water electrolysis as soon as the voltage got



Figure 4.10 Wind power and water electrolysis control in the container

above 25 V This limit for starting electrolysis was to prevent discharge of the batteries. If the batteries remain in a discharged state for a long period e.g. in times of no wind, the voltage level of 25 V at the beginning of such a period gives the



Figure 4.11 Container from the outside

maximum possible buffer to avoid battery discharge (E. McPherson, personal communication). Three solar panels with 48 W output each were installed on the container roof as an additional support for battery charging using a second Xantrex C40 charge controller connected in series.

It is planned to interface the Massey and the IRL systems at a later stage by connecting both wind turbines to one battery bank controlled by Massey's dump load control system, if higher power input is required. The current system configuration including the 500 W PEM electrolyser requires only the Air-X wind turbine as the power source. The Proven wind turbine is planned to power a larger alkaline electrolyser which is currently developed by IRL.

4.6 HyLink versus Power Line

Table 4.1 confronts the most significant characteristics of the both technologies which can be utilised to connect the wind turbine with the community. It can be anticipated that in case of large-scale storage the battery cost will outweigh the hydrogen tank/pipeline cost. Also, the price and the lifetime of the fuel cell and the electrolyser are based on the factual values and can change rapidly in the future.

| Characteristic | HyLink System | Power Line | |
|---|--|---|--|
| Initial cost incl. labour | NZ\$55,000 - current configuration - incl. pipeline mole ploughing | NZ\$60,000 -NZ\$100,000 - underground wiring requires a trench - overhead wiring complicated due to difficult terrain | |
| Cost of conversion devices | NZ\$17,000 - electrolysis setup NZ\$16,000 - fuel cell system | 2 x NZ\$2,500 - step up and step down transformers | |
| Energy loss at conversion devices | ηe/conv = 60% - converter/electrolyser subsystem ηpemfc/inv = 35% (electr.) - fuel cell/inverter subsystem | 2 x 200 W power loss - power consumption at both transformers | |
| Lifetime | 50 years - MDPE gas pipeline 4,000 operational hrs - ReliOn PEM fuel cell 10,000 operational hrs - PEM electrolyser | 60 years | |
| Energy Storage | Hydrogen pipeline/tank - easy to scale up | Batteries - expensive for large-scale storage | |

Table 4.1 HyLink comparison with the alternative power line installation

5. Pressure Tests

5.1 Estimating the Frictional Pressure Drop

The total head loss is regarded as the sum of major losses, due to frictional effects in fully developed flow in constant-area tubes, and minor losses, resulting from entrances, fittings, area changes, and so on (Fox, McDonald & Pritchard, 2004). For the present investigation only the major losses are considered.

At the current stage the PEM fuel cell operates in a batch-wise mode, repeatedly filling and draining the pipeline, so there is no continuous hydrogen gas flow through the pipe. Nevertheless, an estimation of the maximal frictional pressure drop for the current configuration of the HyLink system, which is at the maximal fuel cell electrical output of 1 kW (15 SLPM or 0.00025 std m³ s⁻¹ hydrogen flow), will illustrate the importance of frictional pressure drop.

The hydrogen flow regime in the pipeline can be determined by calculating the Reynolds number *Re* which has to be less than 2300 for the laminar case.

$$\operatorname{Re} = \frac{\overline{V}d_i}{V} = \frac{1.24\frac{m}{s} * 0.016m}{1.88 * 10^{-5}\frac{m^2}{s}} = 1057$$
(5.1)

 \overline{V} mean hydrogen velocity [m/s] i.e. flow rate/pipe cross sectional area, (1.24 m s⁻¹)

- d_i internal diameter of the pipe (0.016 m)
- v kinematic viscosity of hydrogen [m²/s] i.e. $v = \mu/\rho$
- μ dynamic viscosity of hydrogen (8.35*10⁻⁶ Ns/m²)
- ρ density of hydrogen (0.089 kg m⁻³ at 273 K and 101325 Pa, which corresponds with 0.445 kg m⁻³ at 4 barg)
- A cross sectional area of the pipe (0.0002 m^2)

In laminar flow the friction factor f is a function of Reynolds number only; it is independent of roughness (Fox, McDonald & Pritchard, 2004).

$$f_{lam} = \frac{64}{\text{Re}} = 0.061 \tag{5.2}$$

The frictional pressure drop in the pipeline with the length L of 2000 m can be now calculated either using the Darcy-Weisbach equation:

$$\Delta p = \frac{L}{d_i} * \frac{\rho \overline{V}^2}{2} * f_{lam} = 2.6 k P a = 0.026 b a r$$
(5.3)

or the Hagen-Poiseuille equation:

$$\Delta p = \frac{32\mu \overline{V}L}{{d_i}^2} = 2.6kPa = 0.026bar$$
(5.4)

5.2 Hydrogen Diffusion Rate Measurement

After connecting the pipeline to the hydrogen production subsystem on the hilltop and the hydrogen consumption subsystem at the woolshed, the system's leaks, underground and aboveground, were eliminated. Finally, the pipeline was ready for the hydrogen diffusion measurement. The results from the previous study at MU were used as a benchmark.

Prior to filling in hydrogen, the pipeline was flushed with oxygen-free nitrogen to make sure there was no oxygen inside, which could create an explosive mixture together with hydrogen. Then hydrogen was injected using an appropriate pressure regulator at the top-riser up to about 4 barg. After closing the valve at the top, the pressure was released at the bottom valve in order to release the heavier nitrogen first. This procedure was repeated to make sure that the pipe is filled with pure hydrogen. Finally, the pipe was pressurised with hydrogen at 4.1 barg and left. Industrial grade hydrogen (>99.5%) compressed at 152 bar (at 15°C) in an E-size cylinder from BOC



Figure 5.1 Pressurising the pipe with hydrogen at the top riser

was used. After one week the pressure drop in the pipe was recorded. The result of two experiments was a pressure drop of 42.5 kPa/week.

This value can be converted into power loss as follows. The volume of the pipe is 402 L which provides space for 18 mol of a gas at STP. The pipe was set at absolute pressure of 5.1 bar, hence 91.8 mol. The absolute pressure recorded after one week was 4.675 bar, hence 84.2 mol. As a result, the weekly hydrogen loss was 7.5 mol or 168 stdL. That implies 0.015 kg/week and 0.5 kWh/week at hydrogen's LHV. As a result, the average power loss throughout a week was 3 W.

Considering that the current HyLink design plans to have the fuel cell operating at pipeline pressure between 1 barg (2 bar absolute) and 2 barg (3 bar absolute), the above power loss of 3 W must be recalculated with focus on the average pressure of 1.5 barg (2.5 bar absolute) during the fuel cell's operation. The equation (2.2) can be therefore converted into the following form.

$$Q = \frac{P * A_{mean} * t * \Delta p}{z}$$

From this equation can be derived that the pressure Δp and the amount of the permeating gas Q are directly proportional. This means that at Δp of 2.5 bar abs, Q can be expected to be 3.8 mol. Consequently, the average power loss due to hydrogen diffusion during the fuel cell operation will be about 1.5 W at the current system configuration.

5.3 Permeability Comparison with Previous Studies at Massey University

The obtained hydrogen diffusion results were compared to the records from the previous hydrogen diffusion studies at Massey University. The hydrogen permeability was therefore calculated using the formulas (2.1) and (2.2).

$$A_{mean} = 2\pi * \frac{r_o - r_i}{\ln r_o - \ln r_i} * L = 115.52m^2$$

$$P = \frac{Q * z}{A_{mean} * t * \Delta p} = \frac{7.5mol * 0.0025m}{115.52m^2 * 604800s * 488750Pa} = 5.5 * 10^{-16} \frac{mol \cdot m}{m^2 \cdot s \cdot Pa}$$

The above value for permeability is half the amount calculated for the 20 m MDPE pipe at MU (see Table 2.3). The previous studies predicted hydrogen losses of about 15 mol per week, rather than 7.5 mol per week measured at Totara Valley.

At this point it is important to note that the pipes used for gas permeability testing were manufactured by two different companies (Iplex, and Waters & Farr). However, as both companies are subject to Australian & New Zealand Standards AS/NZS 4131 'PE Compounds' and AS/NZS 4130 'PE Pipes, Pressure Applications', the MDPE material used for both pipes can be considered to be the same.

Worth mentioning is that the previous gas permeability studies at Massey University showed a significantly lower permeability coefficient for the 20 m MDPE pipe, compared to the shorter MDPE pipes. No scientific reasoning could explain this.

The most reasonable reason for the low permeability coefficient measured at Totara Valley is the lower outside temperature. This can be supported with the Arrhenius equation describing the temperature dependence of the permeability as follows.

$$P = P_0 * e^{\frac{-E_p}{RT}}$$
(5.5)

- *P* permeability coefficient
- E_P activation energy of permeation
- P_0 frequency factor
- *T* temperature
- *R* universal gas constant

The previous experiments at Massey University were performed at room temperature of about 20°C. The general rule of thumb for Arrhenius equations says that for every 10°C increase in temperature the rate of reaction doubles. This conclusion corresponds with the outcome that the permeability rate obtained from the previous study was twice as high as the permeation measured at Totara Valley at average 10°C.

In order to obtain the permeability coefficient P as a function of temperature T, it is recommended to solve the equation (5.5). A common way to solve the Arrhenius equation is by recording the permeability coefficients at different temperatures. In order to simplify the calculations it is useful to recast the equation in logarithmic form. Taking the natural logarithm of both sides of the Arrhenius equation gives the following formula.

$$\ln P = \ln P_0 - \frac{E_P}{RT}$$

By rearrangement, this equation can be put in the form of a straight line.

$$\ln P = -\frac{E_P}{R} * \frac{1}{T} + \ln P_0$$

Then, a plot of lnP versus 1/T can be made or linear regression performed after the permeability coefficients have been determined for permeation experiments carried out at several temperatures. The slope of the line is $-E_P/R$, from which the activation energy of permeation can be obtained. The intercept is lnP_0 .

5.4 Methane Test

The pipe at Totara Valley was pressurised with natural gas in order to provide a benchmark. The experiment was performed the same way as in case of hydrogen. The pipe was set at 4.1 barg and the pressure drop was recorded after one week. Compressed natural gas at 152 bar in a G-size cylinder was used. The experiment was performed twice and the recorded pressure drop was in both cases approximately 15 kPa/week.

Comparing this result with hydrogen's diffusion rate of 42.5 kPa/week, it was found, that the diffusion rates of the both gases are subject to the Graham's Law of Effusion.

$$\frac{Rate1}{Rate2} = \sqrt{\frac{M_2}{M_1}}$$
(5.6)

| Rate1 | rate of effusion of gas 1 |
|-------|---------------------------|
| Rate2 | rate of effusion of gas 2 |
| M_1 | molar mass of gas 1 |
| M_2 | molar mass of gas 2 |

$$\frac{42.5kPa / week}{15kPa / week} = 2.8 = \sqrt{\frac{16g / mol}{2g / mol}}$$

It could be thought that an incorrect value for the molar mass M_2 was used, as natural gas doesn't consist of 100% methane. The natural gas composition was as follows: CH₄ – 82%, C₂H₆ – 9.9%, C₃H₈ – 3.3%, CO₂ – 3.2%, et al (Vector, 2007). However, considering that methane (CH₄) is the lightest of all the components, it will diffuse most readily (S. Broome, personal communication). Hence, the value of 2.8 is correct also on the right hand side of the above equation.



Figure 5.2 Pressurising the pipe with CNG (left) and nitrogen (right) at the bottom riser

At this point it is important to note that effusion and permeation of gases through solid materials are two different phenomena, which are subject to different physical laws. Graham's Law does not apply, if the passage way is very small, as it occurs for dimensions of passage ways in-between the polymer chains in materials such as solid rubber.⁸ The industry provides the following permeability coefficients for PE 80B pipes at 23°C (James Hardie Pipelines, 1997):

- Hydrogen: $2.8 \times 10^{-6} \text{ m}^3 \text{ m}^{-1} \text{ MPa}^{-1} \text{ day}^{-1}$
- Methane: $0.56 * 10^{-6} \text{ m}^3 \text{ m}^{-1} \text{ MPa}^{-1} \text{ day}^{-1}$

These values produce a ratio of 1:5 and not 1:2.8 as it is in case of effusion.

The above conclusions reveal a contradiction between the both last subchapters. On the one hand, the permeability comparison with the previous study at Massey

⁸ www.getnitrogen.org/pdf/graham.pdf

University suggests that the pressure drop in the pipe at Totara Valley is solely caused by permeation of hydrogen through the pipe walls. On the other hand, the diffusion rates ratio of hydrogen and methane is subject to the Graham's Law of Effusion. As the first step to solve this discrepancy, it is recommended to measure the permeability of the both gases at exactly the same ambient temperature.

5.5 Estimating the Maximal Power Transfer through the Pipeline

Finally, the maximal hydrogen flowrate through the pipeline was estimated. The pipeline was therefore pressurised up to 4 barg and the bottom valve was opened. Then, the time needed to release the hydrogen gas from 4 barg to 1 barg through a ¹/₄ inch vent was recorded. It took approximately fifty seconds to decrease the pipeline pressure by 3 barg, which corresponds with the release of 1.2 Nm³ of hydrogen, and thus, with 12 MJ of energy at hydrogen's lower heating value. This means that the present pipeline is capable of transferring of about 240 kW of power when working in the pressure range of 1 barg to 4 barg.



Figure 5.3 The maximum energy flowrate of hydrogen versus nozzle or pipe size, over a 4 bar pressure differential (IRL)

The outlet flowrate is limited by the flow of gas through the smallest restriction in the pipeline, which peaks at the speed of sound for the gas. For hydrogen the speed of sound is approximately 1270 m s⁻¹. ⁹ Figure 5.3 shows the maximum energy flowrate of hydrogen gas through various nozzle sizes, over a 4 bar pressure differential (S. Broome, personal communication).

⁹ http://hyperphysics.phy-astr.gsu.edu/hbase/sound/souspe.html#c4

6. HyLink Modelling with HOMER – Data Inputs

A good modelling is paramount to the analysis of innovative energy systems. HOMER's well developed hydrogen module and the willingness of its developers to extend the software on new tasks were the crucial points for its selection as the simulation tool for the HyLink system.

6.1 Electricity Load Data

HOMER requires mean hourly electricity demand values for each month. The values for the simulation were derived and averaged from the previous studies at Massey University (see 2.3.1) using the yearly average load of 6.7 kW as a benchmark.



Figure 6.1 *Mean hourly electricity load profiles for the whole Totara Valley community including the domestic load, the farm load and the water heating*

Figure 6.2 shows the primary load window in HOMER after entering the mean hourly electricity load data for the whole community from Figure 6.1. The hourly peak demand of 15.8 kW appears too low given the yearly average demand of 6.7 kW. This is due to the averaging of the monthly values to achieve the seasonal profiles. In addition to this, the overall load data consisting of mean daily profiles for each season (see Figure 6.2 DMap) appeared very synthetic. In that case, the addition of the daily and hourly random variability of 20% proved advantageous.



Figure 6.2 The primary load inputs in HOMER

That way, the strong rounded hourly load data obtained a more realistic character (compare DMaps from Figure 6.2 and 6.3) and the hourly peak load was prevented from underestimation, now 26.7 kW. At this stage it is important to note that HOMER makes energy balance calculations only on an hourly basis. The most of the community's daily 10-minutes peak loads were measured at around 20 kW in the previous studies. The highest yearly 10-minutes peak load was measured at 70 kW (probably during the shearing period). This reveals the community's strong dependence on the grid capacity.



Figure 6.3 The primary load inputs in HOMER after applying random variability

As the community's electricity demand massively outweighs the current HyLink configuration, the baseline data of 160 kWh/d was scaled to 20 kWh/d, an average demand of one of the eight monitored sites at Totara Valley. After this modulation the yearly average load became 0.83 kW and the hourly peak 3.32 kW within the simulation (see Figure 6.3). As noted in Chapter 1 the present paper focuses only on the HyLink system itself and not the other technologies providing renewable power to the community.

6.2 Wind Resource Data

HOMER calculates the wind turbine power output for each hour of the year. The calculations are based on the monthly mean wind speeds. The wind speeds used in the present simulation are obtained from the NASA website¹⁰. They are free of charge and refer to a long term monitoring period of over ten years. The NASA wind speeds for Totara Valley¹¹ with the annual average of 5.62 m/s match Murray's and NIWA's annual estimations. The wind speed data from all of the three sources refers to the anemometer height of 10 m.

In order to allow the user to control how the 8760 hourly values are generated from the 12 monthly values, HOMER provides four settable parameters: the Weibull shape factor k, the autocorrelation factor, the diurnal pattern strength (DPS), and the hour of the peak wind speed. The parameters are defined as follows:

- Weibull shape factor *k* describes the breadth of the distribution of wind speeds over the year (typically 1.5-2.5).
- Autocorrelation factor is a measure of how strongly the wind speed in one hour depends (on average) on the wind speed in the previous hour (typically (0.8-0.95).
- DPS is a measure of how strongly the wind speed depends on the time of day (typically 0.0-0.4).

¹⁰ http://eosweb.larc.nasa.gov/cgi-bin/sse/retscreen.cgi?email=rets@nrcan.gc.ca

¹¹ The NASA wind speeds are based on the latitude $40^{\circ}23'$ S (40.38 S) and the longitude 176°03' E (176.05 E) obtained via Google Earth as geographical location of Totara Valley.

• Hour of peak wind speed indicates the time of day that tends to be windiest on average throughout the year (typically 14-16).



Figure 6.4 Wind resource inputs in HOMER

For the present HOMER simulation the values from Table 2.4 for Wind Site 1 (see Chapter 2) were used as they represent the genuine values for the underlying site resulting from the previous studies at Massey University. The wind speed variation with height can be influenced in HOMER either by choosing the most suitable surface roughness length in case of the logarithmic calculation or by choosing the right power law exponent in case of the power law calculation (see Figure 6.5).



Figure 6.5 Wind speed variation with height in HOMER

The complexity of the terrain surrounding the subject site has significant effects on the magnitude of the autocorrelation factor (Lilienthal et al., 2003). Thus the impact of the hilly terrain around Totara Valley on the wind speed is partially implied in the value of this parameter.



Figure 6.6 Weibull probability density distribution of the simulated wind speed data

Figure 6.6 portrays the Weibull probability density distribution HOMER uses to describe the frequency of the wind speed occurrence. The Weibull shape factor k has a main impact on this statistical probability density function.

6.3 Solar Resource Data

The NASA solar resource data based on long term monitoring was chosen to predict the power output of the three 48 W solar panels used for additional battery charging



Figure 6.7 Solar resource inputs in HOMER

within the HyLink system. The solar radiation measured in previous studies at MU in year 2000 shows a lower mean value ($3.0 \text{ kWh/m}^2/\text{d}$) caused probably by the below average clearness of the atmosphere surrounding the subject site in the year of the monitoring.



Figure 6.8 Global horizontal solar radiation (kW/m²) daily profiles for each month at the subject site

Figure 6.8 shows the expected trend of the global horizontal solar radiation over a year which is the result of the long term monitoring at NASA.

6.4 Grid Inputs

At the current stage there is no national regulatory framework in NZ encouraging distributed generation. The view of the NZ power industry seems to be, that any electricity that leaks onto the network locally should be treated exactly the same as electricity which originated hundreds of kilometres from the point of use, and that it should be effectively sold through the wholesale market (IRL, 2006). Currently, Meridian Energy supplies electricity to Totara Valley via Scanpower as the line company. Meridian Energy is the country's largest electricity generator and the only energy provider with certified carbon neutral electricity. The company generates using only renewable resources.

According to the energy bill from May 2007 obtained from a Totara Valley resident, the contracts between the local residents and the utility are based on two types of charges relating to separate meters, the MeridianPlus Anytime (20.1 cents/kWh) and the MeridianPlus Controlled (19.54 cents/kWh). The latter rate is for the controlled supply of electricity to those appliances that are constantly wired to a separate meter, for example a hot water cylinder. In this case the electricity supply can be turned off during peak times for an allocated period specified by the utility. Within the scope of the present simulation a general rate of 20 cents per kWh was used. The daily fix rate (MeridianPlus Daily) of 51.47 cents per connection was involved as HOMER's yearly standby charge of NZ\$188 per connection. The Electricity Commission levy charge of about 60 cents per month was neglected.



Figure 6.9 The entered grid values for HOMER simulation

The net metering was activated within the simulation, which means that the meter runs backwards when surplus onsite generated power is being supplied to the grid, and hence the customers are charged only for the net electricity amount purchased. The sellback rate was set at the same value as the purchase price.¹² There is no charge applied to the peak hourly electric load each month by Meridian Energy so that no value was entered into HOMER's demand rate window.

6.5 Wind Turbine Inputs

The Air–X wind turbine represents the power source for the micro configuration of the HyLink system. The turbine's specifications used for the system modelling are

¹² When net metering applies, it is not necessary to set the sellback rate equal to the power price. If the sellback rate is equal to the power price, that is better than net metering because it means that the power being sold to the grid is always worth the retail price even when more is generated than consumed. With net metering, the value of the power sold to the grid typically drops to zero once the generation is higher than the consumption (Lilienthal et al., 2003).

| Turbine type | Air-X | • | Details | New Delete | |
|--|--------------|--------------------|-------------|-------------------|-------------------------------------|
| Turbine prope | rties | | | | |
| Abbreviatio | on: Air-X | (used for column l | neadings) | | 0.6 Power Curve |
| Manufacturer: Southwest Windpower | | | | | |
| Website: <u>http://www.windenergy.com/index_wind.htm</u> | | | 20.4 | | |
| Current: DC | | | §0.2 | | |
| | | | | | |
| | | | | | 0 5 10 15 20 25 Wind Speed (m/s) |
| Costs | | | | Sizes to consider | Cost Curve |
| Quantity | Capital (\$) | Replacement (\$) | 0&M (\$/yr) | Quantity | 2,500 |
| 1 | 2300 | 1500 | 0 | 0 | 2,000 |
| | | | | 1 | €1,500 |
| | | | | | 5 1,000 |
| | {} | {} | {} | | 500 |
| Other | | | | | |
| Lifeti | ma (ura) | 15 () | 1 | | 0.0 0.2 0.4 0.6 0.8 1.0 Quentity |
| Lilet | me (Ma) | | - | | — Capital — Replacement |
| Hub | height (m) | 12 {} | | | |

Figure 6.10 Air-X wind turbine inputs in HOMER

shown in Figure 6.10. The capital costs include the costs of the mast, the wiring and the installation; therefore the generator replacement costs are lower. The start-up wind speed of the Air-X turbine is 3.58 m/s and the stall mode activation wind speed is 15.6 m/s. This can be read off from the turbine's power curve. The input of the two different quantities means that HOMER will consider two energy systems, one including the wind turbine and another one without the wind turbine.

The power curve for the Air-X wind turbine used in the simulation is taken from the manufacturer's website (see Figure 6.11).



Figure 6.11 Air-X power curve provided by the manufacturer
6.6 Photovoltaic Inputs

The three solar panels installed on the hilltop provide a total of 144 Wp. The capital costs were based on the rate of NZ\$4.30/Watt and NZ\$200 for the controller. The

| Costs Capital (\$) Re 0.144 820 | placement (\$) D&M (\$/yr) 820 0 | Sizes to consider Size (kW) 0.000 0.144 | 1,000 Cost Curve |
|--|--|--|--|
| Properties | 25 () Output | current: C AC C DC | 0.00 0.04 0.08 0.12 0.16 Size (kW) Capital — Replacement |
| Tracking system Slope (degrees) Azimuth (degrees W of S) Ground reflectance (%) | No Tracking 40 () 180 () 20 () | - | Help Cancel OK |

Figure 6.12 PV inputs in HOMER

angle at which the panels are mounted, called the slope, matches the latitude of the subject site. The azimuth angle of 180° indicates that the panels are tilted towards North. No tracking systems for power output optimisation were applied. The PV derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated (Lilienthal et al., 2003).

6.7 Electrolyser Inputs

According to the VI curve recorded at 60°C by Lynntech (see Figure 3.9), the PEM electrolyser used at Totara Valley can handle up to 550 W electrical power input. This value matches the Air-X wind turbine's maximal power output based on the power curve provided by Southwest Windpower Inc. At this stage, it is important to note that under real conditions both components are not anticipated to reach the maximum of 550 W. The wind turbine due to its much lower outputs obtained from experience (Figure 6.11), and the electrolyser due to operation at lower stack temperature¹³ (Figure 3.9). As such both components meet their power characteristics, however, at a

 $^{^{13}}$ The uncontinuous Air-X wind turbine operation and the cooling effect of the ambient air will hardly allow for heating up of the electrolyser, although the impressed cell voltage (2.1 V) is much higher than the thermoneutral cell voltage (1.48 V).

maximal level of approximately 250 W, and consequently, clear represent the bottleneck of the system. For the simulation it was also assumed that the distilled anode water circulates solely by the means of the gas lift, so that the water pump power consumption (12 W) during electrolyser operation was not considered.



Figure 6.13 Electrolyser inputs in HOMER

In addition to the stack cost, the capital costs include electrolyser electronics (laptop, dc/dc converter, pressure sensors, and charge controller), distilled water supply assembly as well as the hydrogen treatment assembly cost. The replacement costs of the PEM electrolyser are assumed to be lower than the capital costs because some of the components included in the capital costs have a longer lifetime than the stack itself. The efficiency of the dc/dc converter ($\eta_{converter} > 85\%$) was combined with the electrolyser's efficiency ($\eta_e = 66\%$). Furthermore, it was assumed that the electrolyser runs always during the wind turbine operation i.e. approximately 6000 hrs/year (see Chapter 7). As PEM electrolysers' durability is about 10000 operational hours at the current stage of the worldwide research, a durability of 2 years was given the Lynntech electrolyser within the scope of the present simulation.

6.8 Hydrogen Tank Inputs

Considering the pipeline's internal diameter of 16 mm and the length of 2 km it represents a tank with a volume of 402.12 Litres. For any ideal gas, moles (n) and

volumes (*V*) are directly related by the simplest equation of state namely the classical ideal gas law:

$$pV = nRT \tag{6.1}$$

Hence the molar volume (V_M) of any ideal gas at 0°C and atmospheric pressure is:

$$V_{M} = \frac{V}{n} = \frac{RT}{p} = \frac{8.314 * 273.15}{101325} \frac{m^{3}}{mol} = 22.4 \frac{L}{mol}$$
(6.2)

This means that the MDPE pipeline can store 18 moles of hydrogen molecules at 1 barg and 54 moles at 3 barg. Consequently, at 3 barg pressurised hydrogen gas weighs 108 g at 0°C. The pipeline was modelled as a 108 g hydrogen tank because the gas pressure in the pipe was originally planned to oscillate between 1 barg and 4 barg. The hydrogen loss due to diffusion through the pipe walls was neglected.



Figure 6.14 Hydrogen tank inputs in HOMER

The pipeline capital costs shown in Figure 6.14 include mole ploughing under right weather conditions as well as the pipeline system costs including the pipeline, the joiners, the both pressure gauges and the electrofusion equipment hire.

6.9 Fuel Cell Inputs

The PEM fuel cell capital costs include also the costs of the inverter, the controller and the gel cell battery bank. The replacement costs are estimated to be lower because some of the costs involved in the capital costs refer to components which have a longer durability than the stack itself. The information about the lifetime of the Independence 1000 J48C was derived from the Center for Fuel Cell Research and Applications at the Houston Advanced Research Center (HARC, 2004).



Figure 6.15 PEM fuel cell inputs in HOMER

The fuel cell/inverter system was modelled as an ac generating fuel cell. That way HOMER recognises that there is no electrical connection between the renewable sources and the load. The power losses at the inverter ($\eta_{inverter} = 97\%$) were included in the fuel cell's efficiency curve.



Figure 6.16 Schematic of the HyLink system in HOMER after accomplishing the data inputs

HOMER describes the efficiency of a fuel cell depending on its output in form of the efficiency curve. Therefore it requires the fuel consumption data for at least two values of the power output. The values used in the current simulation are based on the following fuel consumption data provided by ReliOn: 15 SLPM at 1 kW and 7.5 SLPM at 500 W which corresponds with 15.46 SLPM at 1 kW and 7.73 SLPM at 500 W considering the inverter's efficiency of 97%.



Figure 6.17 The ReliOn's hydrogen consumption in HOMER

The fuel cell's fuel curve specifies how much electricity it produces for a given fuel input. As the ReliOn PEMFC is only used for electricity generation, the remaining fuel energy was not considered to be converted to heat. Hence, the heat recovery ratio was set at zero. Furthermore, no fixed time schedule was chosen in the HOMER's generator schedule chart at this stage, so that the fuel cell operates at any time of a day.

The efficiency curve from Figure 6.17 shows that the PEMFC achieves its near maximal efficiency at about 500 W power output. For this reason, the minimum allowable load on the fuel cell was set at 50% of its full capacity (see Figure 6.15). That means that the simulated ReliOn fuel cell will operate only at 500 W or above.

According to HARC, the efficiency of the ReliOn J48C is seen to have a maximum of about 40% near 750 W and is about 25% less at the output of 250 W (HARC, 2004a). The efficiency curve used in the simulation (Figure 6.17) is more optimistic at ReliOn's lower power output.

7. Simulation of the Current HyLink Configuration

First of all the HOMER version 2.42 beta (used for test simulations) was replaced by the recently developed version 2.67 beta which can handle the unique HyLink system in a better way, in particular, it can better recognise that the modelled HyLink system acts as a dc/ac conversion device. The previous version listed illogical system configurations, like for example grid/fuel cell, in its optimisation results window. The new HOMER version recognises that the fuel cell should operate only as a part of the HyLink component chain; however, it still fails to recognise it with regards to the hydrogen tank (see Table 7.3).



Figure 7.1 File Preferences in HOMER

This happened although HOMER was forced to omit illogical system configurations in the file *Preferences* and despite the allowed option to consider zero sizes (see actual data inputs), and thus to ignore the single HyLink components. All in all, the HyLink system contributed by the way to the further development of the HOMER software.

7.1 PV Role within the HyLink System

As mentioned in the previous chapters, the batteries' task is not to store energy to meet the community's load requirements. The hydrogen pipeline takes this role. The batteries store energy for electrical needs within the HyLink system; for the monitoring and control system as well as the data logger and the data transmitter. As the batteries are not included in the HyLink model, compensation needed to be done

to account for this HyLink-internal power demand. The solar panel power output was therefore investigated.



Figure 7.2 Simulated PV power output over a year

According to the calculations made by HOMER, the PV panels installed on the hilltop provide a yearly average power of 20 W; in the summer 25 W and in the winter 15 W. This will hardly meet the required system-internal load, especially in the winter, considering that the main background energy consumer of the initial HyLink system configuration, the laptop, needs to be continuously in the on- mode.

| Quantity | Value | Units | Quantity | Value | Units |
|------------------|-------|--------|--------------------|-------|--------|
| Rated capacity | 0.144 | kW | Minimum output | 0.00 | k₩ |
| Mean output | 0.02 | kW | Maximum output | 0.16 | kW |
| Mean output | 0.520 | kWh/d | PV penetration | 0.323 | % |
| Capacity factor | 15.0 | % | Hours of operation | 4,375 | hr/yr |
| Total production | 190 | kWh/yr | Levelized cost | 0.338 | \$/kWh |

Table 7.1 Summarised yearly PV data

In order to generalise and simplify the HyLink model, and thus, to enable a less complicated modelling and analysis of another HyLink configurations, it was assumed that the solar panels meet exactly the overall HyLink-internal energy losses occurring at the hilltop hydrogen generation subsystem as well as at the woolshed hydrogen consumption subsystem. This means that there are no batteries and no solar panels in the HOMER's system schematic.



Figure 7.3 Wind power based HyLink system schematic

7.2 Air-X Power Output

The Air-X wind turbine provides the net electricity to run the electrolyser. Given the high whole community demand, the sizes of the both units (max. 550 W) reveal that the present HyLink system configuration was developed for R&D purposes rather than for commercial application. Figure 7.4 illustrates the Air-X wind turbine's power output calculated by HOMER based on the wind resource inputs from Chapter 6 and the power curve provided by the turbine manufacturer.



Figure 7.4 Simulated Air-X power output over a year based on the power curve provided by the manufacturer

The Air-X power output is estimated to be 80 W in yearly average. The monthly averages are higher in the winter with approx. 100 W and lower in the summer with approx. 60 W. The yearly wind turbine generation pattern matches the yearly pattern

of the community's energy demand which is also higher in the winter; however, obviously in a much smaller scale.

| | | | Quantity | Value | Units |
|----------------------|-------|--------|--------------------|-------|--------|
| Quantity | Value | Units | Minimum output | 0.00 | kW |
| Total rated capacity | 0.550 | kW | Maximum output | 0.52 | kW |
| Mean output | 0.08 | kW | Wind penetration | 1.17 | % |
| Capacity factor | 14.3 | % | Hours of operation | 6,130 | hr/yr |
| Total production | 689 | kWh/yr | Levelized cost | 0.319 | \$/kWh |

Table 7.2 Summarised yearly Air-X data

7.3 First Simulation Run

HOMER simulates system configurations with all of the combinations of components that are specified in the components inputs. The software discards from the results all infeasible system configurations, which are those that do not adequately meet the load given either the available resource or constraints that have been specified (Lilienthal et al., 2003).

HOMER ranks energy systems based on their total net present cost C_{NPC} (or *total* NPC), sometimes called lifecycle cost. The most cost-effective energy system appears on the top of the optimisation results list. C_{NPC} in HOMER equals to the ratio of the total annualised cost $C_{ann,tot}$ of the system and the capital recovery factor CRF, used in order to imply the present value of money. $C_{ann,tot}$ is the sum of the annualised costs of each system component including its annualised capital and replacement cost as well as the annual operating and fuel (if applicable) cost, based on the prescribed project lifetime, currently set at 25 years. The salvage value *S* compensates discrepancies between the component and the project lifetimes. The equations HOMER uses to calculate these economic values are listed below.

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})}$$

 $C_{ann,tot}$ total annualised cost [\$/yr]CRF()capital recovery factor

iinterest rate [%] R_{proj} project lifetime [yr]

$$CRF(i, N) = \frac{i(1+i)^{N}}{(1+i)^{N} - 1}$$

N number of years

$$S = C_{rep} * \frac{R_{rem}}{R_{comp}}$$

| C_{rep} | replacement cost [\$] |
|-------------------|---|
| R _{rem} | remaining life of the component at the end of the project |
| | lifetime |
| R _{comp} | component lifetime [yr] |

Since the grid is unlike any other component, HOMER calculates the costs associated with the grid in a unique way. The grid capital cost is equal to the interconnection charge, a one–time fee charged by the utility for allowing a power system to be connected to the grid. HOMER does not apply this fee to grid-only systems, but rather to grid-connected systems that include some other generation source like for example a fuel cell. For the present simulation the interconnection charge is set at zero. HOMER calculates the annualised capital cost of the grid the same as it calculates the annualised capital cost of the grid is always zero. The grid O&M cost is equal to the annual cost of buying electricity from the grid minus any income from the sale of electricity to the grid. The O&M cost also includes the yearly standby charge.

Table 7.3 shows the optimisation results of the first simulation run with grid alone ranking first as more cost–effective than grid-connected HyLink system ranking fourth. The both system configurations in the middle are listed because HOMER

doesn't recognise the hydrogen tank as a fixed part of the HyLink component chain. Both systems are illogical and should be ignored.

| Se | Sensitivity Results Optimization Results | | | | | | | | | | | | |
|----|--|-------|---------------|---------------|-----------------|--------------|--------------------|---------------------------|--------------|-----------------|---------------|----------------------|----------------|
| Do | Double click on a system below for simulation results. | | | | | | | | | | | | |
| 4 | <u>م الم</u> | Air-X | PEMFC (kW) | Elec. (kW) | H2 Tank (kg) | Grid (kW) | Initial Capital | Operating Cost (\$/yr) | Total NPC | COE (\$/kWh) | Ren. Frac. | Capacity Shortage | PEMFC (hrs) |
| 4 | <u>^</u> | | | | | 1000 | \$0 | 1,460 | \$ 18,664 | 0.200 | 0.00 | 0.00 | |
| 14 | ~ | | | | 0.108 | 1000 | \$ 8,500 | 1,383 | \$ 26,173 | 0.280 | 0.00 | 0.00 | |
| 14 | 🗼 🎖 | 1 | 1 | 0.55 | | 1000 | \$ 35,300 | 6,149 | \$ 113,909 | 1.221 | 0.09 | 0.00 | 0 |
| 1 | 🗼 🐉 | 1 | 1 | 0.55 | 0.108 | 1000 | \$ 43,800 | 6,072 | \$ 121,419 | 1.301 | 0.09 | 0.00 | 0 |

Table 7.3 Optimisation results of the first simulation run

The most noticeable result of the first simulation run is that HyLink's fuel cell has zero operational hours. The reason that stops HOMER from using the fuel cell is its cost. The fuel cell's replacement cost is \$12,000 and its lifetime is 4000 hours. That means that at its full output of 1 kW, it would produce power for \$3/kWh, without considering the cost of the remaining HyLink components which supply the fuel cell with hydrogen. As the grid provides the same product for \$0.20/kWh at any time, HOMER decides to buy grid power and never turn on the fuel cell. At this stage the fuel cell durability and cost are revealed as still existing barriers in the implementation of hydrogen technology.

The fuel cell's high fixed generation cost of 3 \$/kWh implies that the levelised cost of energy (*COE*) provided by the HyLink system alone will be much higher. The calculated *COE* equals 1.3 \$/kWh (see Table 7.3) because in that simulation the complete load requirements are covered solely by the grid. The equation HOMER uses to calculate *COE* is listed below.

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{grid}} \,.$$

 E_{prim} primary load served [kWh/yr] E_{grid} total grid sales [kWh/yr]

The currently available HOMER versions offer following options to enable the HyLink system simulation:

- removing the grid as a competitor and considering HyLink as a stand alone system
- lowering the HyLink system related cost or extending its durability (in particular the fuel cell) so it can compete with the grid
- constraining the grid capacity at a requested value
- scheduling the fuel cell to be on in certain times of the day or the year on the generator schedule chart

7.4 HyLink as a Stand-Alone System in HOMER

Removing grid from the system configuration and considering HyLink as a standalone system in HOMER allows for a better focus on the HyLink system itself. In this case HyLink has no competitor so that its full capacity is used to supply power.



Figure 7.5 HyLink stand-alone system schematic

7.4.1 Economic Considerations

The cost summary for the HyLink stand-alone system over the project lifetime of 25 years is shown in Table 7.4. *Total NPC* is estimated to be \$106 thousands. Clear to see is the significant impact of the energy conversion devices, electrolyser and fuel

| Component | Capital (\$) | Replacement (\$) | O&M (\$) | Fuel (\$) | Salvage (\$) | Total (\$) |
|---------------|--------------|------------------|----------|-----------|--------------|------------|
| Air-X | 2,300 | 626 | 0 | 0 | -116 | 2,809 |
| PEMFC ReliOn | 16,000 | 4,562 | 0 | 0 | -1,381 | 19,182 |
| Electrolyzer | 17,000 | 60,924 | 0 | 0 | -1,165 | 76,759 |
| Hydrogen Tank | 8,500 | 0 | 0 | 0 | -990 | 7,510 |
| System | 43,800 | 66,112 | 0 | 0 | -3,652 | 106,260 |

 Table 7.4 Cost of the HyLink stand-alone system over the project lifetime of 25 years

cell, on the overall HyLink costs. Their initial costs and in particular their replacement costs far outweigh the expenses for the wind turbine and the pipeline. The above mentioned durability is an issue not only for the fuel cell (max. 4000 operational hours) but also for the electrolyser (approx. 10000 operational hours). The electrolyser is much more affected by the durability because according to the simulation results it operates 6100 hours per year, while the fuel cell only 241 hours per year. The reason for this is that the fuel cell is forced to work only at a power output above 500 W (see Chapter 6). The higher replacement costs of the electrolyser are well emphasised in Figure 7.6.



Figure 7.6 Costs of the HyLink components - overview

Figure 7.7 displays the cash flows of the HyLink system over the project lifetime of 25 years by distinguishing its respective components. It indicates that the electrolyser must be replaced every two years and the fuel cell first in the Year 17. The wind turbine and the pipeline replacement costs play only a minor part in this HyLink configuration.

The maintenance and operation costs of the HyLink system are not significant because of the low amount on moving parts, fuel autonomy and automation of the technical processes.



Figure 7.7 HyLink related cash flows over the project lifetime of 25 years

7.4.2 Energy Flow within the HyLink System

The HyLink system configuration installed at Totara Valley serves as a demonstration and for this reason is sized in small dimensions. When the electrolyser runs at its maximal output of 550 W, it fills the 0.1 kg H₂ tank (pipe), which corresponds with a 3.3 kWh tank¹⁴, within 6 hours. The pipe has two main tasks which can be best described as follows. During long wind periods, the pipe can be used as an energy transportation media and the fuel cell as a constant electricity provider at power output constrained by the overall system efficiency. During short wind periods, the pipe can be used as an energy storage media for times when energy is required e.g. peak demand or emergency. In this case the fuel cell can supply up to 1 kW electricity one hour long (due to 35% electr. efficiency) using the stored 3 bar of hydrogen.

¹⁴ Lower heating value (LHV) of hydrogen equals 33.3 kWh/kg



Figure 7.8 Comparison of the mean hourly power profiles - primary load, wind turbine output and fuel cell output

Figure 7.8 displays the hourly power profiles of the simulated HyLink configuration throughout several days of December. Looking at this, it must be kept in mind that the load represents an average load of one of the eight monitored sites at Totara Valley so that the overall community load is eight times higher. Comparing the Air-X's and the ReliOn's power output profiles, remarkable is the impact of the energy losses at the converter/electrolyser subsystem ($\eta_{e/conv} = 60\%$) and the fuel cell/inverter subsystem ($\eta_{pemfc/inv} = 35\%$, electrical) on the overall HyLink efficiency.



Figure 7.9 Ratio of the wind turbine and the fuel cell generation

Considering however that within that process an energy carrier is produced and consumed, and that the thermal potential of the fuel cell is not involved, the loss is lower than one would expect – thinking of the Carnot Cycle constrained combustion processes.

Tables 7.5 and 7.6 summarise the yearly fuel cell data calculated by HOMER. They contain some already mentioned values. The energy losses due to conversion are the reason that from 690 kWh per year generated by the Air-X, 124 kWh per year will reach the consumer. The fuel cell's mean electrical output of 0.517 kW refers only to the time of operation. The mean electrical efficiency of 35.7% refers to the ReliOn/Inverter subsystem and the output of 0.517 kW.

| Quantity | Value | Units |
|--------------------------|-------|-----------|
| Hours of operation | 241 | hr/yr |
| Number of starts | 241 | starts/yr |
| Operational life | 16.6 | yr |
| Capacity factor | 1.42 | % |
| Fixed generation cost | 3.00 | \$/hr |
| Marginal generation cost | 0.00 | \$/kWh |

Table 7.5 Summarised yearly fuel cell data

| Quantity | Value | Units | Quantity | Value | Units |
|------------------------|-------|--------|----------------------------|-------|--------|
| Electrical production | 124 | kWh/yr | Hydrogen consumption | 10.4 | kg/yr |
| Mean electrical output | 0.517 | kW | Specific fuel consumption | 0.084 | kg/kWh |
| Min. electrical output | 0.500 | kW | Fuel energy input | 348 | kWh/yr |
| Max. electrical output | 0.593 | kW | Mean electrical efficiency | 35.7 | % |

Table 7.6 Summarised yearly fuel cell performance data

Figure 7.10 indicates that current versions of HOMER don't offer to consume the stored hydrogen after a specific level in the tank was reached. The fuel cell operates whenever HOMER decides there is enough hydrogen to fuel it and it is cheaper than buying from elsewhere (T. Lambert, personal communication). As a result the simulated tank level oscillates in the lower area of its 0.1 kg capacity, which can be seen in Figure 7.10.



Figure 7.10 Pipe content distribution

7.5 Simulation of the Grid-Connected HyLink System

The ReliOn's high fixed generation cost of \$3 per kWh made it non-competitive against the grid. Different options lend themselves to activate HyLink as a grid supplement in HOMER.

7.5.1 HyLink Cost Reduction

The expenses entered in the input windows in Chapter 6 represent the effectively paid amounts. The electrochemical energy conversion devices, the electrolyser and the fuel cell, have a massive impact on the lifecycle costs of the system. Considering the fact that these appliances are in the early market stage and as such represent limited-lot products, their costs are commercially sensitive and after a market adoption period can drop rapidly. Furthermore, the continuous improvements in the product durability contribute to considerable replacement cost reductions.

In order to make the fuel cell competitive against grid in HOMER, its fixed generation cost must be scaled down to the grid electricity price of 0.2\$/kWh. This can be achieved either by reducing the fuel cell's replacement cost to \$800 or enhancing its lifetime to 60,000 hours. The most suitable was to modulate both quantities with a following possible result: replacement cost \$4,000 and lifetime 20,000 hours, which is within the bounds of possibility. In all three cases HOMER allowed fuel cell to supplement grid with 124 kWh/yr, the same amount as in the stand-alone option. The monthly average electric production of all three generators is given in Figure 7.11.



Figure 7.11 Ratio of the grid, Air-X and PEMFC generation

As HOMER compares only generators with each other, the remaining components of the HyLink system are not included in the above consideration. Their cost can be partially compensated with the higher initial cost of the alternative power line installation or should be considered as subsidised at the current stage of development.

7.5.2 Constraining the Grid Capacity

Another way to simulate the HyLink system as a grid supplement in HOMER is by constraining the grid purchase capacity in the advanced grid inputs window. As the hourly peak of the simulated primary load is 3.3 kW, the value of 2.3 kW was chosen as the maximal grid purchase capacity. That way the 1 kW ReliOn fuel cell was given the potential to shave every occurring peak demand throughout the year. Within the scope of this simulation, the fuel cell was permitted to work at any output within the range from 0 W to 1 kW. Applying these settings HOMER turns on the fuel cell regardless its costs or its lifetime when needed. Figure 7.12 indicates that HOMER also uses the fuel cell when the peak demand is slightly underneath 2.3 kW, for example on 15th of May.



Figure 7.12 HyLink fully compensating the peak demand in May



Figure 7.13 HyLink's not optimal peak demand compensation in July

The above figures illustrate two examples for how HyLink can handle the occurring peak demand. They show the grid covering the lower peak demand in the morning and HyLink balancing the higher evening peak load. While the HyLink is able to



Figure 7.14 Wind turbine's output flows prior to capacity shortages

compensate it fully in May, the higher peak load in July leads to still occurring capacity shortages. The reason for that are not only the higher peak loads but also windless periods.



Figure 7.15 Daily pipeline filling process with hydrogen

Figure 7.14 displays the same cut-out as Figure 7.13 with included wind turbine performance profile. Clear to see are Air-X's output lows prior to every capacity shortage. The first shortage, on 24th of July, could have been avoided when the capacity of the wind turbine and the electrolyser were larger, and thus, the HyLink's response faster.

After the above simulation, the fuel cell's yearly electrical production was estimated to be about 78.5 kWh and the yearly unmet load 10.7 kWh by HOMER. This means that the HyLink system was capable of covering approximately 88% of the peak demand above 2.3 kW. This result confirms HyLink's potential as a peak demand compensation device.

A closer consideration of the fourth option of simulating the HyLink system, namely by scheduling the fuel cell, was not undertaken because it would overlap with the last described option - by constraining the grid capacity. At current system configuration the fuel cell can provide about 1 kWh/day at good wind conditions. Obviously, it would be scheduled at the time of the daily evening peak load.

At this stage it is important to note that batch-wise fuel cell operation involves a large number of starts, and hence, additional energy consumption to go over the fuel cell's cold-state, which also delays the system response. In addition to this, the hydrogen diffusion rate through the pipeline wall can become relevant as the gas pressure in the pipe often reaches 4 barg.



Figure 7.16 Pipe content frequency for HyLink as a peak demand compensation unit

In the following chapter the fuel cell's continuous operation mode is investigated for the present HyLink configuration.

7.6 HyLink in the Load Following Operation Mode

The above considerations refer to batch-wise fuel cell operation. The fuel cell was forced to operate at the minimal power output of 500 W in the subchapter 7.4 and turned on only during the higher daily evening peak loads in the subchapter 7.5. The present subchapter aims to analyse the load following operation mode of the fuel cell for the current HyLink configuration.

| Component | Capital (\$) | Replacement (\$) | 0&M (\$) | Fuel (\$) | Salvage (\$) | Total (\$) |
|---------------|--------------|------------------|----------|-----------|--------------|------------|
| Air-X | 2,300 | 626 | 0 | 0 | -116 | 2,809 |
| PEMFC ReliOn | 16,000 | 156,099 | 0 | 0 | -664 | 171,435 |
| Electrolyzer | 17,000 | 60,924 | 0 | 0 | -1,165 | 76,759 |
| Hydrogen Tank | 8,500 | 0 | 0 | 0 | -990 | 7,510 |
| System | 43,800 | 217,649 | 0 | 0 | -2,936 | 258,513 |

Table 7.7 Cost of the HyLink in load following operation mode over the projectlifetime of 25 years

The stand-alone system schematic from subchapter 7.4 was therefore used and the fuel cell was permitted to operate at any output in the range from 0 kW to 1 kW. Table 7.7 shows the massive impact of the fuel cell cost on the overall system lifecycle cost (compare with Table 7.4).



Figure 7.17 Cost of the HyLink components in the load following operation mode

Figure 7.17 shows clearly that in the load following operation mode the fuel cell cost outweighs the electrolyser cost due to fuel cell's shorter lifetime and higher replacement cost (compare with Figure 7.6).

Table 7.8 indicates the reason for the increased lifecycle cost of the HyLink working in the load following mode compared with its batch-wise operation (see Table 7.5). It is the fuel cell's high number of operational hours which makes its replacement more frequent. Noticeable is the extremely low capacity factor of the fuel cell caused by the small wind turbine/electrolyser subsystem dimension and the low overall system efficiency.

The most important result from Table 7.9 is the low fuel cell efficiency (compare with Table 7.6) when working in the load following mode, which can be explained with its efficiency curve from Figure 6.17.

| Quantity | Value | Units |
|--------------------------|-------|-----------|
| Hours of operation | 4,122 | hr/yr |
| Number of starts | 1,246 | starts/yr |
| Operational life | 0.970 | yr |
| Capacity factor | 0.885 | % |
| Fixed generation cost | 3.00 | \$/hr |
| Marginal generation cost | 0.00 | \$/kWh |

 Table 7.8 Summarised yearly fuel cell data in the load following operation mode

| Quantity | Value | Units | Quantity | Value | Units |
|------------------------|-------------|--------|----------------------------|-------|--------|
| Electrical production | 77.5 | kWh/yr | Hydrogen consumption | 10.5 | kg/yr |
| Mean electrical output | 0.0188 | kW | Specific fuel consumption | 0.135 | kg/kWh |
| Min. electrical output | 0.000000487 | kW | Fuel energy input | 349 | kWh/yr |
| Max. electrical output | 0.0965 | kW | Mean electrical efficiency | 22.2 | % |

| Table 7.9 Summarised yearly fuel cell performance | data in the load following |
|---|----------------------------|
| operation mode | |

The mean electrical output indicates that the fuel cell operating in the load following mode would be massively under-utilised.



Figure 7.18 Pipe content frequency for HyLink in the load following operation mode

Figure 7.18 shows the low average gas content in the pipeline for HyLink's load following operation mode, which implies low losses due to hydrogen permeability through polyethylene.

8. HyLink Optimisation Modelling

8.1 Investigating the Wind Generator/Electrolyser Arrangement

To find the optimal wind turbine/electrolyser arrangement is difficult due to the fluctuating nature of wind power. In addition to this the following factors must be considered in this context:

- higher electrolyser cost compared with wind turbine considering the same size
- the danger of stack overheating by operating above its rated output
- excess heat production at high current densities

8.1.1 Current System Configuration

In the current system configuration the rated power output of the Air-X corresponds with the rated power output of the electrolyser, and the electrolyser's power input capacity can handle the wind turbine's maximal output. This means that the whole wind power can be converted into hydrogen and theoretically there is no need for the dump load.

There is one thing which can be improved in this arrangement, namely the capacity factor CF_e of the electrolyser¹⁵, which was estimated to be 14.3% by HOMER in Chapter 7.

$$CF_e = \frac{689kWh/yr}{8760h*0.55kW} = 0.143$$
(8.1)

This can be done by relative over-sizing of the wind turbine and dumping of the power output outweighing electrolyser's input capacity. This would lead at the same time to reduction of electrolyser's levelised cost, and hence, to the improvement of the overall system economics.

¹⁵ Capacity factor of the electrolyser in HOMER corresponds with its average yearly power input divided by its maximal yearly capacity.

In order to find the economically most suitable wind turbine/electrolyser arrangement for the present HyLink system configuration in the load following operation mode, the Air-X wind turbine was taken as a fixed constant and the electrolyser capacity as a variable. HOMER calculated then the system's *COE* and the electrolyser's CF_e for each arrangement. The results are shown in Table 8.1.

| Electrolyser Capacity [kW] | Relative System COE [%] | CF _e [%] | Electrolyser/Air-X Capacity [%] | Fuel Cell [hrs/yr] |
|-------------------------------|----------------------------|------------------------|------------------------------------|-----------------------|
| 0.05 | 272.7 | 57.9 | 9.1 | 2671 |
| 0.1 | 238.5 | 46.1 | 18.2 | 4122 |
| 0.15 | 145.8 | 37.8 | 27.3 | 4122 |
| 0.2 | 118.8 | 31.8 | 36.4 | 4122 |
| 0.25 | 106.9 | 27.4 | 45.5 | 4122 |
| 0.3 | 101.2 | 23.9 | 54.5 | 4122 |
| 0.35 | 98.5 | 21.2 | 63.6 | 4122 |
| 0.4 | 97.3 | 19 | 72.7 | 4122 |
| 0.45 | 97.3 | 17.2 | 81.8 | 4122 |
| 0.5 | 98.1 | 15.7 | 90.9 | 4122 |
| 0.55 | 100.0 | 14.3 | 100.0 | 4122 |

 Table 8.1 HyLink's relative levelised cost and electrolyser's capacity factor at

 different electrolyser capacities

Table 8.1 and Figure 8.1 show the increasing capacity factor of the electrolyser by lowering its capacity in relation to the Air-X wind turbine. The Hylink's levelised cost curve indicates that the system's *COE* reaches its minimum at electrolyser's capacity of about 450 W. This means that the most economic wind generator/electrolyser arrangement will be achieved by under-sizing the electrolyser by about 80% in relation to the wind turbine. This would result in the increase of electrolyser's capacity factor from 14.3% to about 17-18%. The fuel cell's operational hours for every simulation run indicate that its replacement cost has no impact on the differences in the resulting system levelised costs (see Table 8.1).

The pattern of the relative system COE curve indicates that the electrolyser undersizing down to 50% (0.275 kW) of the wind turbine size can make sense, if high electrolyser capacity factor is required (up to 25%). The system's levelised cost doesn't increase significantly until this point (see Figure 8.1).



Figure 8.1 Graphical presentation of HyLink's COE in relation to the electrolyser's capacity factor and the electrolyser/wind turbine arrangement

Figure 8.2 displays the anticipated excess generation by Air-X in relation to different electrolyser capacities. It is clear to see that the excess electricity increase is high for the electrolyser size between 0.3kW and lower, while it is less significant for electrolyser capacities between 0.3 kW and 0.55 kW.



Figure 8.2 Air-X's excess generation versus electrolyser capacity

In analogy to Figure 8.2, Figure 8.3 shows the relation between the electrolyser/Air-X capacity ratio and the excess wind energy fraction. It indicates that the electrolyser under-sizing down to 50% of the Air-X's capacity will entail the dumping of only 10% of the available wind electricity. It indicates also that further under-sizing of the electrolyser would result in a rapid increase of the excess wind energy fraction.



Figure 8.3 Electrolyser/Air-X capacity ratio versus excess wind generation fraction

8.1.2 Planned System Configuration

It is planned to integrate both wind turbines into the system, Proven and Air-X (together about 2.5 kW), using a larger 1 kW electrolyser being currently developed at IRL. Similar to the subchapter before, the arrangement of the both wind turbines with different electrolyser sizes was investigated. As the Proven wind turbine has the main influence on the overall output of the both turbines, the power curve of a 2.5 kW Proven wind turbine provided by the manufacturer¹⁶ as well as the hub height of 6.5 m was used for the simulation.

¹⁶ http://www.provenenergy.co.uk/



Figure 8.4 Air-X/Proven inputs in HOMER

Unlike 14.3% for the Air-X wind turbine (see Table 7.2), HOMER calculated the capacity factor of 23.7% for the Proven wind turbine. This result is linked with the more advantageous power curve of the Proven wind turbine, especially at the high wind speeds. This turbine has also a slightly longer time of operation, 6462 hours/year instead of 6130 hours/year, due to a wider range of wind speed it can operate at. Despite that, the electrolyser's lifetime was left at the value of two years. The fuel cell's time of the load following operation was estimated to be 5811 hours/year instead of 4122 hours/year (see Table 7.8), which causes a slightly more frequent replacement of the fuel cell in this simulation. In analogy to Table 8.1, Table 8.2 comprises the HyLink's relative levelised cost at different electrolyser capacities using a 2.5 kW Proven power curve.

| Electrolyser | Relative System | CF _e | Electrolyser/ProvenAir-X | Fuel Cell |
|--------------|-----------------|-----------------|--------------------------|-----------|
| | | [/0] | | [[[[5/y]] |
| 0.55 | 132.8 | 49.8 | 22 | 5811 |
| 1 | 99.8 | 40.6 | 40 | 5811 |
| 1.5 | 91.2 | 33.8 | 60 | 5811 |
| 2 | 92.3 | 28.4 | 80 | 5811 |
| 2.5 | 100.0 | 23.6 | 100 | 5811 |

Table 8.2 Relative levelised cost and electrolyser's capacity factor at different

 electrolyser capacities for the planned system configuration

From Figure 8.5 can be derived that the lowest system levelised cost can be expected by selecting a 1.5 kW or a 2 kW electrolyser. The choice of a 1 kW electrolyser will increase HyLink's *COE* slightly by 10%, and the utilisation of smaller electrolysers will lead to a steep slope of the system's levelised cost profile. Thus, the economically most advantageous arrangement will be achieved by under-sizing the electrolyser by 60% to 80% in relation to the 2.5 kW wind turbine, and hence, running the electrolyser at its capacity factor of about 30%. Considering the danger of overheating and the electrolyser's lower efficiency at higher performance, 70% to 80% are recommended. This result corresponds with the outcomes obtained for the current system configuration (see subchapter 8.1.1). The reason for the higher capacity factor of the electrolyser is the above mentioned higher capacity factor of the 2.5 kW Proven in relation to the Air-X wind turbine.





Figure 8.6 shows that the extent of the excess Proven generation due to electrolyser under-sizing is expected to be more significant than in case of the current system configuration. The excess energy values include small amounts (up to 19 kWh/year) of excess power produced by the fuel cell.



Figure 8.6 Both wind turbines' excess generation versus electrolyser capacity

Figure 8.7 indicates that under-sizing of the electrolyser by 50% in relation to the Proven wind turbine will result in dumping of about 20% of the wind electricity available. This is a considerably larger amount than estimated for the current system configuration (see Figure 8.3). The above recommended electrolyser/wind turbine capacity ratio of 70%-80% will involve approximately 5%-10% of excess wind power, which is still acceptable.



Figure 8.7 Electrolyser/wind turbines capacity ratio vs. excess wind power fraction

The discrepancy between the both simulation outcomes is clearly explained in Figure 8.8. It is justified with the different exploitation of the high wind speeds by the both wind turbines. While Air-X's control system activates the stall mode at wind speeds over 15.6 m/s, the Proven wind turbine keeps generating at nearly rated output. Consequently, there is a different impact of the dumping of the excess power. In case of the Air-X based system it results in curtailing of single peak columns, and in case of the Proven based system, in curtailing of wider peak areas.



Figure 8.8 Comparison of Air-X and Proven power output profiles

8.2 Investigating the Overall System Arrangement

8.2.1 Using Present Pipeline Size

The simulation of the HyLink system in the load following operation mode reveals that the fuel cell and the pipeline are under-utilised (Figure 7.18, Table 7.8, Table 7.9), which contributes to the rise of the system's levelised cost. In order to identify the economically most optimal system arrangement, modelling of different system configurations was undertaken and their relative *COE* compared. The pipeline volume and the fuel cell capacity were therefore left at the same value. The size of the wind turbine/electrolyser subsystem, including electrolyser down-rating of 80% in relation to the wind turbine, was varied (see Table 8.3). The wind turbine capacity was altered

by multiplying the 2.5 kW Proven power curve. The primary load was set at a very high value to prevent fuel cell's excess power production.

| Proven | Electrolyser | Relative System | CF_{fc} | CF _{pipe} | FC |
|---------------|---------------|-----------------|-----------|--------------------|----------|
| Capacity [kW] | Capacity [kW] | COE [%] | [%] | [%] | [hrs/yr] |
| 2.5 | 2 | 100.0 | 9.8 | 8.3 | 5811 |
| 5 | 4 | 78.7 | 19.5 | 15.7 | 6107 |
| 7.5 | 6.25 | 88.3 | 24.3 | 19.4 | 6225 |
| 10 | 8 | 95.8 | 27.4 | 21.7 | 6283 |
| 12.5 | 10 | 106.6 | 29.8 | 23.4 | 6313 |
| 15 | 12 | 117.3 | 31.6 | 24.8 | 6339 |
| 17.5 | 14 | 128.4 | 33.1 | 25.9 | 6356 |

 Table 8.3 Relative system COE and component capacity factors at different wind

 turbine/electrolyser subsystem capacities

The relative system *COE* curve indicates that the hydrogen generation subsystem comprising two 2.5 kW Proven wind turbines and a 4 kW electrolyser represents the economically most feasible configuration at fuel cell's capacity factor of 19.5%. From Table 8.3 can be derived that higher fuel cell capacities can be achieved. However, this would require a significant over-sizing of the expensive wind turbine/electrolyser subsystem.



Figure 8.9 Relative system levelised cost at different wind turbine/electrolyser subsystem capacities

Figure 8.10 illustrates the trends of the capacity factors of the HyLink components at increasing wind turbine/electrolyser subsystem capacity. Clear to see is the decreasing slope of the fuel cell's and the pipeline's capacity factor curves. This is not caused by the electrolyser, whose constant capacity factor would produce a linear slope of the both curves. The increasing excess hydrogen production is the reason, despite the relatively low capacity factor of the fuel cell. The surplus production is induced by the low storage capacity of the pipeline (3.3 kWh).



Figure 8.10 Capacity factors of the HyLink components at different wind turbine/electrolyser subsystem capacities

8.2.2 Using Different Pipeline Capacities

Consequently the impact of different pipeline sizes on the HyLink's levelised cost was evaluated. The pipe's storage capacity was therefore set at four sequent multiples of the present 0.108 kg hydrogen storage capacity. The fuel cell was programmed to operate in the load following mode. Its maximal power output was kept at 1 kW for the whole system optimisation modelling.

| Proven | Electrolyser | Relative System COE [%] | | | | |
|--------------------------------|--------------|-------------------------|----------|----------|---------|-------|
| Capacity Capacity [kW] [kW] | 0.108 kg | 0.216 kg | 0.324 kg | 0.432 kg | 0.54 kg | |
| 2.5 | 2 | 100.0 | 101.4 | 102.8 | 104.0 | 105.4 |
| 5 | 4 | 78.7 | 76.3 | 76.9 | 77.7 | 78.3 |
| 7.5 | 6.25 | 88.3 | 70.4 | 69.8 | 70.2 | 70.4 |
| 10 | 8 | 95.8 | 72.2 | 69.4 | 68.0 | 67.2 |
| 12.5 | 10 | 106.6 | 78.1 | 74.4 | 72.0 | 70.6 |
| 15 | 12 | 117.3 | 84.7 | 80.1 | 77.3 | 75.3 |
| 17.5 | 14 | 128.4 | 91.7 | 86.5 | 83.3 | 80.9 |

Table 8.4 Relative system levelised cost at different pipeline sizes and different wind

 turbine/electrolyser subsystem capacities

Figure 8.11 indicates that increased pipeline storage capacity to five times the present value leads to lower system *COE*. This is achieved thanks the low cost and the high durability of the pipeline in relation to the electrochemical conversion devices. HOMER assigns the cost to the different pipe sizes linearly based on the cost of the present pipe. It is clear to see that every pipe-related system profile has its levelised



Figure 8.11 Impact of different pipeline sizes on the relative system levelised cost at different wind turbine/electrolyser subsystem capacities
cost minimum, which shifts with increasing pipeline size. It is also evident that at electrolyser capacity higher than 4 kW (wind turbine > 5 kW) a larger pipeline makes the system more cost effective in relation to the current system configuration.

| Proven | Electrolyser | <i>CF_{tc}</i> [%] | | | | |
|------------------|------------------|----------------------------|----------|----------|----------|---------|
| Capacity [kW] | Capacity [kW] | 0.108 kg | 0.216 kg | 0.324 kg | 0.432 kg | 0.54 kg |
| 2.5 | 2 | 9.76 | 9.76 | 9.76 | 9.76 | 9.76 |
| 5 | 4 | 19.5 | 20.3 | 20.3 | 20.3 | 20.3 |
| 7.5 | 6.25 | 24.3 | 30.7 | 31.1 | 31.2 | 31.2 |
| 10 | 8 | 27.4 | 36.6 | 38.3 | 39.3 | 39.9 |
| 12.5 | 10 | 29.8 | 40.7 | 43 | 44.6 | 45.8 |
| 15 | 12 | 31.6 | 43.9 | 46.6 | 48.5 | 50 |
| 17.5 | 14 | 33.1 | 46.6 | 49.5 | 51.6 | 53.3 |

 Table 8.5 Fuel cell capacity factor at different pipeline sizes

Figure 8.12 shows the impact of the various pipe sizes on the fuel cell capacity factor. It reveals that especially at larger wind turbine/electrolyser subsystem capacities (wind turbine > 5 kW, electrolyser > 4 kW) the upgrading of the pipeline is necessary, in order to exploit the available wind energy more efficiently. Particularly during the windy periods, a larger pipeline or an additional tank will be capable of



Figure 8.12 Impact of different pipeline sizes on the fuel cell capacity factor

buffering and not dumping the hydrogen amount outweighing the fuel cell's capacity. This will improve the fuel cell's capacity factor and allow for its more constant operation, which involves reduced amount of starts, and hence, lower power losses.

| Proven | Electrolyser | CF _{pipe} [%] | | | | |
|------------------|------------------|------------------------|----------|----------|----------|---------|
| Capacity [kW] | Capacity [kW] | 0.108 kg | 0.216 kg | 0.324 kg | 0.432 kg | 0.54 kg |
| 2.5 | 2 | 8.3 | 4.1 | 2.7 | 2.0 | 1.6 |
| 5 | 4 | 15.7 | 8.1 | 5.4 | 4.0 | 3.2 |
| 7.5 | 6.25 | 19.4 | 14.0 | 10.4 | 8.0 | 6.5 |
| 10 | 8 | 21.7 | 18.3 | 17.6 | 16.2 | 14.9 |
| 12.5 | 10 | 23.4 | 21.1 | 21.7 | 21.5 | 21.1 |
| 15 | 12 | 24.8 | 23.1 | 24.7 | 25.3 | 25.5 |
| 17.5 | 14 | 25.9 | 24.9 | 27.1 | 28.2 | 28.8 |

 Table 8.6 Pipeline capacity factor at different system configurations

Figure 8.13 illustrates the capacity factor profiles for different pipeline sizes at increasing wind turbine/electrolyser subsystem capacity. The decreasing slope of the smaller pipelines at higher hydrogen supply is caused by the increasing excess hydrogen production. This results in sinking of their capacity factors in relation to the larger pipelines over a year.



Figure 8.13 Annual capacity factors for pipes with different storage capacities

| Proven | Electrolyser Capacity [kW] | Fuel Cell [hrs/yr] | | | | | |
|------------------|----------------------------------|--------------------|----------|----------|----------|---------|--|
| Capacity [kW] | | 0.108 kg | 0.216 kg | 0.324 kg | 0.432 kg | 0.54 kg | |
| 2.5 | 2 | 5811 | 5812 | 5812 | 5813 | 5813 | |
| 5 | 4 | 6107 | 6108 | 6109 | 6109 | 6109 | |
| 7.5 | 6.25 | 6225 | 6227 | 6229 | 6230 | 6230 | |
| 10 | 8 | 6283 | 6285 | 6300 | 6318 | 6335 | |
| 12.5 | 10 | 6313 | 6315 | 6341 | 6368 | 6408 | |
| 15 | 12 | 6339 | 6343 | 6378 | 6426 | 6469 | |
| 17.5 | 14 | 6356 | 6361 | 6407 | 6461 | 6521 | |

 Table 8.7 Fuel cell's operational hours at different system configurations

Table 8.7 confirms that the fuel cell's operational hours have an irrelevant impact on the changes in the system *COE* within this simulation (compare Table 8.4). This can be justified with the small differences in the fuel cell's yearly working time, and hence, insignificant changes in its replacement costs, given the increase in initial cost of the larger wind turbine/electrolyser subsystem capacities.



Figure 8.14 Annual fuel cell operational hours for modelled system configurations

In addition to this, Figure 8.14 shows that there is no clear similarity between the relative system *COE* profiles (Figure 8.11) and the fuel cell operational hours profiles. While the first increase almost constantly after a steep fall, the slope of the others decreases with increasing wind turbine/electrolyser subsystem capacity.

The relative system *COE* curves from Figure 8.15 indicate that the economic optimum of HyLink configurations including larger pipelines requires higher fuel cell capacity factors. The profiles confirm also that an under-utilised fuel cell, a component accounting for a significant part of the overall system expenses, is a reason for considerable rise of the system's levelised cost. The *COE* increase following its minimum, especially in case of the smaller pipes, is the result of the low energy buffer capability of those pipes and the increasing impact of the electrolyser cost.



Figure 8.15 Relative system COE versus fuel cell capacity factor

The main intention to include Figure 8.16 was to show, that especially the more voluminous pipelines at annual capacity factor higher than 5%, act not only as energy but also as system cost compensators. This is due to their lower cost in relation with the remaining HyLink components.



Figure 8.16 Relative System COE versus pipeline capacity factor

9. Conclusion

The performance of the Lynntech PEM electrolyser was investigated. VI curves at different stack temperatures were therefore recorded at IRL's laboratory, which indicate that the hydrogen production increases at the same voltage with higher stack temperature. This is caused by improvement of the kinetics of the electrochemical reactions and the decreased thermodynamic energy requirement of water electrolysis. The electrolyser efficiency measurement at the half of its full power input resulted in 66%. Thereby the stack temperature attained less than half of the allowed limit of 80°C. The capture of the excess heat by insulation can improve electrolyser's efficiency. The potential impact of the frost on the water-sated polymer membrane at Totara Valley during the winter time remains an issue. A continuous electrolyser operation requiring a larger battery bank and wind turbine capacity represents a solution. At the current stage, the constant water circulation through the anode is being tested as a protection against membrane freezing. Worth mentioning is that the recent operation proved the electrolyser to be undamaged despite the both winter times at Totara Valley.

The PEM electrolyser and DCI-1200 alkaline fuel cell efficiency was determined by measuring the hydrogen pressure drop/increase in the pipe. The overall system efficiency at the current stage was estimated to be about 25%, however it is aimed for an efficiency of over 40% by optimising the fuel cell's and the electrolyser's energy conversion.

The system transition from IRL's laboratory to Totara Valley was documented. The electrofusion method to connect the single pipeline sectors as well as the crimping method to connect the pipeline ends with the risers proved to be capable. Both wind turbines being tested operated underneath the levels of their theoretical performance. The mechanically controlled Proven wind turbine operated at about one quarter and the electronically controlled Air-X at about one half of its expected power output. The Proven's rotor blockage indicated mechanical issues within the rotational system of the turbine.

Pressure tests were performed on the 2 km long pipe at Totara Valley using hydrogen and natural gas in order to test their permeability. The results were compared with previous studies at Massey University and with data obtained from the industry. The hydrogen permeability was measured to be 5.5×10^{-16} mol m m⁻² s⁻¹ Pa⁻¹ for the present 2 km MDPE pipe. This is a half to a third of the result obtained from previous studies on hydrogen permeability through MDPE at Massey University, which were undertaken at room temperatures. The reason for this discrepancy is likely to be the lower ambient temperature during the measurement at Totara Valley, which can be supported with the Arrhenius equation. In order to obtain the permeability coefficient *P* as a function of temperature *T*, it is recommended to solve the equation (5.5) as described in Chapter 5. It was furthermore measured that the power loss due to hydrogen diffusion through the pipeline walls during the fuel cell operation will be about 1.5 W at the current system operation mode.

A techno-economic analysis of the system was undertaken applying the micro-power optimisation software HOMER as a simulation tool. Two operation modes of the system were investigated, the load following and the peak demand compensating. The simulation results reveal that the durability and the cost of the electrochemical energy conversion devices, electrolyser and fuel cell, are the main hurdles which need to be overcome on the path to introducing hydrogen based energy systems like HyLink.

Finally, economic optimisation modelling of the small-scale system by best component alignment was performed. It was found out that the electrolyser capacity down-rating of 80% in relation to the wind turbine capacity leads to the minimal system levelised cost due to improvement of the capacity factor of the expensive electrolyser. In addition to this, the impact of various wind turbine/electrolyser subsystems and pipeline storage capacities on the fuel cell capacity factor and the system levelised cost in the load following operation mode, was analysed. The results reveal that enhancing of the fuel cell's capacity factor reduces system's *COE*, provided the pipeline has an adequate volume. The further outcome of the analysis is that the upgrading of the pipe size has a less significant impact on the system cost.

10. Appendices

Appendix A

The following VI curves were recorded at different temperatures. It is important to note that every single recording causes change of temperature. The higher the temperature fluctuation is, the less accurate is the respective VI curve. The VI curves are arranged by increasing temperature of anode side circulating water. The last VI curve at 60°C was provided by the manufacturer of the stack and can be used as a benchmark. The temperature during this recording was assumed to be constant.



Figure 10.1 *VI curve at* 8 - 9°*C*



Figure 10.2 *VI curve at* 8 – 10.5°*C*



Figure 10.3 VI curve at $9 - 10^{\circ}C$



Figure 10.4 *VI curve at 11 – 13°C*



Figure 10.5 *VI curve at 16* – *18*°*C*



Figure 10.6 *VI curve at* $22 - 24^{\circ}C$



Figure 10.7 *VI curve at* $23 - 24^{\circ}C$



Figure 10.8 *VI curve at* 26.5 – 28.5°*C*



Figure 10.9 *VI curve at 30 – 31°C*



Figure 10.10 *VI curve at 34 – 36°C*



Figure 10.11 *VI curve at 36 – 37.5°C*



Figure 10.12 VI curve at 60°C

Appendix B

During the time of the following Proven performance measurement there was a large amount of optimal wind speed periods (>12 m/s).



O xibn9qqA

The current measurement of the following Air-X recordings has an offset of approximately -1.3 A (personal communication E. Pilbrow). Considering this, the maximal Air-X output during the given time period is about 220 W.



Appendix D

The following figure explains the thermodynamic requirements for water electrolysis.



Appendix E

The following figure represents the process diagram of the HyLink setup at IRL's laboratory.



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